Electronics & Microcontrollers

First edition · 10 units · 50 lessons · A video for every lesson

FIRST EDITION

Course guide

This is a full high-school course in electronics and microcontrollers for students who have finished Algebra I. In ten units and fifty lessons you will learn the physics of charge, voltage, current and power; analyze series and parallel circuits with Ohm's and Kirchhoff's laws; get to know every common component, from the resistor and capacitor to the diode, LED, relay, transistor and MOSFET; solder a finished circuit of your own; work through binary, logic gates and flip-flops to the inside of a computer; and then program real hardware, first an Arduino Uno and then a Raspberry Pi Pico in MicroPython, ending with serial buses, radio, Wi-Fi and a capstone project that you design, build, test and present.

Every lesson follows the same path. **The story** is a real moment from history: Volta's pile, Ohm's careful wires, Kirchhoff's laws written as a student, Joseph Henry's relay, the transistor at Bell Labs in December 1947, Kilby's and Noyce's first chips, Hans Camenzind's 555, Boole and Shannon, Babbage and Lovelace, the Arduino born in Ivrea, the Raspberry Pi born in Cambridge. Then **how they figured it out**, **the physics** with its equations, and **the engineering**: how the idea becomes a safe, reliable, affordable device. Each lesson has worked examples, a practice set with answers, and a build that you plan, wire, measure, debug and improve. Two of the Arduino builds are toys (a reaction-time game and a servo-driven automaton), because toys are some of the best-engineered things in the house.

God made an orderly world, and electricity is one of its most orderly parts: the same laws hold in a lightning bolt and in a single LED. Many of the people who discovered those laws, among them Volta, Faraday, Joseph Henry and Maxwell, were believing Christians who saw their work as reading what God had written into creation. Electronics is also a field where honesty and care protect people, because a wrong number can start a fire. The old Latin saying *Fabricando fit faber*, "by making, one

becomes a maker," is the method of the whole course: you will understand a circuit best after you have built it, measured it and fixed it.

> Videos come from trusted teaching channels chosen lesson by lesson: The Engineering Mindset, Paul McWhorter, Ben Eater, GreatScott!, Collin's Lab (Adafruit), SparkFun, DroneBot Workshop, Khan Academy, The Organic Chemistry Tutor, Branch Education, the Computer History Museum, Arduino and Raspberry Pi, and a few others. Every one was checked in preview for content and accuracy. High-school videos run longer (up to about 30 minutes for a full Arduino or Pico tutorial), and the "when" note in each lesson says which part matters most. Some open with a sponsor message; skip it. A few presenters mention projects that use wall power: in this course, everything runs from batteries or a USB cable only.

Start with Lesson 1.1 →

Who it is for

Written for students in grades 9–12 who have finished Algebra I (solving equations, working with fractions, exponents and scientific notation). No previous electronics is needed. Students work fairly independently, with a parent or mentor checking work, signing off the safety rules and supervising soldering. This course requires one Arduino Uno–compatible starter kit (such as the official Arduino Starter Kit or an Elegoo Uno starter kit) and a digital multimeter for the whole year, plus a Raspberry Pi Pico (about $4–6) for Units 9–10, and a temperature-controlled soldering iron for Unit 5. Everything runs from batteries or a USB cable; nothing in the course uses wall power.

How to use this course

1. **The weekly rhythm.** The year has 50 lessons. Each lesson takes three sessions of about 50 minutes: (1) the video, teaching and worked examples; (2) the build and the engineer's notebook; (3) the practice set and corrections. With a test day after each unit and review and exam days for the midterm and final, the year fits about 33 weeks at five sessions a week.
2. **Story, then physics, then engineering.** Read the core ideas carefully, then cover the page and explain the lesson's main idea aloud or in writing. Work every

worked example on paper before you open its solution. The tests use the same kinds of problems.

3. **Numbers with units.** Write the formula, substitute the numbers with their units, and box the answer with its unit. Use engineering prefixes (mA, kΩ, µF) and check each answer for sense: a 9 V battery does not deliver 40 A.
4. **Practice sets.** Each lesson has 8–12 problems marked easy, medium, hard and challenge. Do them all, check your answers, and correct every miss in a different color: write what went wrong, not only the right number.
5. **Picture study.** Each lesson has a historic photograph, patent drawing or engineering drawing. Look at it quietly for two minutes, put it away, tell back what you saw, then work through the "look closely" items and questions, which point to the physics and engineering.
6. **The engineer's notebook.** Keep a bound graph-paper notebook all year. For every build: the date, a schematic, predictions, a data table with units, a graph where it fits, the comparison of measured and predicted values, the bugs you found and how you fixed them, and "what I would change." Honest records matter more than perfect results: "a just weight is his delight" (Proverbs 11:1).
7. **Code.** Arduino builds use the free Arduino IDE; Raspberry Pi Pico builds use MicroPython in the free Thonny editor. The builds describe each program line by line. Type the code yourself rather than pasting it, save each version, and comment your code. The free Wokwi simulator (wokwi.com) can run both Arduino and Pico circuits if a part is missing or broken.
8. **Optional kits.** Some units list optional extras such as a Raspberry Pi 4 or 5, a Pico W, sensor packs or the Snap Circuits sets. The required kit and multimeter cover every lesson.
9. **Tests, midterm and final.** Each unit ends with a 100-point unit test with calculations, concept questions and one short essay, and a portfolio build. The midterm covers Units 1–5 and the final covers the whole course. Calculators are allowed; show work and units.
10. **Safety.** Read the safety box before every build and follow it exactly. Batteries and USB power only, never the outlets in the wall or anything plugged into them. Never short a battery, and never cut, puncture, crush or charge a damaged lithium battery. Soldering is done with safety glasses, a stand, a fan and an adult nearby. These rules are part of the course content and part of the grade.

11. **The capstone.** Unit 10 ends with a capstone: a device of your own design for a real person or need, with requirements, a budget and schedule, a schematic, commented code, test data and a presentation to family or friends.

Scope and sequence

UNIT 1 · WEEKS 1–4

Electricity Fundamentals and Safety

Volta's pile and the nature of charge and current; voltage as energy per charge; Ohm's law from Ohm's own experiments; power and Joule heating; and the multimeter, with the lab-safety rules for the whole year.

1.1 Volta's Pile: Charge and Current

1.2 Voltage and Energy

1.3 Ohm's Law: Georg Ohm's Wires

1.4 Power: Watt, Joule and Heat

1.5 The Multimeter and Lab Safety

UNIT 2 · WEEKS 4–7

DC Circuits

Series and parallel circuits and why Edison wired his lamps in parallel; Kirchhoff's current and voltage laws; voltage dividers and sensors; reading and drawing schematics; and systematic troubleshooting, from the first computer "bug" to half-splitting.

2.1 Series and Parallel: Edison's Parallel Lamps

2.2 Kirchhoff's Laws

2.3 Voltage Dividers and the Wheatstone Bridge

2.4 Reading and Drawing Schematics

2.5 Troubleshooting: Grace Hopper's Moth

UNIT 3 · WEEKS 7–10

Components

Resistors and the color code; capacitors from the Leyden jar to RC timing; inductors, Joseph Henry and the relay; diodes and rectifiers; and LEDs with current-limiting resistors.

3.1 Resistors and the Color Code

3.2 Capacitors and RC Timing: From the Leyden Jar

3.3 Inductors and Relays: Joseph Henry's Coils

3.4 Diodes and Rectifiers: Fleming's Valve

3.5 LEDs and Current Limiting

UNIT 4 · WEEKS 10–13

Transistors and Semiconductors

The point-contact transistor at Bell Labs in 1947; the bipolar transistor as a switch; amplifiers and the first transistor radio; MOSFETs for driving motors and lamps; and the integrated circuit of Kilby and Noyce.

4.1 Bell Labs, 1947: The First Transistor

4.2 The Transistor as a Switch

4.3 Amplifiers, Simply: The Transistor Radio

4.4 MOSFETs and Driving Loads

4.5 The Integrated Circuit: Kilby and Noyce

UNIT 5 · WEEKS 13–17

Building Real Circuits

From breadboard to perfboard; soldering safely; Hans Camenzind's 555 timer; batteries, regulators and lithium safety; and a finished, soldered, enclosed project.

5.1 From Breadboard to Perfboard

5.2 Soldering Safely

5.3 The 555 Timer: Hans Camenzind's Chip

5.4 Power Supplies, Batteries and Lithium Safety

5.5 A Finished Soldered Project

UNIT 6 · WEEKS 17–20

Digital Logic

Boole's algebra and Shannon's switching circuits; binary and hexadecimal; logic gates and truth tables built from real parts; flip-flops and counters; and from Babbage's engines and Lovelace's notes to the modern CPU.

6.1 Boole and Shannon: Logic in Switches

6.2 Binary and Hexadecimal: Leibniz's Ones and Zeros

6.3 Logic Gates and Truth Tables

6.4 Flip-Flops and Counters: Memory from Gates

6.5 From Gates to a Computer: Babbage, Lovelace and the CPU

UNIT 7 · WEEKS 20–23

Arduino I: Programming a Microcontroller

The Arduino story, the Uno board and the IDE; digital output and loops; buttons, pull-up resistors and debouncing, with a reaction-time game; analog input and the ADC; and PWM, from LED fading to color mixing.

7.1 The Arduino: The Board and the IDE

7.2 Digital Output and Loops: A Traffic Signal

7.3 Digital Input and Buttons: A Reaction-Time Game

7.4 Analog Input: From Kelvin's Tide Machine to the ADC

7.5 PWM and Fading: Fooling the Eye

UNIT 8 · WEEKS 23–26

Arduino II: Sensors and Actuators

Temperature, light and ultrasonic distance sensors; servos and a servo-driven automaton toy; DC motors and the H-bridge; character LCD displays; and a data logger that records and graphs a real experiment.

8.1 Sensors: Temperature, Light and Distance

8.2 Servos and a Mechanical Automaton

8.3 DC Motors and the H-Bridge

8.4 Displays: From Segments to the LCD

8.5 A Data Logger: Maury's Paths of the Seas

UNIT 9 · WEEKS 27–30

Raspberry Pi and Python

The Raspberry Pi story; Linux and the command line; Python basics; the Pico and MicroPython; and GPIO in Python: buttons, PWM and the analog-to-digital converter.

9.1 The Raspberry Pi Story: Eben Upton and Cambridge

9.2 Linux and the Command Line

9.3 Python Basics

9.4 The Pico and MicroPython

9.5 GPIO with Python: Buttons, PWM and the ADC

UNIT 10 · WEEKS 30–33

Communication and Capstone

Serial, I^2C and SPI; radio from Hertz and Marconi to Bluetooth, with an infrared remote build; Wi-Fi devices and internet safety; capstone design with requirements, schedule and budget; and the build, test and presentation.

10.1 Serial, I^2C and SPI: How Chips Talk

10.2 Radio from Marconi to Bluetooth

10.3 Wi-Fi Devices and Internet Safety

10.4 Capstone Design: Requirements, Budget and Schedule

10.5 Build, Test and Present

Weekly pacing calendar

WEEK	PLAN
1	• Day 1: Lesson 1.1 Volta's Pile: Charge and Current: video, teaching and worked examples • Day 2: Lesson 1.1: build and notebook • Day 3: Lesson 1.1: practice set and corrections • Day 4: Lesson 1.2 Voltage and Energy: video, teaching and worked examples • Day 5: Lesson 1.2: build and notebook *Five sessions a week of about 50 minutes. Families on a four-day week can combine the practice day of one lesson with the teaching day of the next.*
2	• Day 1: Lesson 1.2: practice set and corrections • Day 2: Lesson 1.3 Ohm's Law: Georg Ohm's Wires: video, teaching and worked examples • Day 3: Lesson 1.3: build and notebook • Day 4: Lesson 1.3: practice set and corrections • Day 5: Lesson 1.4 Power: Watt, Joule and Heat: video, teaching and worked examples
3	• Day 1: Lesson 1.4: build and notebook • Day 2: Lesson 1.4: practice set and corrections • Day 3: Lesson 1.5 The Multimeter and Lab Safety: video, teaching and worked examples • Day 4: Lesson 1.5: build and notebook • Day 5: Lesson 1.5: practice set and corrections

WEEK	PLAN
4	• Day 1: Unit 1 test • Day 2: Lesson 2.1 Series and Parallel: Edison's Parallel Lamps: video, teaching and worked examples • Day 3: Lesson 2.1: build and notebook • Day 4: Lesson 2.1: practice set and corrections • Day 5: Lesson 2.2 Kirchhoff's Laws: video, teaching and worked examples
5	• Day 1: Lesson 2.2: build and notebook • Day 2: Lesson 2.2: practice set and corrections • Day 3: Lesson 2.3 Voltage Dividers and the Wheatstone Bridge: video, teaching and worked examples • Day 4: Lesson 2.3: build and notebook • Day 5: Lesson 2.3: practice set and corrections
6	• Day 1: Lesson 2.4 Reading and Drawing Schematics: video, teaching and worked examples • Day 2: Lesson 2.4: build and notebook • Day 3: Lesson 2.4: practice set and corrections • Day 4: Lesson 2.5 Troubleshooting: Grace Hopper's Moth: video, teaching and worked examples • Day 5: Lesson 2.5: build and notebook
7	• Day 1: Lesson 2.5: practice set and corrections • Day 2: Unit 2 test • Day 3: Lesson 3.1 Resistors and the Color Code: video, teaching and worked examples • Day 4: Lesson 3.1: build and notebook • Day 5: Lesson 3.1: practice set and corrections
8	• Day 1: Lesson 3.2 Capacitors and RC Timing: From the Leyden Jar: video, teaching and worked examples • Day 2: Lesson 3.2: build and notebook • Day 3: Lesson 3.2: practice set and corrections • Day 4: Lesson 3.3 Inductors and Relays: Joseph Henry's Coils: video, teaching and worked examples • Day 5: Lesson 3.3: build and notebook
9	• Day 1: Lesson 3.3: practice set and corrections

WEEK	PLAN
	• Day 2: Lesson 3.4 Diodes and Rectifiers: Fleming's Valve: video, teaching and worked examples • Day 3: Lesson 3.4: build and notebook • Day 4: Lesson 3.4: practice set and corrections • Day 5: Lesson 3.5 LEDs and Current Limiting: video, teaching and worked examples
10	• Day 1: Lesson 3.5: build and notebook • Day 2: Lesson 3.5: practice set and corrections • Day 3: Unit 3 test • Day 4: Lesson 4.1 Bell Labs, 1947: The First Transistor: video, teaching and worked examples • Day 5: Lesson 4.1: build and notebook
11	• Day 1: Lesson 4.1: practice set and corrections • Day 2: Lesson 4.2 The Transistor as a Switch: video, teaching and worked examples • Day 3: Lesson 4.2: build and notebook • Day 4: Lesson 4.2: practice set and corrections • Day 5: Lesson 4.3 Amplifiers, Simply: The Transistor Radio: video, teaching and worked examples
12	• Day 1: Lesson 4.3: build and notebook • Day 2: Lesson 4.3: practice set and corrections • Day 3: Lesson 4.4 MOSFETs and Driving Loads: video, teaching and worked examples • Day 4: Lesson 4.4: build and notebook • Day 5: Lesson 4.4: practice set and corrections
13	• Day 1: Lesson 4.5 The Integrated Circuit: Kilby and Noyce: video, teaching and worked examples • Day 2: Lesson 4.5: build and notebook • Day 3: Lesson 4.5: practice set and corrections • Day 4: Unit 4 test • Day 5: Lesson 5.1 From Breadboard to Perfboard: video, teaching and worked examples
14	• Day 1: Lesson 5.1: build and notebook • Day 2: Lesson 5.1: practice set and corrections • Day 3: Lesson 5.2 Soldering Safely: video, teaching and worked examples • Day 4: Lesson 5.2: build and notebook • Day 5: Lesson 5.2: practice set and corrections

WEEK	PLAN
15	• Day 1: Lesson 5.3 The 555 Timer: Hans Camenzind's Chip: video, teaching and worked examples • Day 2: Lesson 5.3: build and notebook • Day 3: Lesson 5.3: practice set and corrections • Day 4: Lesson 5.4 Power Supplies, Batteries and Lithium Safety: video, teaching and worked examples • Day 5: Lesson 5.4: build and notebook
16	• Day 1: Lesson 5.4: practice set and corrections • Day 2: Lesson 5.5 A Finished Soldered Project: video, teaching and worked examples • Day 3: Lesson 5.5: build and notebook • Day 4: Lesson 5.5: practice set and corrections • Day 5: Unit 5 test
17	• Day 1: Review day for the midterm • Day 2: Midterm exam • Day 3: Lesson 6.1 Boole and Shannon: Logic in Switches: video, teaching and worked examples • Day 4: Lesson 6.1: build and notebook • Day 5: Lesson 6.1: practice set and corrections
18	• Day 1: Lesson 6.2 Binary and Hexadecimal: Leibniz's Ones and Zeros: video, teaching and worked examples • Day 2: Lesson 6.2: build and notebook • Day 3: Lesson 6.2: practice set and corrections • Day 4: Lesson 6.3 Logic Gates and Truth Tables: video, teaching and worked examples • Day 5: Lesson 6.3: build and notebook
19	• Day 1: Lesson 6.3: practice set and corrections • Day 2: Lesson 6.4 Flip-Flops and Counters: Memory from Gates: video, teaching and worked examples • Day 3: Lesson 6.4: build and notebook • Day 4: Lesson 6.4: practice set and corrections • Day 5: Lesson 6.5 From Gates to a Computer: Babbage, Lovelace and the CPU: video, teaching and worked examples
20	• Day 1: Lesson 6.5: build and notebook • Day 2: Lesson 6.5: practice set and corrections

WEEK	PLAN
	• Day 3: Unit 6 test • Day 4: Lesson 7.1 The Arduino: The Board and the IDE: video, teaching and worked examples • Day 5: Lesson 7.1: build and notebook
21	• Day 1: Lesson 7.1: practice set and corrections • Day 2: Lesson 7.2 Digital Output and Loops: A Traffic Signal: video, teaching and worked examples • Day 3: Lesson 7.2: build and notebook • Day 4: Lesson 7.2: practice set and corrections • Day 5: Lesson 7.3 Digital Input and Buttons: A Reaction-Time Game: video, teaching and worked examples
22	• Day 1: Lesson 7.3: build and notebook • Day 2: Lesson 7.3: practice set and corrections • Day 3: Lesson 7.4 Analog Input: From Kelvin's Tide Machine to the ADC: video, teaching and worked examples • Day 4: Lesson 7.4: build and notebook • Day 5: Lesson 7.4: practice set and corrections
23	• Day 1: Lesson 7.5 PWM and Fading: Fooling the Eye: video, teaching and worked examples • Day 2: Lesson 7.5: build and notebook • Day 3: Lesson 7.5: practice set and corrections • Day 4: Unit 7 test • Day 5: Lesson 8.1 Sensors: Temperature, Light and Distance: video, teaching and worked examples
24	• Day 1: Lesson 8.1: build and notebook • Day 2: Lesson 8.1: practice set and corrections • Day 3: Lesson 8.2 Servos and a Mechanical Automaton: video, teaching and worked examples • Day 4: Lesson 8.2: build and notebook • Day 5: Lesson 8.2: practice set and corrections
25	• Day 1: Lesson 8.3 DC Motors and the H-Bridge: video, teaching and worked examples • Day 2: Lesson 8.3: build and notebook • Day 3: Lesson 8.3: practice set and corrections

WEEK	PLAN
	• Day 4: Lesson 8.4 Displays: From Segments to the LCD: video, teaching and worked examples • Day 5: Lesson 8.4: build and notebook
26	• Day 1: Lesson 8.4: practice set and corrections • Day 2: Lesson 8.5 A Data Logger: Maury's Paths of the Seas: video, teaching and worked examples • Day 3: Lesson 8.5: build and notebook • Day 4: Lesson 8.5: practice set and corrections • Day 5: Unit 8 test
27	• Day 1: Lesson 9.1 The Raspberry Pi Story: Eben Upton and Cambridge: video, teaching and worked examples • Day 2: Lesson 9.1: build and notebook • Day 3: Lesson 9.1: practice set and corrections • Day 4: Lesson 9.2 Linux and the Command Line: video, teaching and worked examples • Day 5: Lesson 9.2: build and notebook
28	• Day 1: Lesson 9.2: practice set and corrections • Day 2: Lesson 9.3 Python Basics: video, teaching and worked examples • Day 3: Lesson 9.3: build and notebook • Day 4: Lesson 9.3: practice set and corrections • Day 5: Lesson 9.4 The Pico and MicroPython: video, teaching and worked examples
29	• Day 1: Lesson 9.4: build and notebook • Day 2: Lesson 9.4: practice set and corrections • Day 3: Lesson 9.5 GPIO with Python: Buttons, PWM and the ADC: video, teaching and worked examples • Day 4: Lesson 9.5: build and notebook • Day 5: Lesson 9.5: practice set and corrections
30	• Day 1: Unit 9 test • Day 2: Lesson 10.1 Serial, I^2C and SPI: How Chips Talk: video, teaching and worked examples • Day 3: Lesson 10.1: build and notebook • Day 4: Lesson 10.1: practice set and corrections • Day 5: Lesson 10.2 Radio from Marconi to Bluetooth: video, teaching and worked examples

WEEK	PLAN
31	• Day 1: Lesson 10.2: build and notebook • Day 2: Lesson 10.2: practice set and corrections • Day 3: Lesson 10.3 Wi-Fi Devices and Internet Safety: video, teaching and worked examples • Day 4: Lesson 10.3: build and notebook • Day 5: Lesson 10.3: practice set and corrections
32	• Day 1: Lesson 10.4 Capstone Design: Requirements, Budget and Schedule: video, teaching and worked examples • Day 2: Lesson 10.4: build and notebook • Day 3: Lesson 10.4: practice set and corrections • Day 4: Lesson 10.5 Build, Test and Present: video, teaching and worked examples • Day 5: Lesson 10.5: build and notebook
33	• Day 1: Lesson 10.5: practice set and corrections • Day 2: Unit 10 test • Day 3: Review day for the final • Day 4: Final exam

Materials

Required: an Arduino Uno–compatible starter kit

For the whole year. It must include an Uno board and USB cable, a breadboard, jumper wires, LEDs (including an RGB LED), resistors, push buttons, a potentiometer, a photoresistor, a temperature sensor, an ultrasonic distance sensor, a micro servo, a small DC motor with a motor-driver chip (L293D) or module, a 16×2 LCD, an NPN transistor, a diode, capacitors, a piezo buzzer and a 9 V battery clip. The official Arduino Starter Kit or an Elegoo “Most Complete” or “Super” Uno starter kit covers it.

Required: a digital multimeter

An inexpensive auto-ranging or manual meter with voltage, current (mA and 10 A jacks), resistance, continuity and diode-test modes, from Unit 1 on.

Required for Units 9–10: a Raspberry Pi Pico (about $4–6), with header pins and a micro-USB data cable

The Pico W (Wi-Fi) version, a dollar or two more, is recommended because it also covers the Wi-Fi lesson in Unit 10. Buy it with pre-soldered headers, or solder

them yourself in Unit 5.

Required for Unit 5: a temperature-controlled soldering iron with a stand and tip cleaner, rosin-core solder (lead-free preferred), flush cutters, wire strippers, a small fan, safety glasses and a solder sucker or wick

Soldering is done with an adult nearby. A small perfboard or a solderable breadboard-pattern board, a 555 timer chip and a battery holder are needed for the soldered project.

Batteries and holders: AA cells with 2- and 4-cell holders, a 9 V battery, and a USB power bank

The only power sources in this course. No wall adapters, transformers or anything plugged into the outlets in the wall.

A computer (Windows, macOS, Linux or a Chromebook with the web editor) with the free Arduino IDE, the free Thonny editor and a web browser

The free online tools Falstad's circuit simulator, CircuitVerse and Wokwi are used throughout.

Engineer's notebook (bound graph-paper composition book) and a scientific calculator

For schematics, predictions, data tables, graphs, calculations with units and "what I would change."

Extra parts (inexpensive): assorted resistors, 0.1 µF and 100 µF capacitors, 1N4001 and 1N4148 diodes, 2N2222 or 2N3904 NPN transistors, a logic-level N-channel MOSFET (such as an IRLZ44N), a 5 V relay module, a 74HC00 NAND chip, and alligator clip leads

Most starter kits include some of these; the rest cost a few dollars together.

Optional: a Raspberry Pi 4 or 5 with its power supply and a microSD card

Never required. Unit 9 can be done with any computer's terminal and the Pico. Note that the Raspberry Pi's own power supply plugs into the wall; an adult connects it, and the student never opens or modifies it.

Optional: a microSD card module, extra sensors (a DHT11 or DS18B20), a small OLED display, an IR receiver and remote (in many kits)

For students who want to extend the Unit 8 and Unit 10 builds.

Grading

Grades come from the practice sets, the builds, the engineer's notebook, the unit tests and the two exams. A calculation earns full credit when the formula, the numbers with units and the answer with its unit are shown. A build earns full credit when it works or when its failure is honestly measured, debugged and documented.

PART	%
Practice sets (completed and corrected)	**15**
Builds and portfolio builds (working, tested and improved)	**25**
Engineer's notebook (schematics, data, graphs, debugging records)	**10**
Unit tests	**30**
Midterm exam	**10**
Final exam	**10**

Scale: A 90–100, B 80–89, C 70–79, D 60–69. Below 60: review the unit, redo the practice set and retake an alternate test.

- Grade practice sets on completion and corrections, not on first-try accuracy. A practice set with honest corrections is worth full marks.
- In unit tests and exams, give partial credit for a correct formula and setup with units even if the arithmetic slips. A missing or wrong unit, or an unsafe answer, is the more serious error.
- A build is graded on the requirements it meets, the measurements recorded, the debugging documented and the improvement made. Safety violations (wall power, unattended soldering, a shorted battery) earn no credit for that build until the build is redone safely.
- Keep each unit's portfolio build pages, photographs and code in one folder. With the capstone report they make a strong record for a transcript: this course is

worth one high-school credit in technology or engineering, and with the Unit 9–10 programming it may also count toward computer science.

A note to parents

You do not need to know electronics to supervise this course. Your jobs are to check that the work is done and corrected, to sign off the safety rules at the start of Unit 1 and Unit 5, and to be nearby for soldering. Ask the questions good engineering teachers ask most: “What did you predict?”, “What did you measure?” and “How do you know?” The course requires one Arduino Uno–compatible starter kit and a digital multimeter for the year, a Raspberry Pi Pico for Units 9–10, and a soldering iron with safety glasses for Unit 5. All of the power in the course comes from batteries and USB cables.

Expect circuits that do not work the first time. A wire one row off on a breadboard, an LED turned backward or a missing semicolon in the code are the everyday experience of every engineer, and the course teaches a calm, systematic way to find them. Praise careful measurement and honest debugging more than quick success. *Fabricando fit faber*: by making, one becomes a maker.

Two safety topics deserve your attention. Soldering irons run at about 350 °C and solder fumes should be blown away from the face; Lesson 5.2 sets out the rules in full. Lithium batteries, in phones, power banks and many hobby projects, can overheat and catch fire if they are shorted, punctured, crushed or charged when damaged; Lesson 5.4 teaches how to handle them. The course never uses wall power and never asks a student to open an appliance or a power supply.

UNIT 1

Electricity Fundamentals and Safety

Every circuit you will build this year, from a blinking LED to a Wi-Fi sensor, runs on four quantities: charge, current, voltage and power. In this unit you will meet them the way scientists first did, through Volta's pile of 1800, Ohm's careful wires, and Joule's jars of warming water, and you will measure each one yourself with a digital multimeter.

You will also learn the safety rules for the whole course and the one tool you will use more than any other. By the end of the unit you should be able to look at any battery and resistor and say, with numbers and units, what current will flow, how much power will be turned to heat, and how long the battery will last.

PREREQUISITES

- Algebra I: solving and rearranging equations such as $V = IR$ for any variable
- Scientific notation and powers of ten
- Reading and making a graph with a best-fit line
- An Arduino Uno–compatible starter kit and a digital multimeter

MASTERY CHECKLIST

- ☐ I can define charge, current, voltage, resistance and power, with their units, and convert between prefixes.
- ☐ I can use $I = Q/t$, $V = W/Q$, $R = \rho L/A$, and $P = VI = I^2R = V^2/R$ $W = Pt$.
- ☐ I can calculate a battery's stored energy and estimated life from its capacity and a power budget.
- ☐ I can measure voltage, current, resistance, continuity and diode drop with a multimeter, connected correctly.
- ☐ I can state and follow the course safety rules, including the rules for batteries and lithium cells.

OPTIONAL KITS FOR THIS UNIT

- **Arduino Starter Kit**: Ages 13 and up. The official kit: an Arduino Uno, breadboard, components and a project book. It includes an LCD, servo, DC motor, motor-driver chip and temperature sensor; add an ultrasonic distance sensor (a few dollars) and the extra parts in the course materials list.
- **ELEGOO Uno starter kits**: Ages 12 and up. Uno-compatible kits; the larger "Super" and "Most Complete" kits include the ultrasonic sensor, servo, motor driver, LCD, IR remote and many other parts used in this course.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

1.1	**Volta's Pile: Charge and Current**	3 sessions of 50 minutes
1.2	**Voltage and Energy**	3 sessions of 50 minutes
1.3	**Ohm's Law: Georg Ohm's Wires**	3 sessions of 50 minutes
1.4	**Power: Watt, Joule and Heat**	3 sessions of 50 minutes
1.5	**The Multimeter and Lab Safety**	3 sessions of 50 minutes

Unit 1 test

Time: 50 minutes. A scientific calculator is allowed. Show the formula, the substitution with units and the answer with its unit for every calculation; correct setup earns partial credit. Write complete sentences for explanations. The test is worth 100 points.

1. **6 pts** **Lesson 1.1**

   A current of 0.25 A flows for 4.0 minutes. How much charge passes, and how many electrons is that?

2. **5 pts** **Lesson 1.1**

   Explain the disagreement between Galvani and Volta and how Volta settled it.

3. **6 pts** **Lesson 1.2**

   A 6.0 V battery pack delivers 1,200 C. How much energy is that, in J and Wh?

4. **6 pts** **Lesson 1.2**

   Two power banks: one is 5,000 mAh at 3.7 V, the other 15 Wh. Which stores more energy? Show your work.

5. **5 pts** **Lesson 1.2**

   Four AA cells (1.5 V, 2,500 mAh) are in series. Give the pack's voltage and capacity.

6. **8 pts** **Lesson 1.3**

   A 2.2 kΩ resistor is connected across 9.0 V. Find the current in mA. What resistor would give 10 mA instead?

7. **7 pts** **Lesson 1.3**

   Find the resistance of 25 m of copper wire with a cross-sectional area of $0.50\ \text{mm}^2$. ($\rho = 1.68 \times 10^{-8}\ \Omega \cdot \text{m}$.)

8. **6 pts** **Lesson 1.3**

   What is the difference between an ohmic and a non-ohmic part? Give one example of each and describe its V–I graph.

9. **8 pts** **Lesson 1.4**

   A 47 Ω resistor is placed across 5.0 V. Find the current and the power. Is a 1/4 W resistor suitable? What rating would you choose?

10. **8 pts** **Lesson 1.4**

    A circuit draws 60 mA from a 9.0 V battery rated 500 mAh. Find its power and the battery's ideal life. Why will the real life be shorter?

11. **6 pts** **Lesson 1.4**

    Explain, using $P = I^2R$, why shorting a battery with a wire is dangerous even though the wire's resistance is almost zero.

12. **7 pts** **Lesson 1.5**

    Draw (describe) how to connect a meter to measure (a) the voltage across a resistor and (b) the current through it. Which jack and function is used for each?

13. **8 pts** **Lesson 1.5**

Two 470 kΩ resistors in series are across 12 V. A meter with 10 MΩ input resistance measures the bottom resistor. What does it read? What is the percent error?

14. **6 pts** **Lesson 1.5**

State four of this course's safety rules, including one about lithium batteries.

15. **8 pts** **Lesson 1.4**

Essay (one paragraph). Joule found that heat is proportional to the square of the current, not to the current. Explain how careful measurement led him to that result, and why this law matters to an engineer designing a circuit today.

ANSWER KEY

1. $Q = It = (0.25)(240) = 60$ C; $n = 60 / 1.602 \times 10^{-19} = 3.7 \times 10^{20}$
2. Galvani thought the frog's tissue made "animal electricity." Volta thought the two metals made it and the frog only detected it. Volta built a pile of metals and brine-soaked cardboard with no frog at all, and it produced a steady current.
3. $W = QV = 7200$ J $= 2.0$ Wh
4. $5.0 \times 3.7 = 18.5$ Wh > 15 Wh: the first stores more.
5. 6.0 V; 2,500 mAh (capacity does not add in series)
6. $I = 9.0 / 2.2 = 4.1$ mA; $R = 9.0 / 0.010 = 900\ \Omega$
7. $R = (1.68 \times 10^{-8})(25) / (0.50 \times 10^{-6}) = 0.84\ \Omega$
8. Ohmic: constant R, straight-line V–I graph through the origin, e.g. a resistor. Non-ohmic: R changes with voltage or current, curved graph, e.g. an LED (almost no current below about 1.8 V, then a steep rise) or a lamp filament.
9. $I = 106$ mA; $P = 25 / 47 = 0.53$ W; no, it exceeds 0.25 W; choose at least a 1 W resistor (about twice the real power).
10. $P = 0.54$ W; $500 / 60 = 8.3$ h. Real batteries deliver less than their rating at higher currents, and the voltage falls as they discharge.
11. The only resistance left is the battery's small internal resistance, so the current is very large. Heat in the battery is $I^2 R_{\text{internal}}$, which is many watts in a small space; the battery heats, can leak, rupture or (for lithium) catch fire.
12. (a) Meter across the resistor, in parallel; red lead in V jack, DC volts. (b) Break the circuit and insert the meter so the current passes through it, in series; red lead in mA jack, DC current.
13. $R_{\parallel} = (0.47 \times 10) / (10.47) = 0.449\ \text{M}\Omega$; $V = 12 \times 0.449 / (0.47 + 0.449) = 5.86$ V vs 6.00 V; error about 2.3% low.
14. Any four, with lithium included: batteries and USB only, never wall power; never short a battery; never cut, puncture, crush or charge a damaged lithium battery and never leave one charging unattended; meter in series for current with the right jack; disconnect hot parts; safety glasses; coin cells away from children.
15. A strong answer mentions: Joule's coils in water, sensitive thermometers, insulation, stirring and correction for losses, repeated trials; doubling the current gave four times the heat, which the data forced. Today $P = I^2 R$ sets resistor and wire ratings, explains why shorts are dangerous and why high

current wastes power, and drives designs toward lower currents and adequate margins.

PORTFOLIO PIECE: A CHARACTERIZED POWER SOURCE AND ITS SAFETY CARD

Choose a battery pack you will use this year (for example, the 4-AA holder). Characterize it: its open-circuit voltage; its voltage under three loads (1 kΩ, 220 Ω and 100 Ω), with the current measured each time; its internal resistance calculated from the voltage drop; its energy in Wh; and the predicted run time of a 20 mA LED lamp on it. Present the data in a table and a graph of terminal voltage against current, and finish with a one-page safety card for your bench covering the course rules and the correct use of your meter.

LOOK FOR	WHAT IT MEANS
Measurements	Open-circuit and loaded voltages and currents measured correctly, with the meter connected the right way and units recorded.
Calculations	Internal resistance, power, energy and run time calculated with formulas and units shown.
Graph and analysis	A labeled graph of terminal voltage against current with a best-fit line, and a sentence explaining what its slope means.
Safety card	Clear, complete course safety rules and a meter checklist, signed by student and parent.

1.1 Volta's Pile: Charge and Current

OBJECTIVES

- Tell the story of Galvani's frogs and Volta's pile, and explain why the pile was the first source of steady current.
- Define electric charge and current, with their units (coulomb and ampere), and use $I = Q/t$ and $Q = ne$.
- Explain conventional current and electron flow, and why a light comes on instantly even though electrons drift slowly.
- Build a voltaic pile from coins and washers and measure how its voltage depends on the number of cells.

> **Warm-up.** Find any battery in the house (AA, 9 V, a phone power bank) and read every number printed on it. Write them down. Which number do you think tells how hard the battery pushes, and which tells how long it will last? Keep your guesses; you will check them in this lesson and the next.

WATCH

What is CURRENT– electric current explained, electricity basics

The Engineering Mindset · 11:39

https://www.youtube.com/watch?v=8Posj4WMo0o

> **WHEN TO WATCH**
> After the story and before the physics paragraph. Pause when the animation shows electrons drifting and compare it with the drift-speed paragraph below.

BACKUP VIDEO

Collin's Lab: History of the Battery @adafruit #adafruit

Adafruit Industries · 8:15

https://www.youtube.com/watch?v=4bUxdLtG8PI

Optional, for the history: Collin Cunningham builds a simple voltaic cell and tells the story from Galvani to the modern battery.

KEY TERMS

electric charge

A basic property of matter that makes particles push or pull on each other. Electrons carry negative charge and protons positive. Unit: the coulomb (C).

coulomb (C)

The SI unit of charge: the charge of about 6.24×10^{18} electrons. One electron carries $e = 1.602 \times 10^{-19}$ C.

electric current

The rate at which charge flows past a point: $I = Q/t$. Unit: the ampere (A), one coulomb per second.

conventional current

Current drawn as flowing from the positive terminal through the circuit to the negative terminal, the direction Benjamin Franklin chose. Electrons in a wire actually move the other way.

voltaic cell

Two different metals in an electrolyte (a liquid or paste that conducts ions). Chemical reactions at the metals push charge around a circuit. Several cells stacked together make a battery.

CORE IDEAS

The story. In the 1780s Luigi Galvani, an anatomy professor in Bologna, noticed that the legs of dissected frogs twitched when touched with two different metals. He believed he had found "animal electricity" stored in living tissue. His friend and rival Alessandro Volta, professor of physics at Pavia, was not convinced. Volta suspected the electricity came from the two metals, and the frog was only a sensitive detector. To prove it he took the frog away. On March 20, 1800 he wrote to Sir Joseph Banks of the Royal Society describing a stack of zinc and copper (or silver) discs, each pair separated by cardboard soaked in salt water. The "pile" gave a small, steady electric push for hours. For the first time in history, people had a continuous electric current to study.

How they figured it out. Volta had no meters. He compared metal pairs by the sting on his tongue and the flicker of a sensitive electroscope, ranked the metals in order, and found that stacking more pairs gave a stronger effect. Within weeks of his letter,

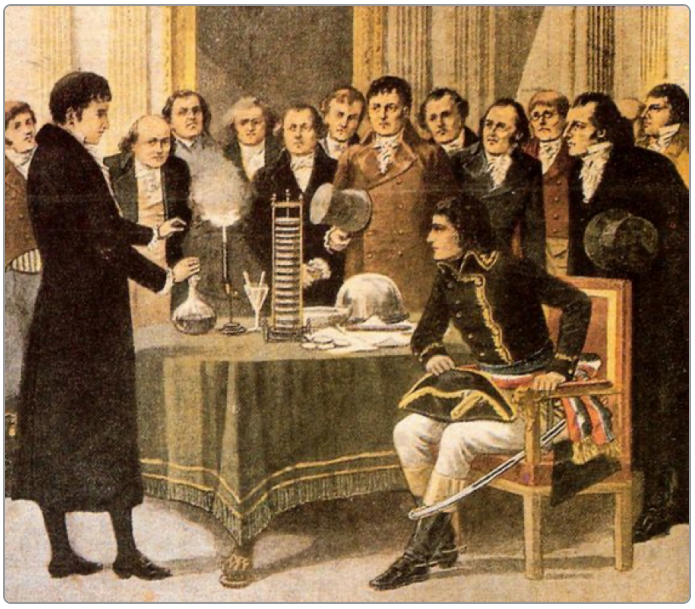
William Nicholson and Anthony Carlisle in London used a pile to split water into hydrogen and oxygen, and Humphry Davy soon built giant piles that discovered new elements. In 1801 Volta showed the pile in Paris before Napoleon and the French Institute. Volta, a lifelong Christian, saw no conflict between careful experiment and faith; he once wrote out a confession of his belief so that no one could doubt it.

The physics. Matter is made of atoms with positive protons and negative electrons. In a metal, some electrons are free to move. **Charge** is measured in coulombs; one electron carries $e = 1.602 \times 10^{-19}$ C, so a coulomb is about 6.24×10^{18} electrons. **Current** is the rate of flow of charge, $I = Q/t$: one ampere is one coulomb per second. A current of 20 mA through an LED means about 1.25×10^{17} electrons pass each second. Franklin had guessed, before anyone knew about electrons, that "positive" fluid flows from + to −. Engineers still draw **conventional current** that way; the electrons themselves drift from − to +. The two pictures give the same answers in every circuit calculation. Surprisingly, electrons drift slowly, often less than a millimeter per second in a wire. A lamp lights at once because the wire is already full of electrons and the push travels through it at a large fraction of the speed of light, like water in a full hose.

The engineering. Every battery today follows Volta's plan: two different materials, an electrolyte between them, and many cells stacked for more push. Engineers rate a battery's stored charge in **milliampere-hours** (mAh): a 2,000 mAh cell can deliver 2,000 mA for one hour, or 20 mA for 100 hours, in the ideal case. That is a charge of $2.0\ \text{A} \times 3600\ \text{s} = 7200\ \text{C}$. Real batteries deliver less at high current, so designers keep currents modest and test under real loads. The unit of current is named for André-Marie Ampère, who worked out the forces between currents in the 1820s, and the volt, as you will see next lesson, for Volta.

Try it. In your build you will make Volta's pile from coins and washers and measure it with the multimeter. Count your cells as you add them: you are repeating Volta's experiment of 1800, with an instrument he would have loved to have.

PICTURE STUDY



Volta Presents His Invention to Napoleon, Unknown illustrator, event of 1801 · Print · Wikimedia Commons

Image: Wikimedia Commons, public domain

In November 1801 Volta traveled to Paris and showed his pile to the French Institute, with Napoleon, then First Consul, in the audience. This print, made long afterward, imagines the scene.

Look closely

- Find the pile itself. How many discs do you think it has, and why would Volta make it so tall?
- Look for wires or cups leading from the pile. What do you think is being shown with them?
- Notice who is watching. What does the audience tell you about how important this invention seemed in 1801?
- Compare the apparatus with the battery in your house. What is still the same idea?

Talk about it

1. Why would showing the pile in front of the leading scientists of Paris matter to Volta's argument with Galvani's followers?
2. If each zinc-copper pair gives about 0.8 V, how many pairs would Volta need to make about 30 V?

3. What could make a tall wet pile stop working after a few hours?

Safety first. Batteries and USB power only: never the outlets in the wall or anything plugged into them. Never connect a bare wire straight across a battery; even an AA cell can push several amperes through a short and get hot enough to burn. Wash your hands after handling coins, salt water or old batteries, and keep coin cells away from small children. Do not taste or touch the salt water to your mouth (as Volta did); the multimeter is your detector.

BUILD

A Coin Pile: Repeating Volta's Experiment

You will build a voltaic pile from coins, zinc-plated washers and salt-water cardboard, measure its voltage as you add cells, graph voltage against the number of cells, and then improve it until it can light an LED.

You will need

- 10 copper or copper-plated coins (U.S. pennies from before 1982 are solid copper; newer pennies are copper-plated zinc and still work if not scratched)
- 10 zinc-plated (galvanized) washers about the size of the coins
- Thin cardboard or paper towel cut into coin-size discs, and a cup of salt water (1 tablespoon salt in 1 cup water)
- Digital multimeter, two alligator clip leads, a red LED
- Tape, paper towels, and a plastic plate to work on

Steps

1. In your notebook, predict the voltage of one cell and of a five-cell pile, and how the voltage will grow with the number of cells. Sketch a graph of your prediction.
2. Set the multimeter to DC volts (the 2 V or 20 V range, or auto). Touch the red probe to the red lead and the black probe to the black; you will use this setting all through the build.
3. Make one cell: coin, then a cardboard disc dipped in salt water and squeezed so it does not drip, then a washer. Measure the voltage from the washer to the coin. Record it. Note which side is positive.
4. Stack a second cell on top in the same order (coin, wet disc, washer). Do not let salt water bridge from one cell to the next down the side. Measure. Repeat until you have 8–10 cells, measuring after each one.
5. Make a data table (cells, voltage in V) and graph voltage against number of cells. Draw a best-fit line. Its slope is the voltage per cell.

6. Set the meter to the 20 mA or 200 mA DC current range (red lead in the mA jack). Touch the probes across the whole pile for only one or two seconds and record the current. This tiny pile cannot be harmed, but never do this with a real battery: a meter on a current range is nearly a short circuit.
7. Return the red lead to the volts jack. Connect a red LED across the pile (long leg to the positive end). Does it glow? If not, find how many cells it needs, or try it in a dark room.
8. **Improve it.** Change one thing at a time: saltier water, vinegar instead of salt water, cleaner coins (rub with vinegar and salt), bigger cardboard discs, or pressing the stack together. Measure the voltage and current again after each change and record which change helped most.
9. Take the pile apart, rinse and dry the coins and washers, and wash your hands.

Tips

- If the voltage stops rising as you add cells, salt water is probably leaking down the side and shorting cells together. Dry the outside with a towel.
- A pile's voltage is respectable but its current is tiny, because the wet cardboard has a high internal resistance. That is why your LED is dim.
- Turn the meter off when you finish; leaving it on drains its own battery.

Check your work

- ☐ I measured the voltage of 1 to 8 or more cells and graphed it with a best-fit line.
- ☐ I can explain why voltage adds when cells are stacked.
- ☐ I can define current and calculate it from charge and time.
- ☐ I recorded at least one improvement and its effect.

ENGINEER'S NOTEBOOK

1. A labeled cross-section drawing of your pile showing the coin, wet disc and washer of each cell, with + and − marked.
2. Your data table and graph of voltage against number of cells, with the slope (volts per cell) calculated.
3. A comparison: Galvani's explanation and Volta's explanation of the twitching frog, and the experiment that decided between them.

4. What I would change: one improvement you would test next and what you predict it would do.

KEY FORMULAS

$$I = \frac{Q}{t}$$

$$Q = ne, \qquad e = 1.602 \times 10^{-19}\ \text{C}$$

$$1\ \text{mAh} = 3.6\ \text{C}$$

From history. Humphry Davy, at the Royal Institution in London, built a pile of hundreds of plates and in 1807–1808 used it to isolate potassium, sodium, calcium and other elements for the first time. His young assistant, Michael Faraday, would go on to discover electromagnetic induction.

WORKED EXAMPLES

Example 1. A phone charges at a steady 0.50 A for 2.0 hours. How much charge flows into it, and how many electrons is that?

Show solution

1. Convert time to seconds: $t = 2.0\ \text{h} \times 3600\ \text{s/h} = 7200\ \text{s}$.
2. Charge: $Q = It = (0.50\ \text{A})(7200\ \text{s}) = 3600\ \text{C}$.
3. Electrons: $n = Q/e = 3600\ \text{C} \div 1.602 \times 10^{-19}\ \text{C} = 2.25 \times 10^{22}$.

Answer: 3600 C, about 2.2×10^{22} electrons

Example 2. An LED draws 20 mA. How many electrons pass through it each second?

Show solution

1. Convert: $I = 20\ \text{mA} = 0.020\ \text{A} = 0.020\ \text{C/s}$.
2. Each second $Q = 0.020\ \text{C}$ passes, so $n = Q/e = 0.020 \div 1.602 \times 10^{-19} = 1.25 \times 10^{17}$.

Answer: About 1.25×10^{17} electrons per second

Example 3. A AA cell is rated 2,000 mAh. Ideally, how long could it run a circuit that draws 25 mA, and what total charge would it deliver?

Show solution

1. Time: $t = 2000\ \text{mAh} \div 25\ \text{mA} = 80\ \text{h}$.
2. Charge: $Q = (2.000\ \text{A})(1\ \text{h}) = (2.000\ \text{A})(3600\ \text{s}) = 7200\ \text{C}$.
3. Check: $(0.025\ \text{A})(80 \times 3600\ \text{s}) = 7200\ \text{C}$. The two agree.

Answer: About 80 h; 7200 C (in practice somewhat less)

PRACTICE

1. Easy A current of 3.0 A flows for 5.0 minutes. How much charge passes?

   Show answer

   $Q = It = (3.0)(300\ \text{s}) = 900\ \text{C}$

2. Easy Convert 350 mA to amperes, and 0.0042 A to milliamperes.

   Show answer

   $0.350\ \text{A}$; $4.2\ \text{mA}$

3. Easy In which direction does conventional current flow through a circuit outside the battery, and in which direction do electrons move?

   Show answer

   Conventional current flows from + through the circuit to −; electrons drift from − to +.

4. Medium 4.5×10^{18} electrons pass a point in 2.0 s. What is the current?

   Show answer

   $Q = (4.5 \times 10^{18})(1.602 \times 10^{-19}) = 0.72\ \text{C}$; $I = 0.72/2.0 = 0.36\ \text{A}$

5. Medium A 3,000 mAh power bank supplies 150 mA. Ideally, how long does it last, and how many coulombs does it hold?

   Show answer

   $20\ \text{h}$; $Q = 3.0\ \text{A} \times 3600\ \text{s} = 10{,}800\ \text{C}$

6. Medium Show that 1 mAh equals 3.6 C.

Show answer

$1\ \text{mAh} = 0.001\ \text{A} \times 3600\ \text{s} = 3.6\ \text{C}$

7. Medium Galvani believed the frog made the electricity. Describe the experiment that let Volta show the metals were the source.

Show answer

Volta removed the frog entirely: two different metals separated by brine-soaked cardboard, stacked in a pile, still produced electricity, so the frog had only been a detector.

8. Hard Electrons drift at about 0.1 mm/s in a house wire. How long would one electron take to drift 3.0 m from a switch to a lamp? Why does the lamp light at once anyway?

Show answer

$t = 3.0\ \text{m} \div 1 \times 10^{-4}\ \text{m/s} = 30{,}000\ \text{s} \approx 8.3\ \text{h}$. The wire is already full of electrons; the electric push travels through it almost at light speed, so all the electrons start moving together.

9. Hard A sensor draws 0.80 mA for 10 ms once every second and almost nothing in between. What is its average current, and how long would a 220 mAh coin cell last?

Show answer

Average $= 0.80\ \text{mA} \times (0.010/1) = 0.0080\ \text{mA}$; $220 \div 0.0080 = 27{,}500\ \text{h} \approx 3.1$ years (ideal).

10. Hard Your coin pile gives 0.35 mA into a short circuit through the meter. How long would it take to deliver one coulomb?

Show answer

$t = Q/I = 1 \div 0.00035 = 2860\ \text{s} \approx 48\ \text{min}$

11. Challenge A copper wire carries 1.0 A. It has 8.5×10^{28} free electrons per cubic meter and a cross-section of 1.0 mm^2. Use $I = nAve$ to find the drift speed.

Show answer

$v = I/(nAe) = 1.0 \div [(8.5 \times 10^{28})(1.0 \times 10^{-6})(1.602 \times 10^{-19})] = 7.3 \times 10^{-5}\ \text{m/s}$, about 0.07 mm/s.

COMMON MISTAKES

- Forgetting to convert mA to A or hours to seconds before using $Q = It$.
- Thinking current is "used up" in a circuit. The same current flows out of a lamp as flows in; it is energy, not charge, that the lamp uses.
- Leaving the meter's red lead in the current (mA or 10 A) jack and then measuring voltage. That shorts the circuit through the meter and can blow its fuse.

Make it a game · Galvani to Volta. Teach-back. In sixty seconds, tell your parent the story of Galvani's frogs and Volta's pile, and why the pile gave steady current. Your parent sneaks in one wrong fact. Catch it for a point. Then solve two drills from memory: I = Q ÷ t, and the number of electrons, Q = ne. Personal record: five right in a row.

Scripture. "And he is before all things, and by him all things consist." (Colossians 1:17, KJV)

The electric forces that hold every atom together are part of the order by which all things "consist," or hold together. Volta and Ampère studied that order as men who believed it had an Author.

1.2 Voltage and Energy

OBJECTIVES

- Define voltage as energy per unit charge and use $V = W/Q$.
- Calculate the energy stored in a battery from its voltage and capacity, in joules and watt-hours.
- Explain why cells in series add their voltages, and why voltage is always measured between two points.
- Measure battery voltages, fresh and used, and the 5 V and 3.3 V supplies of an Arduino.

> **Warm-up.** Imagine water in a tank on a hill pushing through a pipe to a water wheel. Which matters more for how hard the water hits the wheel: how much water there is, or how high the tank is? Write a sentence, then compare it with the “height” idea in this lesson.

WATCH

Voltage Explained - What is Voltage? Basic electricity potential difference

The Engineering Mindset · 10:52

https://www.youtube.com/watch?v=w82aSjLuD_8

> **WHEN TO WATCH**
> After the physics paragraph. Watch the water-pressure analogy, then pause and explain to yourself why voltage is measured between two points.

BACKUP VIDEO

Voltage | Introduction to electrical engineering | Electrical engineering | Khan Academy

Khan Academy · 2:58

https://www.youtube.com/watch?v=k9SwNST1eW0

A short Khan Academy definition of voltage as energy per charge; useful before the worked examples.

KEY TERMS

voltage (potential difference)

The energy given to (or taken from) each coulomb of charge moving between two points: $V = W/Q$. Unit: the volt (V), one joule per coulomb.

electromotive force (emf)

The voltage a source such as a battery or generator produces when no current is drawn. The name is old; it is an energy per charge, not a force.

ground

The point in a circuit chosen as 0 V, from which other voltages are measured. In a battery circuit it is usually the negative terminal.

watt-hour (Wh)

A unit of energy: one watt for one hour, or 3600 J. Battery packs are often rated in Wh.

series cells

Cells connected + to −, one after another. Their voltages add; the charge each can deliver stays the same.

CORE IDEAS

The story. Volta called the push of his pile its "electric tension," and he measured it with a straw electroscope, whose two thin straws spread apart in proportion to the tension. By testing pair after pair of metals he found a ranking: silver, copper, iron, tin, lead, zinc, with the biggest tension between metals far apart on the list. Fifty years later physicists understood that his "tension" was a difference in energy per charge. In 1881 the first International Electrical Congress in Paris, gathered to agree on units for the new telegraph and lighting industries, named the unit of potential difference the **volt** in his honor.

How they figured it out. Volta's ranking showed that tension depends on *which two* materials are used, not how big they are: a large zinc-copper cell and a small one gave the same tension, though the large one could supply more current for longer. And stacking cells added their tensions. These two facts separate the two ideas you must keep apart all year: **voltage** (how hard each charge is pushed) and **capacity** (how much charge is available).

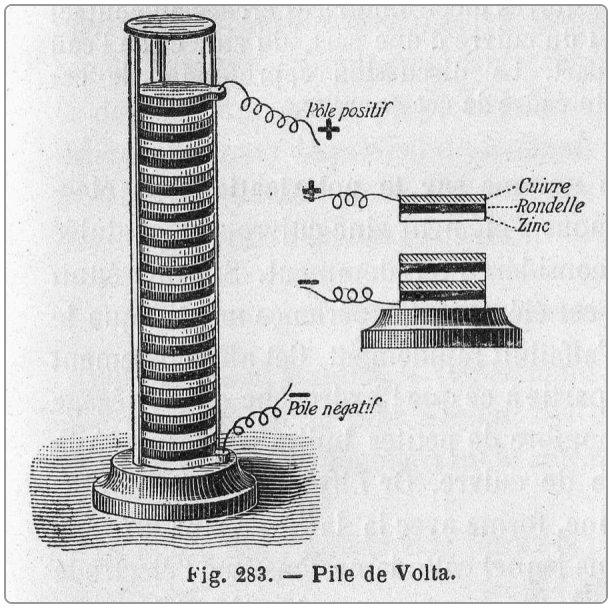
The physics. Voltage is energy per charge: $V = W/Q$, so a volt is a joule per coulomb. A 9 V battery gives each coulomb that passes through it 9 joules of energy,

which the coulomb hands over to a lamp, motor or resistor as it goes around the circuit. Voltage is like the height of a water tank: it is always a difference between two points, so “the voltage at point A” really means “the voltage from ground to A.” Cells in series stack like steps on a staircase: four 1.5 V cells give 6.0 V. The total energy stored in a battery is $W = QV$; using capacity, $W = (\text{capacity in A·h})(V)$ in watt-hours. A AA cell of 2,500 mAh at 1.5 V stores about $2.5 \times 1.5 = 3.75$ Wh, or 13,500 J. For single particles physicists use the **electron-volt**: the energy an electron gains crossing 1 V, 1.602×10^{-19} J.

The engineering. Engineers choose voltage to suit the parts: logic chips run at 5 V or 3.3 V, LEDs need about 2–3 V, small motors 3–12 V. The Arduino Uno you will use takes 5 V from a USB cable and also makes 3.3 V for some sensors; the Raspberry Pi Pico runs at 3.3 V, and a 5 V signal can damage it. A battery’s voltage also tells how full it is: an alkaline AA reads about 1.6 V new and falls toward 1.0 V when it is nearly empty. Power banks store energy in lithium cells at about 3.7 V and boost it to USB’s 5 V; their Wh rating, not their mAh rating, is the fair comparison between packs.

Today. The same idea scales from your bench to the grid. In every case engineers ask the two questions Volta separated: How much push (volts)? How much charge, and so how much energy, is available?

PICTURE STUDY



The Voltaic Pile, Unknown engraver, 1904 · Engraving · Wikimedia Commons

Image: Wikimedia Commons, public domain

A century after Volta's letter, encyclopedias still pictured his pile, because every battery since has been built on its idea: two metals, an electrolyte, and cells stacked in series.

Look closely

- Count the discs or cells you can see. What repeats?
- Find the rods or frame that hold the stack. Why must they be made of an insulator such as glass or wood?
- Find where the wires attach. Which end do you think is positive?
- Look for anything that keeps the wet discs from touching their neighbors down the side.

Talk about it

1. If each cell gives 0.8 V, what voltage would this pile give?
2. Why would a pile like this give a strong voltage but only a weak current?
3. What would happen to the voltage if one cell were put in upside down?

Safety first. Batteries and USB power only: never the outlets in the wall or anything plugged into them. Never connect a bare wire straight across a battery; even an AA cell can push several amperes through a short and get hot enough to burn. Wash your hands after handling coins, salt water or old batteries, and keep coin cells away from small children. When measuring the Arduino's 5 V and 3.3 V pins, touch the probes carefully so the metal tips cannot slip and bridge two pins.

BUILD

A Battery and Supply Survey

You will measure the open-circuit voltage of every battery you can find, test cells in series and in a “wrong-way” arrangement, and measure the Arduino’s own power rails. Then you will calculate the energy in each battery and rank them.

You will need

- Digital multimeter
- AA cells (new and used), a 4-AA holder, a 9 V battery, any spare coin cells or AAA cells
- Arduino Uno and USB cable, computer
- Two jumper wires (male-to-male)

Steps

1. In your notebook, make a table: battery, printed voltage, printed capacity (if any), measured voltage, energy in Wh. Predict which battery stores the most energy.
2. Set the meter to DC volts. Measure each battery alone: red probe on +, black on −. Record to two decimal places. Then reverse the probes once and record the negative reading. What does the sign tell you?
3. Put one, two, three and four AA cells in the 4-cell holder (use jumper wires across empty slots only if your holder allows it, or use a 2-cell holder twice). Measure the total each time and graph total voltage against number of cells.
4. Turn one cell around in a 2-cell holder and measure. Explain the reading using the staircase picture of voltage.
5. Sort your AA cells into “fresh,” “used” and “nearly dead” by voltage (about 1.55 V or more, 1.3–1.5 V, below 1.2 V). Label them with tape; you will want fresh cells for later builds.
6. Plug the Arduino into the computer with the USB cable. With the black probe on a GND pin, measure the 5V pin and the 3.3V pin. Record both. These are the two supply voltages you will use most this year.

7. Calculate the energy of each battery in Wh using its printed or typical capacity (AA alkaline about 2,500 mAh, 9 V about 500 mAh, CR2032 about 220 mAh at 3 V). Rank them.
8. **Improve it.** Test whether a battery's voltage drops when it is working: measure a fresh AA, then measure it again while it lights an LED through a 100 Ω resistor. Repeat with a used AA. Which one's voltage sags more under load, and why might that be the better test of a battery?

Tips

- A meter reading of "1." or "OL" means the range is too low; switch to a higher range.
- Cheap meters read to about ±1%. Write down what you see, not what you expected; honest data are the point.
- Keep the probes off the Arduino's VIN pin; it is connected to the input jack and can be at a different voltage.

Check your work

- ☐ I can explain voltage as energy per charge, with units.
- ☐ I measured cells in series and showed that their voltages add.
- ☐ I calculated the energy stored in several batteries in Wh and J.
- ☐ I measured the Arduino's 5 V and 3.3 V supplies.

ENGINEER'S NOTEBOOK

1. Your survey table and the graph of voltage against number of series cells.
2. A "staircase" diagram of four cells in series with one turned around, labeled with the voltage at each step.
3. A sentence for each: What is voltage? What is capacity? Why are they different?

KEY FORMULAS

$$V = \frac{W}{Q}$$

$$W = QV$$

$$1\ \text{Wh} = 3600\ \text{J}$$

$$1\ \text{eV} = 1.602 \times 10^{-19}\ \text{J}$$

From history. The 1881 Paris congress also named the ampere and the ohm and laid the groundwork for the coulomb and the farad. Lord Kelvin and Hermann von Helmholtz were among the scientists who argued over the definitions, and the system they agreed on is the ancestor of the SI units used today.

WORKED EXAMPLES

Example 1. A 9.0 V battery moves 2.0 C of charge through a circuit. How much energy does it deliver?

Show solution

1. Use $W = QV$.
2. $W = (2.0\ \text{C})(9.0\ \text{V}) = 18\ \text{J}$.

Answer: 18 J

Example 2. An alkaline AA cell is rated 2,500 mAh at 1.5 V. How much energy does it store, in Wh and J? How much would four in series store, and at what voltage?

Show solution

1. Capacity: $2500\ \text{mAh} = 2.5\ \text{Ah}$.
2. Energy: $W = (2.5\ \text{Ah})(1.5\ \text{V}) = 3.75\ \text{Wh}$.
3. In joules: $3.75\ \text{Wh} \times 3600\ \text{J/Wh} = 13{,}500\ \text{J}$.
4. Four in series: voltage $4 \times 1.5 = 6.0\ \text{V}$, capacity still 2.5 Ah, energy $4 \times 3.75 = 15\ \text{Wh}$.

Answer: $3.75\ \text{Wh} = 13{,}500\ \text{J}$; four cells: 6.0 V, 15 Wh

Example 3. Two USB power banks: A is "10,000 mAh" using 3.7 V lithium cells; B is "20 Wh." Which stores more energy?

Show solution

1. Pack A: $W = (10\ \text{Ah})(3.7\ \text{V}) = 37\ \text{Wh}$.
2. Pack B: 20 Wh.
3. Compare in the same unit: $37\ \text{Wh} > 20\ \text{Wh}$.

Answer: Pack A, 37 Wh against 20 Wh

PRACTICE

1. **Easy** How much energy does a 1.5 V cell give to 4.0 C of charge?

   Show answer

   $W = QV = 6.0\ \text{J}$

2. **Easy** Three 1.5 V cells are placed in series. What is the total voltage?

   Show answer

   $4.5\ \text{V}$

3. **Easy** Convert 2.0 Wh to joules.

   Show answer

   $7200\ \text{J}$

4. **Medium** A motor receives 540 J from 60 C of charge. What voltage is across it?

   Show answer

   $V = W/Q = 9.0\ \text{V}$

5. **Medium** A 9 V battery is rated 500 mAh. How much energy does it store in Wh and J?

   Show answer

   $0.5 \times 9 = 4.5\ \text{Wh} = 16{,}200\ \text{J}$

6. **Medium** Why do a D cell and an AAA cell both read about 1.5 V, even though the D cell is much bigger? What is the D cell's advantage?

   Show answer

   Voltage depends on the chemistry (the two materials), not the size. The D cell holds far more charge, so it lasts much longer and can supply more current.

7. **Medium** An electron is accelerated through 5.0 V. How much energy does it gain, in eV and in joules?

   Show answer

   $5.0\ \text{eV} = 5.0 \times 1.602 \times 10^{-19} = 8.0 \times 10^{-19}\ \text{J}$

8. Hard A pocket LED light uses three AAA cells (1.5 V, 1,000 mAh each) in series and draws 120 mA. Find the pack voltage, how long it runs (ideal), and the total energy.

   Show answer

   4.5 V; $1000/120 = 8.3$ h; $W = (1.0\ \text{Ah})(4.5\ \text{V}) = 4.5\ \text{Wh} = 16{,}200\ \text{J}$

9. Hard The 4.5 Wh in a 9 V battery could, in principle, lift how high a 1.0 kg book? ($W = mgh$, $g = 9.8\ \text{m/s}^2$.)

   Show answer

   $h = 16{,}200 \div (1.0 \times 9.8) \approx 1650$ m, over a mile

10. Hard Point A is 5.0 V above ground and point B is 3.3 V above ground. What does a meter read with red on A and black on B? With red on B and black on A?

    Show answer

    $+1.7$ V; -1.7 V

11. Challenge Volta's pile used about 0.8 V per cell. Davy's great battery at the Royal Institution (about 1810) used about 2,000 plate pairs. Estimate its voltage. If each pair could give 0.5 A, why would the whole battery not give 1,000 A?

    Show answer

    About $2000 \times 0.8 = 1600$ V. In series the same current flows through every cell, so the current is limited by one cell's capacity (about 0.5 A), not added; series adds voltage, not current.

COMMON MISTAKES

- Adding mAh ratings for cells in series. In series the voltages add and the capacity stays that of one cell.
- Comparing power banks by mAh when they use different cell voltages; compare Wh instead.
- Saying a battery "has" a certain current. A battery has a voltage; the circuit connected to it decides the current.

Make it a game · Joules in a Battery. Estimation duel. Find a battery label in the house, read its voltage and capacity, and each write a guess of its stored energy in watt-hours before calculating. Closest guess wins the round. Then convert to joules and define voltage as energy per charge in one sentence. Swap labels and play three rounds.

1.3 Ohm's Law: Georg Ohm's Wires

OBJECTIVES

- Tell how Georg Ohm discovered the relation between voltage, current and resistance, and why it was doubted at first.
- Use Ohm's law $V = IR$ in all three forms, with engineering prefixes.
- Calculate the resistance of a wire from $R = \rho L/A$.
- Measure a resistor's current at several voltages, graph V against I, and find R from the slope; contrast it with a non-ohmic LED.

> **Warm-up.** Blow through a drinking straw, then through a coffee stirrer, then through two straws taped end to end. Which is hardest? Write a guess about how a wire's length and thickness might affect the flow of electric current.

WATCH

Ohms Law Explained - The basics circuit theory

The Engineering Mindset · 10:00

https://www.youtube.com/watch?v=HsLLq6Rm5tU

> **WHEN TO WATCH**
> After the story. Pause at each example in the video and solve it before the narrator does.

KEY TERMS

resistance

How strongly a part opposes current: $R = V/I$. Unit: the ohm (Ω), one volt per ampere.

Ohm's law

For many materials at constant temperature, current is proportional to voltage: $V = IR$, with R constant.

resistivity (ρ)

A property of a material that sets how well it conducts: $R = \rho L/A$. Copper: $1.68 \times 10^{-8}\ \Omega \cdot \mathrm{m}$.

ohmic / non-ohmic

An ohmic part has a straight-line V–I graph through the origin (a resistor). A non-ohmic part does not (an LED, a diode, a lamp filament as it heats).

engineering prefixes

Multipliers used for convenient numbers: m (milli, 10^{-3}), μ (micro, 10^{-6}), k (kilo, 10^{3}), M (mega, 10^{6}).

CORE IDEAS

The story. Georg Simon Ohm was the son of a locksmith in Erlangen, Bavaria, who taught his sons mathematics himself. In the 1820s Ohm was a mathematics and physics teacher at the Jesuit gymnasium in Cologne, with little money and no proper laboratory. He set out to answer a question nobody had answered exactly: how does the current in a wire depend on the wire? In 1827 he published *Die galvanische Kette, mathematisch bearbeitet* ("The galvanic circuit investigated mathematically"), with the law that bears his name.

How they figured it out. Ohm's first experiments with voltaic piles failed, because the piles' voltage drifted as they ran. On the advice of the physicist Johann Poggendorff he switched to a **thermocouple**, a junction of copper and bismuth held between boiling water and ice, which gave a steady, small voltage. He measured current with a torsion balance, a magnetic needle hung on a fine wire whose twist showed the strength of the current. He then connected wires of different lengths and thicknesses, and found that the current fell in a precise way as the wire got longer. Some German professors dismissed his mathematical approach, and Ohm left his teaching post in discouragement. But others repeated his measurements, and in 1841 the Royal Society in London awarded him its Copley Medal. The unit of resistance is the ohm.

The physics. Ohm's law says that for many conductors the current is proportional to the voltage: $V = IR$. The constant R is the **resistance**, in ohms (Ω). Rearranged, $I = V/R$ and $R = V/I$. A 1 kΩ resistor across 5 V carries $5\ \text{V}/1000\ \Omega = 5\ \text{mA}$. Resistance depends on the material and the shape: $R = \rho L/A$, longer wires resist more and thicker wires less, exactly as Ohm found. Copper's resistivity is tiny, so wires have almost no resistance; nichrome, used in heaters, has about 65 times as much. Not everything obeys Ohm's law. A lamp filament's resistance rises as it heats, and an LED conducts almost nothing until its voltage reaches about 1.8–2 V and then conducts very easily. Engineers call those parts **non-ohmic**.

The engineering. Ohm's law is the most-used equation in electronics. It sets the resistor that keeps an LED from burning out, the wire size that keeps a cable from overheating, and the current a sensor will draw. Resistors are made in standard values and labeled with color bands (Lesson 3.1). Engineers use prefixes to keep numbers simple: V in volts, I in milliamperes and R in kilohms work together, since $\mathrm{V} = \mathrm{mA} \times \mathrm{k\Omega}$. And your body has resistance too: dry skin is about 100 kΩ or more, which is why a 9 V battery is safe to touch but the outlets in the wall, at more than ten times the voltage, are dangerous.

Try it. In the build you will repeat Ohm's experiment with modern parts: change the voltage, measure the current, and see whether the graph is a straight line.

PICTURE STUDY



Georg Simon Ohm, Unknown artist, 19th century · Portrait print · Wikimedia Commons

Image: Wikimedia Commons, public domain

Ohm spent years as a poorly paid schoolteacher and was mocked by some professors before his law was accepted. This portrait shows him late in life, when he was finally a professor at Munich.

Look closely

- Look at his face and posture. What kind of person does the artist want you to see?
- Ohm worked without a proper laboratory. What tools do you think he had to make himself?
- Picture him at a table with coils of wire of different lengths. What would he be writing down after each trial?

Talk about it

1. Why might an idea that is correct still be rejected at first? What finally persuaded people that Ohm was right?
2. Ohm's law is a model that works for some parts and not others. Why is it still useful?
3. What does Ohm's patience teach about scientific work?

Safety first. Batteries and USB power only: never the outlets in the wall or anything plugged into them. Never connect a bare wire straight across a battery; even an AA cell can push several amperes through a short and get hot enough to burn. Wash your hands after handling coins, salt water or old batteries, and keep coin cells away from small children. When the meter is set to measure current, it must be in series with the resistor, never directly across the battery.

BUILD

Ohm's Experiment on a Breadboard

You will measure the current through a 1 kΩ resistor at five different voltages, graph voltage against current, find the resistance from the slope, and then repeat the test with an LED to see a part that does not obey Ohm's law.

You will need

- Breadboard, jumper wires, 4-AA holder with 1 to 4 fresh cells (or the Arduino's 5 V pin powered by USB)
- Resistors: 1 kΩ, 220 Ω, 10 kΩ; a 10 kΩ potentiometer from the kit
- A red LED
- Digital multimeter (and a second meter if you have one)

Steps

1. Read the bands on a 1 kΩ resistor (brown, black, red) and measure its actual resistance with the meter on the Ω setting, with the resistor out of any circuit. Record it.
2. Wire a circuit: battery + → resistor → meter (set to 20 mA DC, red lead in the mA jack) → battery −. Draw the schematic first.
3. Measure the current with 1, 2, 3 and 4 AA cells (or set the potentiometer as a variable voltage: outer pins to + and −, middle pin feeds the resistor). Each time, also measure the voltage directly across the resistor with the meter (or a second meter) on DC volts.
4. Record a table of V (V) and I (mA). Predict each current from Ohm's law before you measure it.
5. Graph V on the vertical axis against I on the horizontal. Draw a best-fit line. Its slope in V/mA is R in kΩ. Compare with your ohmmeter reading and compute the percent difference.
6. Replace the 1 kΩ resistor with a 220 Ω resistor in series with the red LED. Use the potentiometer to vary the voltage. Measure the voltage across the LED alone and the current, for at least 8 points from 0 to about 15 mA.

7. Graph the LED's voltage against current on the same paper. Describe how its shape differs from the resistor's line.
8. **Improve it.** Repeat the resistor test with the 10 kΩ resistor. Does the meter still read well? Which range did you need? Write one sentence on how the choice of meter range affects precision.

Tips

- Move the red lead back to the V jack as soon as you finish measuring current.
- Breadboard rows of five holes are connected; parts in the same row are joined. Check that the resistor's two legs are in different rows.
- Real resistors are within 5% (gold band) or 1% (brown band) of their marked value. A 1 kΩ that measures 985 Ω is fine.

Check your work

- ☐ My resistor graph is a straight line, and its slope matches the measured resistance within a few percent.
- ☐ My LED graph is curved, and I can explain why that makes it non-ohmic.
- ☐ I can use $V = IR$ in all three forms with prefixes.

ENGINEER'S NOTEBOOK

1. Schematic of your test circuit with the meter shown in series (ammeter) and in parallel (voltmeter).
2. Data tables and both graphs, with the best-fit slope and percent difference for the resistor.
3. In your own words: what Ohm measured, what he changed, and what he kept the same.

KEY FORMULAS

$$V = IR$$

$$I = \frac{V}{R}, \qquad R = \frac{V}{I}$$

$$R = \frac{\rho L}{A}$$

$$\mathrm{V} = \mathrm{mA} \times \mathrm{k\Omega}$$

From history. Ohm's law was later explained from the inside by Paul Drude in 1900, who pictured electrons bumping through the metal's atoms like balls through a pinball machine. Today's quantum theory gives the details, but Ohm's simple equation remains the starting point.

WORKED EXAMPLES

Example 1. A 470 Ω resistor is connected across a 9.0 V battery. What current flows?

Show solution

1. Use $I = V/R$.
2. $I = 9.0\ \text{V} \div 470\ \Omega = 0.0191\ \text{A}$.
3. In milliamperes: $19.1\ \text{mA}$.

Answer: $19\ \text{mA}$

Example 2. A sensor must draw 20 mA from a 5.0 V supply. What resistance does it present?

Show solution

1. Use $R = V/I$ with $I = 0.020\ \text{A}$.
2. $R = 5.0\ \text{V} \div 0.020\ \text{A} = 250\ \Omega$.

Answer: $250\ \Omega$

Example 3. Find the resistance of 10 m of copper wire 0.50 mm in diameter. ($\rho = 1.68 \times 10^{-8}\ \Omega \cdot \text{m}$.)

Show solution

1. Radius: $r = 0.25\ \text{mm} = 2.5 \times 10^{-4}\ \text{m}$.
2. Area: $A = \pi r^2 = \pi(2.5 \times 10^{-4})^2 = 1.96 \times 10^{-7}\ \text{m}^2$.
3. Resistance: $R = \rho L/A = (1.68 \times 10^{-8})(10) \div 1.96 \times 10^{-7} = 0.86\ \Omega$.

Answer: About $0.86\ \Omega$

PRACTICE

1. **Easy** A 1.0 kΩ resistor has 6.0 V across it. Find the current.

   Show answer

   6.0 mA

2. **Easy** A current of 2.0 A flows through a 12 Ω heater element. What voltage is across it?

   Show answer

   24 V

3. **Easy** A part draws 15 mA from 3.0 V. What is its resistance?

   Show answer

   200 Ω

4. **Medium** Express 4,700 Ω, 0.0033 A and 2,200,000 Ω with prefixes.

   Show answer

   4.7 kΩ; 3.3 mA; 2.2 MΩ

5. **Medium** A student measures 1.5 V → 1.5 mA, 3.0 V → 3.0 mA, 4.5 V → 4.5 mA. Find R from the slope. Is the part ohmic?

   Show answer

   $R = \Delta V / \Delta I = 3.0\ \text{V} / 3.0\ \text{mA} = 1.0\ \text{k}\Omega$; yes, the graph is a straight line through the origin.

6. **Medium** If a wire is replaced by one of the same material twice as long and twice the diameter, what happens to its resistance?

   Show answer

   L doubles (×2) and A quadruples (÷4), so R halves.

7. **Medium** Dry skin is about 100 kΩ. What current would flow through a person touching both terminals of a 9 V battery? (About 1 mA can just be felt.)

   Show answer

   $9 \div 100{,}000 = 0.09$ mA: too small to feel. That is why 9 V is safe to touch, and why far higher voltages are not.

8. Hard Find the resistance of 0.50 m of nichrome wire 0.40 mm in diameter ($\rho = 1.10 \times 10^{-6}\ \Omega \cdot \text{m}$). What current would 3.0 V push through it?

Show answer

$A = \pi(2.0 \times 10^{-4})^2 = 1.26 \times 10^{-7}\ \text{m}^2$; $R = 4.4\ \Omega$; $I = 0.68\ \text{A}$

9. Hard Why did Ohm's experiments with voltaic piles give inconsistent results, and how did the thermocouple fix the problem?

Show answer

A pile's voltage changed as it ran (its chemistry polarized and dried), so the push was not constant from one trial to the next. The thermocouple, held between boiling water and ice, gave a steady voltage, so only the wire changed.

10. Hard An LED reads 1.80 V at 1 mA and 1.95 V at 10 mA. Calculate V/I at each point. Is the LED ohmic?

Show answer

1,800 Ω and 195 Ω. The ratio changes by nearly ten times, so the LED is non-ohmic.

11. Challenge A 30 m extension of copper speaker wire (two conductors, out and back, each 1.0 mm² in area) carries 2.0 A. Find the total wire resistance and the voltage lost in the wire.

Show answer

Length of copper $= 60$ m; $R = (1.68 \times 10^{-8})(60)/(1.0 \times 10^{-6}) = 1.0\ \Omega$; $V = IR = 2.0$ V lost.

COMMON MISTAKES

- Mixing units: using mA with Ω gives the voltage in millivolts. Use V, A, Ω together, or V, mA, kΩ together.
- Applying Ohm's law to an LED as though it were a resistor. An LED's voltage stays near 2 V over a wide range of currents.
- Measuring resistance while the part is still powered or still in the circuit; the meter will read nonsense or be damaged.

Make it a game · Ohm's Law Speed Round. Beat the clock. Your parent calls two of V, I and R with engineering prefixes, such as 4.7 kΩ and 2 mA, and you give the third with units in ten seconds. Ten rounds in sixty seconds is the record to beat. Then explain in a sentence why Georg Ohm's result was doubted at first.

1.4 Power: Watt, Joule and Heat

OBJECTIVES

- Use $P = VI$, $P = I^2R$ and $P = V^2/R$ to calculate electrical power, and $W = Pt$ for energy.
- Explain Joule heating and why resistors, wires and batteries have power ratings.
- Choose a resistor with a safe power rating and estimate battery life from a power budget.
- Measure voltage and current in a working LED circuit and compute the power in each part.

> **Warm-up.** Look at the label on any USB charger or power bank (do not unplug anything from the wall). Find the output voltage and current. Multiply them. What unit do you think the answer has, and what does it mean?

WATCH

Volts, Amps, & Watts Explained!

The Organic Chemistry Tutor · 22:10

https://www.youtube.com/watch?v=PyLjnVJVM1s

> **WHEN TO WATCH**
> After the physics paragraph. Watch the first 12 minutes, then pause and solve two of the examples on your own before you continue.

BACKUP VIDEO

Basic Electricity - Power and watts

Afrotechmods · 5:21

https://www.youtube.com/watch?v=VSpB3HivkhY

A short, clear explanation of power and resistor power ratings; good before the build.

KEY TERMS

power

The rate at which energy is transferred: $P = W/t$. Unit: the watt (W), one joule per second.

Joule heating

The heat produced when current flows through resistance, at a rate $P = I^2R$.

power rating

The most power a part can safely turn into heat. Common small resistors are rated 1/4 W (0.25 W).

power budget

A list of every part in a design with its current or power, added up to size the battery or supply.

efficiency

Useful output power divided by input power, often as a percent.

CORE IDEAS

The story. James Prescott Joule grew up in a prosperous family business near Manchester, England, and did his science at home in a laboratory he built himself. In 1840, aged 21, he wrapped coils of wire, put them in jars of water, passed current through them, and measured the rise in temperature with thermometers he could read to a small fraction of a degree. He found that the heat produced was proportional to the resistance times the *square* of the current. Joule went on to show, with his famous paddle-wheel experiment, that heat and mechanical work are two forms of the same thing, energy, and the SI unit of energy is the joule. He was a devout Christian who wrote that, after knowing and obeying the will of God, the next aim of study should be to know His wisdom, power and goodness as shown in His handiwork.

How they figured it out. Joule's problem was measurement: the temperature changes were small and heat leaked away. He used careful insulation, stirred the water, corrected for losses to the room, and repeated each run many times. Doubling the current gave four times the heat, not twice; the data forced him to the squared law. A generation earlier James Watt, improving the steam engine, had defined the horsepower to sell his engines to mine owners. The unit of power, one joule per second, now carries Watt's name.

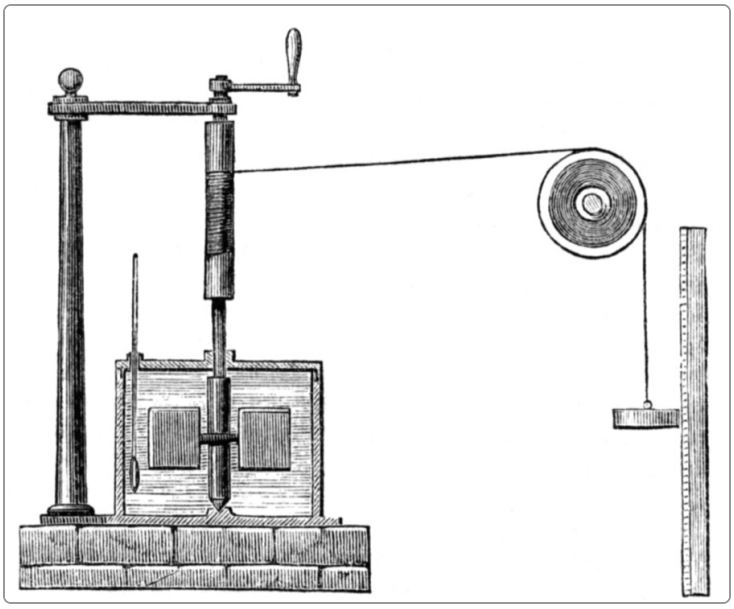
The physics. Each coulomb passing through a voltage V gives up V joules, and I coulombs pass each second, so **power** is $P = VI$. Combining with Ohm's law gives two more forms: $P = I^2R$ and $P = V^2/R$. A 220 Ω resistor across 5 V carries 22.7 mA and dissipates $P = V^2/R = 25/220 = 0.11$ W. Energy is power times time, $W = Pt$; utilities bill it in kilowatt-hours, and battery makers in watt-hours. In a resistor all

the electrical energy becomes heat. In an LED some becomes light and the rest heat; in a motor some becomes motion.

The engineering. Heat is the enemy of electronics. Every resistor, transistor and wire has a power rating, and engineers keep the real power to about half of it for a margin of safety. A 1/4 W resistor run at 0.25 W gets hot enough to burn a finger; at 2 W it smokes. Joule heating is also why a short circuit is dangerous: a fresh AA cell has an internal resistance of about 0.15 Ω, so a bare wire across it lets about 10 A flow and turns some 15 W into heat inside the small cell. And it is why engineers design a **power budget** before choosing a battery: add up every part's current, then divide the battery's capacity by the total to estimate its life.

Try it. You will measure the real voltages and currents in an LED circuit, calculate where the power goes, and check whether your resistor's rating is safe.

PICTURE STUDY



Joule's Apparatus, Jacob Abbott (from Harper's), 1869 · Engraving · Wikimedia Commons

Image: Wikimedia Commons, public domain

This is the apparatus Joule used in the 1840s to show that mechanical work turns into heat in a fixed ratio. His earlier work had shown the same thing for electric current in a wire. Together they proved that heat, work and electrical energy are all one quantity, measured today in joules.

Look closely

- Find the falling weights and the pulleys. Where does their energy go?
- Find the container of water and the paddles inside. Why would stirring water warm it?
- Look for the thermometer. How small a temperature change do you think Joule had to read?
- Compare this setup with a resistor in a jar of water. What plays the part of the paddles?

Talk about it

1. Why did Joule need to stir the water and insulate the container?
2. In an electric circuit, what plays the role of the falling weights, and what plays the role of the paddles?
3. What does Joule's careful work teach about honest measurement?

Safety first. Batteries and USB power only: never the outlets in the wall or anything plugged into them. Never connect a bare wire straight across a battery; even an AA cell can push several amperes through a short and get hot enough to burn. Wash your hands after handling coins, salt water or old batteries, and keep coin cells away from small children. Resistors in this build stay well below their power rating. If any part becomes too hot to touch or smells hot, disconnect the battery at once.

BUILD

A Power Budget for an LED Lamp

You will build a small LED lamp three ways, with different resistors, measure where the voltage and current go, calculate the power in the LED and in the resistor, and use the results to predict battery life and pick the best design.

You will need

- Breadboard, jumper wires, 2-AA holder (3 V) and 4-AA holder (6 V)
- Red or white LEDs, resistors of 100 Ω, 220 Ω and 470 Ω
- Digital multimeter
- A notebook page laid out as a data table

Steps

1. For each resistor (100, 220 and 470 Ω) with the 4-AA pack, predict the current using $I = (V_{\text{battery}} - 2.0\ \text{V})/R$ for a red LED (the LED takes about 2 V). Record predictions.
2. Build battery + → resistor → LED (long leg toward the resistor) → battery −. Measure the battery voltage, the voltage across the resistor and across the LED, and the current (meter in series, mA range).
3. Calculate the power in the resistor ($V_R I$), in the LED ($V_{\text{LED}} I$) and in total ($V_{\text{battery}} I$). Check that the parts add to the total.
4. Repeat for the other two resistors. Note the brightness of each (dim, medium, bright) in a fair test: same room, same viewing distance.
5. Compute the efficiency of each design as LED power ÷ total power. Which design wastes the least energy in the resistor?
6. Repeat the 220 Ω test with the 2-AA pack. Compare the current, brightness and efficiency.
7. Use your power budget to predict how long each design would run on 2,500 mAh AA cells.
8. **Improve it.** Choose the design you would build for a reading lamp that must run a week of evenings (3 hours a night) on one set of batteries, and justify it with your numbers.

Tips

- Measure each current with the meter in series, then return the red lead to the V jack before measuring voltages.
- Lower battery voltage wastes less power in the resistor, but the current becomes more sensitive to the battery running down.
- White and blue LEDs take about 3 V; adjust your predictions if you use them.

Check your work

- ☐ I calculated power in each part and showed that they add to the total.
- ☐ I compared efficiency and brightness for three resistor values.
- ☐ I predicted battery life from a power budget and chose a design using data.

ENGINEER'S NOTEBOOK

1. Your data table for all four tests with predictions, measurements and power calculations.
2. A bar chart of resistor power and LED power for each design.
3. A short design memo: which design you chose for the reading lamp and why, in three to five sentences.

KEY FORMULAS

$$P = VI = I^2R = \frac{V^2}{R}$$

$$W = Pt$$

$$\text{efficiency} = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\%$$

From history. Joule's results were at first dismissed by the Royal Society. At the 1847 British Association meeting in Oxford, the young William Thomson (later Lord Kelvin) heard him and was convinced; the two became lifelong collaborators and together discovered the Joule–Thomson effect, which is used in refrigeration.

WORKED EXAMPLES

Example 1. A 220 Ω resistor is connected across 5.0 V. How much power does it dissipate? Is a 1/4 W resistor safe?

Show solution

1. Use $P = V^2/R$.
2. $P = (5.0\ \text{V})^2 \div 220\ \Omega = 25 \div 220 = 0.114\ \text{W}$.
3. Compare: $0.114\ \text{W}$ is less than half of $0.25\ \text{W}$, a comfortable margin.

Answer: 0.11 W; yes, a 1/4 W resistor is safe

Example 2. A student connects a 10 Ω resistor across a 9.0 V battery. Find the current and power, and say what happens to a 1/4 W resistor.

Show solution

1. Current: $I = V/R = 9.0 \div 10 = 0.90\ \text{A}$.
2. Power: $P = VI = (9.0)(0.90) = 8.1\ \text{W}$.
3. That is more than 30 times the rating: the resistor overheats, smokes and may burn open, and the battery heats too.

Answer: 0.90 A, 8.1 W; the resistor is destroyed

Example 3. A circuit on a 4.5 V battery pack draws 30 mA continuously. What is its power, and how much energy does it use in 8.0 hours? How long would 2,500 mAh cells last?

Show solution

1. Power: $P = VI = (4.5\ \text{V})(0.030\ \text{A}) = 0.135\ \text{W}$.
2. Energy: $W = Pt = (0.135\ \text{W})(8.0 \times 3600\ \text{s}) = 3890\ \text{J}$, or $1.08\ \text{Wh}$.
3. Battery life: $2500\ \text{mAh} \div 30\ \text{mA} = 83\ \text{h}$.

Answer: 0.135 W; about 3,900 J (1.1 Wh); about 83 h

PRACTICE

1. Easy A USB port supplies 5.0 V at 2.0 A. What power is that?

   Show answer

   $10\ \text{W}$

2. Easy A 100 Ω resistor carries 50 mA. What power does it dissipate?

   Show answer

   $P = I^2R = (0.050)^2(100) = 0.25\ \text{W}$

3. Easy How much energy does a 0.50 W circuit use in 3.0 hours, in J and Wh?

   Show answer

   $5400\ \text{J} = 1.5\ \text{Wh}$

4. Medium A 1.0 kΩ resistor is across 12 V. Find its power. Is a 1/4 W resistor a good choice?

   Show answer

   $P = 144/1000 = 0.144$ W; it is under the rating but above half of it, so a 1/2 W resistor would be the better engineering choice.

5. Medium Doubling the current through a resistor multiplies its heat by what factor? Who discovered this?

   Show answer

   By 4, since $P = I^2R$; James Prescott Joule (1840).

6. Medium What is the smallest resistor you can put across 5.0 V if it is rated 1/4 W and you want no more than half its rating?

   Show answer

   $P = 0.125$ W; $R = V^2/P = 25/0.125 = 200\ \Omega$

7. Medium A motor takes 6.0 V and 0.40 A and lifts a load with 1.8 W of mechanical power. What is its efficiency? Where does the rest go?

   Show answer

   $P_{\text{in}} = 2.4$ W; efficiency $= 1.8/2.4 = 75\%$; the rest becomes heat (in the coil resistance and friction) and some sound.

8. Hard A fresh AA cell (1.5 V) has an internal resistance of about 0.15 Ω. Estimate the current and the power turned to heat inside it if it is shorted by a wire. Why is this dangerous?

Show answer

$I \approx 1.5/0.15 = 10$ A; $P = I^2R = 15$ W inside a small cell; it gets hot quickly and can burn, leak or rupture.

9. Hard A project has an Arduino (45 mA), three LEDs (15 mA each) and a sensor (5 mA), all from a 5.0 V power bank of 37 Wh at 85% conversion efficiency. Estimate the run time.

Show answer

Total 95 mA; $P = 5.0 \times 0.095 = 0.475$ W; usable energy $= 0.85 \times 37 = 31.5$ Wh; time $\approx 31.5/0.475 = 66$ h

10. Hard Joule's coil had resistance 2.0 Ω and carried 1.5 A for 10 minutes in 0.50 kg of water. How much heat was produced? What temperature rise would that give if none were lost? ($c = 4186$ J/(kg·°C).)

Show answer

$W = I^2Rt = (2.25)(2.0)(600) = 2700$ J; $\Delta T = 2700/(0.50 \times 4186) = 1.3$ °C

11. Challenge Two resistors, 100 Ω and 400 Ω, are in series across 10 V. Find the current and the power in each. Which gets hotter, and why does the answer reverse if they are placed in parallel instead?

Show answer

Series: $I = 10/500 = 20$ mA; $P_{100} = 0.04$ W, $P_{400} = 0.16$ W; the larger resistor is hotter ($P = I^2R$, same I). In parallel each has 10 V: $P_{100} = 1.0$ W, $P_{400} = 0.25$ W; the smaller is hotter ($P = V^2/R$, same V).

COMMON MISTAKES

- Using the battery voltage for the resistor's power. The resistor gets only the voltage left after the LED takes its share.
- Forgetting to square: $P = I^2R$, not IR.
- Running a resistor right at its power rating. Engineers design for about half.

Make it a game · Power Triple Threat. Duel with three formulas: $P = VI$, $P = I^2R$, $P = V^2 \div R$. Your parent gives you two values; you choose the best formula and name it, then solve. Wrong formula costs a point. Then calculate the energy $W = Pt$ of a pretend device running an hour. First to ten points wins. Record your score.

1.5 The Multimeter and Lab Safety

OBJECTIVES

- Trace the history of electrical meters from the galvanometer to the digital multimeter.
- Measure voltage, current, resistance, continuity and diode drop correctly, with the meter connected the right way for each.
- Explain why a voltmeter has very high resistance and an ammeter very low, and calculate a meter's loading error.
- State and follow the safety rules for the whole course, including batteries, lithium cells, heat and tools.

> **Warm-up.** Look at your multimeter. List every symbol on the dial and every jack on the front. Guess what each one means. Which jack do you think would be the most dangerous to use by mistake?

WATCH

How To Use A Multimeter: The VERY Basics!

Simple Electronics · 11:50

https://www.youtube.com/watch?v=EvAq9zqRB5I

> **WHEN TO WATCH**
> After the physics paragraph, before the build. Follow along with your own meter: continuity, resistance, voltage and current, in that order.

Note: A brief sponsor mention may appear. The presenter works only with low-voltage circuits; this course never measures wall power.

KEY TERMS

galvanometer
A sensitive instrument that shows a small current by the deflection of a needle or coil in a magnetic field.

voltmeter
A meter that measures voltage between two points. It is connected in **parallel** and has a very high resistance (often 10 MΩ) so it draws almost no current.

ammeter

A meter that measures current. It is connected in **series**, so all the current passes through it, and has a very low resistance.

shunt

A small, precise resistor connected across a meter movement so that most of a large current bypasses it.

continuity

A test that beeps when two points are connected by a very low resistance, used to check wires and find breaks.

loading

The change a meter causes in the circuit it measures, because the meter itself draws some current or adds some resistance.

CORE IDEAS

The story. In 1820 Hans Christian Ørsted noticed that a current deflected a compass needle. Within months Johann Schweigger wrapped many turns of wire around a needle to make it more sensitive, the first **galvanometer**. In 1882 Jacques-Arsène d'Arsonval and Marcel Deprez turned the design inside out: a light coil on fine pivots turns between the poles of a fixed magnet, with a spring to return it. Their moving-coil meter was accurate and rugged, and for a century every needle meter worked that way. In 1923 Donald Macadie, a British Post Office engineer tired of carrying separate meters for amps, volts and ohms up telephone poles, designed one instrument that measured all three: the AVO meter, from Amps, Volts, Ohms. Digital multimeters arrived in the 1970s, and today a good one costs less than a pizza.

How they figured it out. The trick behind every multimeter is that one sensitive movement can measure anything with the right resistors around it. A movement that reads full scale at 1 mA becomes a 10 V voltmeter with a 10 kΩ resistor in series, or a 1 A ammeter with a tiny shunt resistor in parallel. Macadie's genius was a switch that chose the right resistor for each range. A digital meter does the same with a chip that measures voltage very precisely; current is measured as the small voltage across a shunt, and resistance by pushing a known small current through the part.

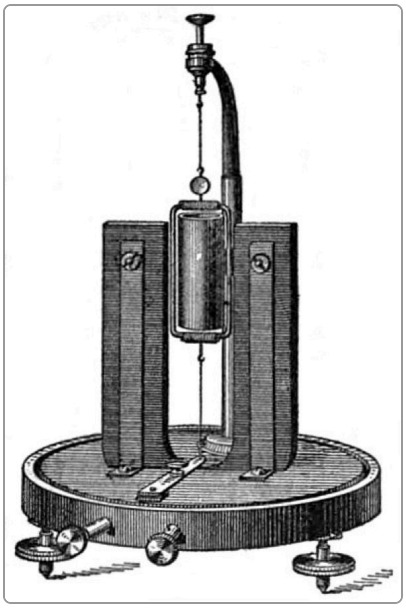
The physics. A **voltmeter** goes across a part, in parallel, and must draw almost no current or it changes the circuit; a digital meter has about 10 MΩ input resistance. An **ammeter** goes in series, in the path of the current, and must have almost no resistance. That is why an ammeter connected straight across a battery is a short circuit: the fuse inside the meter blows, or worse. An **ohmmeter** sends its own small

current, so the part must be unpowered and usually out of the circuit. Even a good meter **loads** a circuit a little. Measuring the middle of two 1 MΩ resistors across 9 V, you expect 4.50 V, but the meter's 10 MΩ in parallel with the bottom resistor makes 0.909 MΩ, and the meter reads 4.29 V.

The engineering and safety. Engineers stay safe by habit, not by luck. These are this course's rules, and they are part of every build: (1) Power comes only from batteries and USB cables, never from the outlets in the wall or anything plugged into them, and you never open an appliance, charger or power supply. (2) Never short a battery; build with the battery disconnected and connect it last. (3) Never cut, puncture, crush, or charge a damaged or swollen lithium battery, and never leave lithium cells charging unattended. (4) Check the meter before each use: right jack, right function, right range; current measurements in series only. (5) Hot parts are unplugged at once; soldering follows the rules in Lesson 5.2. (6) Safety glasses whenever you cut leads, solder, or test anything that spins or can snap. (7) Keep coin cells and small magnets away from small children; they are dangerous if swallowed. (8) Keep drinks off the bench, work on a clear, dry surface, and unplug the USB cable before rewiring.

Today. A multimeter is the first tool every electronics engineer buys and the one used most. Learning to use it well, with the right connection and range every time, is the first real skill of the course.

PICTURE STUDY



The D'Arsonval Galvanometer, New International Encyclopedia, 1905 · Engraving · Wikimedia Commons

Image: Wikimedia Commons, public domain

This encyclopedia engraving shows the moving-coil galvanometer of d'Arsonval and Deprez (1882). The same idea, a coil turning in a magnet's field against a spring, was inside every needle meter for a hundred years.

Look closely

- Find the magnet. What shape is it, and why do you think that shape was chosen?
- Find the coil and the fine wire it hangs from. What happens to that wire when current makes the coil turn?
- Find the terminals where the circuit connects.
- Look for a mirror or pointer that would make a very small turn visible.

Talk about it

1. Why must the coil be very light and the suspension very fine?
2. How could this sensitive instrument be turned into a voltmeter? An ammeter?
3. What advantages does a digital multimeter have over this instrument? What might this one do better?

Safety first. This lesson is the course safety briefing. Read the safety rules in the core ideas aloud with a parent, sign and date them in your notebook, and follow them all year. Use only batteries and USB power. Before every current measurement, check that the meter is in series and the red lead is in the mA jack; afterward, move it back to the V jack. Wear safety glasses when cutting component leads.

BUILD

Meter Mastery and the Safety Sign-Off

You will work through every function of your multimeter on known parts, find the meter's own fuse and limits, measure a hidden fault in a circuit, and finish with a signed safety agreement for the year.

You will need

- Digital multimeter and its manual
- Breadboard, jumper wires, 4-AA holder, resistors (220 Ω, 1 kΩ, 10 kΩ, 1 MΩ), a red LED, a 1N4001 or 1N4148 diode
- A long jumper wire with a hidden break made by a parent (or any old cable)
- Safety glasses

Steps

1. Read your meter's manual and label a sketch of its dial and jacks in your notebook. Find the fuse ratings printed near the current jacks. Which jack is unfused, if any?
2. **Resistance.** Measure each resistor out of circuit. Record the marked value, measured value and percent difference. Pinch both probe tips in your fingers and read your own skin resistance; then wet your fingers and measure again.
3. **Continuity.** Test several jumper wires and the hidden-break wire. Find the break. Test which holes of the breadboard are connected to each other and draw a map.
4. **Diode test.** Measure the diode and the LED both ways. Record the forward drop (about 0.6 V for a silicon diode, 1.8 V for a red LED; the LED may glow faintly) and the reverse reading (OL).
5. **Voltage.** Build two 1 MΩ resistors in series across the 4-AA pack. Predict and measure the voltage across the bottom one. Repeat with two 1 kΩ resistors. Explain the difference using loading.
6. **Current.** With the battery disconnected, build battery → 1 kΩ → meter (mA) → back to battery. Connect the battery, read the current, compare with

Ohm's law, disconnect, and move the red lead back to V.

7. **Fault hunt.** Have a parent build an LED circuit and secretly add one fault (a resistor in the wrong row, an LED backward, a dead cell). Use only measurements, no guessing, to find it. Record each measurement and what it told you.
8. **Improve it.** Write a one-page "meter checklist" to tape inside your notebook cover: what to check before each measurement. Then read the course safety rules aloud, sign them with a parent, and date them.

Tips

- Most meter mistakes are wrong-jack mistakes. Make "check the red lead" a habit.
- Hold probes like pencils, by the insulated part, and keep fingers off the metal tips when measuring high resistances or your body adds a parallel path.
- If your meter suddenly reads 0 mA on every current test, its fuse may be blown. Replace it only with the exact type in the manual.

Check your work

- ☐ I measured voltage, current, resistance, continuity and diode drop correctly.
- ☐ I can explain loading and calculate a meter's effect on a high-resistance circuit.
- ☐ I found a hidden fault by measurement.
- ☐ I signed the course safety rules with a parent.

ENGINEER'S NOTEBOOK

1. A labeled sketch of your meter's dial and jacks, with the fuse ratings.
2. Your measurement table for resistors, diode, LED, and the two dividers with the loading calculation.
3. The record of your fault hunt: each measurement, what it showed, and the fault you found.
4. The signed and dated safety rules.

KEY FORMULAS

$$R_{\text{shunt}} = \frac{I_m R_m}{I - I_m}$$

$$R_{\parallel} = \frac{R_1 R_2}{R_1 + R_2} \text{ (for loading)}$$

From history. The Fluke 8020A of 1977 was one of the first handheld digital multimeters that working engineers could afford, and it helped make the digital meter the standard tool of the trade. Analog meters are still used where a moving needle shows a changing value better than flickering digits.

WORKED EXAMPLES

Example 1. A d'Arsonval movement reads full scale at 1.0 mA and has a coil resistance of 50 Ω. What shunt makes it read 1.0 A full scale?

Show solution

1. At full scale the coil carries $I_m = 0.0010$ A and has $V = I_m R_m = (0.0010)(50) = 0.050$ V across it.
2. The shunt carries the rest: $1.0 - 0.0010 = 0.999$ A at the same 0.050 V.
3. $R_{\text{shunt}} = 0.050 \text{ V} \div 0.999 \text{ A} = 0.0501\ \Omega$.

Answer: About $0.050\ \Omega$

Example 2. Two 1.0 MΩ resistors in series are connected across 9.0 V. A meter with 10 MΩ input resistance measures the voltage across the bottom resistor. What does it read?

Show solution

1. Without the meter, the bottom resistor has $9.0/2 = 4.50$ V.
2. Meter in parallel with the bottom resistor: $R_{\parallel} = (1.0 \times 10)/(1.0 + 10) = 0.909$ MΩ.
3. Now the divider is 1.0 MΩ over 0.909 MΩ: $V = 9.0 \times 0.909/1.909 = 4.29$ V.
4. The meter reads about 5% low because it loads the circuit.

Answer: 4.29 V instead of 4.50 V

Example 3. A student accidentally connects an ammeter (0.10 Ω including leads) directly across a 9.0 V battery whose internal resistance is 1.5 Ω. Estimate the current.

Show solution

1. Total resistance: $0.10 + 1.5 = 1.6\ \Omega$.
2. $I = 9.0 \div 1.6 = 5.6\ \text{A}$.
3. That exceeds a typical 200 mA fuse by more than 25 times, so the fuse blows; on the 10 A jack (often unfused) the battery and leads heat quickly.

Answer: About 5.6 A: the meter fuse blows

PRACTICE

1. Easy Is a voltmeter connected in series or in parallel with the part it measures? An ammeter?

   Show answer

   Voltmeter in parallel (across the part); ammeter in series (in the path of the current).

2. Easy Why must a circuit be unpowered when you measure resistance?

   Show answer

   The ohmmeter supplies its own current; an outside voltage gives a false reading and can damage the meter.

3. Easy What did Donald Macadie's AVO meter combine, and why did he want it?

   Show answer

   Amps, volts and ohms in one instrument, so a Post Office engineer did not have to carry three meters.

4. Medium A movement reads full scale at 1.0 mA and has 50 Ω resistance. What series resistor makes it a 10 V voltmeter?

   Show answer

   Total $R = 10/0.001 = 10{,}000\ \Omega$; series resistor $= 10{,}000 - 50 = 9950\ \Omega$

5. Medium Your meter reads “OL” on the 2 V range when measuring a 9 V battery. What should you do?

Show answer

Switch to a higher range (20 V) or auto-range; OL means over limit.

6. Medium A circuit has two 10 kΩ resistors in series across 6.0 V. A 10 MΩ meter reads the middle point. Estimate the loading error.

Show answer

$R_{\parallel} = 9.99$ kΩ; $V = 6.0 \times 9.99/19.99 = 2.998$ V vs 3.000 V, an error under 0.1%: negligible.

7. Medium List four of this course’s safety rules from memory.

Show answer

Any four: batteries and USB only, never wall power or opening appliances; never short a battery; never cut, puncture, crush or charge a damaged lithium battery; check jack, function and range before measuring, current in series only; disconnect hot parts; safety glasses; coin cells and magnets away from children; dry, clear bench.

8. Hard Why does the continuity test beep for a wire but not for a 1 kΩ resistor?

Show answer

Continuity beeps only below a small threshold (often about 30–50 Ω). A wire is nearly 0 Ω; 1 kΩ is far above the threshold.

9. Hard A 10 V voltmeter built from a 1 mA movement has 10 kΩ total resistance. It measures the middle of two 10 kΩ resistors across 10 V. What does it read, and what does this show about old needle meters?

Show answer

Bottom becomes $10 \parallel 10 = 5$ kΩ; $V = 10 \times 5/15 = 3.33$ V instead of 5.00 V. Low-resistance needle meters loaded circuits badly; that is why high-impedance digital meters are better.

10. Hard Design a shunt that makes a 1.0 mA, 50 Ω movement read 100 mA full scale.

Show answer

$V = 0.050$ V; shunt current 0.099 A; $R = 0.050/0.099 = 0.505$ Ω

11. **Challenge** A digital meter's 200 mA range uses a 1.0 Ω shunt, so the meter drops 1.0 mV per mA. You measure the current of an LED circuit on 3.0 V with a 100 Ω resistor and an LED that takes 2.0 V. What current do you expect, what does the meter read, and why are they different?

    Show answer

    Without the meter: $I = 1.0/100 = 10$ mA. With the meter's 1 Ω added: $I = 1.0/101 \approx 9.9$ mA (the LED voltage shifts very slightly). The difference is the meter's burden voltage, a loading effect of the ammeter.

COMMON MISTAKES

- Measuring voltage with the red lead still in the current jack: this shorts the circuit through the meter.
- Measuring current with the meter across the part (in parallel) instead of in series.
- Touching both probe tips with your fingers while measuring a large resistance, which puts your body's resistance in parallel.

Make it a game · Meter Mastery Quiz. Quiz the quiz-master. Draw a meter on paper and, from memory, show how it connects to measure voltage, current, resistance and continuity, and why current is different. Your parent plays inspector and hides one wrong placement. Catch it. Then recite the lab safety rules you signed. Perfect recall earns the sign-off.

Scripture. "A false balance is abomination to the LORD: but a just weight is his delight." (Proverbs 11:1, KJV)

A meter is a balance for electricity. Using it correctly, and recording what it really shows rather than what you hoped, is a matter of honesty as well as skill.

UNIT 1

Electricity Fundamentals and Safety

Every circuit you will build this year, from a blinking LED to a Wi-Fi sensor, runs on four quantities: charge, current, voltage and power. In this unit you will meet them the way scientists first did, through Volta's pile of 1800, Ohm's careful wires, and Joule's jars of warming water, and you will measure each one yourself with a digital multimeter.

You will also learn the safety rules for the whole course and the one tool you will use more than any other. By the end of the unit you should be able to look at any battery and resistor and say, with numbers and units, what current will flow, how much power will be turned to heat, and how long the battery will last.

PREREQUISITES

- Algebra I: solving and rearranging equations such as $V = IR$ for any variable
- Scientific notation and powers of ten
- Reading and making a graph with a best-fit line
- An Arduino Uno–compatible starter kit and a digital multimeter

MASTERY CHECKLIST

- ☐ I can define charge, current, voltage, resistance and power, with their units, and convert between prefixes.
- ☐ I can use $I = Q/t$, $V = W/Q$, $R = \rho L/A$, and $P = VI = I^2R = V^2/R$ $W = Pt$.
- ☐ I can calculate a battery's stored energy and estimated life from its capacity and a power budget.
- ☐ I can measure voltage, current, resistance, continuity and diode drop with a multimeter, connected correctly.
- ☐ I can state and follow the course safety rules, including the rules for batteries and lithium cells.

OPTIONAL KITS FOR THIS UNIT

- **Arduino Starter Kit**: Ages 13 and up. The official kit: an Arduino Uno, breadboard, components and a project book. It includes an LCD, servo, DC motor, motor-driver chip and temperature sensor; add an ultrasonic distance sensor (a few dollars) and the extra parts in the course materials list.
- **ELEGOO Uno starter kits**: Ages 12 and up. Uno-compatible kits; the larger "Super" and "Most Complete" kits include the ultrasonic sensor, servo, motor driver, LCD, IR remote and many other parts used in this course.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

1.1	**Volta's Pile: Charge and Current**	3 sessions of 50 minutes
1.2	**Voltage and Energy**	3 sessions of 50 minutes
1.3	**Ohm's Law: Georg Ohm's Wires**	3 sessions of 50 minutes
1.4	**Power: Watt, Joule and Heat**	3 sessions of 50 minutes
1.5	**The Multimeter and Lab Safety**	3 sessions of 50 minutes

Unit 1 test

Time: 50 minutes. A scientific calculator is allowed. Show the formula, the substitution with units and the answer with its unit for every calculation; correct setup earns partial credit. Write complete sentences for explanations. The test is worth 100 points.

1. **6 pts** **Lesson 1.1**

   A current of 0.25 A flows for 4.0 minutes. How much charge passes, and how many electrons is that?

2. **5 pts** **Lesson 1.1**

   Explain the disagreement between Galvani and Volta and how Volta settled it.

3. **6 pts** **Lesson 1.2**

   A 6.0 V battery pack delivers 1,200 C. How much energy is that, in J and Wh?

4. **6 pts** **Lesson 1.2**

   Two power banks: one is 5,000 mAh at 3.7 V, the other 15 Wh. Which stores more energy? Show your work.

5. **5 pts** **Lesson 1.2**

   Four AA cells (1.5 V, 2,500 mAh) are in series. Give the pack's voltage and capacity.

6. **8 pts** **Lesson 1.3**

   A 2.2 kΩ resistor is connected across 9.0 V. Find the current in mA. What resistor would give 10 mA instead?

7. **7 pts** **Lesson 1.3**

   Find the resistance of 25 m of copper wire with a cross-sectional area of $0.50\ \text{mm}^2$. ($\rho = 1.68 \times 10^{-8}\ \Omega \cdot \text{m}$.)

8. **6 pts** **Lesson 1.3**

   What is the difference between an ohmic and a non-ohmic part? Give one example of each and describe its V–I graph.

9. **8 pts** **Lesson 1.4**

   A 47 Ω resistor is placed across 5.0 V. Find the current and the power. Is a 1/4 W resistor suitable? What rating would you choose?

10. **8 pts** **Lesson 1.4**

    A circuit draws 60 mA from a 9.0 V battery rated 500 mAh. Find its power and the battery's ideal life. Why will the real life be shorter?

11. **6 pts** **Lesson 1.4**

    Explain, using $P = I^2R$, why shorting a battery with a wire is dangerous even though the wire's resistance is almost zero.

12. **7 pts** **Lesson 1.5**

    Draw (describe) how to connect a meter to measure (a) the voltage across a resistor and (b) the current through it. Which jack and function is used for each?

13. **8 pts** **Lesson 1.5**

Two 470 kΩ resistors in series are across 12 V. A meter with 10 MΩ input resistance measures the bottom resistor. What does it read? What is the percent error?

14. **6 pts** **Lesson 1.5**

State four of this course's safety rules, including one about lithium batteries.

15. **8 pts** **Lesson 1.4**

Essay (one paragraph). Joule found that heat is proportional to the square of the current, not to the current. Explain how careful measurement led him to that result, and why this law matters to an engineer designing a circuit today.

ANSWER KEY

1. $Q = It = (0.25)(240) = 60$ C; $n = 60 / 1.602 \times 10^{-19} = 3.7 \times 10^{20}$
2. Galvani thought the frog's tissue made "animal electricity." Volta thought the two metals made it and the frog only detected it. Volta built a pile of metals and brine-soaked cardboard with no frog at all, and it produced a steady current.
3. $W = QV = 7200$ J $= 2.0$ Wh
4. $5.0 \times 3.7 = 18.5$ Wh > 15 Wh: the first stores more.
5. 6.0 V; 2,500 mAh (capacity does not add in series)
6. $I = 9.0 / 2.2 = 4.1$ mA; $R = 9.0 / 0.010 = 900\ \Omega$
7. $R = (1.68 \times 10^{-8})(25) / (0.50 \times 10^{-6}) = 0.84\ \Omega$
8. Ohmic: constant R, straight-line V–I graph through the origin, e.g. a resistor. Non-ohmic: R changes with voltage or current, curved graph, e.g. an LED (almost no current below about 1.8 V, then a steep rise) or a lamp filament.
9. $I = 106$ mA; $P = 25 / 47 = 0.53$ W; no, it exceeds 0.25 W; choose at least a 1 W resistor (about twice the real power).
10. $P = 0.54$ W; $500 / 60 = 8.3$ h. Real batteries deliver less than their rating at higher currents, and the voltage falls as they discharge.
11. The only resistance left is the battery's small internal resistance, so the current is very large. Heat in the battery is $I^2 R_{\text{internal}}$, which is many watts in a small space; the battery heats, can leak, rupture or (for lithium) catch fire.
12. (a) Meter across the resistor, in parallel; red lead in V jack, DC volts. (b) Break the circuit and insert the meter so the current passes through it, in series; red lead in mA jack, DC current.
13. $R_{\parallel} = (0.47 \times 10) / (10.47) = 0.449\ \text{M}\Omega$; $V = 12 \times 0.449 / (0.47 + 0.449) = 5.86$ V vs 6.00 V; error about 2.3% low.
14. Any four, with lithium included: batteries and USB only, never wall power; never short a battery; never cut, puncture, crush or charge a damaged lithium battery and never leave one charging unattended; meter in series for current with the right jack; disconnect hot parts; safety glasses; coin cells away from children.
15. A strong answer mentions: Joule's coils in water, sensitive thermometers, insulation, stirring and correction for losses, repeated trials; doubling the current gave four times the heat, which the data forced. Today $P = I^2 R$ sets resistor and wire ratings, explains why shorts are dangerous and why high

current wastes power, and drives designs toward lower currents and adequate margins.

PORTFOLIO PIECE: A CHARACTERIZED POWER SOURCE AND ITS SAFETY CARD

Choose a battery pack you will use this year (for example, the 4-AA holder). Characterize it: its open-circuit voltage; its voltage under three loads (1 kΩ, 220 Ω and 100 Ω), with the current measured each time; its internal resistance calculated from the voltage drop; its energy in Wh; and the predicted run time of a 20 mA LED lamp on it. Present the data in a table and a graph of terminal voltage against current, and finish with a one-page safety card for your bench covering the course rules and the correct use of your meter.

LOOK FOR	WHAT IT MEANS
Measurements	Open-circuit and loaded voltages and currents measured correctly, with the meter connected the right way and units recorded.
Calculations	Internal resistance, power, energy and run time calculated with formulas and units shown.
Graph and analysis	A labeled graph of terminal voltage against current with a best-fit line, and a sentence explaining what its slope means.
Safety card	Clear, complete course safety rules and a meter checklist, signed by student and parent.

UNIT 2

DC Circuits

With charge, current, voltage and resistance in hand, you are ready for real circuits. In this unit you will learn why Edison wired his lamps in parallel, how a 21-year-old student named Kirchhoff found the two laws that solve any network, how a pair of resistors becomes a sensor or a precision measuring instrument, and how engineers draw and read circuits in the language of schematics.

The unit ends with the skill that separates engineers from hobbyists: finding what is wrong. Starting from the famous moth in the Harvard Mark II, you will learn a calm, systematic troubleshooting method and use it to find faults hidden in your own circuits.

PREREQUISITES

- Unit 1: Ohm's law, power and the multimeter
- Algebra I: solving a system of two linear equations
- Fractions and reciprocals (for parallel resistance)

MASTERY CHECKLIST

- ☐ I can find equivalent resistance, currents and voltage drops in series, parallel and series-parallel circuits.
- ☐ I can write and solve Kirchhoff's current and voltage equations, including a negative current.
- ☐ I can design a voltage divider, explain loading, and explain a balanced Wheatstone bridge.
- ☐ I can read and draw schematics with standard symbols and translate them to a breadboard.
- ☐ I can find opens and shorts systematically by measurement and keep a debugging log.

OPTIONAL KITS FOR THIS UNIT

- **A resistor assortment**: An inexpensive set of 1/4 W resistors (for example 10 Ω to 1 MΩ, about 30 values) from any electronics supplier makes Units 2–3 easier. Not required; the starter kit has the values used in the builds.
- **KiCad (free software)**: Free, open-source, professional schematic and circuit-board software for Windows, macOS and Linux. Optional for Lesson 2.4 and for the capstone in Unit 10.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

2.1	**Series and Parallel: Edison's Parallel Lamps**	3 sessions of 50 minutes
2.2	**Kirchhoff's Laws**	3 sessions of 50 minutes
2.3	**Voltage Dividers and the Wheatstone Bridge**	3 sessions of 50 minutes
2.4	**Reading and Drawing Schematics**	3 sessions of 50 minutes
2.5	**Troubleshooting: Grace Hopper's Moth**	3 sessions of 50 minutes

Unit 2 test

Time: 50 minutes. A scientific calculator is allowed. Show the formula, the substitution with units and the answer with its unit for each calculation; correct setup earns partial credit. Draw a schematic for any circuit problem where it helps. The test is worth 100 points.

1. **6 pts** **Lesson 2.1**
   Find the equivalent resistance of 220 Ω, 330 Ω and 470 Ω (a) in series and (b) in parallel.

2. **8 pts** **Lesson 2.1**
   A 9.0 V battery drives 1.0 kΩ in series with a parallel pair of 2.0 kΩ and 2.0 kΩ. Find the total current, the voltage across the pair, and the current in each 2.0 kΩ resistor.

3. **6 pts** **Lesson 2.1**

   Explain why Edison wired lamps in parallel, and why that required a high-resistance filament.

4. **6 pts** **Lesson 2.2**

   Currents of 15 mA and 8 mA flow into a node; a third wire carries 30 mA out. What is the current in the fourth wire, and which way?

5. **8 pts** **Lesson 2.2**

   A 12 V source feeds node A through 1.0 kΩ; from A, 3.0 kΩ and 6.0 kΩ each go to ground. Use node voltage to find V_A and the source current.

6. **8 pts** **Lesson 2.2**

   A 9.0 V source through 100 Ω and a 6.0 V source through 200 Ω both feed node A, and 200 Ω connects A to ground. Find V_A and the current from each source.

7. **6 pts** **Lesson 2.2**

   State Kirchhoff's two laws and the conservation law behind each.

8. **6 pts** **Lesson 2.3**

   Design a voltage divider that produces 1.5 V from 6.0 V. Give resistor values and check them.

9. **8 pts** **Lesson 2.3**

   A 4.7 kΩ / 4.7 kΩ divider on 5.0 V feeds a 4.7 kΩ load. Find the output with and without the load.

10. **6 pts** **Lesson 2.3**

    A Wheatstone bridge balances with $R_1 = 1.0\ \text{k}\Omega$, $R_2 = 3.3\ \text{k}\Omega$, $R_3 = 2.2\ \text{k}\Omega$. Find R_4. Why does balance need no calibrated meter?

11. **6 pts** **Lesson 2.4**

    What do these designators mean: R7, C2, D1, Q3, U1, SW2? What does a dot on crossing lines mean?

12. **6 pts** **Lesson 2.4**

    Explain why two resistors drawn far apart on a schematic can still be in parallel.

13. **8 pts** **Lesson 2.5**

On 6.0 V, a series string of 1.0 kΩ, 1.0 kΩ and 4.0 kΩ should read 1.0 V, 1.0 V and 4.0 V. You measure 1.2 V, 0 V and 4.8 V. Diagnose the fault and check it with numbers.

14. **4 pts** **Lesson 2.5**

How many tests does half-splitting need to find a fault among 32 stages?

15. **8 pts** **Lesson 2.5**

Essay (one paragraph). Using the story of the Harvard Mark II moth, explain why engineers troubleshoot by measuring and logging rather than by guessing, and describe your own routine.

ANSWER KEY

1. (a) 1020 Ω; (b) $1/(1/220 + 1/330 + 1/470) = 103\ \Omega$
2. Pair 1.0 kΩ; total 2.0 kΩ; $I = 4.5$ mA; pair voltage 4.5 V; 2.25 mA each
3. Parallel lets each lamp have full voltage and be switched alone, and one failure does not darken the others. But currents add, so with low-resistance lamps the total current and copper cost would be enormous; high-resistance lamps draw small currents.
4. In 23 mA, out 30 mA, so the fourth carries 7 mA into the node.
5. $(12 - V)/1 = V/3 + V/6 \rightarrow 12 - V = 0.5V \rightarrow V_A = 8.0$ V; source current 4.0 mA
6. $(9 - V)/100 + (6 - V)/200 = V/200 \rightarrow 2(9 - V) + (6 - V) = V \rightarrow V_A = 6.0$ V; 30 mA from the 9 V source, 0 mA from the 6 V source
7. KCL: current in = current out at a node (charge). KVL: voltages around a loop sum to zero (energy).
8. Ratio 1/4: for example $R_1 = 3.0$ kΩ, $R_2 = 1.0$ kΩ (6.0 × 1/4 = 1.5 V); any 3:1 pair.
9. Unloaded 2.50 V; loaded: bottom $= 2.35$ kΩ, $V = 5.0 \times 2.35/7.05 = 1.67$ V
10. $R_4 = R_3R_2/R_1 = 7.26$ kΩ. At balance the meter reads zero; a null needs only sensitivity.
11. Resistor, capacitor, diode, transistor, integrated circuit, switch. A dot means the lines are connected.
12. A schematic shows connections, not positions. If both ends of each resistor are on the same two nodes, they are in parallel however they are drawn.
13. The middle resistor is shorted (0 V across it while current still flows). Check: without it the total is 5.0 kΩ, $I = 6.0/5000 = 1.2$ mA, and the drops are 1.2 V and 4.8 V, exactly as measured.
14. 5
15. A strong answer: the team found the fault by testing operations and tracing signals to one relay, and logged it; measurement narrows the search logically and half-splitting is fast; changing one thing at a time keeps cause and effect clear; logs prevent repeating work and teach others. The routine: observe, power, ground, half-split, compare with expected values, fix one thing, retest, log.

PORTFOLIO PIECE: A DOCUMENTED SENSOR CIRCUIT

Design, simulate, build and document a circuit that turns light into a voltage and indicates it: a photoresistor divider that drives a meter reading, plus a second divider set by a potentiometer as an adjustable "threshold," and an LED indicator branch. Draw a full schematic with designators and values, predict every node voltage with Kirchhoff's laws, compare the simulation and the real measurements in a table, and include a debugging log of at least two faults you found while building it.

LOOK FOR	WHAT IT MEANS
Schematic	Standard symbols, designators, values, labeled nodes, + at top and ground at bottom.
Analysis	Node voltages predicted with dividers and Kirchhoff's laws, with the algebra shown.
Measurement	Simulated, predicted and measured values compared in a table with percent differences explained.
Debugging log	At least two faults recorded with symptom, measurement, cause and fix.

2.1 Series and Parallel: Edison's Parallel Lamps

OBJECTIVES

- Explain why early arc lamps were wired in series and why Edison wired his lamps in parallel.
- Calculate total resistance, current and voltage drops for series and parallel resistors, and simplify series-parallel combinations.
- Explain why series parts share one current and parallel parts share one voltage.
- Build and measure series and parallel circuits and test what happens when one part is removed.

> **Warm-up.** Think of an old string of holiday lights where one bad bulb makes the whole string go dark, and the lights in your house, where one lamp can burn out and the rest stay on. Sketch how you think each one is wired.

WATCH

DC parallel circuits explained - The basics how parallel circuits work working principle

The Engineering Mindset · 16:00

https://www.youtube.com/watch?v=5uyJezQNSHw

> **WHEN TO WATCH**
> After the physics paragraph. Pause at each example and calculate the total resistance and currents before the narrator does.

BACKUP VIDEO

DC Series circuits explained - The basics working principle

The Engineering Mindset · 11:29

https://www.youtube.com/watch?v=VV6tZ3Aqfuc

The companion video on series circuits; watch it if series voltage drops are still unclear.

KEY TERMS

series

Parts connected end to end in a single path, so the same current flows through each. $R_{\text{total}} = R_1 + R_2 + \cdots$

parallel

Parts connected across the same two points, so each has the same voltage. $1/R_{\text{total}} = 1/R_1 + 1/R_2 + \cdots$

equivalent resistance

The single resistance that would draw the same current from the source as a whole network of resistors.

voltage drop

The voltage across one part of a circuit, $V = IR$ for a resistor.

current divider

Parallel branches split the total current; the smaller resistance takes the larger share.

CORE IDEAS

The story. The first electric street lights were arc lamps, brilliant sparks between carbon rods. In 1878 Paris and London lit boulevards with Pavel Yablochkov's "candles," wired in **series**: one long loop from the dynamo through every lamp and back. Series wiring needed only one wire, but it had two great faults: the voltage of the loop was the sum of all the lamps, thousands of volts, and when one lamp failed, the circuit opened and every lamp went dark. Thomas Edison wanted electric light in homes, where every lamp could be switched on and off by itself. That meant wiring lamps in **parallel**, each one connected directly across the supply. On September 4, 1882, his Pearl Street Station in lower Manhattan began supplying parallel-wired lamps at about 110 V to its first customers.

How they figured it out. Parallel wiring had a hidden problem that stopped others: every lamp draws its own current from the mains, and the currents add. With the low-resistance lamps of the day, a street of houses would need copper conductors as thick as a man's arm. Edison and his mathematician Francis Upton worked through Ohm's and Joule's laws and saw the answer: make the lamp's filament a *high* resistance, about 100 Ω or more when hot, so each lamp draws well under an ampere. Edison's team tested thousands of filament materials before settling on carbonized cotton thread, then bamboo, which could survive at high resistance in a vacuum bulb. The physics of parallel circuits had set the requirement, and the engineering went looking for a material to meet it.

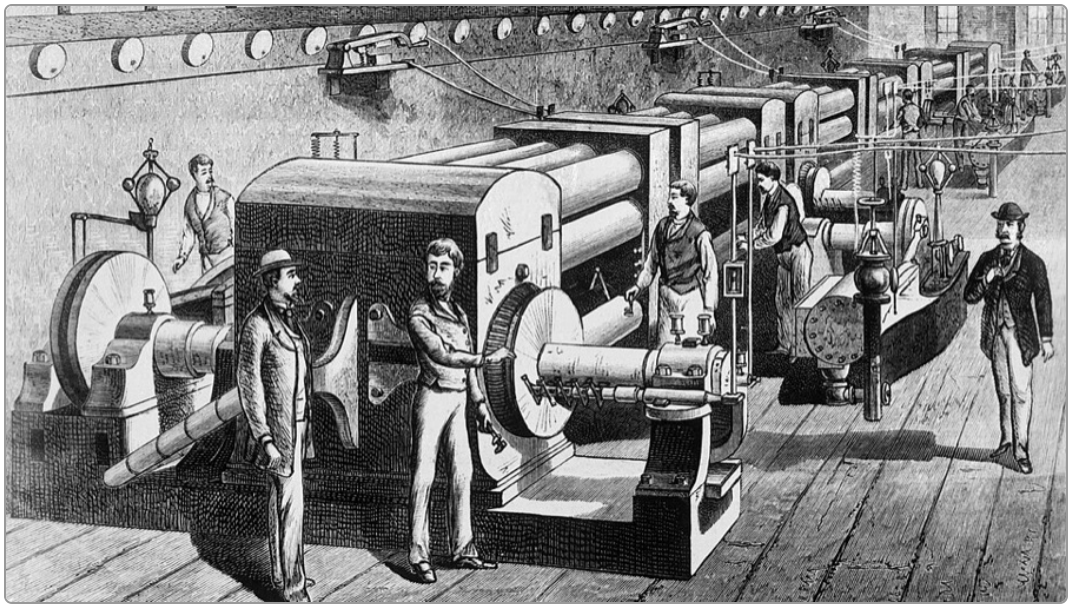
The physics. In a **series** circuit there is only one path, so the same current flows through every part, and the voltages add up to the source voltage. The total resistance is the sum: $R = R_1 + R_2 + \cdots$. Each part's share of the voltage is $V = IR$, so the largest resistor takes the largest share. In a **parallel** circuit every branch sits

across the same two points, so each gets the full voltage, and the branch currents add to the total current. The total resistance is less than the smallest branch: $1/R = 1/R_1 + 1/R_2 + \cdots$. For two resistors there is a handy form, $R = R_1 R_2/(R_1 + R_2)$, "product over sum." Mixed circuits are simplified one step at a time: replace each parallel group with its equivalent, then add the series parts.

The engineering. Almost everything is wired in parallel: the outlets in a house, the parts on a circuit board, the lamps in a building, because each part needs the full supply voltage and must work independently. Series wiring is used where the same current must pass through each part: cells stacked in a battery, a current-limiting resistor in line with an LED, a fuse or switch in line with what it protects, and some LED strings, where a small shunt in each bulb keeps the string lit if one fails. Engineers choose between them deliberately, as Edison did.

Try it. You will build both kinds of circuit with LEDs and resistors, pull one part out of each, and measure the currents and voltages to see why Edison's choice mattered.

PICTURE STUDY



Edison's Pearl Street Power Plant, Unknown engraver, about 1885 · Engraving · Wikimedia Commons

Image: Wikimedia Commons, public domain

Pearl Street Station, opened in 1882, was the first central power station built to light homes and offices with parallel-wired incandescent lamps. Each of its large "Jumbo" dynamos could light about 1,200 lamps.

Look closely

- Find the dynamos. How are they driven?
- Look for the heavy conductors leaving the machines. Why would they need to be thick?
- Count how many machines you see. Why build several machines instead of one giant one?
- Look for any instruments or switches on the walls. What would the operators need to watch?

Talk about it

1. Why did parallel wiring make the station's total current so large?
2. Why did Edison need a high-resistance lamp to make his system practical?
3. If one dynamo stopped, what would happen to the lamps it fed? How might engineers protect against that?

> **Safety first.** Batteries and USB power only, never wall power. Build with the battery disconnected and connect it last. Never put the meter on a current range directly across a battery.

BUILD

Series against Parallel: Pull One Out

You will build three LED-and-resistor branches in series and then in parallel, measure the currents and voltages in each, remove one part from each arrangement, and use Ohm's law to explain every reading.

You will need

- Breadboard, jumper wires, 4-AA holder (6 V) or Arduino 5 V pin on USB
- Three red LEDs and three 220 Ω resistors
- Resistors: 1.0 kΩ, 2.2 kΩ, 4.7 kΩ
- Digital multimeter

Steps

1. **Resistors in series.** Measure 1.0 kΩ, 2.2 kΩ and 4.7 kΩ separately, then connected in series. Predict the total and compare. Put the series string across the battery and measure the current and each voltage drop. Check that the drops add to the battery voltage.
2. **Resistors in parallel.** Connect the same three across the battery in parallel. Measure the voltage across each and the current in each branch (meter in series with that branch only) and in the total lead. Check that the branch currents add up.
3. **Equivalent resistance.** Measure the parallel group with the ohmmeter (battery disconnected). Compare with $1/R = 1/R_1 + 1/R_2 + 1/R_3$.
4. **Lamps in parallel.** Build three LED branches, each LED with its own 220 Ω resistor, all across 5 or 6 V. Measure the total current. Remove one LED. What happens to the other two, and to the total current?
5. **Lamps in series.** Now try three LEDs in series with one 220 Ω resistor across 6 V. Do they light? Measure the current. Remove one LED. What happens?
6. Predict, using about 2.0 V per red LED, what current the series string should draw at 6.0 V, and explain the difference between prediction and measurement (hint: the battery and LEDs are not exact).

7. Record everything in a table with predicted value, measured value and percent difference.
8. **Improve it.** Design a lamp that lights four LEDs from the 6 V pack at about 10 mA each with the fewest resistors. Calculate, build, measure and compare with your design.

Tips

- Measure branch currents by breaking only that branch and putting the meter in the gap.
- If a series string of LEDs will not light, the supply voltage may be less than the LEDs' total forward voltage; two in series is safer at 6 V.
- Use one color of jumper wire for + and another for − to make mistakes easy to see.

Check your work

- ☐ My measurements showed equal current in series and equal voltage in parallel.
- ☐ I calculated equivalent resistances and they matched my ohmmeter within a few percent.
- ☐ I can explain from my own data why Edison chose parallel wiring.

ENGINEER'S NOTEBOOK

1. Schematics of every circuit you built, with measured currents and voltages written on the wires and parts.
2. A table of predicted and measured values with percent differences.
3. A paragraph: Why did Edison need a high-resistance lamp? Use the numbers from practice problem 8.

KEY FORMULAS

$$R_{\text{series}} = R_1 + R_2 + R_3 + \cdots$$

$$\frac{1}{R_{\text{par}}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots$$

$$R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2}$$

From history. Edison's Pearl Street system used direct current. Within a few years George Westinghouse and Nikola Tesla promoted alternating current, which could be raised to high voltage with transformers for long-distance lines and lowered for homes. Both systems still wired lamps in parallel, as every house does today.

WORKED EXAMPLES

Example 1. Resistors of 100 Ω, 220 Ω and 470 Ω are in series across 9.0 V. Find the current and the voltage across each.

Show solution

1. Total: $R = 100 + 220 + 470 = 790\ \Omega$.
2. Current: $I = 9.0\ \text{V} \div 790\ \Omega = 11.4\ \text{mA}$.
3. Drops: $V_{100} = (0.0114)(100) = 1.14\ \text{V}$, $V_{220} = 2.51\ \text{V}$, $V_{470} = 5.35\ \text{V}$.
4. Check: $1.14 + 2.51 + 5.35 = 9.00\ \text{V}$.

Answer: 11.4 mA; 1.14 V, 2.51 V, 5.35 V

Example 2. A 1.0 kΩ and a 2.2 kΩ resistor are in parallel across 9.0 V. Find each branch current, the total current and the equivalent resistance.

Show solution

1. Each branch has 9.0 V: $I_1 = 9.0/1000 = 9.0\ \text{mA}$; $I_2 = 9.0/2200 = 4.1\ \text{mA}$.
2. Total: $I = 9.0 + 4.1 = 13.1\ \text{mA}$.
3. Equivalent: $R = (1000)(2200)/(3200) = 688\ \Omega$; check $9.0/688 = 13.1\ \text{mA}$.

Answer: 9.0 mA and 4.1 mA; 13.1 mA total; 688 Ω

Example 3. A 220 Ω resistor is in series with two 1.0 kΩ resistors that are in parallel with each other. The circuit is across 9.0 V. Find the total current and the voltage across the parallel pair.

Show solution

1. Parallel pair: $1000 \parallel 1000 = 500\ \Omega$.
2. Total: $220 + 500 = 720\ \Omega$; $I = 9.0/720 = 12.5\ \text{mA}$.
3. Voltage across the pair: $V = (0.0125)(500) = 6.25\ \text{V}$; each 1 kΩ carries $6.25\ \text{mA}$.

Answer: 12.5 mA; 6.25 V across the pair

PRACTICE

1. Easy Find the total resistance of 330 Ω, 330 Ω and 330 Ω in series, and in parallel.

   Show answer

   990 Ω; 110 Ω

2. Easy Two resistors in parallel: 4.7 kΩ and 4.7 kΩ. What is the equivalent resistance?

   Show answer

   2.35 kΩ

3. Easy In a parallel circuit, what is the same for every branch? In a series circuit?

   Show answer

   Parallel: the voltage. Series: the current.

4. Medium A 6.0 V battery drives 1.0 kΩ and 2.0 kΩ in series. Find the current and each voltage drop.

   Show answer

   2.0 mA; 2.0 V and 4.0 V

5. Medium Three lamps of 12 Ω each are in parallel on 6.0 V. Find the total current and the power of each lamp.

   Show answer

   Each 0.50 A; total 1.5 A; $P = 3.0$ W each

6. Medium Show that the equivalent of two resistors in parallel is always smaller than the smaller one, using 100 Ω and 10 kΩ.

Show answer

$R = 100 \times 10{,}000/10{,}100 = 99\ \Omega$, less than 100 Ω: adding a path always lets more current flow.

7. Medium Why did Yablochkov's series street lights all go dark when one lamp failed?

Show answer

In series there is only one path; an open lamp breaks the path, so no current flows through any lamp.

8. Hard Edison's system put 100 lamps in parallel at 110 V, each drawing 0.50 A. Find the total current and the resistance of one hot lamp. If the same lamps were wired in series, what supply voltage would they need?

Show answer

50 A total; $R = 110/0.50 = 220\ \Omega$ each; in series $100 \times 110 = 11{,}000$ V.

9. Hard A 470 Ω resistor is in series with a parallel group of 1.0 kΩ and 1.5 kΩ, across 5.0 V. Find the total current and the current in the 1.5 kΩ resistor.

Show answer

Group $= 600\ \Omega$; total $1070\ \Omega$; $I = 4.67$ mA; $V_{\text{group}} = 2.80$ V; $I_{1.5k} = 1.87$ mA

10. Hard You have only 1 kΩ resistors. Show two ways to make 1.5 kΩ.

Show answer

One 1 kΩ in series with two 1 kΩ in parallel: $1000 + 500 = 1500\ \Omega$. Or three in series (3 kΩ) in parallel with another three in series (3 kΩ): $3 \parallel 3 = 1.5\ \text{k}\Omega$.

11. Challenge Two LEDs, each with its own 220 Ω resistor, are in parallel on 5.0 V. Each LED takes 2.0 V. Find the total current. Then explain why engineers do not put two LEDs in parallel with one shared resistor.

Show answer

Each branch: $(5.0 - 2.0)/220 = 13.6$ mA; total 27.3 mA. With one shared resistor, small differences between LEDs make one take most of the current, so it overheats and the other is dim; each LED needs its own resistor.

COMMON MISTAKES

- Adding parallel resistances as if they were in series. The parallel total is always smaller than the smallest branch.
- Using product-over-sum for three resistors at once. It works for two at a time; combine two, then combine the result with the third.
- Thinking the first part in a series string gets “more current.” Every part in series has the same current.

> **Make it a game · Series or Parallel?.** Draw four circuits on cards, a mix of series, parallel and combinations, with resistor values. Shuffle and flip one at a time. Name the type, then calculate equivalent resistance in thirty seconds. Wrong answers return the card to the pile. Clear the pile with the fewest misses. Explain why Edison chose parallel lamps.

2.2 Kirchhoff's Laws

OBJECTIVES

- State Kirchhoff's current law and voltage law and explain them as conservation of charge and energy.
- Write junction and loop equations for a circuit and solve them as a system of linear equations.
- Interpret a negative current as a current flowing opposite to the assumed direction.
- Measure every current and voltage in a resistor network and verify both laws with real data.

> **Warm-up.** Water flows into a T-joint in a pipe at 5 liters per minute. One outlet carries 2 liters per minute. What must the other carry? Now walk up a staircase and back down to where you started: what is your total change in height? Keep both answers; they are Kirchhoff's two laws.

WATCH

Kirchhoff's Rules of Electrical Circuits

Flipping Physics · 14:44

https://www.youtube.com/watch?v=d0O-KUKP4nM

> **WHEN TO WATCH**
> After the physics paragraph. Pause after the rules are stated and write each one in your own words before the example.

BACKUP VIDEO

Kirchhoff's voltage law | Circuit analysis | Electrical engineering | Khan Academy

Khan Academy · 6:50

https://www.youtube.com/watch?v=Bt6V7D5av9A

A short Khan Academy explanation of the voltage law, good for review before the practice set.

KEY TERMS

node (junction)

A point where two or more circuit elements connect.

Kirchhoff's current law (KCL)

The total current flowing into a node equals the total current flowing out. Charge is not created or destroyed.

Kirchhoff's voltage law (KVL)

Around any closed loop, the sum of the voltage rises equals the sum of the voltage drops. Energy is conserved.

loop

Any closed path through a circuit that returns to its starting point.

node-voltage method

Choosing one node as ground, writing KCL at each other node in terms of unknown node voltages, and solving.

CORE IDEAS

The story. In 1845 Gustav Robert Kirchhoff was a 21-year-old student at the University of Königsberg in Prussia, working in the seminar of the physicist Franz Neumann. Ohm's law told how a single wire behaved, but telegraph engineers were building networks of wires, batteries and instruments joined in complicated ways, and no one had a general method to calculate the currents in them. In a student paper, Kirchhoff gave two rules that solve any such network. He later became one of the great physicists of the century, and with the chemist Robert Bunsen he founded spectroscopy, identifying elements by the colors of light they give off.

How they figured it out. Kirchhoff did not discover new physics so much as state old physics precisely. Charge does not pile up in a wire, so whatever current flows into a junction must flow out. And energy is conserved, so a charge that goes once around any closed loop must lose exactly as much energy as it gained. From those two ideas he showed that a network with several unknown currents gives exactly as many independent equations as unknowns, so it can always be solved. It was the same move Shannon would make a century later with Boole's algebra: turning a messy practical problem into mathematics.

The physics. The **current law** (KCL): at every node, $\sum I_{\text{in}} = \sum I_{\text{out}}$. The **voltage law** (KVL): around every loop, $\sum V = 0$, counting rises as positive and drops as negative.

To solve a circuit, choose a direction for each unknown current (any direction; a negative answer just means it flows the other way), write KCL at the nodes and KVL around enough loops, and solve the system of equations, exactly as in Algebra I. Often it is quickest to use **node voltages**: pick a ground, call the voltage of a junction V, write each branch current as (voltage difference)/(resistance), and apply KCL.

The engineering. Every circuit simulator on a computer, from the free Falstad simulator you will use to the professional SPICE program developed at Berkeley in the early 1970s, works by writing Kirchhoff's equations for every node and solving them, millions of times a second. Engineers use the laws by hand to check simulations, to find the current in a branch they cannot easily measure, and to spot measurement mistakes: if your currents into a node do not add up, a meter or a wire is wrong.

Try it. You will build a network with five resistors, measure everything, and check whether Kirchhoff's sums come out to zero within your meter's accuracy.

PICTURE STUDY



Kirchhoff, Bunsen and Roscoe, Unknown photographer, 1862 · Photograph · Wikimedia Commons

Image: Wikimedia Commons, public domain

This photograph shows Kirchhoff (left) with the chemist Robert Bunsen and the English chemist Henry Roscoe, about 1862, when Kirchhoff and Bunsen were at Heidelberg discovering new elements by their spectra.

Look closely

- Look at how the three men are posed. What does the photograph suggest about how they worked?
- Kirchhoff was physically frail and later used crutches. Look for any sign of that in the picture.
- Find anything in the image that tells you this is a photograph from the 1860s rather than a painting.

Talk about it

1. Kirchhoff's laws came from a student paper. What does that suggest about young people doing real science?
2. Why do you think a physicist and a chemist worked so well together?
3. Kirchhoff's laws are "just" conservation of charge and energy. Why was writing them down precisely so useful?

> **Safety first.** Batteries and USB power only, never wall power. Build with the battery disconnected and connect it last. Never put the meter on a current range directly across a battery.

BUILD

Kirchhoff's Laws on the Bench

You will build a five-resistor network from one battery, predict every current and voltage with Kirchhoff's laws, measure them all, and check that the currents at each node and the voltages around each loop add to zero. Then you will check your answers in a free online simulator.

You will need

- Breadboard, jumper wires, 4-AA holder (6 V)
- Resistors: 1.0 kΩ (two), 2.2 kΩ, 3.3 kΩ, 4.7 kΩ
- Digital multimeter
- A computer with Falstad's circuit simulator (falstad.com/circuit), free in a browser

Steps

1. Draw this circuit in your notebook: battery + → R_1 (1.0 kΩ) → node A. From A, R_2 (2.2 kΩ) → node B, and R_3 (3.3 kΩ) → node C. From B, R_4 (4.7 kΩ) → ground. From C, R_5 (1.0 kΩ) → node B. Label every node and choose a direction for every current.
2. Write KCL at nodes A and B and KVL around each loop. Solve for the currents (or use node voltages for A, B and C). Write predicted currents and node voltages on your schematic. (Hint: R_3 and R_5 are in series between A and B, and that pair is in parallel with R_2.)
3. Measure each resistor out of the circuit and use the measured values in a second, corrected prediction.
4. Build the circuit, connect the battery and measure the battery voltage and the voltage of nodes A, B and C relative to ground.
5. Measure every branch current by breaking the branch and inserting the meter. Record each with its direction.
6. Check KCL at A and B and KVL around both loops with your measured numbers. Calculate the percent error for each sum.

7. Build the same circuit in the Falstad simulator and compare its currents with your predictions and measurements.
8. **Improve it.** Change one resistor (for example, replace R_5 with 4.7 kΩ), predict the new node voltages first, then measure. Did Kirchhoff's laws predict the change correctly?

Tips

- Use the measured battery voltage in your predictions, not 6.0 V; fresh cells read about 6.3 V.
- Write currents with signs. A current flowing opposite to your arrow is negative.
- Measure node voltages first (no rewiring), then currents; it is faster and causes fewer mistakes.

Check your work

- ☐ My predicted and measured currents agree within about 5%.
- ☐ My KCL and KVL sums are close to zero, and I can explain any error.
- ☐ I solved a circuit with two loops using a system of equations.

ENGINEER'S NOTEBOOK

1. The labeled schematic with predicted values in pencil and measured values in pen.
2. Your KCL and KVL equations, the algebra that solves them, and the error table.
3. A screenshot or sketch of the simulator result beside your measurements.

KEY FORMULAS

$\sum I_{\text{in}} = \sum I_{\text{out}}$ (KCL)
$\sum_{\text{loop}} V = 0$ (KVL)
$I_{\text{branch}} = \dfrac{V_a - V_b}{R}$

From history. Kirchhoff's laws are an approximation that holds when circuits are small compared with the wavelength of the signals in them. In very fast circuits and antennas, engineers must use Maxwell's full equations, which Kirchhoff's laws come from.

Example 1. At a node, 25 mA flows in from one wire. Two wires leave: one carries 9 mA. A fourth wire is also connected and carries 4 mA *into* the node. What current leaves in the third wire?

Show solution

1. KCL: currents in = currents out.
2. In: $25 + 4 = 29$ mA. Out: $9 + I$.
3. $I = 29 - 9 = 20$ mA leaving.

Answer: 20 mA out of the node

Example 2. A 9.0 V battery feeds a 1.0 kΩ resistor in series with a 2.0 kΩ resistor and an unknown resistor R. The 1.0 kΩ resistor has 1.5 V across it. Find the current and R using KVL.

Show solution

1. Current: $I = 1.5\ \text{V}/1000\ \Omega = 1.5$ mA.
2. Drop across 2.0 kΩ: $(1.5\ \text{mA})(2.0\ \text{k}\Omega) = 3.0$ V.
3. KVL: $9.0 - 1.5 - 3.0 - V_R = 0$, so $V_R = 4.5$ V.
4. $R = 4.5\ \text{V}/1.5\ \text{mA} = 3.0\ \text{k}\Omega$.

Answer: 1.5 mA; $R = 3.0$ kΩ

Example 3. Two sources share a load. A 9.0 V source connects through $R_1 = 100\ \Omega$ to node A; a 3.0 V source connects through $R_2 = 100\ \Omega$ to the same node A; and $R_3 = 100\ \Omega$ connects A to ground (both sources' negative terminals are at ground). Find the node voltage and all three currents.

Show solution

1. Let the node voltage be V. Currents into A: $(9.0 - V)/100$ and $(3.0 - V)/100$. Current out through R_3: $V/100$.
2. KCL: $\dfrac{9.0 - V}{100} + \dfrac{3.0 - V}{100} = \dfrac{V}{100}$, so $12.0 - 2V = V$ and $V = 4.0$ V.
3. $I_1 = (9.0 - 4.0)/100 = 50$ mA into A; $I_3 = 4.0/100 = 40$ mA to ground.
4. $I_2 = (3.0 - 4.0)/100 = -10$ mA: the negative sign means 10 mA flows *out* of A and backward into the 3.0 V source.
5. Check KCL: $50 = 40 + 10$.

Answer: $V_A = 4.0$ V; 50 mA from the 9 V source, 40 mA to ground, 10 mA back into the 3 V source

PRACTICE

1. Easy Three wires meet at a node. Currents of 12 mA and 7 mA flow in. What flows out in the third wire?

   Show answer

   19 mA

2. Easy A 6.0 V battery drives three resistors in series. Two drops are 1.5 V and 2.5 V. What is the third?

   Show answer

   2.0 V

3. Easy Which conservation law is behind KCL, and which behind KVL?

   Show answer

   KCL: conservation of charge. KVL: conservation of energy.

4. Medium A 12 V source drives 2.0 kΩ in series with a parallel pair of 3.0 kΩ and 6.0 kΩ. Find all three currents and check KCL at the junction.

Show answer

Pair $= 2.0$ kΩ; total 4.0 kΩ; $I = 3.0$ mA; pair voltage 6.0 V; $I_{3k} = 2.0$ mA, $I_{6k} = 1.0$ mA; $3.0 = 2.0 + 1.0$ ✓.

5. Medium You measure currents into a node of 4.95 mA and out of 2.02 mA and 2.71 mA. What is the KCL error? Is something wrong?

Show answer

Out $= 4.73$ mA; error 0.22 mA, about 4%. That is larger than a typical meter error (about 1%): recheck for a missed branch or a misread meter.

6. Medium In a loop, a 9.0 V battery and drops of 3.3 V and 4.1 V across two resistors. What must the third part drop?

Show answer

1.6 V

7. Medium Why is it fine to guess the direction of an unknown current when you set up Kirchhoff's equations?

Show answer

If the guess is wrong, the answer comes out negative, which just means the current flows the other way; the magnitude is still correct.

8. Hard Solve by node voltage: a 10 V source through 1.0 kΩ to node A; from A, 2.0 kΩ to ground and 2.0 kΩ to ground. Find V_A and the source current.

Show answer

$(10 - V)/1 = V/2 + V/2$ (kΩ, mA) $\rightarrow 10 - V = V \rightarrow V = 5.0$ V; source current 5.0 mA.

9. Hard A 6.0 V source through $R_1 = 200\ \Omega$ to node A; a 6.0 V source through $R_2 = 300\ \Omega$ to node A; $R_3 = 600\ \Omega$ from A to ground. Find V_A.

Show answer

$(6 - V)/200 + (6 - V)/300 = V/600 \rightarrow 3(6 - V) + 2(6 - V) = V \rightarrow 30 = 6V \rightarrow V = 5.0$ V

10. Hard Kirchhoff wrote his laws for telegraph networks. Why would a telegraph engineer of 1845 need a way to calculate currents in a network rather than a single wire?

Show answer

Telegraph systems joined batteries, long lines, instruments and branches to several stations; the current in each instrument depended on the whole network, so a general method was needed to design and test them.

11. Challenge Set up two loop equations for this circuit and solve: a 12 V source drives $R_1 = 1.0\ \text{k}\Omega$ into node A; from A, $R_2 = 2.0\ \text{k}\Omega$ to ground and also $R_3 = 1.0\ \text{k}\Omega$ in series with $R_4 = 1.0\ \text{k}\Omega$ to ground. Find all currents.

Show answer

Right branch is 2.0 kΩ, so A sees 2 kΩ ∥ 2 kΩ = 1.0 kΩ. Total 2.0 kΩ; $I_1 = 6.0\ \text{mA}$; $V_A = 6.0\ \text{V}$; $I_2 = 3.0\ \text{mA}$; $I_{3,4} = 3.0\ \text{mA}$. Loop equations give the same: $12 = 1I_1 + 2I_2$, $2I_2 = 2I_3$, $I_1 = I_2 + I_3$.

COMMON MISTAKES

- Mixing signs in KVL: decide once whether you count drops as negative, and do it the same way all around the loop.
- Writing more equations than you need from the same loop, then getting confused. Each new loop must include at least one new part.
- Forgetting that the meter on a current range must replace a wire, not sit across a resistor.

Make it a game · Loop and Junction. Draw a two-loop circuit on paper. Your parent hides one current. Write the KCL junction equation and the KVL loop equation, then solve the system for the missing number. Check your answer by plugging back in. Swap roles and invent a circuit for your parent. Whoever solves faster earns the round.

Scripture. “Let all things be done decently and in order.” (1 Corinthians 14:40, KJV)

Kirchhoff’s method is order brought to a tangle: label every node, choose every direction, write every equation. The same orderly habit will save you hours on the bench.

2.3 Voltage Dividers and the Wheatstone Bridge

OBJECTIVES

- Derive and use the voltage-divider equation $V_{\text{out}} = V_{\text{in}} R_2/(R_1 + R_2)$.
- Explain how a potentiometer and a sensor such as a photoresistor make variable dividers.
- Explain loading and why a divider cannot power a load.
- Explain the Wheatstone bridge as two dividers compared, and build a light-sensing divider and a balanced bridge.

> **Warm-up.** Turn a volume knob or a light dimmer slowly (on a battery-powered device, or just picture it). What do you think is changing inside as the knob turns? Write your guess.

WATCH

Voltage divider | Circuit analysis | Electrical engineering | Khan Academy

Khan Academy · 6:39

https://www.youtube.com/watch?v=t_hPrz7rs34

> **WHEN TO WATCH**
> Before the worked examples. Pause when the formula is derived and derive it yourself from Ohm's law.

BACKUP VIDEO

Voltage divider tutorial

Afrotechmods · 3:53

https://www.youtube.com/watch?v=XxLKfAZrhbM

A short practical tutorial on dividers with real parts; good before the build.

KEY TERMS

voltage divider

Two resistors in series across a source; the voltage at the point between them is a fixed fraction of the source: $V_{\text{out}} = V_{\text{in}} R_2/(R_1 + R_2)$.

potentiometer

A resistor with a sliding contact (the wiper). With its ends across a source, the wiper gives any voltage from 0 to the full source: a variable divider.

photoresistor (LDR)

A light-dependent resistor whose resistance falls as light increases, from perhaps 100 kΩ or more in the dark to about 1 kΩ in bright light.

loading

The drop in a divider's output when a load draws current from it, because the load is in parallel with the lower resistor.

Wheatstone bridge

Two voltage dividers across the same source with a sensitive meter between their midpoints. When the meter reads zero, the bridge is balanced: $R_1/R_2 = R_3/R_4$.

CORE IDEAS

The story. In 1833 the English mathematician Samuel Hunter Christie described a clever circuit for comparing resistances, and ten years later Charles Wheatstone, professor at King's College London and co-inventor of the electric telegraph, made it famous in a lecture to the Royal Society. Wheatstone gave Christie the credit, but the circuit has carried Wheatstone's name ever since. Telegraph engineers used the **Wheatstone bridge** to find where an underground or undersea cable was damaged: by comparing the resistance of the line from each end, they could calculate how many miles from the station the fault lay.

How they figured it out. Meters of the 1840s were sensitive but not accurate: a galvanometer could tell whether a current flowed, but not exactly how much. Christie and Wheatstone turned the problem around. Instead of measuring a voltage, they built two voltage dividers from the same battery and adjusted a known resistor until the galvanometer between their midpoints read *zero*. A null reading needs no calibration at all, only a sensitive needle. At balance, the two dividers have the same ratio, and the unknown resistance follows from the known ones.

The physics. Two resistors in series carry the same current $I = V_{\text{in}}/(R_1 + R_2)$. The voltage across the bottom one is IR_2, so $V_{\text{out}} = V_{\text{in}}\dfrac{R_2}{R_1 + R_2}$. Equal resistors halve the voltage; a 1 kΩ over a 2 kΩ gives two-thirds. A **potentiometer** is a divider whose ratio you set by turning a knob. Replace one resistor with a **sensor** whose resistance changes, such as a photoresistor or a thermistor, and the divider turns light or

temperature into a voltage a microcontroller can read. But a divider is a poor power supply. A load connected to its output sits in parallel with R_2, lowering the effective bottom resistance and pulling the voltage down: this is **loading**. A bridge is two dividers side by side; it is balanced when $R_1/R_2 = R_3/R_4$.

The engineering. Dividers are everywhere: to scale a 9 V battery voltage down to the 0–5 V an Arduino can measure, to set a reference voltage, to read a potentiometer knob or a sensor. Engineers keep the load's resistance at least ten times larger than R_2, or use a buffer amplifier or a regulator when real current is needed. Bridges are still at the heart of precise sensors: the strain gauges in a digital kitchen scale and in bridge-monitoring systems are wired as Wheatstone bridges, so that a tiny change in one resistance gives a clean, measurable voltage.

Try it. You will build a light-meter divider with a photoresistor and a balanced bridge that measures an unknown resistor, as telegraph engineers did.

PICTURE STUDY

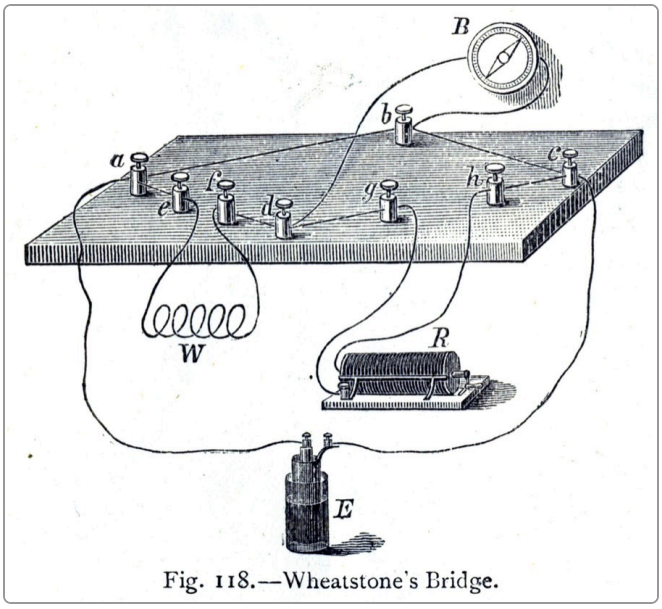


Fig. 118.—Wheatstone's Bridge.

The Wheatstone Bridge, Unknown engraver, 1890 · Engraving · Wikimedia Commons

Image: Wikimedia Commons, public domain

A laboratory bridge of the 1890s, from an electrical textbook. Engineers used instruments like this to measure resistance precisely and to locate faults in telegraph cables.

Look closely

- Find the terminals where the battery and the galvanometer would connect.
- Look for the plugs, coils or sliding contact that set the known resistances. How would you change a resistance?
- Find the four arms of the bridge. Which two make one divider, and which two make the other?
- Why is the base made of wood or another insulator?

Talk about it

1. At balance, why does the galvanometer read zero?
2. How could a telegraph engineer use a bridge to tell how far away a cable fault was?
3. How is a modern kitchen scale's strain gauge like this instrument?

Safety first. Batteries and USB power only, never wall power. Build with the battery disconnected and connect it last. Never put the meter on a current range directly across a battery. The potentiometer's wiper must never be connected straight to either end of the battery with nothing in between; always keep a resistor or a meter (on volts) between the wiper and the circuit.

BUILD

A Light Meter and a Bridge

You will build a fixed divider and check the equation, map a potentiometer, build a photoresistor light meter and calibrate it against light levels in your house, measure loading, and finally measure an unknown resistor with a balanced bridge.

You will need

- Breadboard, jumper wires, 4-AA holder or Arduino 5 V pin on USB
- Resistors: 1.0 kΩ, 2.2 kΩ, 4.7 kΩ, 10 kΩ (two), and an "unknown" resistor chosen by a parent with the bands covered by tape
- The kit's 10 kΩ potentiometer and photoresistor
- Digital multimeter, a flashlight

Steps

1. **Fixed divider.** Build 10 kΩ over 4.7 kΩ. Predict and measure V_{out}. Then swap the resistors and repeat.
2. **Potentiometer.** Connect the pot's outer pins across the supply and measure the wiper voltage at five knob positions. Mark the positions on a paper scale taped behind the knob.
3. **Light meter.** Build 10 kΩ (top) over the photoresistor (bottom). Measure the output in a dark closet, in room light, by a window and under a flashlight. Also measure the LDR's resistance alone in each place (unpowered).
4. Check: does the divider equation, using the measured LDR resistance, predict the measured output in each place?
5. **Loading.** Return to 10 kΩ over 10 kΩ. Measure the output, then connect a 1.0 kΩ resistor from the output to ground and measure again. Predict both first.
6. **Bridge.** Build two dividers side by side across the supply: 10 kΩ over 10 kΩ on the left; on the right, the potentiometer (as a variable resistor, using one end and the wiper) over the unknown resistor. Put the meter (DC volts, lowest range) between the two midpoints.

7. Turn the pot until the meter reads as close to zero as you can. Remove the pot carefully without turning it and measure its resistance. At balance, the unknown equals the pot's resistance (because the left side is 1:1). Peel the tape and compare with the color bands.
8. **Improve it.** Swap the fixed 10 kΩ / 10 kΩ divider for the photoresistor and 10 kΩ, and design a light meter whose output is close to 2.5 V in normal room light. Show your calculation.

Tips

- Use the lowest volts range near balance; the closer you get to zero, the more sensitive the bridge becomes.
- Photoresistors are slow; wait a few seconds after changing the light before you read.
- A potentiometer used as a variable resistor needs only two of its pins: one end and the wiper.

Check your work

- ☐ My measured divider outputs matched the equation within a few percent.
- ☐ I measured and explained the loading effect.
- ☐ I found an unknown resistance with a balanced bridge and checked it.

ENGINEER'S NOTEBOOK

1. Schematics of the divider, light meter and bridge.
2. A table of light level, LDR resistance, predicted and measured output.
3. A graph of potentiometer position against wiper voltage.
4. One paragraph: why a null measurement can be more accurate than a direct one.

KEY FORMULAS

$$V_{\text{out}} = V_{\text{in}} \frac{R_2}{R_1 + R_2}$$

Balanced bridge: $\dfrac{R_1}{R_2} = \dfrac{R_3}{R_4}$

From history. Wheatstone also invented the concertina, an early stereoscope and, with William Cooke, the five-needle telegraph of 1837, which ran along British railways before Morse's single-wire system won out.

WORKED EXAMPLES

Example 1. A 10 kΩ resistor (R_1, on top) and a 4.7 kΩ resistor (R_2, to ground) divide a 9.0 V battery. Find V_{out}.

Show solution

1. $V_{\text{out}} = 9.0 \times \dfrac{4.7}{10 + 4.7} = 9.0 \times 0.320 = 2.88\ \text{V}$.

Answer: 2.88 V

Example 2. A photoresistor is the bottom resistor of a divider on 5.0 V, under a fixed 10 kΩ top resistor. Its resistance is 1.0 kΩ in bright light and 100 kΩ in the dark. Find the output in each case.

Show solution

1. Bright: $V = 5.0 \times 1.0/(10 + 1.0) = 0.45\ \text{V}$.
2. Dark: $V = 5.0 \times 100/(10 + 100) = 4.55\ \text{V}$.
3. The output swings almost the whole 5 V range: an excellent light sensor for an Arduino.

Answer: 0.45 V bright, 4.55 V dark

Example 3. A divider of $R_1 = 1.0$ kΩ over $R_2 = 2.0$ kΩ on 5.0 V should give 3.33 V. What does it give with a 1.0 kΩ load connected to the output?

Show solution

1. Unloaded: $5.0 \times 2/3 = 3.33\ \text{V}$.
2. Loaded: the bottom becomes $2.0 \parallel 1.0 = 0.667$ kΩ.
3. $V = 5.0 \times 0.667/(1.0 + 0.667) = 2.0\ \text{V}$. The load has pulled the output voltage down by 40%.

Answer: 2.0 V instead of 3.33 V

PRACTICE

1. Easy Two 4.7 kΩ resistors divide 6.0 V. What is the output?

   Show answer

   3.0 V

2. **Easy** $R_1 = 2.0\ \text{k}\Omega$, $R_2 = 1.0\ \text{k}\Omega$, $V_{\text{in}} = 9.0\ \text{V}$. Find V_{out}.

   Show answer

   3.0 V

3. **Easy** A 10 kΩ potentiometer is across 6.0 V. Its wiper is 30% of the way from the ground end. What does the wiper read?

   Show answer

   1.8 V

4. **Medium** Design a divider to make about 3.3 V from 5.0 V using standard values. Check your choice.

   Show answer

   For example $R_1 = 1.8\ \text{k}\Omega$, $R_2 = 3.3\ \text{k}\Omega$: $5.0 \times 3.3/5.1 = 3.24\ \text{V}$; or 10 kΩ over 20 kΩ: 3.33 V.

5. **Medium** An Arduino can measure 0–5 V. Design a divider so it can measure a battery up to 10 V.

   Show answer

   Halve the voltage: two equal resistors, such as 10 kΩ and 10 kΩ (draws 0.5 mA at 10 V).

6. **Medium** In the photoresistor divider of Example 2, what fixed resistor would make the output exactly 2.5 V when the LDR is 10 kΩ?

   Show answer

   10 kΩ (equal resistors give half)

7. **Medium** Why can you not power a 100 Ω motor from a 10 kΩ / 10 kΩ divider on 6 V?

   Show answer

   The motor in parallel with the bottom 10 kΩ makes about 99 Ω; the output collapses to $6 \times 99/10{,}099 \approx 0.06\ \text{V}$. A divider can only feed loads far larger than its resistors.

8. Hard A bridge has $R_1 = 1.0\ \text{k}\Omega$, $R_2 = 2.2\ \text{k}\Omega$ in one divider and $R_3 = 470\ \Omega$ in the other. What value of R_4 balances it?

Show answer

$R_4 = R_3 R_2 / R_1 = 470 \times 2.2 = 1034\ \Omega$

9. Hard A bridge on 5.0 V has all four arms 1.00 kΩ, and then one bottom arm rises to 1.01 kΩ when strained. Find the voltage between the midpoints.

Show answer

Unstrained side: 2.500 V; strained side: $5.0 \times 1.01/2.01 = 2.5124$ V; difference about 12 mV.

10. Hard Why could Wheatstone measure resistance precisely with a galvanometer that was not accurately calibrated?

Show answer

At balance the galvanometer reads zero; a null needs only sensitivity, not calibration. The answer depends only on the known resistors' ratios.

11. Challenge A divider must give 2.5 V from 5.0 V and stay within 1% when a 100 kΩ load is attached. What is the largest equal-resistor value you can use?

Show answer

With R and $R \parallel 100\text{k}$ the output is $5 \cdot R_p/(R + R_p)$. Requiring at least 2.475 V gives $R_p/(R + R_p) \geq 0.495$, so $R_p \geq 0.980R$, which means $100/(R + 100) \geq 0.980$ (with R in kΩ), so $R \leq 2.0\ \text{k}\Omega$. Use about 2 kΩ or less.

COMMON MISTAKES

- Putting R_1 in the numerator. The output is across R_2, the resistor to ground, so R_2 goes on top of the fraction.
- Expecting a divider to drive a motor, LED or speaker. Use a divider only to make a signal or a reference.
- Turning the potentiometer while removing it from the bridge, which loses the balance setting.

> **Make it a game · Divider Guess.** Name that voltage. Your parent gives V_in, R1 and R2, and you say V_out within ten seconds using R2 ÷ (R1 + R2). Then change the bottom resistor to a photoresistor and predict what happens in the dark. Ten right answers in a row beats the record. Explain loading in one sentence.

2.4 Reading and Drawing Schematics

OBJECTIVES

- Recognize the standard symbols for sources, resistors, capacitors, diodes, LEDs, transistors, switches, ground and meters.
- Read a schematic as a map of connections (nodes), not of physical layout, and translate it into a breadboard layout.
- Draw neat, conventional schematics with reference designators, values and net labels.
- Simulate a schematic, build it, and compare measured and simulated results.

> **Warm-up.** Draw a quick picture of your last build from Lesson 2.1 the way it looks on the breadboard. Then try to draw it again using only lines and simple symbols. Which drawing would let a friend rebuild it fastest?

WATCH

Collin's Lab: Schematics

Make: · 6:10

https://www.youtube.com/watch?v=9cps7Q_IrX0

> **WHEN TO WATCH**
> At the start of the lesson, before the symbol table. Collin's Lab is short and friendly; keep a pencil ready to copy each symbol as it appears.

BACKUP VIDEO

How to Read a Schematic - Another Teaching Moment | Digi-Key Electronics

DigiKey · 5:03

https://www.youtube.com/watch?v=-dzHDgJVJh4

A short follow-up from DigiKey on reading the connections in a real schematic.

KEY TERMS

schematic

A diagram of a circuit that shows each part as a standard symbol and each connection as a line. It shows what connects to what, not where parts sit.

net (node)

Every wire and terminal that is connected together at the same voltage. Every point on a net is electrically the same point.

reference designator

The label that identifies a part: R1, C2, D1, Q1, U3, SW1, LED1.

junction dot

A dot where crossing lines are joined. Lines that cross without a dot are not connected.

ground symbol

A symbol marking the 0 V reference. Every ground symbol in a schematic is connected to every other.

CORE IDEAS

The story. In the early 1920s radio swept America. Thousands of young people built receivers at kitchen tables from diagrams printed in magazines such as Hugo Gernsback's *Radio News*, founded in 1919. Some diagrams were drawings of the actual parts; the most useful were schematics, which showed only symbols and connections, so that a builder could arrange the parts however he liked. Edwin Armstrong's regenerative receiver of 1912–1914, one of the most important radio circuits ever invented, was patented with a schematic that any trained reader could build from. The schematic became the shared language of engineers, as precise as a sentence and far shorter.

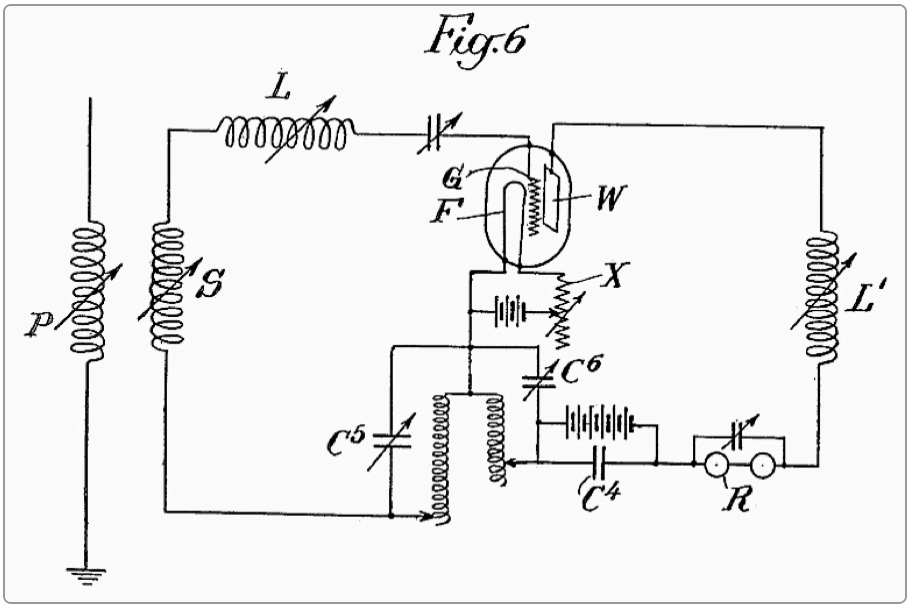
How they figured it out. Early electrical drawings varied from company to company and country to country. As the electrical and radio industries grew, engineering societies agreed on standard symbols, so that a drawing made in one place could be read in another. In the United States today the standard is IEEE 315, and internationally IEC 60617; the two differ in small ways (for example, a resistor is a zigzag in the American standard and a small rectangle in the European one). Learn both; you will see both in datasheets.

The physics. A schematic is a map of **nodes**. Every line connected together, however long or bent, is one node at one voltage. That is why you can redraw a circuit with parts moved around and it is still the same circuit, as long as every connection is kept. Reading a schematic means asking, for each part: which node is each end on? Two parts are in parallel if both ends share the same two nodes; they are in series if they share one node that nothing else touches. Convention helps the reader: positive supply at the top, ground at the bottom, signals flowing left to right, and a dot wherever wires join.

The engineering. Engineers draw schematics before they build, and they keep them up to date after every change, because a circuit without a correct schematic cannot be fixed by anyone else. Free tools such as KiCad draw professional schematics and lay out printed circuit boards from them; simulators such as Falstad or the one in Tinkercad Circuits run them before any part is bought. Good schematics label every part with a designator and value (R1 10k, C1 100µ), name important nets (VCC, GND, SENSOR), and include notes such as the battery type and the expected current.

Try it. In the build you will take a schematic, simulate it, translate it to a breadboard, and check that your measurements match the simulation.

PICTURE STUDY



Armstrong's Regenerative Receiver Patent, Figure 6, Edwin H. Armstrong, filed 1913, granted 1914 · Patent drawing · U.S. Patent 1,113,149

Image: Wikimedia Commons, public domain

Edwin Armstrong's regenerative circuit fed part of a vacuum tube's output back to its input, multiplying its sensitivity. This patent figure is a true schematic: symbols and connections, not a picture of parts.

Look closely

- Find the antenna and the ground connection at the left.
- Find the vacuum tube, with its filament, grid and plate. Which symbol is it?
- Find the batteries. How many are there, and why might a tube need more than one?
- Trace a path from the antenna to the earphones. Which coil feeds the output back toward the input?

Talk about it

1. Which symbols are still used today, and which have changed?
2. Why must a patent drawing show the connections so precisely?
3. Feedback can make a circuit more sensitive but also make it squeal. Why might feeding output back to input cause oscillation?

> **Safety first.** Batteries and USB power only, never wall power. Build with the battery disconnected and connect it last. Never put the meter on a current range directly across a battery.

BUILD

Schematic to Simulation to Breadboard

You will redraw your earlier builds as proper schematics, then take a new schematic, simulate it in a free online simulator, build it on the breadboard, and check that the real circuit matches the simulation node by node.

You will need

- Graph paper and pencil (and optionally the free KiCad schematic editor)
- A computer with Falstad's simulator (falstad.com/circuit) or Tinkercad Circuits
- Breadboard, jumper wires, 4-AA holder, resistors: 1.0 kΩ (two), 2.0 kΩ or 2.2 kΩ (two), 220 Ω; a red LED; a push button from the kit
- Digital multimeter

Steps

1. Redraw two of your earlier circuits (from Lessons 2.1 and 2.3) as clean schematics: + at top, ground at bottom, designators and values on every part, dots at every junction.
2. Copy this schematic: 6 V battery; R1 (1.0 kΩ) from + to node A; R2 (1.0 kΩ) from A to node B; R3 (2.2 kΩ) from B to ground; R4 (2.2 kΩ) from A to ground; and from node B, a push button SW1 in series with R5 (220 Ω) and LED1 to ground.
3. Before simulating, label every node and predict V_A and V_B with the button open (practice problem 8 is very close to this).
4. Build it in the simulator. Record the node voltages with the button open and closed. Note what pressing the button does to V_B, and why (the LED branch loads node B).
5. Plan the breadboard layout on paper: assign each node to a breadboard row or rail. Write the row numbers on your schematic.
6. Build the circuit. Before connecting the battery, use the continuity test to check that each node is connected where it should be and nowhere else.

7. Connect the battery, measure V_A and V_B with the button open and pressed, and compare with the simulation.
8. **Improve it.** Have someone else build your circuit from your schematic alone, without help. Note every question they ask; each one marks something your schematic did not make clear. Revise the schematic.

Tips

- Draw with a ruler and leave room; crowded schematics cause wiring mistakes.
- In the simulator, wires turn colors with voltage and moving dots show current; use them to check your understanding.
- Mark each node on the breadboard plan with a different colored pencil.

Check your work

- ☐ My schematics use standard symbols, designators, values and junction dots.
- ☐ I translated a schematic into a breadboard layout that worked the first time or after a documented fix.
- ☐ My measured node voltages match the simulation within a few percent.

ENGINEER'S NOTEBOOK

1. The redrawn schematics of two earlier builds.
2. The new schematic with nodes labeled, predicted, simulated and measured voltages in three colors.
3. The list of questions your helper asked, and the changes you made.

> **From history.** Armstrong later invented the superheterodyne receiver (1918), used in nearly every radio for a century, and wide-band FM radio (1933). He fought long patent battles over regeneration and lost one before the Supreme Court in 1934, though most engineers credited him as its inventor.

Example 1. A schematic shows a 9.0 V battery, R1 = 1.0 kΩ from the + terminal to node A, and R2 = 2.0 kΩ and R3 = 2.0 kΩ each drawn from node A to ground. Describe the connections in words and find the current in each resistor.

Show solution

1. Nodes: + terminal to R1; node A joins R1, R2 and R3; ground joins R2, R3 and the battery −.
2. R2 and R3 share both nodes (A and ground), so they are in parallel: $2.0 \parallel 2.0 = 1.0\ \text{k}\Omega$.
3. R1 is in series with that pair: total $2.0\ \text{k}\Omega$; $I_1 = 9.0/2000 = 4.5\ \text{mA}$.
4. Node A: $V_A = (4.5\ \text{mA})(1.0\ \text{k}\Omega) = 4.5\ \text{V}$; $I_2 = I_3 = 4.5/2000 = 2.25\ \text{mA}$.

Answer: $I_1 = 4.5\ \text{mA}$, $I_2 = I_3 = 2.25\ \text{mA}$

Example 2. Two lines cross on a schematic with no dot, and elsewhere two lines meet in a T with a dot. A student wires both as connections. What goes wrong, and what is the rule?

Show solution

1. Lines crossing without a dot are *not* connected; they only pass over each other.
2. A dot (or a T-junction) means connected.
3. Wiring the crossing as a connection joins two nodes that should be separate, which can short a supply or bypass a part.

Answer: No dot means no connection; draw T-junctions with dots to avoid ambiguity

Example 3. Translate this schematic to a breadboard plan: 5 V → R1 (220 Ω) → LED1 anode; LED1 cathode → GND.

Show solution

1. Place the LED's two legs in two different rows, say row 10 (anode, long leg) and row 11 (cathode).
2. Put R1 from the + rail to row 10: that makes the node between R1 and the anode.
3. Run a jumper from row 11 to the − (ground) rail.
4. Connect the rails to the Arduino's 5V and GND pins. Every schematic node is now one breadboard row or rail.

Answer: Rows 10 and 11 become the two nodes; R1 bridges the + rail to row 10; a jumper takes row 11 to ground

PRACTICE

1. Easy Draw (or describe) the symbols for a resistor (both standards), a battery, an LED and ground.

   Show answer

   Resistor: zigzag (IEEE) or rectangle (IEC); battery: long and short parallel lines (long is +); LED: a triangle pointing to a bar with two small arrows pointing out; ground: three shrinking horizontal lines (or a downward triangle).

2. Easy What does the designator U2 usually mean? C4? Q1?

   Show answer

   U: an integrated circuit; C: a capacitor; Q: a transistor.

3. Easy On a schematic, two lines cross with no dot. Are they connected?

   Show answer

   No.

4. Medium A schematic shows R1 and R2 both drawn from node VCC to node X. Are they in series or in parallel?

   Show answer

   Parallel: both ends share the same two nodes.

5. **Medium** Why do engineers draw schematics with the positive supply at the top and ground at the bottom?

Show answer

Convention: it lets the reader see voltage “falling” down the page and current flowing top to bottom, so the circuit can be understood at a glance.

6. **Medium** How many nodes are in the circuit of Worked Example 1?

Show answer

Three: the + terminal node, node A, and ground.

7. **Medium** On a breadboard, which holes in a numbered row are connected? What about the long rails along the edges?

Show answer

The five holes on one side of the center gap in each row are connected; the long rails are connected along their length (on some boards each rail is split in the middle).

8. **Hard** A schematic shows 6.0 V, R1 = 1.0 kΩ to node A, R2 = 1.0 kΩ from A to node B, R3 = 2.0 kΩ from B to ground and R4 = 2.0 kΩ from A to ground. Find V_A and V_B.

Show answer

R2 + R3 = 3.0 kΩ, parallel with R4 = 2.0 kΩ gives 1.2 kΩ; total 2.2 kΩ; $I = 2.73\ \text{mA}$; $V_A = 6.0 \times 1.2/2.2 = 3.27\ \text{V}$; $V_B = 3.27 \times 2/3 = 2.18\ \text{V}$

9. **Hard** In *Radio News*, why would a schematic be more useful to a reader than a drawing of the finished radio?

Show answer

A schematic shows exactly what connects to what, with no confusion from part shapes or positions, so the reader can build with different parts or a different layout and still get every connection right.

10. **Challenge** A schematic has a ground symbol in three places and no wire drawn between them. A student builds it with the three ground points left unconnected and nothing works. Explain.

    Show answer

    All ground symbols are the same node. They are drawn separately only to keep the drawing tidy. On the breadboard they must all be joined to the ground rail and the battery's − terminal.

COMMON MISTAKES

- Drawing a schematic that copies the breadboard layout, with wires looping everywhere. Draw the connections clearly instead; the layout is a separate drawing.
- Leaving out junction dots, or using a four-way crossing as a junction. Use T-junctions with dots.
- Forgetting that separate ground symbols must all be connected on the real board.

> **Make it a game · Symbol Speed Draw.** Beat the clock. Draw as many standard schematic symbols as you can from memory in sixty seconds: source, resistor, capacitor, diode, LED, transistor, switch, ground, meter. Your parent checks each. Then trace one schematic and say where the nodes are. Record your count and try to beat it tomorrow.

2.5 Troubleshooting: Grace Hopper's Moth

OBJECTIVES

- Use a systematic troubleshooting method: observe, check power, half-split, compare with expected values, fix one thing, retest.
- Predict the voltages a healthy circuit should show, and use the difference from measured values to locate opens and shorts.
- Recognize the most common faults on a breadboard and in code.
- Keep a debugging log and find several hidden faults by measurement.

> **Warm-up.** Think of the last time something did not work: a bicycle, a game, a recipe. What did you check first? Did you guess or test? Write down the steps you took, in order.

WATCH

How to Debug a Circuit (Lesson #3)

Science Buddies · 5:33

https://www.youtube.com/watch?v=9GLaU-BCEQM

> **WHEN TO WATCH**
> After the core ideas, before the build. Watch how each problem is found by checking, not guessing; pause at each prompt and predict the fault first.

BACKUP VIDEO

10 Common Beginner Circuit Mistakes

Ben Finio · 23:05

https://www.youtube.com/watch?v=0Kdas77paY4

Ben Finio walks through ten common beginner circuit mistakes on a breadboard; watch it before the fault-finding challenge and keep the list beside your bench.

KEY TERMS

open circuit

A break in a path, so no current can flow: a broken wire, a loose jumper, a part in the wrong row. Across an open, you usually measure the full supply voltage.

short circuit

An unintended low-resistance path that bypasses part of a circuit. Across a short, you measure nearly 0 V; through it, a large current.

half-splitting

Testing at the middle of a signal path to tell which half holds the fault, then halving again, so a fault in n steps is found in about $\log_2 n$ tests.

known good

A part, circuit or value that is known to work, used for comparison.

debugging log

A dated record of each symptom, test, result and change, so that a fault is found once and remembered.

CORE IDEAS

The story. On September 9, 1947, the operators of the Harvard Mark II, a large relay computer, traced a fault to Relay #70 on Panel F. Wedged between its contacts was a moth. They removed it, taped it into the logbook, and wrote beside it: “First actual case of bug being found.” Grace Hopper, a mathematician and U.S. Navy officer on the Harvard team who later led the development of COBOL, loved to tell the story, and the logbook page is now at the Smithsonian. Engineers had called faults “bugs” since at least Edison’s day; the joke on the page was that this one was real.

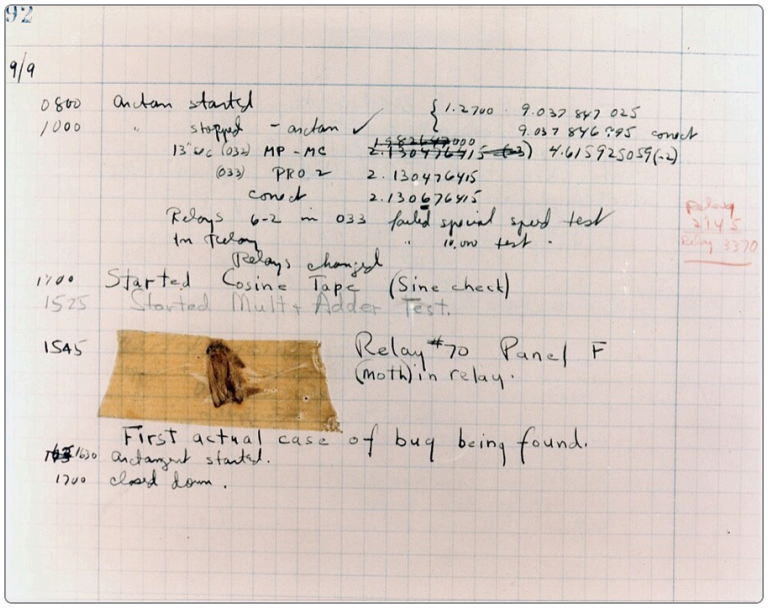
How they figured it out. The Mark II team did not guess. The machine gave wrong answers; they ran test problems to see which operation failed, followed the signal through the panels, and checked relay after relay until they found the one that did not close. That is the method every good engineer uses: observe the symptom exactly, form a hypothesis, test it with a measurement, and narrow the search. The logbook itself is part of the method. A fault written down, with what was tried, is a fault that teaches.

The physics. Troubleshooting is applied Ohm's and Kirchhoff's laws. Before you measure, know what a healthy circuit should read. In a series circuit with an **open**, no current flows, so there is no voltage drop across the good resistors (0 V) and the *whole* supply voltage appears across the break. With a **short** across a part, that part reads 0 V and the rest of the circuit takes more voltage and more current. A reading of exactly the supply voltage or exactly 0 V where you expected something in between is the clearest clue you will ever get.

The engineering. A dependable routine: (1) Observe and describe the symptom exactly. (2) Check power first: is the battery voltage right at the circuit, not just at the battery? (3) Check ground: is every ground connected? (4) Half-split: measure in the middle of the path and decide which half is bad. (5) Compare with expected values or a known-good circuit. (6) Fix *one* thing, then retest. (7) Write it down. On a breadboard, the usual faults are a part one row off, a lead not pushed in, an LED or diode backward, a missing ground, a jumper in the wrong rail, a split power rail, a dead battery, and a broken jumper wire. In code (Units 7–10) the usual faults are the wrong pin number, a missing semicolon or colon, and a variable changed in the wrong place.

Try it. A parent will hide faults in your circuits, and you will find them by measurement alone, logging every step.

PICTURE STUDY



The First Computer Bug, U.S. Navy (Harvard Mark II team), September 9, 1947 · Logbook page with a moth taped in · Smithsonian National Museum of American History

Image: Wikimedia Commons, public domain

This is the logbook page from the Harvard Mark II on which the operators taped the moth they found in Relay #70. It is a record of a debugging session, written as it happened.

Look closely

- Find the moth. Where on the page is it, and what is written beside it?
- Read the times written down the left side. What do they tell you about how the team worked?
- Find words like “started,” “stopped” or “test.” What were the operators doing before they found the moth?
- Look at the handwriting. Was this written neatly afterward or during the work?

Talk about it

1. Why would a team keep a logbook like this?
2. How did the team know which relay to look in?
3. What would you write in your own debugging log after finding a fault?

> **Safety first.** Batteries and USB power only, never wall power. Build with the battery disconnected and connect it last. Never put the meter on a current range directly across a battery. Hidden faults set by a parent must never include a short directly across the battery; they may include open connections, reversed LEDs, wrong resistor values, a dead cell or a misplaced jumper.

BUILD

The Fault-Finding Challenge

You will build three known-good circuits and record their healthy voltages. A parent will then add one hidden fault at a time, and you will find each by measurement alone, keeping a debugging log.

You will need

- Breadboard, jumper wires, 4-AA holder (and one deliberately weak or dead AA cell)
- Resistors: 1.0 kΩ, 2.0 kΩ or 2.2 kΩ, 3.3 kΩ, 220 Ω (three), 10 kΩ (two); three red LEDs
- Digital multimeter
- A helper to set faults

Steps

1. Build circuit A: 1.0 kΩ, 2.2 kΩ and 3.3 kΩ in series on the battery. Circuit B: three LED branches in parallel, each LED with a 220 Ω resistor. Circuit C: a 10 kΩ / 10 kΩ divider.
2. For each circuit, write the expected voltages at every node and across every part, then measure and record the healthy values. This is your known-good reference.
3. Write your troubleshooting routine on a card: observe, power, ground, half-split, compare, fix one thing, retest, log.
4. Leave the room while your helper adds one fault to one circuit (an open, a backward LED, a part one row off, a wrong resistor value, a weak cell, a jumper on the wrong rail).
5. Return and find it using only your eyes and the meter. Do not pull parts out to test them until your measurements point to one part. Log every measurement and what it told you.
6. Fix the fault, retest the whole circuit against the known-good values, and record how many measurements it took.

7. Repeat for at least five faults. Then trade places: set faults for your helper and watch their method.
8. **Improve it.** Look back over your log. Which measurement found faults fastest? Rewrite your routine card with what you learned.

Tips

- Measure voltages to ground with the black probe clipped to the ground rail; you then need only one hand to probe.
- Wiggle a suspect jumper while watching the meter. A reading that jumps means a bad contact.
- Say aloud what you expect before each measurement. Surprise is information.

Check your work

- ☐ I found at least five hidden faults by measurement.
- ☐ I kept a debugging log of symptom, test, result and fix for each.
- ☐ I can explain how an open and a short each show up on a voltmeter.

ENGINEER'S NOTEBOOK

1. Schematics of circuits A, B and C with their healthy (known-good) values.
2. Your debugging log for every fault.
3. Your revised troubleshooting routine card.

KEY FORMULAS

tests needed $\approx \log_2 n$ (half-splitting)

$V_{\text{open}} \approx V_{\text{supply}}, \quad V_{\text{short}} \approx 0$

From history. Grace Hopper, who retired as a rear admiral, went on to write one of the first compilers (programs that translate human-readable code into machine instructions) and to lead the work that produced the COBOL language, still used in banking. She kept a short piece of wire, about 30 cm long, to show people how far light travels in a nanosecond.

Example 1. A 9.0 V battery drives R1 = 1.0 kΩ, R2 = 2.0 kΩ and R3 = 3.0 kΩ in series. Healthy drops should be 1.5 V, 3.0 V and 4.5 V. You measure 0 V, 9.0 V and 0 V. What is wrong?

Show solution

1. No drop across R1 and R3 means no current is flowing.
2. The full 9.0 V across R2 means the break is at R2: it is open (or one of its legs is not in the right row).
3. Fix: reseat or replace R2, then remeasure all three drops.

Answer: R2 (or its connection) is open

Example 2. Same circuit. Now you measure 2.25 V, 0 V and 6.75 V. What is wrong?

Show solution

1. 0 V across R2 with current still flowing means R2 is shorted (for example, a jumper or both legs in the same row).
2. Check: with R2 gone, total $= 4.0\ \text{k}\Omega$, $I = 2.25\ \text{mA}$, drops $2.25\ \text{V}$ and $6.75\ \text{V}$, exactly as measured.

Answer: R2 is shorted

Example 3. A signal passes through 16 stages before it reaches an output that does not work. How many measurements does half-splitting need, at most, to find the one bad stage? How many would checking stage by stage take in the worst case?

Show solution

1. Each test halves the possibilities: $16 \to 8 \to 4 \to 2 \to 1$.
2. That is $\log_2 16 = 4$ tests.
3. Stage by stage from the start could take up to 15 or 16 tests.

Answer: 4 tests by half-splitting, against up to 16

PRACTICE

1. Easy In a series circuit on 6.0 V, you measure the full 6.0 V across one resistor and 0 V across the others. What kind of fault is it, and where?

Show answer

An open, at the resistor showing 6.0 V.

2. Easy What should you always check first when a circuit does nothing?

Show answer

Power and ground: the supply voltage measured at the circuit itself, and that ground is connected.

3. Easy Where is the Harvard Mark II logbook page with the moth today?

Show answer

At the Smithsonian's National Museum of American History.

4. Medium An LED circuit (6 V, 220 Ω, red LED) does not light. You measure 6.0 V across the LED and 0 V across the resistor. What are two likely causes?

Show answer

No current is flowing and the LED has the full voltage: the LED is in backward, or one LED leg is not connected (open at the LED).

5. Medium How many tests does half-splitting need for a path of 64 stages?

Show answer

$\log_2 64 = 6$

6. Medium Why should you change only one thing at a time when debugging?

Show answer

If you change several things and it starts working (or gets worse), you do not know which change mattered, and you may have introduced a new fault.

7. Medium A divider of two 10 kΩ resistors on 6.0 V reads 6.0 V at the midpoint. Give two possible faults.

Show answer

The bottom resistor is open (or not connected to ground), or the top resistor is shorted.

8. Hard A parallel circuit of three LED branches on 5 V: one branch is dark and the other two are fine. Where do you not need to look, and where do you look?

   Show answer

   Power, ground and the shared rails are fine, since two branches work. Look only in the dark branch: its LED orientation, its resistor and its jumpers.

9. Hard Your 4-AA pack reads 6.2 V on the bench but the circuit on the breadboard gets only 3.1 V at the + rail. What does that tell you, and what do you check?

   Show answer

   Half the supply is lost before the circuit: likely a bad connection or a split rail with a jumper missing, or a cell not touching its contact. Measure along the path from the battery to the rail to find where the voltage drops.

10. Challenge In Worked Example 1, suppose instead you measure 1.5 V, 3.0 V and 0 V, and the battery reads 9.0 V. What is odd about these readings, and what do you do?

    Show answer

    The drops add to only 4.5 V, which breaks Kirchhoff's voltage law, so a measurement must be wrong. If R3 were really shorted, the current would double to 3.0 mA and R1 and R2 would read 3.0 V and 6.0 V; they read healthy values, so R3 almost certainly does have 4.5 V across it. The probe was probably on the wrong node, or the meter was on the wrong function or range. Remeasure: a reading that breaks Kirchhoff's law is almost always a measurement mistake.

COMMON MISTAKES

- Changing parts at random hoping the problem goes away. Measure first; let the numbers point to the fault.
- Measuring the battery off the circuit and assuming the circuit gets the same voltage.
- Stopping once the symptom is gone without retesting the whole circuit, which can leave a second fault hidden.

Make it a game · Find the Fault. Troubleshooting duel. Your parent draws a small circuit and secretly marks one open or short. You ask for pretend meter readings and use half-splitting to locate the fault in as few questions as possible. Say the expected voltage before each reading. Fewest questions wins. Swap and write a debugging log.

Scripture. “It is the glory of God to conceal a thing: but the honour of kings is to search out a matter.” (Proverbs 25:2, KJV)

Debugging is searching out a matter, patiently and in order. Every fault has a cause, and finding it by careful measurement is honorable work.

UNIT 2

DC Circuits

With charge, current, voltage and resistance in hand, you are ready for real circuits. In this unit you will learn why Edison wired his lamps in parallel, how a 21-year-old student named Kirchhoff found the two laws that solve any network, how a pair of resistors becomes a sensor or a precision measuring instrument, and how engineers draw and read circuits in the language of schematics.

The unit ends with the skill that separates engineers from hobbyists: finding what is wrong. Starting from the famous moth in the Harvard Mark II, you will learn a calm, systematic troubleshooting method and use it to find faults hidden in your own circuits.

PREREQUISITES

- Unit 1: Ohm's law, power and the multimeter
- Algebra I: solving a system of two linear equations
- Fractions and reciprocals (for parallel resistance)

MASTERY CHECKLIST

- ☐ I can find equivalent resistance, currents and voltage drops in series, parallel and series-parallel circuits.
- ☐ I can write and solve Kirchhoff's current and voltage equations, including a negative current.
- ☐ I can design a voltage divider, explain loading, and explain a balanced Wheatstone bridge.
- ☐ I can read and draw schematics with standard symbols and translate them to a breadboard.
- ☐ I can find opens and shorts systematically by measurement and keep a debugging log.

OPTIONAL KITS FOR THIS UNIT

- **A resistor assortment**: An inexpensive set of 1/4 W resistors (for example 10 Ω to 1 MΩ, about 30 values) from any electronics supplier makes Units 2–3 easier. Not required; the starter kit has the values used in the builds.
- **KiCad (free software)**: Free, open-source, professional schematic and circuit-board software for Windows, macOS and Linux. Optional for Lesson 2.4 and for the capstone in Unit 10.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

2.1	**Series and Parallel: Edison's Parallel Lamps**	3 sessions of 50 minutes
2.2	**Kirchhoff's Laws**	3 sessions of 50 minutes
2.3	**Voltage Dividers and the Wheatstone Bridge**	3 sessions of 50 minutes
2.4	**Reading and Drawing Schematics**	3 sessions of 50 minutes
2.5	**Troubleshooting: Grace Hopper's Moth**	3 sessions of 50 minutes

Unit 2 test

Time: 50 minutes. A scientific calculator is allowed. Show the formula, the substitution with units and the answer with its unit for each calculation; correct setup earns partial credit. Draw a schematic for any circuit problem where it helps. The test is worth 100 points.

1. **6 pts** **Lesson 2.1**

   Find the equivalent resistance of 220 Ω, 330 Ω and 470 Ω (a) in series and (b) in parallel.

2. **8 pts** **Lesson 2.1**

   A 9.0 V battery drives 1.0 kΩ in series with a parallel pair of 2.0 kΩ and 2.0 kΩ. Find the total current, the voltage across the pair, and the current in each 2.0 kΩ resistor.

3. **6 pts** **Lesson 2.1**

   Explain why Edison wired lamps in parallel, and why that required a high-resistance filament.

4. **6 pts** **Lesson 2.2**

   Currents of 15 mA and 8 mA flow into a node; a third wire carries 30 mA out. What is the current in the fourth wire, and which way?

5. **8 pts** **Lesson 2.2**

   A 12 V source feeds node A through 1.0 kΩ; from A, 3.0 kΩ and 6.0 kΩ each go to ground. Use node voltage to find V_A and the source current.

6. **8 pts** **Lesson 2.2**

   A 9.0 V source through 100 Ω and a 6.0 V source through 200 Ω both feed node A, and 200 Ω connects A to ground. Find V_A and the current from each source.

7. **6 pts** **Lesson 2.2**

   State Kirchhoff's two laws and the conservation law behind each.

8. **6 pts** **Lesson 2.3**

   Design a voltage divider that produces 1.5 V from 6.0 V. Give resistor values and check them.

9. **8 pts** **Lesson 2.3**

   A 4.7 kΩ / 4.7 kΩ divider on 5.0 V feeds a 4.7 kΩ load. Find the output with and without the load.

10. **6 pts** **Lesson 2.3**

    A Wheatstone bridge balances with $R_1 = 1.0\ \text{k}\Omega$, $R_2 = 3.3\ \text{k}\Omega$, $R_3 = 2.2\ \text{k}\Omega$. Find R_4. Why does balance need no calibrated meter?

11. **6 pts** **Lesson 2.4**

    What do these designators mean: R7, C2, D1, Q3, U1, SW2? What does a dot on crossing lines mean?

12. **6 pts** **Lesson 2.4**

    Explain why two resistors drawn far apart on a schematic can still be in parallel.

13. **8 pts** **Lesson 2.5**

On 6.0 V, a series string of 1.0 kΩ, 1.0 kΩ and 4.0 kΩ should read 1.0 V, 1.0 V and 4.0 V. You measure 1.2 V, 0 V and 4.8 V. Diagnose the fault and check it with numbers.

14. **4 pts** **Lesson 2.5**

How many tests does half-splitting need to find a fault among 32 stages?

15. **8 pts** **Lesson 2.5**

Essay (one paragraph). Using the story of the Harvard Mark II moth, explain why engineers troubleshoot by measuring and logging rather than by guessing, and describe your own routine.

ANSWER KEY

1. (a) 1020 Ω; (b) $1/(1/220 + 1/330 + 1/470) = 103\ \Omega$
2. Pair 1.0 kΩ; total 2.0 kΩ; $I = 4.5$ mA; pair voltage 4.5 V; 2.25 mA each
3. Parallel lets each lamp have full voltage and be switched alone, and one failure does not darken the others. But currents add, so with low-resistance lamps the total current and copper cost would be enormous; high-resistance lamps draw small currents.
4. In 23 mA, out 30 mA, so the fourth carries 7 mA into the node.
5. $(12 - V)/1 = V/3 + V/6 \rightarrow 12 - V = 0.5V \rightarrow V_A = 8.0$ V; source current 4.0 mA
6. $(9 - V)/100 + (6 - V)/200 = V/200 \rightarrow 2(9 - V) + (6 - V) = V \rightarrow V_A = 6.0$ V; 30 mA from the 9 V source, 0 mA from the 6 V source
7. KCL: current in = current out at a node (charge). KVL: voltages around a loop sum to zero (energy).
8. Ratio 1/4: for example $R_1 = 3.0$ kΩ, $R_2 = 1.0$ kΩ (6.0 × 1/4 = 1.5 V); any 3:1 pair.
9. Unloaded 2.50 V; loaded: bottom $= 2.35$ kΩ, $V = 5.0 \times 2.35/7.05 = 1.67$ V
10. $R_4 = R_3R_2/R_1 = 7.26$ kΩ. At balance the meter reads zero; a null needs only sensitivity.
11. Resistor, capacitor, diode, transistor, integrated circuit, switch. A dot means the lines are connected.
12. A schematic shows connections, not positions. If both ends of each resistor are on the same two nodes, they are in parallel however they are drawn.
13. The middle resistor is shorted (0 V across it while current still flows). Check: without it the total is 5.0 kΩ, $I = 6.0/5000 = 1.2$ mA, and the drops are 1.2 V and 4.8 V, exactly as measured.
14. 5
15. A strong answer: the team found the fault by testing operations and tracing signals to one relay, and logged it; measurement narrows the search logically and half-splitting is fast; changing one thing at a time keeps cause and effect clear; logs prevent repeating work and teach others. The routine: observe, power, ground, half-split, compare with expected values, fix one thing, retest, log.

PORTFOLIO PIECE: A DOCUMENTED SENSOR CIRCUIT

Design, simulate, build and document a circuit that turns light into a voltage and indicates it: a photoresistor divider that drives a meter reading, plus a second divider set by a potentiometer as an adjustable "threshold," and an LED indicator branch. Draw a full schematic with designators and values, predict every node voltage with Kirchhoff's laws, compare the simulation and the real measurements in a table, and include a debugging log of at least two faults you found while building it.

LOOK FOR	WHAT IT MEANS
Schematic	Standard symbols, designators, values, labeled nodes, + at top and ground at bottom.
Analysis	Node voltages predicted with dividers and Kirchhoff's laws, with the algebra shown.
Measurement	Simulated, predicted and measured values compared in a table with percent differences explained.
Debugging log	At least two faults recorded with symptom, measurement, cause and fix.

UNIT 3

Components

Every electronic device is built from a small vocabulary of parts. In this unit you will meet the five most important passive and semiconductor components one by one: the resistor, the capacitor, the inductor (and its useful cousin, the relay), the diode and the LED. Each has a story, from the Leyden jar of 1746 that gave Cunaeus the shock of his life to the blue LED that won a Nobel Prize in 2014.

For each part you will learn its physics, its equations, how to read its markings and ratings, and how engineers choose it. And you will measure each one yourself: a resistor batch test, an RC charging curve, a relay switching a separate circuit, a diode's I–V curve, and a set of LED circuits designed by the numbers.

PREREQUISITES

- Units 1–2: Ohm's law, power, series and parallel, Kirchhoff's laws, schematics
- Exponents and powers of ten; a scientific calculator with e^x and ln

MASTERY CHECKLIST

- ☐ I can read resistor color codes and use standard values and tolerances in a design.
- ☐ I can use $Q = CV$, $E = \frac{1}{2}CV^2$, and $\tau = RC$, and describe charging and discharging curves.
- ☐ I can explain inductance, the inductive kick, relays and flyback diodes.
- ☐ I can use the 0.7 V diode model and explain half-wave and bridge rectifiers and polarity protection.
- ☐ I can design a current-limiting resistor for any LED and check its

power.

OPTIONAL KITS FOR THIS UNIT

- **A component assortment**: An inexpensive assortment of electrolytic and ceramic capacitors, 1N4001 and 1N4148 diodes and extra LEDs from any electronics supplier fills gaps in a starter kit. Not required.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

3.1	**Resistors and the Color Code**	3 sessions of 50 minutes
3.2	**Capacitors and RC Timing: From the Leyden Jar**	3 sessions of 50 minutes
3.3	**Inductors and Relays: Joseph Henry's Coils**	3 sessions of 50 minutes
3.4	**Diodes and Rectifiers: Fleming's Valve**	3 sessions of 50 minutes
3.5	**LEDs and Current Limiting**	3 sessions of 50 minutes

Unit 3 test

Time: 50 minutes. A scientific calculator is allowed. Show the formula, the substitution with units and the answer with its unit for each calculation; correct setup earns partial credit. The test is worth 100 points.

1. **6 pts** **Lesson 3.1**

   Read: (a) red-violet-orange-gold; (b) green-blue-brown-gold; (c) the surface-mount code 222.

2. **6 pts** **Lesson 3.1**

   A 330 Ω ±5% resistor measures 342 Ω. Find the percent error and say whether it passes.

3. **6 pts** **Lesson 3.1**

   Explain why standard resistor values are spaced by equal percentages rather than equal steps.

4. **8 pts** **Lesson 3.2**

   A 220 µF capacitor charges through 22 kΩ from 6.0 V. Find τ, the voltage after 4.84 s, and the approximate full-charge time.

5. **6 pts** **Lesson 3.2**

   Find the charge and energy of a 470 µF capacitor at 9.0 V.

6. **6 pts** **Lesson 3.2**

   Describe the Leyden jar and what Franklin's experiment showed about where its charge was stored.

7. **8 pts** **Lesson 3.3**

   A 5 V relay coil of 125 Ω has $L = 0.15$ H. Find its current, power and L/R time constant. Why does it need a transistor and a flyback diode to be driven by an Arduino?

8. **6 pts** **Lesson 3.3**

   Explain how Joseph Henry's relay made long telegraph lines possible.

9. **6 pts** **Lesson 3.3**

   Find the voltage across a 20 mH inductor when its current falls 0.50 A in 0.10 ms.

10. **8 pts** **Lesson 3.4**

    A 6.0 V battery feeds a silicon diode and 470 Ω in series, diode forward. Find the current. Then the battery is reversed: what is the current, and what voltage is across the diode?

11. **6 pts** **Lesson 3.4**

    Explain how a bridge rectifier lets a device work with batteries inserted either way, and its cost in voltage.

12. **6 pts** **Lesson 3.4**

    Describe a p–n junction and its depletion region in two or three sentences.

13. **8 pts** **Lesson 3.5**

Design resistors for (a) a yellow LED ($V_F = 2.1$ V) at 12 mA from 5.0 V and (b) a white LED ($V_F = 3.2$ V) at 15 mA from 5.0 V. Give calculated and standard values and the resistor power.

14. **6 pts** **Lesson 3.5**

Why does each LED in parallel need its own resistor?

15. **8 pts** **Lesson 3.5**

Essay (one paragraph). Trace the history of the LED from Round's glowing crystal to the white LED, and explain why the blue LED was the key step.

ANSWER KEY

1. (a) 27 kΩ ±5%; (b) 560 Ω ±5%; (c) 2.2 kΩ
2. +3.6%; passes (allowed 313.5–346.5 Ω)
3. So that every needed value is within a fixed percentage (the tolerance) of a standard value at every scale, with no wasted values.
4. $\tau = 4.84$ s; $V = 6.0(1 - e^{-1}) = 3.79$ V; about 24 s (5τ)
5. $Q = 4.23$ mC; $E = 0.019$ J
6. A glass jar with conductors (water or foil) inside and foil outside; the glass is the dielectric. Franklin poured the water into a new jar and found the charge stayed with the original glass.
7. 40 mA; 0.20 W; 1.2 ms. 40 mA exceeds a pin's safe current, and switching the coil off produces a large voltage spike that the diode absorbs.
8. A weak current from the long line moved a light armature that closed a separate local circuit with its own battery, renewing the signal for the next section.
9. $V = 0.020 \times 0.50 / 0.0001 = 100$ V
10. $(6.0 - 0.7)/470 = 11.3$ mA; reversed: about 0, with 6.0 V across the diode.
11. Four diodes route current so it always flows the same way through the load, whichever terminal is positive; two diodes conduct at a time, losing about 1.4 V.
12. p-type silicon (holes) meets n-type (extra electrons); carriers near the boundary cancel, leaving a thin region with no free carriers and a built-in voltage (about 0.6–0.7 V in silicon) that blocks current until forward bias overcomes it.
13. (a) 242 Ω → 270 Ω (about 10.7 mA, 0.03 W); (b) 120 Ω → 120 Ω (15 mA, 0.027 W)
14. LEDs' forward voltages differ slightly; with one shared resistor, the LED with the lowest V_F takes most of the current, overheats and fails.
15. A strong answer: Round 1907 (carborundum glow), Losev 1920s, Holonyak 1962 red LED at GE, then decades of red/green indicators; blue required pure gallium nitride, achieved by Akasaki, Amano and Nakamura in the early 1990s (Nobel 2014); blue plus a yellow phosphor gives white, so efficient LED lighting became possible.

PORTFOLIO PIECE: A BATTERY-POWERED FADE-OUT NIGHT LIGHT

Design and build a small night light, powered by the 4-AA pack, that turns on with a push button and fades out slowly over 20–60 seconds when released, using a capacitor discharging through an LED and resistor. Include reverse-polarity protection with a diode. Calculate the resistor for the LED's maximum current, the time constant and the expected glow time; build it; measure the actual glow time and LED current; and explain any difference. Present a schematic, a parts list with values and ratings, your calculations and test data.

LOOK FOR	WHAT IT MEANS
Design calculations	LED resistor, time constant and expected glow time calculated with units, using standard values.
Correct components	Electrolytic polarity and voltage rating correct; protection diode correctly placed; every LED has its resistor.
Testing	Measured glow time and current recorded and compared with the predictions.
Documentation	Neat schematic, parts list with values and ratings, and a short report on one improvement.

3.1 Resistors and the Color Code

OBJECTIVES

- Read 4-band and 5-band resistor color codes and write values with prefixes and tolerance.
- Explain standard (E-series) values, tolerance and power rating, and why resistors are made this way.
- Combine standard resistors in series and parallel to make a needed value.
- Measure a batch of resistors and analyze their spread against the marked tolerance.

> **Warm-up.** Pick up five resistors from your kit. Without a chart, try to sort them from smallest to largest by their bands alone. What pattern do you notice? Write your guess about how the bands might encode a number.

WATCH

Resistor Color Code Chart Tutorial Review - Physics

The Organic Chemistry Tutor · 10:10

https://www.youtube.com/watch?v=G1mZutobxDU

> **WHEN TO WATCH**
> Before the worked examples. Pause at each resistor the presenter shows and read its value before he does.

BACKUP VIDEO

How to Read Resistor Color Codes | 4-Band Resistor Values and Tolerance

Engineering Technology Simulation Learning Videos · 2:46

https://www.youtube.com/watch?v=GLD7AgAYqwA

A short animated review of 4-band codes and tolerance; good the night before the test.

KEY TERMS

color code

Bands of color that give a resistor's value: digits, then a multiplier (a power of ten), then tolerance. Black 0, brown 1, red 2, orange 3, yellow 4, green 5, blue 6, violet 7, gray 8, white 9.

tolerance

How far the real resistance may differ from the marked value: gold ±5%, silver ±10%, brown ±1%.

E-series (preferred values)

Standard resistor values spaced so that each is about the same percentage above the last. E12 (for ±10%): 1.0, 1.2, 1.5, 1.8, 2.2, 2.7, 3.3, 3.9, 4.7, 5.6, 6.8, 8.2, times any power of ten.

power rating

The most heat a resistor can safely shed. Small through-hole resistors are usually 1/4 W; size is a rough guide.

carbon film / metal film

Common resistor types: a thin film of carbon or metal alloy on a ceramic rod, cut in a spiral to set the value. Metal film is more precise (often 1%).

CORE IDEAS

The story. The radio boom of the 1920s put millions of resistors into homes, and they were tiny cylinders with no room for printed numbers. Manufacturers painted them in colors, but each company used its own scheme, and repairmen had to keep charts for every brand. In the 1920s the Radio Manufacturers Association in the United States agreed on a single color code, using the colors of the rainbow in order for the digits 0–9, with black and brown at the low end and gray and white at the top. With small changes, it is the code you will read today on every through-hole resistor in the world.

How they figured it out. A second problem was which values to make. A factory cannot make every possible resistance, and early resistors were not precise anyway: a part marked 1,000 Ω might really be anywhere from 900 to 1,100 Ω. Engineers realized that if each standard value were about 20% above the last, every possible resistance would fall within ±10% of some standard value, and no values would be

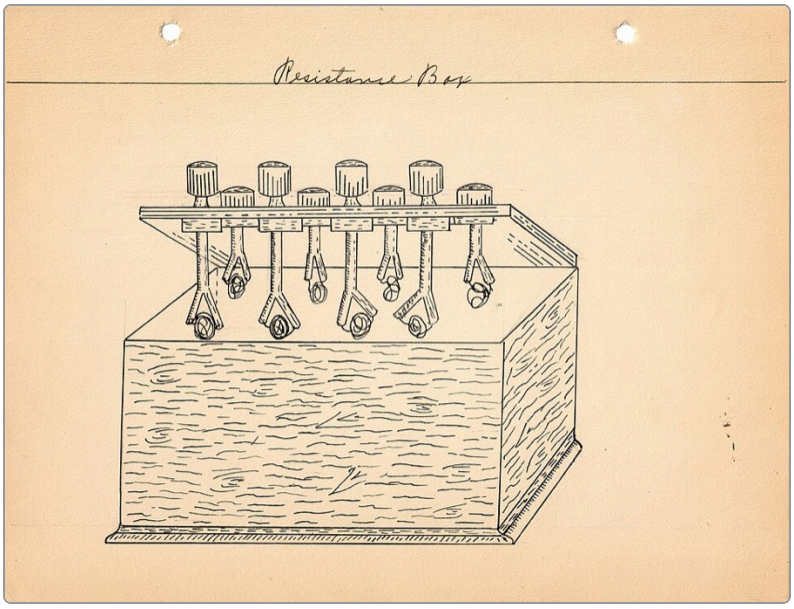
wasted. That gives twelve values per decade, the **E12 series**: 10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68, 82, and then 100, 120, 150 and so on. Precise resistors use finer series (E24, E96). The series was later standardized internationally (IEC 60063).

The physics. A film resistor is a ceramic rod coated with a thin film of carbon or metal. A laser or a diamond wheel cuts a spiral groove through the film, making a long, thin path; remember $R = \rho L / A$, so a longer, narrower path means more resistance. The maker trims the spiral until the measured value is right. To read the code on a 4-band resistor, hold the tolerance band (gold or silver) on the right; the first two bands are digits and the third is the number of zeros. Yellow-violet-red-gold is 4, 7, two zeros: 4,700 Ω = 4.7 kΩ, ±5%. A 5-band resistor has three digits, a multiplier and a tolerance band: brown-black-black-red-brown is 100 × 100 = 10 kΩ, ±1%.

The engineering. Engineers design with standard values and tolerances in mind. If a calculation says 250 Ω, they choose 220 or 270 Ω and check that the circuit still works across the whole tolerance range; a design that needs an exact value is a fragile design. Where a precise or unusual value is truly needed, they use a 1% resistor, combine two standard values, or add a trimmer potentiometer. Surface-mount resistors, far smaller than through-hole ones, use a printed number code instead of colors: “472” means 47 followed by two zeros, 4.7 kΩ.

Try it. In the build you will measure a batch of resistors and find out whether they really fall inside their tolerance, the way a factory’s quality inspector would.

PICTURE STUDY



A Resistance Box, Milton Wend, 1927 · Drawing · Wikimedia Commons

Image: Wikimedia Commons, public domain

Before cheap, precise resistors, laboratories used resistance boxes: coils of wire of known value inside a case, selected by plugs or dials. This one was drawn in 1927, the same decade the color code was agreed.

Look closely

- Find the plugs or dial positions. How do you think removing a plug adds a resistance?
- Look for numbers marking each coil. Do they follow a pattern?
- Why is the top made of an insulator, with brass blocks for the contacts?

Talk about it

1. How is a resistance box like a set of standard weights on a balance?
2. Why would engineers in the 1920s need standard values and tolerances?
3. What advantage does a modern film resistor have over a coil of wire in a box? What disadvantage?

Safety first. Batteries and USB power only, never wall power. Build with the battery disconnected and connect it last. Wear safety glasses when trimming component leads; cut ends fly.

BUILD

Quality Inspector: A Resistor Batch Test

You will read and measure a batch of resistors, calculate each one's percent error, make a histogram of the errors, and decide whether the batch passes inspection. Then you will build exact values from standard parts.

You will need

- At least 20 resistors of one marked value (for example, all the 1 kΩ or 220 Ω in your kit), plus 10 assorted resistors
- Digital multimeter
- Graph paper or a spreadsheet
- A color-code chart only for checking (try to read without it first)

Steps

1. Read the 10 assorted resistors by their bands and write each value. Then measure each and check your reading. Record any you misread and why.
2. Number the 20 identical resistors with tape. Measure each one, holding it by one lead only (your fingers in parallel can change high values).
3. Calculate each one's percent error from the marked value.
4. Make a histogram: bins of 0.5% from −5% to +5%. Find the mean, the lowest and the highest.
5. Decide: does the batch pass its marked tolerance? Write an inspection report of three sentences.
6. Measure the resistance of your meter's own leads (touch the probes together) and subtract it from low-value readings. How much did it matter for 220 Ω? For 10 Ω?
7. Using only standard values from your kit, build 1.6 kΩ, 50 Ω and 7.5 kΩ from combinations. Predict, then measure, each.
8. **Improve it.** Choose the two resistors from your batch that are closest to each other. Why might an engineer select matched resistors for a voltage divider or a bridge?

Tips

- Hold the resistor with the gold or silver band on your right before reading.
- Brown and red, or blue and violet, can be hard to tell apart under yellow light; read near a window.
- If two bands look the same color but different shades, measure: the meter settles the question.

Check your work

- ☐ I can read 4- and 5-band codes and the 3-digit surface-mount code.
- ☐ I made a histogram of a resistor batch and judged it against its tolerance.
- ☐ I built nonstandard values from standard parts and checked them.

ENGINEER'S NOTEBOOK

1. Your color-code chart, written from memory and then checked.
2. The batch data table, histogram, mean and inspection report.
3. Drawings of your three combination resistors with predicted and measured values.

KEY FORMULAS

$$R = (\text{digits}) \times 10^{\text{multiplier}}$$

$$\text{percent error} = \frac{R_{\text{measured}} - R_{\text{marked}}}{R_{\text{marked}}} \times 100\%$$

From history. A common memory aid for the colors is the order of the rainbow (red, orange, yellow, green, blue, violet) with black and brown before it and gray and white after. Some engineers simply make up their own sentence from the first letters, B-B-R-O-Y-G-B-V-G-W.

WORKED EXAMPLES

Example 1. Read these resistors: (a) brown-black-orange-gold; (b) red-red-brown-gold; (c) orange-orange-yellow-silver.

Show solution

1. (a) brown 1, black 0, orange multiplier 10^3: $10 \times 1000 = 10{,}000\ \Omega = 10\ \text{k}\Omega$, ±5%.
2. (b) red 2, red 2, brown 10^1: $22 \times 10 = 220\ \Omega$, ±5%.
3. (c) orange 3, orange 3, yellow 10^4: $33 \times 10{,}000 = 330\ \text{k}\Omega$, ±10%.

Answer: (a) 10 kΩ ±5%; (b) 220 Ω ±5%; (c) 330 kΩ ±10%

Example 2. A 4.7 kΩ ±5% resistor measures 4.61 kΩ. Is it within tolerance? What is the allowed range?

Show solution

1. Allowed: $4.7 \times 0.95 = 4.465\ \text{k}\Omega$ to $4.7 \times 1.05 = 4.935\ \text{k}\Omega$.
2. Error: $(4.61 - 4.70)/4.70 \times 100\% = -1.9\%$.
3. 4.61 is inside the range.

Answer: Yes: −1.9%, within 4.47–4.94 kΩ

Example 3. A circuit needs 1.6 kΩ, which is not an E12 value. Make it from E12 resistors.

Show solution

1. Series option: $1.5\ \text{k}\Omega + 100\ \Omega = 1.6\ \text{k}\Omega$ (100 Ω is E12: 10 × 10).
2. Parallel option: $3.3\ \text{k}\Omega \parallel 3.3\ \text{k}\Omega = 1.65\ \text{k}\Omega$, within 3%.
3. Choose the series pair for accuracy, or check whether 1.5 kΩ or 1.8 kΩ would simply do.

Answer: 1.5 kΩ + 100 Ω in series (or two 3.3 kΩ in parallel ≈ 1.65 kΩ)

PRACTICE

1. **Easy** Read yellow-violet-red-gold.

   Show answer

   4.7 kΩ ±5%

2. **Easy** What colors would mark a 1.0 kΩ ±5% resistor?

   Show answer

   Brown-black-red-gold

3. **Easy** What does a surface-mount resistor marked “103” mean?

   Show answer

   10 followed by three zeros: 10 kΩ

4. **Medium** Read the 5-band resistor brown-black-black-red-brown.

   Show answer

   100 × 100 = 10 kΩ ±1%

5. **Medium** Give the allowed range of a 220 Ω ±5% resistor.

   Show answer

   209 Ω to 231 Ω

6. **Medium** Your calculation gives 390 Ω for an LED resistor. Is 390 Ω an E12 value? If you only have E6 values (10, 15, 22, 33, 47, 68), which would you choose and why?

   Show answer

   Yes, 390 is E12. From E6, choose 470 Ω (the next higher), which gives a little less current, the safe direction for an LED.

7. **Medium** Why are the E12 values spaced by about 20% rather than evenly (100, 200, 300…)?

   Show answer

   Equal percentage steps mean every value is within ±10% of a standard value, at the low end and the high end alike; equal steps would be far too coarse at the low end and wastefully fine at the high end.

8. Hard Check that E12 steps are about equal ratios: compute 12/10, 15/12, 18/15, 22/18 and $10^{1/12}$.

Show answer

1.20, 1.25, 1.20, 1.22; $10^{1/12} = 1.21$

9. Hard Make 50 Ω from E12 values two different ways.

Show answer

Two 100 Ω in parallel (50 Ω); or 47 Ω + 3.3 Ω in series (50.3 Ω).

10. Hard Twenty 1.0 kΩ ±5% resistors have a mean of 0.987 kΩ, with the lowest 0.962 kΩ and highest 1.012 kΩ. Are they all within tolerance? What does the mean suggest about the factory?

Show answer

Yes: the allowed range is 0.950–1.050 kΩ. The mean is 1.3% low, suggesting the factory trims slightly toward the low side, still well inside spec.

11. Challenge A divider uses 10 kΩ ±5% over 10 kΩ ±5% on 5.00 V. What are the lowest and highest possible outputs?

Show answer

Lowest: top 10.5 kΩ, bottom 9.5 kΩ: $5 \times 9.5/20 = 2.375$ V. Highest: top 9.5, bottom 10.5: 2.625 V. Range 2.375–2.625 V (±5%).

COMMON MISTAKES

- Reading the code backward. The tolerance band (gold/silver) goes on the right; the first band is closest to one end.
- Treating the third band of a 4-band resistor as a digit. It is the number of zeros (the power of ten).
- Expecting an exact match. A 5% resistor that reads 3% off is a good resistor.

> **Make it a game · Color Code Cards.** Make cards with colored bands drawn in crayon. Your parent shows a card; you read its value with tolerance in five seconds. Then name the next standard E-series value above 4.7 kΩ. Ten correct earns a record. Switch and make a hard five-band card for your parent to read.

3.2 Capacitors and RC Timing: From the Leyden Jar

OBJECTIVES

- Tell the story of the Leyden jar and explain how a capacitor stores charge and energy.
- Use $Q = CV$, $E = \frac{1}{2}CV^2$ and the time constant $\tau = RC$.
- Describe the exponential charging and discharging curves and the 63% and five-time-constant rules.
- Measure the charging curve of a capacitor, graph it and compare the measured time constant with RC.

> **Warm-up.** Fill a bucket with a small hole in the bottom from a hose. Does the water level rise at a steady rate, or does it slow as it gets fuller? Sketch a graph of level against time. (You do not need to do it; imagine it.) You will see the same curve today in an electric circuit.

WATCH

Capacitors Explained - The basics how capacitors work working principle

The Engineering Mindset · 8:42

https://www.youtube.com/watch?v=X4EUwTwZ110

> **WHEN TO WATCH**
> After the story and before the physics paragraph. Watch how the capacitor is built and how it charges; pause at the time-constant section.

BACKUP VIDEO

Capacitor charge time calculation - time constants

The Engineering Mindset · 5:59

https://www.youtube.com/watch?v=FDmHVRC6pQk

A short worked calculation of charging time with time constants; watch before the practice set.

KEY TERMS

capacitor

Two conductors separated by an insulator (the dielectric). Charge stored on one plate draws an equal and opposite charge to the other.

capacitance (C)

Charge stored per volt: $C = Q/V$. Unit: the farad (F); practical values are in μF, nF and pF.

time constant (τ)

$\tau = RC$, the time for a charging capacitor to reach about 63% of the supply voltage, or a discharging one to fall to about 37%.

electrolytic capacitor

A capacitor with large capacitance in a small can. It is polarized: the stripe marks the negative lead, and it must never be connected backward or above its voltage rating.

dielectric

The insulating layer between a capacitor's plates: air, glass, ceramic, plastic film, or a thin oxide in an electrolytic.

CORE IDEAS

The story. In 1745 and 1746, Ewald Georg von Kleist in Pomerania and Pieter van Musschenbroek and his assistant Andreas Cunaeus at Leiden in Holland independently tried to "store" electricity in a glass jar of water. Cunaeus held the jar in one hand while charging it from a friction machine, then touched the wire with his other hand and received a shock so violent that Musschenbroek wrote he would not repeat it for the kingdom of France. The **Leyden jar**, soon made with metal foil inside and out, was the first capacitor. Benjamin Franklin studied it in Philadelphia and showed that the charge lived not in the water but on the glass between the two conductors.

How they figured it out. Franklin took a charged jar apart, poured out the water into a new jar, and found the new jar was not charged; then he poured fresh water into the original glass, and it still gave a shock. The charge was held by the glass. He also connected several jars together and called the set a "battery," after a battery of cannon; the word later passed to Volta's piles. A century later Michael Faraday

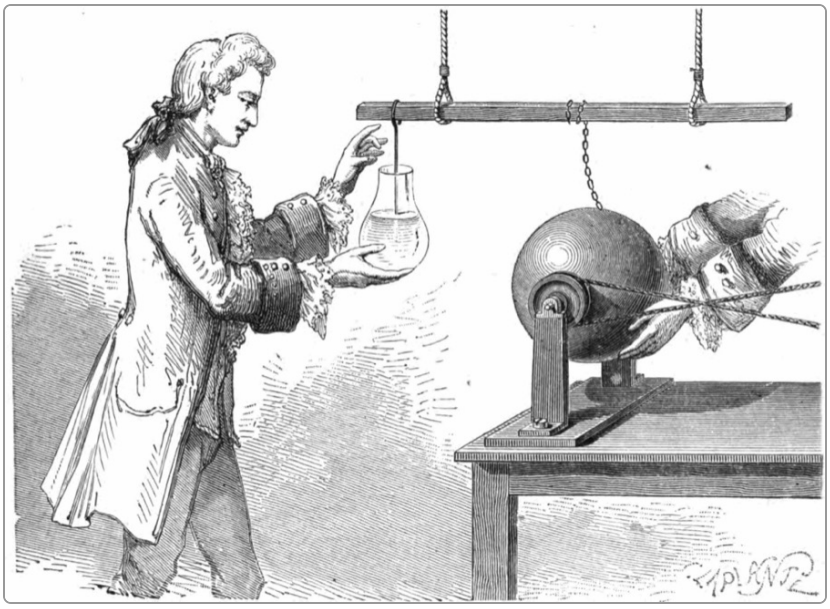
measured how different insulators between the plates increase the stored charge, and the unit of capacitance, the farad, is named for him.

The physics. A capacitor's plates store charge $Q = CV$. The energy stored is $E = \frac{1}{2}CV^2$. When a capacitor charges through a resistor, the current is large at first and falls as the capacitor's voltage rises to meet the supply, so the voltage follows a curve, not a straight line: $V(t) = V_s\left(1 - e^{-t/RC}\right)$. The product RC is the **time constant** τ; with R in ohms and C in farads, τ is in seconds. After one time constant the capacitor reaches 63% of the supply, after two 86%, after three 95%, and after five more than 99%, "fully charged" for engineers. Discharging, $V(t) = V_0 e^{-t/RC}$: the voltage falls to 37% after one τ. With 10 kΩ and 100 µF, $\tau = 10{,}000 \times 0.0001 = 1.0$ s.

The engineering. Capacitors are in nearly every circuit. They smooth a supply by filling in the dips; a 0.1 µF **decoupling capacitor** sits beside every chip to supply quick bursts of current. They block steady DC but pass changing signals, which is how audio is coupled from one stage to the next. And with a resistor they make a timer: the delay before a light goes out, the blink rate of a flasher, the 555 timer in Unit 5. Engineers respect two ratings: the voltage (exceed it and the dielectric breaks down) and, for electrolytics, the polarity. A large charged capacitor can deliver a painful jolt or a spark even after the power is off, so they are discharged through a resistor, never with a screwdriver.

Try it. You will charge a capacitor through a resistor, read its voltage every few seconds, and see Volta's and Franklin's stored charge follow an exponential curve that you can predict to the second.

PICTURE STUDY



Cunaeus Discovers the Leyden Jar, Unknown engraver, 19th century (event of 1746) · Engraving · Wikimedia Commons

Image: Wikimedia Commons, public domain

This engraving imagines the moment at Leiden when Andreas Cunaeus, holding a jar of water connected to an electrical machine, touched the conductor with his other hand and received a tremendous shock.

Look closely

- Find the friction machine that makes the charge. What part would be rubbed to make it?
- Find the jar. What conductor is inside it, and what is outside it?
- Trace the path the charge would take through Cunaeus's body when he touches the conductor.
- Look at the faces and gestures. What is the artist trying to show?

Talk about it

1. In this experiment, what played the part of the two plates of a capacitor, and what was the dielectric?
2. Why did the shock happen only when he touched the conductor with his other hand?
3. What safety lesson does this story teach about charged capacitors today?

Safety first. Batteries and USB power only, never wall power. Build with the battery disconnected and connect it last. Wear safety glasses when trimming component leads; cut ends fly. Electrolytic capacitors must go in the right way (stripe to negative) and never above their voltage rating; use 16 V or higher parts on these 6 V circuits. Discharge capacitors through a 1 kΩ resistor, never by shorting the leads.

BUILD

Measuring an RC Charging Curve

You will charge a large capacitor through a resistor, read its voltage at regular times, graph the curve, find the time constant from the graph, and compare it with RC. Then you will discharge it and repeat.

You will need

- Breadboard, jumper wires, 4-AA holder (6 V) or the Arduino 5 V pin on USB
- Electrolytic capacitors: 100 µF and 1000 µF (16 V or higher)
- Resistors: 10 kΩ and 47 kΩ, and a 1 kΩ for discharging
- Digital multimeter, a phone to video the meter (or a stopwatch and a partner)
- A red LED and a 220 Ω resistor for the extension

Steps

1. Calculate τ for 1000 µF with 47 kΩ (about 47 s) and for 100 µF with 47 kΩ (about 4.7 s). Predict the voltage at 1, 2, 3 and 5 time constants for the 6 V supply.
2. Build supply + → 47 kΩ → capacitor + lead; capacitor − (stripe) → ground. Put a jumper across the capacitor to keep it at 0 V. Connect the meter (DC volts) across the capacitor.
3. Start the phone video showing the meter and a clock or stopwatch. Remove the jumper. Let the capacitor charge for at least 4 minutes.
4. From the video, record the voltage every 10 seconds. Make a table and graph voltage against time.
5. Find the time at which the voltage reached 63% of the final value. That is your measured τ. Compare it with RC and compute the percent difference. (Capacitors are often ±20%.)
6. Discharge: disconnect the supply end of the resistor and connect it to ground instead. Record the falling voltage and find the time to fall to 37%.

7. Note: a 10 MΩ meter in parallel slightly changes the discharge. Estimate its effect: compare 47 kΩ with 10 MΩ.
8. **Improve it.** Build a "fade-out" light: charge the 1000 µF capacitor from the supply through a push button, and let it discharge through 220 Ω and an LED. Time how long the LED glows. Predict the change if you double the capacitance, then test it with two 1000 µF capacitors in parallel (or swap in 470 µF).

Tips

- The final voltage is the supply's actual voltage; measure it rather than assuming 6.0 V.
- Electrolytics leak a little current, so the curve may level off slightly below the supply.
- A spreadsheet can plot $V_s(1 - e^{-t/\tau})$ on the same graph as your data so you can compare shapes.

Check your work

☐ My charging graph is a curve that levels off, and I found τ at 63%.

☐ My measured τ is within the capacitor's tolerance of

RC.

☐ I can use

$Q = \cancel{E}C\cancel{V} \frac{1}{2} CV^2$

an $\tau = RC$.

d

ENGINEER'S NOTEBOOK

1. The schematic, data table and charging and discharging graphs, with the 63% and 37% points marked.
2. Your comparison of measured τ and RC with percent difference.
3. A labeled sketch of a Leyden jar and of a modern electrolytic capacitor, showing the plates and dielectric of each.

KEY FORMULAS

$Q = CV$
$E = \frac{1}{2}CV^2$
$\tau = RC$
$V(t) = V_s\left(1 - e^{-t/RC}\right)$ (charging)
$V(t) = V_0\, e^{-t/RC}$ (discharging)

From history. Franklin's kite experiment of 1752, if he flew it as described, charged a Leyden jar from a thundercloud and showed that lightning is electricity. It was extremely dangerous: Georg Richmann died in St. Petersburg in 1753 trying a similar experiment. Never fly a kite near storms or power lines.

WORKED EXAMPLES

Example 1. A 100 μF capacitor is charged to 9.0 V. How much charge and energy does it store?

Show solution

1. $Q = CV = (100 \times 10^{-6}\ \text{F})(9.0\ \text{V}) = 9.0 \times 10^{-4}\ \text{C} = 0.90\ \text{mC}$.
2. $E = \frac{1}{2}CV^2 = \frac{1}{2}(100 \times 10^{-6})(9.0)^2 = 4.05 \times 10^{-3}\ \text{J}$.

Answer: 0.90 mC; about 4.1 mJ

Example 2. A 100 μF capacitor charges through 10 kΩ from 5.0 V. Find the time constant, the voltage after 1.0 s and 2.0 s, and roughly when it is fully charged.

Show solution

1. $\tau = RC = (10{,}000\ \Omega)(100 \times 10^{-6}\ \text{F}) = 1.0\ \text{s}$.
2. At 1.0 s: $V = 5.0(1 - e^{-1}) = 5.0(0.632) = 3.16\ \text{V}$.
3. At 2.0 s: $V = 5.0(1 - e^{-2}) = 5.0(0.865) = 4.32\ \text{V}$.
4. "Fully charged" at about $5\tau = 5.0$ s (above 99%).

Answer: τ = 1.0 s; 3.16 V at 1 s; 4.32 V at 2 s; about 5 s to charge

Example 3. How long does the capacitor in Example 2 take to reach 3.3 V?

Show solution

1. Set $3.3 = 5.0(1 - e^{-t/1.0})$, so $e^{-t} = 1 - 0.66 = 0.34$.
2. Take natural logs: $-t = \ln 0.34 = -1.08$.
3. $t = 1.08$ s.

Answer: About 1.08 s

PRACTICE

1. Easy Find the time constant of 47 µF with 100 kΩ.

   Show answer

   $\tau = 4.7$ s

2. Easy A 1,000 µF capacitor is at 6.0 V. How much charge does it hold?

   Show answer

   6.0 mC

3. Easy What fraction of the supply voltage does a charging capacitor reach after one time constant? After five?

   Show answer

   About 63%; more than 99%

4. Medium A capacitor charged to 9.0 V discharges through a resistor with $\tau = 2.0$ s. What is its voltage after 3.0 s?

   Show answer

   $9.0e^{-1.5} = 2.0$ V

5. Medium What resistor with a 100 µF capacitor gives a 0.50 s time constant?

   Show answer

   $R = 0.50/100 \times 10^{-6} = 5.0$ kΩ (use 4.7 kΩ or 5.1 kΩ)

6. Medium Why must an electrolytic capacitor be connected the right way round?

   Show answer

   Its dielectric is a thin oxide layer formed for one polarity; reversed, the layer breaks down, current flows, the capacitor heats and can vent or burst.

7. Medium What did Franklin's experiment of pouring out the water show?

Show answer

That the charge was held by the glass between the conductors, not by the water.

8. Hard A Leyden jar of about 1.0 nF is charged to 20,000 V. Find its charge and energy. Why was Cunaeus's shock so violent even though the energy is small?

Show answer

$Q = 20\ \mu\text{C}$; $E = \frac{1}{2}(10^{-9})(2\times10^{4})^2 = 0.20$ J. The very high voltage drives a large current through the body for a very short time.

9. Hard In Example 2, find the current at the instant the switch closes and after one time constant.

Show answer

At $t = 0$ the capacitor has 0 V, so $I = 5.0/10{,}000 = 0.50$ mA; after 1τ, $I = 0.50e^{-1} = 0.18$ mA.

10. Hard Two 100 µF capacitors in parallel act like one of what value? In series? (Capacitors combine the opposite way to resistors.)

Show answer

Parallel: 200 µF; series: 50 µF.

11. Challenge A delay circuit must turn off an LED 10 s after a button is released, when a capacitor discharging from 5.0 V through R falls to 1.5 V. With a 470 µF capacitor, what R is needed?

Show answer

$1.5 = 5.0e^{-10/\tau} \to \tau = 10/\ln(5.0/1.5) = 10/1.204 = 8.31$ s; $R = 8.31/470\times10^{-6} = 17.7$ kΩ (use 18 kΩ).

COMMON MISTAKES

- Using µF as if it were F. 100 µF is 100×10^{-6} F $= 1\times10^{-4}$ F.
- Expecting a straight-line charge. The current falls as the capacitor fills, so the voltage curve flattens.
- Putting an electrolytic in backward. The stripe (and the shorter lead) is negative.

Make it a game · Time Constant Guess. Prediction duel. Your parent calls a resistor and a capacitor value. Write the time constant $\tau = RC$ and guess the voltage after one, two and five time constants as a fraction of the supply. Then calculate $Q = CV$ and $E = \frac{1}{2}CV^2$. Closest guess wins. Retell the Leyden jar story in thirty seconds.

Scripture. “Canst thou send lightnings, that they may go, and say unto thee, Here we are?” (Job 38:35, KJV)

Franklin’s jars caught a little of what God commands in every storm. Engineers handle stored charge with respect, knowing how small our power is beside His.

3.3 Inductors and Relays: Joseph Henry's Coils

OBJECTIVES

- Tell how Joseph Henry built powerful electromagnets, discovered self-induction and invented the relay.
- Explain inductance and the voltage $V = L\,\Delta I/\Delta t$ an inductor produces when its current changes.
- Explain how a relay lets a small current switch a separate circuit, and why a flyback diode is needed across a coil.
- Measure a relay coil's resistance and current, use it to switch a second circuit, and see an inductive kick safely.

> **Warm-up.** Push a heavy cart or wagon to get it moving, then try to stop it quickly. Which is harder: starting it, stopping it, or keeping it rolling? Write one sentence. Inductors do to current what mass does to motion.

WATCH

How Relays Work - Basic working principle electronics engineering electrician amp

The Engineering Mindset · 14:01

https://www.youtube.com/watch?v=n594CkrP6xE

> **WHEN TO WATCH**
> After the story. Watch how the coil pulls the armature and moves the contacts; pause to label the coil, armature, spring and contacts in your notebook.

BACKUP VIDEO

Inductors Explained - The basics how inductors work working principle

The Engineering Mindset · 10:20

https://www.youtube.com/watch?v=KSylo01n5FY

A clear animated explanation of inductors and back voltage; watch before the physics paragraph.

KEY TERMS

inductor

A coil of wire, often around an iron core, that stores energy in its magnetic field and opposes changes in current.

inductance (L)

How strongly a coil opposes a change in current: $V = L\,\Delta I/\Delta t$. Unit: the henry (H).

relay

An electrically operated switch: current through a coil pulls an iron armature, which opens or closes separate contacts.

NO / NC / COM

A relay's contacts: common (COM), normally open (NO, closed only when the coil is on) and normally closed (NC, open when the coil is on).

flyback diode

A diode across a coil, pointing backward to the supply, that gives the coil's current a safe path when it is switched off and stops a damaging voltage spike.

CORE IDEAS

The story. Joseph Henry was a teacher at the Albany Academy in New York in the late 1820s, with classes to teach and only summer holidays for research. William Sturgeon in England had made an electromagnet by winding bare wire loosely on a varnished iron horseshoe. Henry insulated his wire by wrapping it with silk, some of it reportedly from his wife's petticoat, so he could wind many tight layers. His magnets lifted hundreds of pounds; one built for Yale in 1831 lifted more than a ton. Henry also found that the coil itself resisted changes in current: when he broke the circuit of a long coil he got a bright spark and a shock. He called it self-induction. The unit of inductance, the henry, honors him. Henry, a devout Presbyterian, became the first Secretary of the Smithsonian Institution in 1846.

How they figured it out. Henry experimented systematically with how the coils were wound. Many turns in series gave a magnet that worked at the end of a long wire with a high-voltage battery, which he called an "intensity" magnet; several coils in parallel gave a strong magnet from a single low-voltage cell, a "quantity" magnet. In the early 1830s he strung about a mile of wire around a room at Albany and rang a

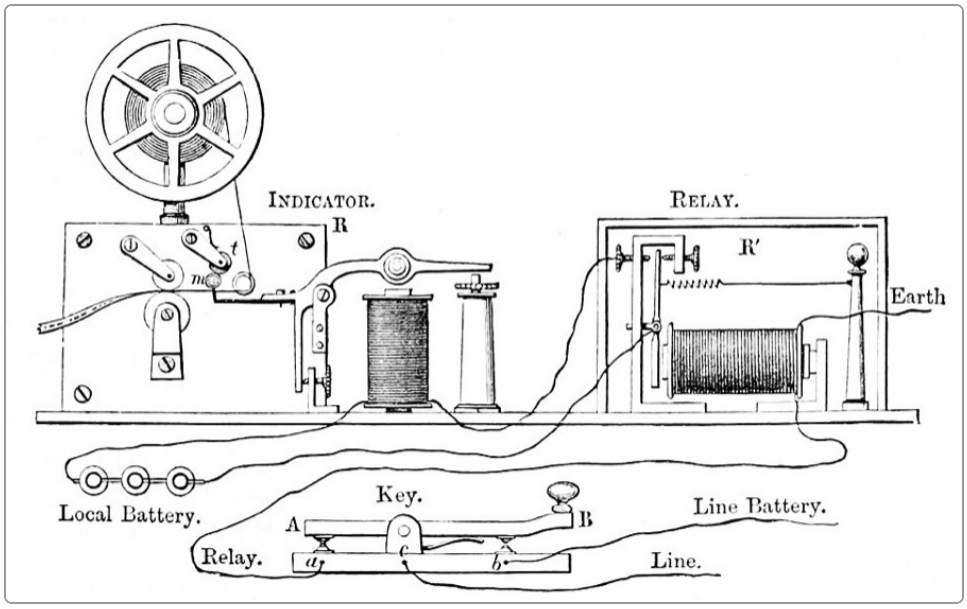
bell at the far end with an intensity magnet, an early telegraph. He also understood that a weak current at the end of a long line could operate a small electromagnet that closed a *second* circuit with its own battery. That is the **relay**, the device that let telegraph signals be renewed again and again across a continent.

The physics. Current in a coil makes a magnetic field, and the field stores energy, $E = \tfrac{1}{2} L I^2$. If the current tries to change, the changing field induces a voltage in the coil that opposes the change: $V = L\,\Delta I / \Delta t$. A coil with an iron core has much more inductance than one without. When you switch an inductor *off*, Δt is tiny, so the voltage can be enormous: a 0.1 H relay coil carrying 70 mA switched off in a microsecond tries to produce $V = 0.1 \times 0.07 / 10^{-6} = 7{,}000$ V. That is the spark Henry saw, and it can destroy a transistor or a microcontroller pin in an instant. A **flyback diode** across the coil gives the current a gentle path to die away, limiting the spike to less than a volt above the supply.

The engineering. Relays are still everywhere: in cars, appliances, elevators and industrial controls, wherever a small, safe signal must switch a large or separate circuit. A relay's coil and contacts are electrically isolated, so a 5 V microcontroller can control a separate circuit, and its contacts have tiny resistance when closed. Their drawbacks are wear, slow switching (milliseconds) and the coil's current, more than a microcontroller pin can supply, so a transistor drives the coil (Unit 4). Ready-made relay modules for Arduino include the transistor and the flyback diode. Inductors without contacts are used in filters, in the switching power supplies inside every charger, and in the coils of motors and loudspeakers.

Try it. You will measure a relay's coil, use it to switch a separate LED circuit, and use an LED to see the inductive kick when a coil is switched off.

PICTURE STUDY



Morse's Telegraph with a Relay, Popular Science Monthly, 1873 · Engraving · Popular Science Monthly, vol. 3

Image: Wikimedia Commons, public domain

By the 1870s every telegraph office had a relay like this one, using Henry's principle: the weak current from the line moves a light armature, which closes a local circuit with its own battery to operate the recording instrument.

Look closely

- Find the relay's electromagnet: the pair of coils. Where is the armature it pulls?
- Find the contacts the armature closes. Which circuit do they belong to?
- Find the key and the register (the paper-tape recorder).
- Look for adjusting screws and springs. Why would an operator need to adjust them?

Talk about it

1. Why could the line current be weak, but the register still work strongly?
2. Which part of a modern relay module does the same job as each part here?
3. What would happen at the moment the armature opened if the coil had no protection? Why did that matter less for telegraph relays than for transistors?

> **Safety first.** Batteries and USB power only, never wall power. Build with the battery disconnected and connect it last. Wear safety glasses when trimming component leads; cut ends fly. The relay switches only a separate battery LED circuit in this build; never connect relay contacts to wall power or any appliance. The inductive-kick test uses only 3 V and a small motor or relay coil.

BUILD

Henry's Relay on the Bench

You will measure a relay coil, use a relay module powered from the Arduino's USB 5 V to switch a separate battery-powered LED circuit with a push button, and then make an inductive kick visible with an LED.

You will need

- A 5 V relay module (most starter kits include one) or a bare 5 V relay with a 1N4001 diode
- Arduino Uno on USB (used only as a 5 V supply in this lesson; no code)
- A 2-AA holder, a red LED and 220 Ω resistor for the switched circuit; a second LED (any color)
- Push button, jumper wires, breadboard, multimeter
- The kit's small DC motor (for the inductive-kick test)

Steps

1. With nothing powered, find the relay's coil pins (or the module's VCC, GND and IN pins) and its COM, NO and NC terminals. Measure the coil's resistance if you can reach it. Predict its current at 5 V.
2. Use continuity mode to confirm that COM connects to NC and not to NO while the coil is off.
3. Wire the switched circuit: 2-AA + → COM; NO → 220 Ω → LED → 2-AA −. This circuit has its own battery and is completely separate from the Arduino.
4. Wire the control side: module VCC to Arduino 5V, GND to GND, and IN through the push button to the level that turns your module on (check its label: many modules turn on when IN is pulled LOW to GND; others when IN goes HIGH to 5V).
5. Plug in the USB cable. Press the button: listen for the click and watch the LED. Move the LED circuit from NO to NC and repeat. Explain the difference.
6. Measure the control current: put the meter (mA) in the VCC lead to the module and press the button. Compare with your prediction.

7. **Inductive kick.** Disconnect the relay. Connect the small motor across the 2-AA pack through a jumper you can pull out. Put an LED across the motor *backward* (its long leg toward the battery's − side). With the motor running, the LED is off. Pull the jumper: watch for a brief flash. Explain it with $V = L\,\Delta I/\Delta t$.
8. **Improve it.** Replace the LED with a 1N4001 diode in the same direction (a flyback diode) and listen and watch: the motor coasts down with no flash. Write one sentence on why every coil switched by a transistor needs that diode.

Tips

- Relay modules differ: read the labels on the board. If the relay clicks when the button is *released*, your module is active-low.
- A small motor has much less inductance than a big relay, so its flash is quick; watch in dim light.
- Do not hold the motor jumper in your fingers while pulling it; use the plastic end.

Check your work

- ☐ I measured a relay coil and its current and explained why a pin cannot drive it directly.
- ☐ I switched a separate circuit with a relay and explained NO and NC.
- ☐ I saw an inductive kick and explained the flyback diode.

ENGINEER'S NOTEBOOK

1. A labeled drawing of a relay: coil, core, armature, spring, COM, NO and NC.
2. Schematics of the control circuit and the separate switched circuit, showing that they share no wire.
3. Your measurements and the calculations of coil current and power.
4. A paragraph: How did Henry's relay make long-distance telegraphy possible?

KEY FORMULAS

$V = L\,\dfrac{\Delta I}{\Delta t}$

$E = \frac{1}{2}LI^2$

$\tau = \dfrac{L}{R}$ (coil current rise)

From history. Henry discovered electromagnetic induction (a changing magnetic field producing a current) at about the same time as Michael Faraday in England, but Faraday published first, in 1831, and received the credit. Henry was more generous than most scientists of his day; he later helped Samuel Morse freely with advice on the telegraph.

WORKED EXAMPLES

Example 1. A 5 V relay coil measures 70 Ω. What current and power does it need? Can an Arduino pin (about 20 mA recommended, 40 mA absolute maximum) drive it directly?

Show solution

1. $I = V/R = 5.0/70 = 0.071\ \text{A} = 71\ \text{mA}$.
2. $P = V^2/R = 25/70 = 0.36\ \text{W}$.
3. 71 mA is far over the pin's safe current, so the coil needs a transistor driver (as on a relay module).

Answer: 71 mA, 0.36 W; no, use a transistor

Example 2. The coil above has $L = 0.10$ H. Its 71 mA is switched off in 1.0 µs with no flyback diode. Estimate the voltage spike and the stored energy.

Show solution

1. $V = L\,\Delta I/\Delta t = (0.10)(0.071)/(1.0 \times 10^{-6}) = 7100\ \text{V}$ (in practice a spark or a breaking transistor limits it).
2. $E = \tfrac{1}{2}LI^2 = \tfrac{1}{2}(0.10)(0.071)^2 = 2.5 \times 10^{-4}\ \text{J}$.

Answer: Thousands of volts (about 7 kV in principle); only 0.25 mJ, but enough to destroy a transistor

Example 3. For the same coil, find the time constant L/R and roughly how long the current takes to reach its full value after switch-on.

Show solution

1. $\tau = L/R = 0.10/70 = 1.4 \times 10^{-3}$ s $= 1.4$ ms.
2. Full value after about $5\tau = 7$ ms. The armature then takes a few more milliseconds to move.

Answer: 1.4 ms; about 7 ms (relays switch in several milliseconds)

PRACTICE

1. Easy What are the NO, NC and COM terminals of a relay?

   Show answer

   COM is the moving contact; NO connects to COM only when the coil is energized; NC connects to COM when it is off.

2. Easy What does an inductor oppose: current, or a change in current?

   Show answer

   A change in current.

3. Easy Who discovered self-induction and invented the relay, and where did he later serve?

   Show answer

   Joseph Henry; the first Secretary of the Smithsonian Institution.

4. Medium A 12 V relay coil draws 30 mA. What is its resistance and power?

   Show answer

   400 Ω; 0.36 W

5. Medium Why does a relay module have a diode across its coil? Which way does the diode point?

   Show answer

   To give the coil current a path when switched off, preventing a high-voltage spike. It points backward to the supply (cathode to +), so it does not conduct in normal operation.

6. **Medium** Find the voltage across a 50 mH coil whose current changes by 0.20 A in 2.0 ms.

   Show answer

   $V = 0.050 \times 0.20/0.002 = 5.0$ V

7. **Medium** Why could a relay renew a weak telegraph signal over a long line?

   Show answer

   The weak line current only had to move a light armature; the armature closed a separate local circuit with its own battery, which sent a fresh, strong signal down the next section.

8. **Hard** Henry wound his coils with silk-wrapped wire in many layers. Explain why insulation let him make much stronger magnets than Sturgeon's.

   Show answer

   Insulated wire can be wound in many tight turns and layers without shorting between turns; the magnetic field is proportional to the number of turns times the current, so many more turns gave a far stronger magnet.

9. **Hard** Compare a relay and a transistor switch: give two advantages of each.

   Show answer

   Relay: isolated contacts, very low on-resistance, can switch AC or DC and separate circuits. Transistor: no moving parts or wear, switches in microseconds or faster, silent, needs little drive current.

10. **Hard** A 0.20 H coil carries 0.50 A. How much energy is stored? If that energy all went into a 1.0 μF capacitor, what voltage would the capacitor reach?

    Show answer

    $E = \tfrac{1}{2}(0.20)(0.25) = 0.025$ J; $V = \sqrt{2E/C} = \sqrt{0.05/10^{-6}} = 224$ V

11. **Challenge** A relay coil (70 Ω, 0.10 H) has a flyback diode with a 0.7 V drop. When switched off at 71 mA, the current decays through the coil and diode. Estimate how long it takes to fall to near zero and why the relay releases a little more slowly with the diode than without.

    Show answer

    The current decays with $\tau \approx L/R = 1.4$ ms (slightly faster with the diode's drop), so about 5–7 ms. Without the diode the current would stop almost instantly (with a spark); with it, the magnetic field persists for a few ms, holding the armature slightly longer.

COMMON MISTAKES

- Driving a relay coil straight from a microcontroller pin. The coil needs far more current; use a module or a transistor and a flyback diode.
- Wiring the load to NC by accident, so it is on when you expect it to be off.
- Putting the flyback diode in forward. Then it shorts the supply whenever the coil is switched on.

> **Make it a game · Relay Role-Play.** Act it out. One person is the coil, the other is the contact. Show what happens when current flows, and name NO, NC and COM using hands. Then explain why a flyback diode is placed across the coil and what V = L ΔI ÷ Δt predicts when current stops suddenly. Swap roles twice.

3.4 Diodes and Rectifiers: Fleming's Valve

OBJECTIVES

- Tell how Fleming's valve and the crystal detector became the first diodes, and explain the p–n junction simply.
- Describe a diode's I–V curve, forward drop and reverse blocking, and use the 0.7 V model in calculations.
- Explain half-wave and full-wave (bridge) rectification and reverse-polarity protection.
- Measure a diode's I–V curve and build a bridge that works whichever way the battery is connected.

> **Warm-up.** A check valve in a pipe (or the flap in a pet door that only swings one way) lets flow pass in only one direction. Where else have you seen a one-way device? Write two examples. An electrical diode is a one-way valve for current.

WATCH

Diodes Explained - The basics how diodes work working principle pn junction

The Engineering Mindset · 11:32

https://www.youtube.com/watch?v=Fwj_d3uO5g8

> **WHEN TO WATCH**
> After the story and before the physics. Pause at the p–n junction animation and describe the depletion region in your own words.

BACKUP VIDEO

How AC is turned to DC! EASY! (Rectifiers): Electronics Basics 7

Simply Electronics · 5:35

https://www.youtube.com/watch?v=5cbQNfO0Mwg

A short animated explanation of half-wave and full-wave rectifiers; watch before the rectifier worked example.

KEY TERMS

diode

A two-terminal part that conducts current easily in one direction (anode to cathode) and blocks it in the other. The band marks the cathode.

forward voltage

The voltage a conducting diode drops: about 0.6–0.7 V for silicon, 0.2–0.4 V for Schottky diodes, 1.8–3.3 V for LEDs.

p–n junction

The boundary between p-type and n-type semiconductor. A thin depletion region forms that blocks current until a forward voltage pushes carriers across it.

rectifier

A circuit that changes alternating current (AC) to direct current (DC). A half-wave rectifier uses one diode; a bridge rectifier uses four.

reverse breakdown

The large reverse voltage at which a diode suddenly conducts backward. Zener diodes are made to do this at a set voltage.

CORE IDEAS

The story. In 1904 John Ambrose Fleming, a professor at University College London and scientific adviser to Guglielmo Marconi's wireless company, needed a better detector for radio signals. Years before, he had studied the "Edison effect": in a light bulb with an extra metal plate sealed inside, current flowed from the hot filament to the plate, but only one way. Fleming realized this one-way valve could turn the rapidly alternating radio signal into a direct current that a meter or earphone could detect. He patented the **oscillation valve** in 1904, the first vacuum-tube diode. Fleming, a committed Christian, spoke and wrote often in defense of the faith. At almost the same time, radio amateurs were using crystal detectors, a fine wire (the "cat's whisker") touching a crystal of galena or silicon, which also conducted one way. The crystal detector was the ancestor of today's semiconductor diode.

How they figured it out. Fleming tested his valve by connecting it to an alternating current and a galvanometer: the needle showed a steady direct current, proving the valve passed only half of each cycle. Crystal detectors were unreliable, and for

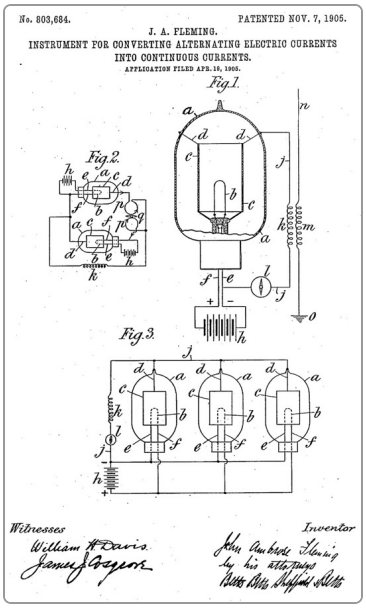
decades no one understood them. The full explanation came only with the quantum theory of solids in the 1930s and 1940s, and in 1940 Russell Ohl at Bell Labs found the first p–n junction in a cracked silicon rod, by accident: one side had a different impurity from the other. That discovery led straight to the transistor (Unit 4).

The physics. Pure silicon conducts poorly. Adding a tiny amount of phosphorus gives extra electrons (**n-type**); adding boron leaves "holes," missing electrons that act like positive carriers (**p-type**). Where p meets n, electrons and holes near the boundary cancel, leaving a thin **depletion region** with a built-in voltage of about 0.6–0.7 V in silicon. Forward bias (positive on the p side, the anode) pushes carriers across, and above about 0.6 V the current rises steeply. Reverse bias widens the barrier, and almost no current flows until breakdown. For calculations, engineers use a simple model: a conducting silicon diode drops 0.7 V. A **half-wave rectifier** passes only the positive halves of an AC wave; a **bridge** of four diodes flips the negative halves to positive, so the output always has the same polarity, at the cost of two diode drops.

The engineering. Diodes are the most common semiconductors after transistors. Every charger and power supply has a rectifier; every relay and motor driver has a flyback diode; many battery-powered devices have a diode or a bridge so that putting the batteries in backward cannot damage them. Engineers choose diodes by maximum current, maximum reverse voltage and forward drop: the 1N4001 (1 A, 50 V) for power, the 1N4148 (fast, small signal), Schottky diodes when every tenth of a volt counts. In this course the AC you rectify will be simulated or come from a spinning motor, never the wall.

Try it. You will measure a diode's curve, see it block current backward, and build a bridge that lights an LED correctly whichever way you connect the battery.

PICTURE STUDY



Fleming's Valve Patent, John Ambrose Fleming, U.S. Patent 803,684, granted 1905 · Patent drawing · U.S. Patent Office

Image: Wikimedia Commons, public domain

Fleming's patent shows his oscillation valve, a light bulb with an extra electrode, connected in a radio receiving circuit. It is the first vacuum-tube diode.

Look closely

- Find the filament and the metal plate or cylinder around it inside the bulb.
- Find the battery that heats the filament. Why must the filament be hot?
- Find the antenna and the meter or telephone receiver. Trace the path of the detected current.
- Look for the arrows or labels that show the one-way direction.

Talk about it

1. Why does current flow only from the hot filament to the plate, not the other way?
2. What part of a modern silicon diode does the same job as the hot filament and plate?
3. What disadvantages would a glass vacuum valve have compared with a small silicon diode?

> **Safety first.** Batteries and USB power only, never wall power. Build with the battery disconnected and connect it last. Wear safety glasses when trimming component leads; cut ends fly. The AC waveforms in this lesson come only from the online simulator or a small motor spun by hand; never use a transformer or anything plugged into the wall.

BUILD

A Diode Curve and a Polarity-Proof Bridge

You will measure a silicon diode's I–V curve and an LED's, show that diodes block reverse current, simulate a rectifier, and build a four-diode bridge that lights an LED correctly whichever way the battery is connected.

You will need

- Breadboard, jumper wires, 4-AA holder
- Four 1N4001 (or 1N4148) diodes, a red LED, resistors 220 Ω and 1 kΩ, the 10 kΩ potentiometer
- Digital multimeter
- Falstad's online simulator
- Optional: the kit's small DC motor and a red LED for a hand-cranked "generator" test

Steps

1. Use the meter's diode-test mode on one 1N4001 both ways and record the readings. Identify the cathode band.
2. Build battery → potentiometer (as a variable divider) → 1 kΩ → diode → ground. Vary the pot and record the voltage across the diode and the current (from the 1 kΩ's voltage ÷ 1000) for at least 10 points from 0 to about 5 mA.
3. Graph the diode's I–V curve. Mark where it "turns on." Repeat for the red LED (use 220 Ω instead of 1 kΩ) on the same graph.
4. Reverse the diode and show that almost no current flows at any setting. Record it.
5. In Falstad's simulator, open the half-wave and full-wave rectifier examples (Circuits menu, Diodes). Watch the input and output waveforms. Add a capacitor across the output and see the ripple shrink.
6. Build a bridge: four diodes in a diamond, with the battery across one diagonal and the LED (with 220 Ω) across the other. Check your wiring against the schematic before connecting.

7. Connect the battery one way, then the other. The LED should light both times. Measure the voltage across the LED-and-resistor branch each way and compare with the battery minus 1.4 V.
8. **Improve it.** Spin the small DC motor by hand quickly with an LED across it, first one way and then the other. Then put the motor across the bridge input. Explain why the LED now lights for both directions of spin.

Tips

- In a bridge, the two diodes on each side point the same way. If the LED lights only one way, one diode is backward.
- The diode current is easiest to find from the voltage across the series resistor.
- A spinning motor makes only a few volts; spin it fast and watch in dim light.

Check your work

- ☐ I graphed the I–V curves of a diode and an LED and explained their shapes.
- ☐ I showed that a diode blocks reverse current.
- ☐ I built a bridge that works with either battery polarity and measured its 1.4 V loss.

ENGINEER'S NOTEBOOK

1. Your I–V data and graph with both curves.
2. The bridge schematic with arrows showing the current path for each battery direction.
3. Sketches of the simulator waveforms: input AC, half-wave output, full-wave output, and with a smoothing capacitor.

KEY FORMULAS

$V_{\text{out}} \approx V_{\text{in}} - 0.7\ \text{V}$ (one silicon diode)
$V_{\text{out,peak}} \approx V_{\text{peak}} - 1.4\ \text{V}$ (bridge)
$I = \dfrac{V_s - V_D}{R}$

From history. Lee de Forest added a third electrode, a grid, to Fleming's valve in 1906, making the Audion triode, which could amplify. Triodes made long-distance telephone calls, radio broadcasting and the first electronic computers possible, until the transistor replaced them.

WORKED EXAMPLES

Example 1. A silicon diode and a 1.0 kΩ resistor are in series across 5.0 V, with the diode forward biased. Find the current. What is the current if the diode is reversed?

Show solution

1. Forward: the diode drops about 0.7 V, so the resistor has $5.0 - 0.7 = 4.3$ V.
2. $I = 4.3\ \text{V} / 1000\ \Omega = 4.3$ mA.
3. Reversed: the diode blocks; the current is essentially zero (nanoamperes), and the diode has the full 5.0 V across it.

Answer: 4.3 mA forward; about 0 reversed

Example 2. A battery-powered device uses 6.0 V and draws 100 mA. A designer adds (a) one series 1N4001 for reverse-polarity protection, or (b) a bridge rectifier so either polarity works. What voltage reaches the device and how much power is lost in each case?

Show solution

1. (a) One diode: $6.0 - 0.7 = 5.3$ V; loss $P = (0.7)(0.10) = 0.07$ W.
2. (b) Bridge: two diodes conduct at a time: $6.0 - 1.4 = 4.6$ V; loss $P = (1.4)(0.10) = 0.14$ W.
3. Trade-off: the bridge is more convenient but wastes twice the power and leaves less voltage.

Answer: (a) 5.3 V, 0.07 W lost; (b) 4.6 V, 0.14 W lost

Example 3. A 6.0 V peak AC wave (from a simulator, or a hand-cranked generator) feeds a half-wave rectifier into a resistor. Estimate the peak output and describe the waveform.

Show solution

1. Positive half-cycles: the diode conducts, output peak $6.0 - 0.7 = 5.3\ \text{V}$.
2. Negative half-cycles: the diode blocks, output 0 V.
3. The output is a series of positive humps with gaps: pulsing DC. A capacitor across the output (Lesson 3.2) fills in the gaps.

Answer: Peak 5.3 V; humps every other half-cycle

PRACTICE

1. Easy Which end of a diode is marked with a band?

   Show answer

   The cathode.

2. Easy About what forward voltage does a silicon diode drop? A Schottky diode?

   Show answer

   About 0.6–0.7 V; about 0.2–0.4 V.

3. Easy What did Fleming invent in 1904, and what was it for?

   Show answer

   The oscillation valve, the first vacuum-tube diode, to detect (rectify) radio signals.

4. Medium A 9.0 V battery, a 1N4148 and a 2.2 kΩ resistor are in series, diode forward. Find the current.

   Show answer

   $(9.0 - 0.7)/2200 = 3.8\ \text{mA}$

5. Medium Why does a bridge rectifier lose about 1.4 V instead of 0.7 V?

   Show answer

   Current passes through two diodes in series on each half-cycle.

6. Medium Explain n-type and p-type silicon in one sentence each.

Show answer

n-type has added atoms (such as phosphorus) that give extra free electrons; p-type has added atoms (such as boron) that leave holes, which act as positive carriers.

7. Medium A diode is placed in series with a 4-AA pack to protect a circuit. If the batteries go in backward, what happens? What if they go in correctly?

Show answer

Backward: the diode blocks, no current flows, and the circuit is safe. Correct: the circuit gets about 0.7 V less than the battery.

8. Hard A Schottky diode (0.3 V) replaces the silicon diode in the protection circuit of Worked Example 2(a). How much voltage and power are saved at 100 mA?

Show answer

0.4 V more reaches the device (5.7 V); loss falls from 0.07 W to 0.03 W, saving 0.04 W.

9. Hard Your measurements give 0.55 V at 0.1 mA, 0.62 V at 1 mA and 0.68 V at 10 mA. Describe the shape of the I–V curve and why the 0.7 V model works well.

Show answer

Each tenfold rise in current adds only about 0.06–0.07 V: the curve is exponential and very steep. Over the useful current range the voltage stays near 0.6–0.7 V, so treating it as a fixed 0.7 V gives small errors.

10. Hard Russell Ohl's 1940 discovery was an accident. What did he notice, and why did it matter?

Show answer

A cracked silicon rod produced a voltage when light shone on it and conducted one way; the crack separated regions with different impurities, a p–n junction. It led to understanding junctions, solar cells and the transistor.

11. **Challenge** A 1N4001 is rated 1 A and 50 V reverse. Could it be used as the flyback diode for the 70 Ω, 5 V relay of Lesson 3.3? Check the current and the reverse voltage it must withstand.

    Show answer

    Yes. It must carry the coil's 71 mA briefly when switched off (well under 1 A) and block 5 V in normal operation (well under 50 V).

COMMON MISTAKES

- Forgetting the diode drop in calculations; at low supply voltages 0.7 V is a big fraction.
- Putting a diode in with no resistor. A forward diode across a battery is a short circuit.
- Thinking a diode has a fixed resistance. Its resistance depends on the current; use the 0.7 V model instead.

> **Make it a game · One-Way Street.** Draw an I–V curve for a diode from memory in thirty seconds, labeling forward drop, reverse blocking and breakdown. Your parent plays skeptic and asks what the 0.7 V model predicts for a 5 V source with a 330 Ω resistor. Answer without notes. Then trace Fleming's valve to the crystal detector.

3.5 LEDs and Current Limiting

OBJECTIVES

- Trace the history of the LED from Round's observation to Holonyak's red LED and the blue LED of the 1990s.
- Explain why an LED needs current limiting, and calculate the series resistor $R = (V_s - V_F)/I$ and its power.
- Relate LED color to forward voltage and photon energy.
- Design, build and test LED circuits for several colors and an RGB LED.

> **Warm-up.** Look at the indicator lights around your house: chargers, appliances, a remote, a car dashboard. List the colors you see. Which colors seem most common, and which seem rare? Why might that be?

WATCH

Electronic Basics #8: Everything about LEDs and current limiting resistors

GreatScott! · 6:27

https://www.youtube.com/watch?v=Qlayua3yjuE

> **WHEN TO WATCH**
> Before the worked examples. Pause when the resistor formula appears and work the presenter's example yourself.

BACKUP VIDEO

How to Find LED Resistor Value

Ben Finio · 11:23

https://www.youtube.com/watch?v=EeCh68a1GEg

A careful walk-through of choosing an LED resistor with a real datasheet; good before the build.

KEY TERMS

LED (light-emitting diode)

A diode that gives off light when current flows forward through it, as electrons drop across the junction and release photons.

forward voltage (V_F)

The voltage across a lit LED: about 1.8–2.2 V for red, yellow and some green; about 2.8–3.4 V for blue, white and true green.

current-limiting resistor

A resistor in series with an LED that sets its current: $R = (V_s - V_F)/I$.

datasheet

The maker's document giving a part's ratings and typical values, such as an LED's maximum current (often 20–30 mA) and forward voltage.

band gap

The energy an electron loses crossing the junction; it sets the photon's energy and so the LED's color.

CORE IDEAS

The story. In 1907 Henry Joseph Round, an engineer in Marconi's company, noticed that a crystal of carborundum (silicon carbide) used as a radio detector gave off a faint yellowish glow when current passed through it. He published a two-paragraph note and moved on. In the 1920s Oleg Losev in Russia studied the glow carefully and even explained it as the reverse of the photoelectric effect, but his work was largely forgotten. The first practical visible LED came in 1962, when Nick Holonyak Jr., working at General Electric in Syracuse, New York, made a red LED from gallium arsenide phosphide. Red LEDs soon appeared in calculator displays and indicator lights. Blue was the great problem: only in the early 1990s did Isamu Akasaki, Hiroshi Amano and Shuji Nakamura in Japan make bright blue LEDs from gallium nitride, which made white LED lighting possible. They received the 2014 Nobel Prize in Physics.

How they figured it out. The color of an LED is set by its material: the energy an electron gives up as it falls across the junction becomes one photon, and a photon's energy fixes its color. Red light needs about 1.9 eV per photon, blue about 2.7 eV. Holonyak chose a mixture of gallium, arsenic and phosphorus whose band gap fell in the red; Nakamura and his colleagues spent years learning to grow pure gallium nitride crystals with the larger gap needed for blue. White LEDs are blue LEDs coated with a phosphor that turns some blue light into yellow, which our eyes see as white.

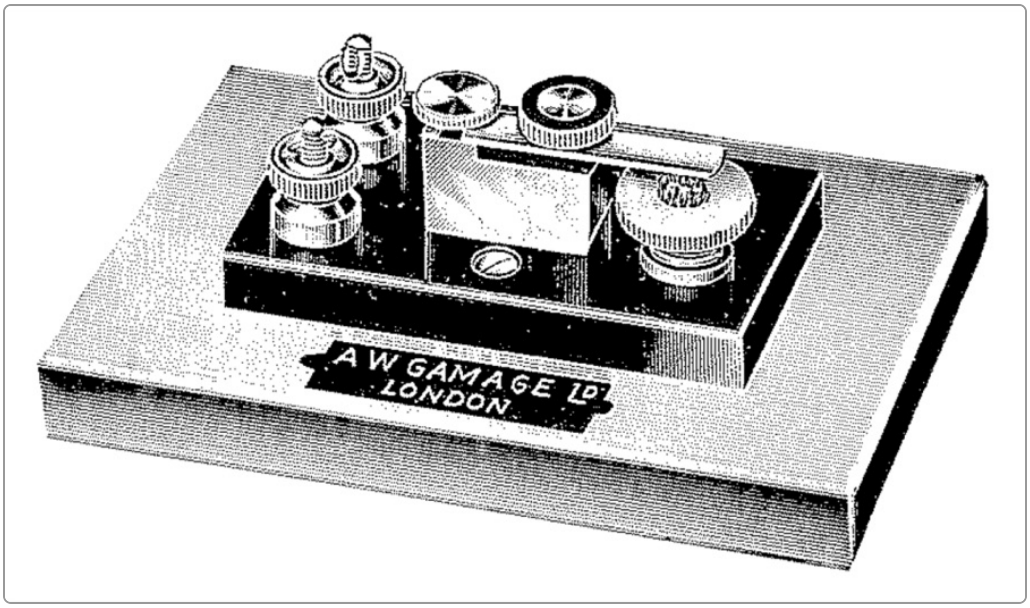
The physics. An LED is a diode, so its current rises very steeply once the forward voltage is reached. A red LED might draw 1 mA at 1.8 V, 10 mA at 1.95 V and 50 mA (destroying it) at 2.1 V. That means you cannot set an LED's current by choosing a

voltage; a tiny change gives a huge change in current. Instead you put a **resistor** in series to set the current: the resistor takes the leftover voltage, so $R = (V_s - V_F)/I$. For a red LED on 5 V at 15 mA: $R = (5.0 - 2.0)/0.015 = 200\ \Omega$; use the next standard value up, 220 Ω. The photon energy matches the forward voltage roughly: $E = hc/\lambda$ gives 1.9 eV for 650 nm red light and 2.8 eV for 450 nm blue, close to the volts each LED needs.

The engineering. Engineers set LED current from the datasheet: usually 5–20 mA for an indicator, well below the 20–30 mA maximum. They check the resistor's power, $P = I^2R$, and for battery products choose the lowest current that is bright enough, because the light output rises with current but the battery life falls. Each LED gets its own resistor, because two LEDs in parallel never share current equally. High-power lighting LEDs use constant-current driver chips instead of resistors, and microcontrollers dim LEDs by switching them on and off rapidly (pulse-width modulation, Lesson 7.5). LED lighting uses a small fraction of the energy of an incandescent bulb for the same light.

Try it. In the build you will design resistors for several LED colors, measure their forward voltages and currents, and mix colors with an RGB LED.

PICTURE STUDY



A Carborundum Crystal Detector, Unknown illustrator, 1922 · Illustration · Wikimedia Commons

Image: Wikimedia Commons, public domain

Crystal detectors like this one, using carborundum (silicon carbide), were common in early radio sets. In 1907 H. J. Round noticed that a carborundum crystal like this gave off a faint glow when current passed through it: the first recorded light-emitting diode.

Look closely

- Find the crystal and the metal contact that touches it.
- Find the adjusting screw or spring. Why did operators need to adjust the contact?
- Find the two terminals where the detector connects to the radio circuit.
- Compare its size with a modern LED. Which parts of an LED do the same jobs?

Talk about it

1. Why would Round's glowing crystal have seemed only a curiosity in 1907?
2. Why did it take until 1962 to make a practical LED?
3. Carborundum is still used in some blue and high-power devices. What does that suggest about old discoveries?

> **Safety first.** Batteries and USB power only, never wall power. Build with the battery disconnected and connect it last. Wear safety glasses when trimming component leads; cut ends fly. Never look straight into a bright LED at close range for long, and never connect an LED without a series resistor.

BUILD

Designing LED Circuits by the Numbers

You will measure the forward voltage of every LED color in your kit, design a resistor for each, build and measure them, test brightness against current, and mix colors with an RGB LED.

You will need

- LEDs of every color in the kit (red, yellow, green, blue, white), an RGB LED (common cathode or common anode; check the kit)
- Resistors: 100 Ω, 150 Ω, 220 Ω, 330 Ω, 470 Ω, 1 kΩ
- Breadboard, jumpers, Arduino 5 V on USB (or 4-AA pack)
- Digital multimeter; optionally a phone light-meter app

Steps

1. Use the meter's diode test to light each LED faintly and read its approximate forward voltage. Record them by color.
2. For each color, design a resistor for 10 mA from 5.0 V using $R = (V_s - V_F)/I$, and choose the nearest standard value at or above it.
3. Build each LED with its resistor. Measure the LED voltage and the current. Compare with your design.
4. Graph forward voltage against color (or wavelength: red 630, yellow 590, green 525 or 570, blue 470 nm; white is a blue LED with a phosphor). Compare with $E = 1240/\lambda$.
5. Brightness test: run the red LED with 1 kΩ, 470 Ω, 330 Ω and 220 Ω. Measure the current and rate the brightness (or measure it with a light-meter app at a fixed distance). Graph brightness against current.
6. RGB LED: identify the common lead (longest) and the three color leads. Give each color its own resistor (220 Ω for red, 100–150 Ω for green and blue). Connect them one at a time, then in pairs, and record the colors you see.
7. Design a pleasant "warm white" by choosing different resistors for the three channels. Record your values.

8. **Improve it.** Design the lowest-power indicator light you would accept on a battery product: find the smallest current at which the red LED is still clearly visible in a lit room, and calculate how long a 2,500 mAh battery pack would run it.

Tips

- Common-cathode RGB LEDs have the long lead to ground; common-anode ones have it to +5 V. Check your kit's datasheet.
- Brightness to the eye is not proportional to current; doubling the current looks less than twice as bright.
- Blue and white LEDs need about 3 V, so they leave less voltage for the resistor.

Check your work

- ☐ I measured forward voltages for several colors and related them to photon energy.
- ☐ I designed resistors by calculation and my measured currents matched within about 10%.
- ☐ I mixed colors with an RGB LED, each channel with its own resistor.

ENGINEER'S NOTEBOOK

1. A table of color, V_F, designed R, standard R, predicted and measured current.
2. Graphs of forward voltage against wavelength and brightness against current.
3. The RGB schematic and your color-mixing results.

KEY FORMULAS

$$R = \frac{V_s - V_F}{I}$$

$$P_R = I^2 R$$

$$E_{\text{photon}} = \frac{hc}{\lambda}, \quad hc = 1240 \text{ eV·nm}$$

From history. Holonyak predicted in 1963 that LEDs would one day replace the incandescent light bulb. It took about fifty years, the blue LED and much engineering of heat and phosphors, but his prediction came true.

WORKED EXAMPLES

Example 1. Design a resistor for a red LED ($V_F = 2.0$ V) at 15 mA from the Arduino's 5.0 V supply. Find the resistor's power and choose a standard value.

Show solution

1. $R = (5.0 - 2.0)/0.015 = 200\ \Omega$.
2. Choose the next standard value up: 220 Ω. Then $I = 3.0/220 = 13.6$ mA.
3. $P = I^2R = (0.0136)^2(220) = 0.041$ W, far below 1/4 W.

Answer: 220 Ω (13.6 mA, 0.04 W)

Example 2. A blue LED ($V_F = 3.1$ V) is to run at 10 mA from a 3.3 V Raspberry Pi Pico pin. Find R. What problem appears?

Show solution

1. $R = (3.3 - 3.1)/0.010 = 20\ \Omega$.
2. Only 0.2 V is left for the resistor, so a small change in V_F (they vary by ±0.2 V) changes the current enormously: at $V_F = 3.0$ the current is 15 mA; at 3.2 V only 5 mA.
3. Better: use a larger resistor and accept a dimmer LED, or drive the LED from 5 V through a transistor.

Answer: About 20 Ω, but the current is poorly controlled; little voltage headroom

Example 3. Two red LEDs in series ($V_F = 2.0$ V each) run from a 9.0 V battery at 20 mA. Find R and compare the power wasted with putting each LED on its own resistor in parallel.

Show solution

1. Series: $R = (9.0 - 4.0)/0.020 = 250\ \Omega$ (use 270 Ω); resistor power $= (0.020)^2(250) = 0.10$ W; total current 20 mA.
2. Parallel: each branch $R = (9.0 - 2.0)/0.020 = 350\ \Omega$; each wastes $(0.020)^2(350) = 0.14$ W, total 0.28 W, and draws 40 mA.
3. Series uses half the current and wastes far less power.

Answer: Series with 250 Ω (270 Ω standard): 20 mA, 0.10 W; parallel: 40 mA, 0.28 W

PRACTICE

1. Easy Find R for a red LED ($V_F = 2.0$ V) at 10 mA from 5.0 V.

   Show answer

   300 Ω (use 330 Ω)

2. Easy Which LED lead is the anode, and which side of the LED body is usually flat?

   Show answer

   The longer lead is the anode (+); the flat side of the rim marks the cathode (−).

3. Easy Who made the first practical visible (red) LED, and when?

   Show answer

   Nick Holonyak Jr., at General Electric, in 1962.

4. Medium A green LED ($V_F = 3.0$ V) at 10 mA from 5.0 V: find R and its power.

   Show answer

   200 Ω; 0.02 W

5. **Medium** Why can you not just connect an LED straight to a 2.0 V source and expect 15 mA?

   Show answer

   The LED's current changes enormously for tiny changes in voltage and with temperature; a small error gives too much current, so the current must be set by a resistor (or a current driver).

6. **Medium** Use $E = 1240/\lambda$ (eV, nm) to find the photon energy of 590 nm yellow light.

   Show answer

   2.1 eV

7. **Medium** A 220 Ω resistor with a red LED is moved from 5 V to a 9 V battery. Find the new current. Is it safe for a 20 mA LED?

   Show answer

   $(9.0 - 2.0)/220 = 32$ mA: too high; use about 390 Ω.

8. **Hard** An indicator LED runs 24 hours a day at 15 mA from a 5.0 V supply with a 220 Ω resistor. How much energy does it use in a year, in kWh?

   Show answer

   $P = 5.0 \times 0.015 = 0.075$ W; $\times 8760$ h $= 657$ Wh $= 0.66$ kWh

9. **Hard** Three white LEDs ($V_F = 3.2$ V) must run from 4 AA cells (6.0 V). Can they go in series? Design a circuit for 15 mA each.

   Show answer

   No: $3 \times 3.2 = 9.6$ V > 6.0 V. Use three parallel branches, each with $R = (6.0 - 3.2)/0.015 = 187$ Ω (use 180 or 200 Ω); total 45 mA.

10. **Hard** Why did white LED lighting have to wait for the blue LED?

    Show answer

    White LEDs use a blue LED to excite a yellow phosphor (or mix red, green and blue). Without an efficient blue source, there was no practical way to make white light.

11. **Challenge** An LED's datasheet gives V_F = 1.9 V minimum, 2.1 V typical, 2.4 V maximum at 20 mA. Design a resistor for a 5.0 V supply so that the current never exceeds 20 mA for any LED. What is the current for a typical LED?

    Show answer

    Worst case for high current is the lowest V_F: $R \geq (5.0 - 1.9)/0.020 = 155\ \Omega$; choose 160 or 180 Ω. With 180 Ω, a typical LED draws $(5.0 - 2.1)/180 = 16$ mA.

COMMON MISTAKES

- Using the supply voltage instead of $V_s - V_F$ in the resistor formula.
- Rounding the resistor down. Round up to the next standard value so the current is a little lower, not higher.
- Using one resistor for several parallel LEDs.

Make it a game · LED Resistor Race. Beat the clock. Your parent names a supply voltage, an LED color with forward voltage, and a current. You calculate R = (V_s − V_F) ÷ I and its power, then pick the nearest standard value. Five calculations in two minutes is the goal. Add a bonus point for naming Holonyak or the blue LED breakthrough.

Scripture. "Neither do men light a candle, and put it under a bushel, but on a candlestick; and it giveth light unto all that are in the house." (Matthew 5:15, KJV)

An LED is a very small candle, but it is placed to give light where it is needed. Our Lord uses the same picture for the way His people should live.

UNIT 3

Components

Every electronic device is built from a small vocabulary of parts. In this unit you will meet the five most important passive and semiconductor components one by one: the resistor, the capacitor, the inductor (and its useful cousin, the relay), the diode and the LED. Each has a story, from the Leyden jar of 1746 that gave Cunaeus the shock of his life to the blue LED that won a Nobel Prize in 2014.

For each part you will learn its physics, its equations, how to read its markings and ratings, and how engineers choose it. And you will measure each one yourself: a resistor batch test, an RC charging curve, a relay switching a separate circuit, a diode's I–V curve, and a set of LED circuits designed by the numbers.

PREREQUISITES

- Units 1–2: Ohm's law, power, series and parallel, Kirchhoff's laws, schematics
- Exponents and powers of ten; a scientific calculator with e^x and ln

MASTERY CHECKLIST

- ☐ I can read resistor color codes and use standard values and tolerances in a design.
- ☐ I can use $Q = CV$, $\tau = RC$, and $\frac{1}{2}CV^2$ and describe charging and discharging curves.
- ☐ I can explain inductance, the inductive kick, relays and flyback diodes.
- ☐ I can use the 0.7 V diode model and explain half-wave and bridge rectifiers and polarity protection.
- ☐ I can design a current-limiting resistor for any LED and check its

power.

OPTIONAL KITS FOR THIS UNIT

- **A component assortment**: An inexpensive assortment of electrolytic and ceramic capacitors, 1N4001 and 1N4148 diodes and extra LEDs from any electronics supplier fills gaps in a starter kit. Not required.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

3.1	**Resistors and the Color Code**	3 sessions of 50 minutes
3.2	**Capacitors and RC Timing: From the Leyden Jar**	3 sessions of 50 minutes
3.3	**Inductors and Relays: Joseph Henry's Coils**	3 sessions of 50 minutes
3.4	**Diodes and Rectifiers: Fleming's Valve**	3 sessions of 50 minutes
3.5	**LEDs and Current Limiting**	3 sessions of 50 minutes

Unit 3 test

Time: 50 minutes. A scientific calculator is allowed. Show the formula, the substitution with units and the answer with its unit for each calculation; correct setup earns partial credit. The test is worth 100 points.

1. **6 pts** **Lesson 3.1**

   Read: (a) red-violet-orange-gold; (b) green-blue-brown-gold; (c) the surface-mount code 222.

2. **6 pts** **Lesson 3.1**

   A 330 Ω ±5% resistor measures 342 Ω. Find the percent error and say whether it passes.

3. **6 pts** **Lesson 3.1**

   Explain why standard resistor values are spaced by equal percentages rather than equal steps.

4. **8 pts** **Lesson 3.2**

   A 220 µF capacitor charges through 22 kΩ from 6.0 V. Find τ, the voltage after 4.84 s, and the approximate full-charge time.

5. **6 pts** **Lesson 3.2**

   Find the charge and energy of a 470 µF capacitor at 9.0 V.

6. **6 pts** **Lesson 3.2**

   Describe the Leyden jar and what Franklin's experiment showed about where its charge was stored.

7. **8 pts** **Lesson 3.3**

   A 5 V relay coil of 125 Ω has $L = 0.15$ H. Find its current, power and L/R time constant. Why does it need a transistor and a flyback diode to be driven by an Arduino?

8. **6 pts** **Lesson 3.3**

   Explain how Joseph Henry's relay made long telegraph lines possible.

9. **6 pts** **Lesson 3.3**

   Find the voltage across a 20 mH inductor when its current falls 0.50 A in 0.10 ms.

10. **8 pts** **Lesson 3.4**

    A 6.0 V battery feeds a silicon diode and 470 Ω in series, diode forward. Find the current. Then the battery is reversed: what is the current, and what voltage is across the diode?

11. **6 pts** **Lesson 3.4**

    Explain how a bridge rectifier lets a device work with batteries inserted either way, and its cost in voltage.

12. **6 pts** **Lesson 3.4**

    Describe a p–n junction and its depletion region in two or three sentences.

13. **8 pts** **Lesson 3.5**

Design resistors for (a) a yellow LED ($V_F = 2.1$ V) at 12 mA from 5.0 V and (b) a white LED ($V_F = 3.2$ V) at 15 mA from 5.0 V. Give calculated and standard values and the resistor power.

14. **6 pts** **Lesson 3.5**

Why does each LED in parallel need its own resistor?

15. **8 pts** **Lesson 3.5**

Essay (one paragraph). Trace the history of the LED from Round's glowing crystal to the white LED, and explain why the blue LED was the key step.

ANSWER KEY

1. (a) 27 kΩ ±5%; (b) 560 Ω ±5%; (c) 2.2 kΩ
2. +3.6%; passes (allowed 313.5–346.5 Ω)
3. So that every needed value is within a fixed percentage (the tolerance) of a standard value at every scale, with no wasted values.
4. $\tau = 4.84$ s; $V = 6.0(1 - e^{-1}) = 3.79$ V; about 24 s (5τ)
5. $Q = 4.23$ mC; $E = 0.019$ J
6. A glass jar with conductors (water or foil) inside and foil outside; the glass is the dielectric. Franklin poured the water into a new jar and found the charge stayed with the original glass.
7. 40 mA; 0.20 W; 1.2 ms. 40 mA exceeds a pin's safe current, and switching the coil off produces a large voltage spike that the diode absorbs.
8. A weak current from the long line moved a light armature that closed a separate local circuit with its own battery, renewing the signal for the next section.
9. $V = 0.020 \times 0.50 / 0.0001 = 100$ V
10. $(6.0 - 0.7)/470 = 11.3$ mA; reversed: about 0, with 6.0 V across the diode.
11. Four diodes route current so it always flows the same way through the load, whichever terminal is positive; two diodes conduct at a time, losing about 1.4 V.
12. p-type silicon (holes) meets n-type (extra electrons); carriers near the boundary cancel, leaving a thin region with no free carriers and a built-in voltage (about 0.6–0.7 V in silicon) that blocks current until forward bias overcomes it.
13. (a) 242 Ω → 270 Ω (about 10.7 mA, 0.03 W); (b) 120 Ω → 120 Ω (15 mA, 0.027 W)
14. LEDs' forward voltages differ slightly; with one shared resistor, the LED with the lowest V_F takes most of the current, overheats and fails.
15. A strong answer: Round 1907 (carborundum glow), Losev 1920s, Holonyak 1962 red LED at GE, then decades of red/green indicators; blue required pure gallium nitride, achieved by Akasaki, Amano and Nakamura in the early 1990s (Nobel 2014); blue plus a yellow phosphor gives white, so efficient LED lighting became possible.

PORTFOLIO PIECE: A BATTERY-POWERED FADE-OUT NIGHT LIGHT

Design and build a small night light, powered by the 4-AA pack, that turns on with a push button and fades out slowly over 20–60 seconds when released, using a capacitor discharging through an LED and resistor. Include reverse-polarity protection with a diode. Calculate the resistor for the LED's maximum current, the time constant and the expected glow time; build it; measure the actual glow time and LED current; and explain any difference. Present a schematic, a parts list with values and ratings, your calculations and test data.

LOOK FOR	WHAT IT MEANS
Design calculations	LED resistor, time constant and expected glow time calculated with units, using standard values.
Correct components	Electrolytic polarity and voltage rating correct; protection diode correctly placed; every LED has its resistor.
Testing	Measured glow time and current recorded and compared with the predictions.
Documentation	Neat schematic, parts list with values and ratings, and a short report on one improvement.

UNIT 4

Transistors and Semiconductors

The transistor is the most important invention of the twentieth century: it is in every radio, phone, car and computer, and more of them have been made than any other manufactured thing. In this unit you will follow its story from the paper-clip prototype at Bell Labs in December 1947, through the pocket radio, the MOSFET and the integrated circuits of Kilby and Noyce, to the billions of transistors in your phone.

You will learn how doped silicon works, how a small current or voltage controls a large one, how to design transistor switches and a simple amplifier, how to choose between a BJT and a MOSFET for a real load, and how to read the datasheets that engineers use every day.

PREREQUISITES

- Unit 3: diodes, the p–n junction, LEDs, relays and flyback diodes
- Ohm's law and Kirchhoff's laws; voltage dividers
- Logarithms base 2 and 10 (introduced in this unit where needed)

MASTERY CHECKLIST

- ☐ I can explain doping, holes, the p–n junction and how an NPN transistor controls current, and use $I_C = \beta I_B$.
- ☐ I can design an NPN low-side switch with a base resistor and overdrive, and calculate its power.
- ☐ I can find the bias point and approximate gain of a common-emitter amplifier, in plain numbers and dB.
- ☐ I can design a logic-level MOSFET switch with gate resistor, pull-down and flyback diode, and choose between a BJT and a MOSFET.
- ☐ I can tell the story of the transistor and the integrated circuit, use Moore's law, and read an IC datasheet and pinout.

OPTIONAL KITS FOR THIS UNIT

- **A transistor and MOSFET assortment**: A small pack of 2N2222 or 2N3904 NPN transistors and a few logic-level MOSFETs (IRLZ44N or similar), plus a 74HC00, from any electronics supplier. Starter kits often include only one or two transistors and a non-logic-level MOSFET.
- **Wokwi (free online simulator)**: Free browser-based simulator for Arduino and Raspberry Pi Pico circuits with LEDs, buttons and many parts. Useful when a part is missing in Units 4–10.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

4.1	**Bell Labs, 1947: The First Transistor**	3 sessions of 50 minutes
4.2	**The Transistor as a Switch**	3 sessions of 50 minutes
4.3	**Amplifiers, Simply: The Transistor Radio**	3 sessions of 50 minutes
4.4	**MOSFETs and Driving Loads**	3 sessions of 50 minutes
4.5	**The Integrated Circuit: Kilby and Noyce**	3 sessions of 50 minutes

Unit 4 Test

Time: 50 minutes. A scientific calculator is allowed. Show the formula, the substitution with units and the answer with its unit for each calculation; correct setup earns partial credit. The test is worth 100 points.

1. **6 pts** **Lesson 4.1**

   A transistor has β = 120 and a base current of 0.25 mA. Find I_C and I_E.

2. **6 pts** **Lesson 4.1**

   Describe how Bardeen and Brattain made the first transistor work, including the problem Bardeen solved.

3. **6 pts** **Lesson 4.1**

   Explain n-type and p-type doping and why an NPN transistor's base is thin.

4. **8 pts** **Lesson 4.2**

   Design a base resistor so a 5 V Arduino pin can switch a 150 mA load with an NPN transistor of minimum β = 100, using 5× overdrive. What is the base current, and is it safe for the pin (20 mA)?

5. **6 pts** **Lesson 4.2**

   A transistor switch has $V_{CE} = 0.2$ V at 150 mA. Find its power. What would it be if it were only half on, with 2.5 V across it?

6. **6 pts** **Lesson 4.2**

   Why must a transistor switch be either fully off or fully on?

7. **8 pts** **Lesson 4.3**

   A common-emitter stage on 12 V has $R_1 = 33$ kΩ, $R_2 = 6.8$ kΩ, $R_E = 680$ Ω, $R_C = 3.3$ kΩ. Find V_B, I_C, V_C and the approximate gain in plain numbers and dB.

8. **6 pts** **Lesson 4.3**

   Explain why the gain of a common-emitter stage with an emitter resistor depends on R_C/R_E rather than on β, and why that matters.

9. **8 pts** **Lesson 4.4**

   A MOSFET with $R_{DS(on)} = 0.022$ Ω switches a 3.0 A load; a BJT with $V_{CE(sat)} = 0.4$ V could do the same. Compare their power dissipation.

10. **8 pts** **Lesson 4.4**

    Draw (describe) a complete logic-level MOSFET motor driver from an Arduino pin, naming and explaining each extra part.

11. **6 pts** **Lesson 4.4**

    Why is a non-logic-level MOSFET a poor choice with a 5 V microcontroller?

12. **8 pts** **Lesson 4.5**

    Using Moore's law (doubling every 2 years), how many transistors would you predict 20 years after a chip of 1.2 million? How many doublings take 2,300 to 2.3 billion?

13. **6 pts** **Lesson 4.5**

    State what Kilby and Noyce each contributed to the integrated circuit.

14. **4 pts** **Lesson 4.5**

    How is pin 1 identified on a DIP chip, and why must unused CMOS inputs be tied high or low?

15. **8 pts** **Lesson 4.1**

    Essay (one paragraph). Explain why the transistor replaced the vacuum tube and how that change led, within twenty years, to the integrated circuit and the pocket calculator.

ANSWER KEY

1. $I_C = 30$ mA; $I_E = 30.25$ mA
2. Shockley's field-effect idea failed because surface states trapped electrons; Bardeen explained this. Brattain pressed two gold contacts, made by slitting gold foil on a plastic wedge, very close together onto germanium; a small signal at one controlled a larger current at the other (December 1947).
3. n-type: added atoms with five outer electrons give free electrons; p-type: atoms with three leave holes. The thin base lets most electrons from the emitter cross to the collector before recombining, giving high gain.
4. $I_{B,\min} = 1.5$ mA; with 5×, 7.5 mA; $R_B = 4.3/0.0075 = 573\ \Omega \rightarrow 560\ \Omega$ (7.7 mA). Safe.
5. 0.03 W; 0.375 W
6. In between, it has both voltage across it and current through it, so it dissipates $V_{CE}I_C$ as heat; fully off ($I \approx 0$) or saturated ($V \approx 0$), it wastes little power.
7. $V_B = 12 \times 6.8/39.8 = 2.05$ V; $I_C \approx 1.35/680 = 1.99$ mA; $V_C = 12 - 6.56 = 5.4$ V; $A_v \approx -4.85$, about 13.7 dB
8. The emitter follows the base signal, so the signal current is v_{in}/R_E, and the output is that current times R_C; β cancels out. Transistors vary, so a gain set by resistors is predictable and repeatable.
9. MOSFET $= 9 \times 0.022 = 0.20$ W; BJT $= 1.2$ W
10. Pin → gate resistor (100–220 Ω, limits the switching spike) → gate; pull-down 10 kΩ gate to source (keeps it off at start-up); source to ground; motor from + supply to drain; flyback diode across the motor (absorbs turn-off spike); grounds joined.
11. Its $R_{DS(on)}$ is specified at about 10 V; at 5 V it is only partly on, so its resistance is high, it heats up and the load gets less voltage.
12. $1.2 \times 10^6 \times 2^{10} \approx 1.2 \times 10^9$; $\log_2(10^6) \approx 20$ doublings.
13. Kilby (Texas Instruments, 1958): all components can be made from one semiconductor, showed on germanium with wire connections. Noyce (Fairchild, 1959): a practical monolithic silicon IC with connections deposited on top of the oxide using the planar process.
14. By the notch or dot; floating CMOS inputs can drift, causing erratic behavior and extra current.

15. A strong answer: tubes were large, hot, power-hungry and short-lived; transistors were tiny, cool, reliable and cheap; transistor radios (1954) and computers followed; but hand-wired transistor circuits hit the tyranny of numbers; Kilby and Noyce integrated parts and wiring on one chip; space and defense orders lowered costs; by 1967–1971 chips held enough logic for handheld calculators and the first microprocessor.

PORTFOLIO PIECE: A TRANSISTOR-DRIVEN LOAD CONTROLLER

Design and build a controller that lets a push button and a light sensor (a photoresistor divider from Lesson 2.3) turn on a real load from the 4-AA pack: a motor-driven fan or a cluster of at least six LEDs. Use a transistor stage to turn the sensor's small voltage into a switching signal, and a logic-level MOSFET (or a properly designed BJT switch) to drive the load, with every protective part in place. Document the design calculations, the datasheet values you relied on, measured voltages and currents, the power in each switch, and one improvement.

LOOK FOR	WHAT IT MEANS
Design	Base or gate resistors, pull-downs, LED resistors and flyback diode chosen by calculation from datasheet values.
Working device	The load turns on and off reliably from the button and the light level; the switching transistor stays cool.
Measurements	Measured V_{CE} or V_{DS}, currents and power compared with the predictions.
Documentation	Schematic, datasheet notes, test table and a paragraph on one improvement made.

4.1 Bell Labs, 1947: The First Transistor

OBJECTIVES

- Tell the story of the point-contact transistor at Bell Labs in December 1947, and why AT&T wanted a replacement for the vacuum tube.
- Explain semiconductors, doping, electrons and holes at a high-school level.
- Describe how a small current or voltage in a transistor controls a large one, and name the terminals of a bipolar transistor.
- Identify and test an NPN transistor's junctions with a multimeter and find its pinout.

> **Warm-up.** Look at a photograph or museum picture of an old vacuum-tube radio (or imagine a box of glowing glass bulbs). List three problems you think tubes would cause: think about heat, size, power and what happens when one fails.

WATCH

The Transistor: a 1953 documentary, anticipating its coming impact on technology

AT&T Tech Channel · 9:37

https://www.youtube.com/watch?v=V9xUQWo4vN0

> **WHEN TO WATCH**
> At the start of the lesson, after the warm-up. This 1953 Bell Labs film was made only six years after the invention; notice what its makers predicted and compare it with your phone.

BACKUP VIDEO

How the first transistor worked

engineerguy · 4:46

https://www.youtube.com/watch?v=RdYHljZi7ys

Bill Hammack (engineerguy) explains, with a working model, exactly how the first point-contact transistor worked; watch after the physics paragraph.

KEY TERMS

semiconductor

A material, such as silicon or germanium, whose conductivity lies between a conductor's and an insulator's and can be controlled by adding impurities.

doping

Adding a tiny, controlled amount of impurity to a semiconductor: phosphorus or arsenic makes n-type (extra electrons); boron or gallium makes p-type (holes).

hole

A missing electron in a semiconductor's bonds. It moves like a positive charge as neighboring electrons fill it in turn.

transistor

A semiconductor device in which a small current or voltage at one terminal controls a much larger current between the other two.

bipolar junction transistor (BJT)

A transistor made of three layers (NPN or PNP) with terminals called emitter, base and collector. A small base current controls a large collector current.

CORE IDEAS

The story. By the 1940s the American telephone network, run by AT&T, depended on millions of vacuum tubes to amplify calls across the continent, and on mechanical relays to switch them. Tubes were large, ran hot, used a great deal of power and burned out. Mervin Kelly, research director of Bell Telephone Laboratories in New Jersey, set up a solid-state physics group after the Second World War to find a replacement made from semiconductors. It was led by William Shockley and included the theorist John Bardeen and the experimenter Walter Brattain. On December 16, 1947, Brattain pressed two gold contacts, a fraction of a millimeter apart, onto a slab of germanium, and a small signal on one contact controlled a larger current through the other. On December 23 they showed to Bell Labs managers that it amplified speech. They called it the **transistor**. Bardeen, Brattain and Shockley shared the 1956 Nobel Prize in Physics.

How they figured it out. Their first attempts failed. Shockley had predicted that an electric field applied to a semiconductor's surface should change its conductivity, but experiments showed almost no effect. Bardeen worked out why: electrons were trapped in "surface states" at the germanium's surface, shielding the inside. To get past the surface, Brattain tried electrolytes, then gold contacts pressed very close together. To make two contacts that close, he wrapped gold foil around a plastic triangle, slit the foil at the point with a razor, and pressed the point into the germanium with a spring. The first transistor was held together with a paper clip. Within weeks Shockley, determined to do better, worked out the theory of the sturdier **junction transistor**, made of three layers of semiconductor; it became the transistor that industry built in millions.

The physics. In silicon, each atom shares its four outer electrons with four neighbors. Pure silicon has few free carriers. Doping with phosphorus (five outer electrons) adds free electrons: **n-type**. Doping with boron (three) leaves holes: **p-type**. An NPN transistor is a thin p-type **base** between an n-type **emitter** and an n-type **collector**. When a small current flows into the base (with the base about 0.7 V above the emitter), electrons pour from the emitter into the thin base; most of them shoot right through it to the collector. So a small base current I_B controls a collector current about β times larger: $I_C = \beta I_B$, where β (the current gain) is often 100–300. With no base current, almost no collector current flows. That is switching and amplifying in one device.

The engineering. Transistors replaced tubes because they were tiny, used milliwatts instead of watts, needed no warm-up, did not burn out and could be made cheaply in huge numbers. They made possible the transistor radio (1954), transistorized computers (late 1950s), and then the integrated circuit (Lesson 4.5). In your kit you will find NPN transistors such as the 2N2222 or PN2222 and the 2N3904 or S8050. Each has three legs whose order depends on the package and maker, so engineers always check the datasheet pinout, or test the junctions with a meter.

Today. A modern phone chip holds more than ten billion transistors, each a few dozen atoms wide in its smallest features. All of them descend from Brattain's gold foil and paper clip.

PICTURE STUDY



Bardeen, Shockley and Brattain, Bell Telephone Laboratories, 1948 · Photograph · AT&T Archives

Image: Wikimedia Commons, public domain

This publicity photograph was made at Bell Labs in 1948, when the transistor was announced to the public. Shockley sits at the apparatus, though in fact Bardeen and Brattain had built the first device; the photograph itself became part of the story of their rivalry.

Look closely

- Find the small apparatus on the bench in front of Shockley. Why would such a tiny device need careful handling?
- Look at the instruments on the bench. What would they measure?
- Look at where each man stands and where he is looking. What does the photographer seem to be saying about who is in charge?

Talk about it

1. Why do you think Bell Labs put a team of physicists, chemists and engineers together in one building?
2. How might the rivalry between Shockley and the other two have helped or hurt the work?
3. What does “Iron sharpeneth iron” suggest about working in teams?

> **Safety first.** Batteries and USB power only, never wall power. Build with the power disconnected and connect it last. Transistors can get hot if wired wrongly: if one is too hot to touch, disconnect at once.

BUILD

Testing Transistors with a Multimeter

You will find the pinout of every transistor in your kit using the meter's diode test, compare it with the datasheet, measure current gain with a simple circuit, and see how a transistor's base current controls its collector current.

You will need

- NPN transistors from the kit (2N2222 or PN2222, 2N3904 or S8050)
- Resistors: 100 kΩ, 220 kΩ, 1 MΩ, 1 kΩ; a red LED
- Breadboard, jumper wires, 4-AA holder (6 V)
- Digital multimeter (two if available)

Steps

1. Read the part number on each transistor and look up its datasheet online (search the part number plus "datasheet"). Draw its pinout with the flat face toward you.
2. Use the diode test on all six pairs of legs. Record the readings in a table and find the base. Decide NPN or PNP. Compare with the datasheet.
3. Many meters have an "hFE" socket. If yours does, insert the transistor correctly and read its β. Otherwise continue with the next step.
4. Build a gain test: 6 V → 1 kΩ → collector; emitter → ground; 6 V → 1 MΩ → base. Measure the voltage across the 1 MΩ (to find I_B) and across the 1 kΩ (to find I_C).
5. Calculate I_B, I_C and β. Repeat with 220 kΩ and then 100 kΩ as the base resistor. Does β stay about the same? What happens to I_C when the voltage across the 1 kΩ approaches 6 V?
6. Replace the 1 kΩ collector resistor with 1 kΩ in series with the LED. With the 1 MΩ base resistor, is the LED lit? Now touch the base resistor's free end with a finger while holding the + terminal with another finger: your skin conducts a tiny current. Describe what happens.
7. Test the other transistors in the kit and compare their β values.

8. **Improve it.** Find, by calculation and test, the largest base resistor that still lights the LED fully. Explain your answer with $I_C = \beta I_B$.

Tips

- Transistor leg order varies: 2N2222 metal-can, PN2222 plastic and S8050 parts may differ. Always check the datasheet.
- β varies widely between transistors of the same type, often by a factor of two or three. Good designs do not depend on an exact β.
- Use the meter's 20 V range for the voltage across the resistors and calculate currents with Ohm's law.

Check your work

- ☐ I found the base and type of each transistor with diode tests.
- ☐ I measured β with three base resistors and explained the results.
- ☐ I can explain how a small base current controls a large collector current.

ENGINEER'S NOTEBOOK

1. Pinout drawings for every transistor in your kit, from the datasheet and from your tests.
2. The table of diode-test readings and the β measurements with calculations.
3. A labeled cross-section of an NPN transistor showing the emitter, thin base and collector, and arrows for the electron flow.

KEY FORMULAS

$I_C = \beta I_B$
$I_E = I_B + I_C$
$V_{BE} \approx 0.7$ V (silicon, conducting)

From history. Shockley later left Bell Labs and founded Shockley Semiconductor in Mountain View, California, in 1956. Eight of his young engineers left in 1957 to found Fairchild Semiconductor, and companies founded by their former colleagues, including Intel, grew into what became known as Silicon Valley.

WORKED EXAMPLES

Example 1. A transistor has β = 150. A base current of 0.10 mA flows. Find the collector and emitter currents.

Show solution

1. $I_C = \beta I_B = 150 \times 0.10\ \text{mA} = 15\ \text{mA}$.
2. $I_E = I_B + I_C = 0.10 + 15 = 15.1\ \text{mA}$.

Answer: $I_C = 15\ \text{mA}$, $I_E = 15.1\ \text{mA}$

Example 2. In 1947 a large vacuum tube amplifier stage used about 2 W for its heater alone. A small-signal transistor stage uses about 10 mW. How many transistor stages could run on one tube's heater power?

Show solution

1. Ratio: $2\ \text{W} \div 0.010\ \text{W} = 200$.

Answer: About 200 transistor stages

Example 3. You test an unknown NPN transistor with the meter's diode test. Between the middle leg and each outer leg you read about 0.65–0.70 V with the red probe on the middle leg, and OL the other way. Between the two outer legs you read OL both ways. Which leg is the base?

Show solution

1. An NPN transistor contains two p–n junctions, base–emitter and base–collector, both with the p side at the base.
2. Red (+) on the base forward-biases both junctions, so both read about 0.7 V; reversed, both block.
3. The emitter and collector have two back-to-back junctions between them, so they block both ways.
4. So the middle leg, the one common to both 0.7 V readings, is the base. (The base–emitter reading is often a few millivolts higher, which helps tell emitter from collector.)

Answer: The middle leg is the base

PRACTICE

1. Easy Name the three terminals of a bipolar transistor.

Show answer

Emitter, base and collector.

2. Easy Who invented the point-contact transistor, where and when?

Show answer

John Bardeen and Walter Brattain, in William Shockley's group at Bell Labs, in December 1947.

3. Easy What impurity makes n-type silicon? p-type?

Show answer

n-type: phosphorus or arsenic (five outer electrons). p-type: boron or gallium (three).

4. Medium A transistor with β = 200 has $I_C = 40$ mA. Find I_B.

Show answer

0.20 mA

5. Medium A transistor's base current is 50 μA and collector current 9.0 mA. Find β and I_E.

Show answer

β = 180; $I_E = 9.05$ mA

6. Medium Give three reasons transistors replaced vacuum tubes.

Show answer

Any three: much smaller; far less power and heat; no filament to burn out (more reliable, longer life); no warm-up; rugged; cheaper in large numbers; can be integrated on chips.

7. Medium Why did Shockley's field-effect idea fail at first, and what did Bardeen discover?

Show answer

The applied field had almost no effect; Bardeen explained that electrons trapped in surface states at the germanium surface shielded the interior.

8. Hard Why must the base of a BJT be very thin?

Show answer

So that most electrons entering the base from the emitter cross it to the collector before they can recombine with holes; a thick base would let them recombine, wasting base current and giving low gain.

9. Hard A meter's diode test on an unknown transistor reads 0.68 V from leg 1 (red) to leg 2, and 0.66 V from leg 1 (red) to leg 3; all other combinations read OL. Is it NPN or PNP? Which leg is the base?

Show answer

NPN (the base is positive when the junctions conduct); leg 1 is the base. Leg 2, with the slightly higher drop, is likely the emitter.

10. Hard Suppose the first transistor had a power gain of about 18. If a 1.0 mW signal went in, how much power came out, and where did the extra energy come from?

Show answer

About 18 mW; the extra energy came from the battery in the output circuit.

11. Challenge Moore's law (Lesson 4.5) says the number of transistors on a chip doubles about every two years. Starting from 1 transistor in 1947, how many doublings would reach 10^{10}, and in how many years? Compare with the real date (about 2020).

Show answer

$\log_2 10^{10} = 33.2$ doublings, about 66 years, giving about 2013: close to the real 2010s–2020s, since chips began with dozens of transistors only in the early 1960s.

COMMON MISTAKES

- Assuming every transistor has the same pin order. Check the datasheet.
- Expecting β to be an exact number. It changes with temperature, current and from part to part.
- Connecting the base straight to the supply with no resistor, which lets a huge base current destroy the transistor.

Make it a game · Transistor Timeline. Race to tell the 1947 Bell Labs story in under ninety seconds without notes: who, why AT&T wanted to replace the vacuum tube, and what a hole is. Your parent counts the key ideas you hit. Then sketch the three BJT pins from memory. Beat your own count on the second run.

Scripture. “Iron sharpeneth iron; so a man sharpeneth the countenance of his friend.” (Proverbs 27:17, KJV)

Bardeen’s theory and Brattain’s hands made the transistor together. Good engineering is almost always the work of people who sharpen one another.

4.2 The Transistor as a Switch

OBJECTIVES

- Explain cutoff and saturation and why a transistor switch wastes little power.
- Design a low-side NPN switch: choose the base resistor with a safety factor (overdrive) for a given load current.
- Calculate the power dissipated in a saturated transistor.
- Build transistor switches that let a tiny current control an LED cluster and a motor, with a flyback diode.

> **Warm-up.** A ship's small wheel moves a huge rudder; a light touch on a car's pedal controls a big engine. List two other examples where a small control moves something large. A transistor switch is the electrical version.

WATCH

Transistors Explained - How transistors work

The Engineering Mindset · 18:19

https://www.youtube.com/watch?v=J4oO7PT_nzQ

> **WHEN TO WATCH**
> Before the physics paragraph. Watch the water-valve analogy and the switching examples; you may stop at the section on transistor types.

KEY TERMS

cutoff

The transistor is fully off: no base current, almost no collector current; it acts like an open switch.

saturation

The transistor is fully on: enough base current that the collector current is limited by the load, not by the transistor; V_{CE} falls to about 0.1–0.3 V.

low-side switch

A switch placed between the load and ground. An NPN transistor is usually used this way, with its emitter to ground.

base resistor

The resistor that sets the base current from a control signal: $R_B = (V_{\text{control}} - 0.7)/I_B$.

overdrive

Supplying several times more base current than I_C/β, so the transistor saturates even with a low-β part.

CORE IDEAS

The story. Early transistors were used mainly as amplifiers, but engineers soon saw that a transistor driven hard on or hard off made an excellent switch: no moving parts, no contact wear, and switching in microseconds instead of the milliseconds of a relay. In 1953 a team at the University of Manchester ran the first transistorized computer, and in 1956 MIT's Lincoln Laboratory completed the TX-0, built from about 3,600 transistors. Every digital device since, from a calculator to a data center, works by transistors switching on and off.

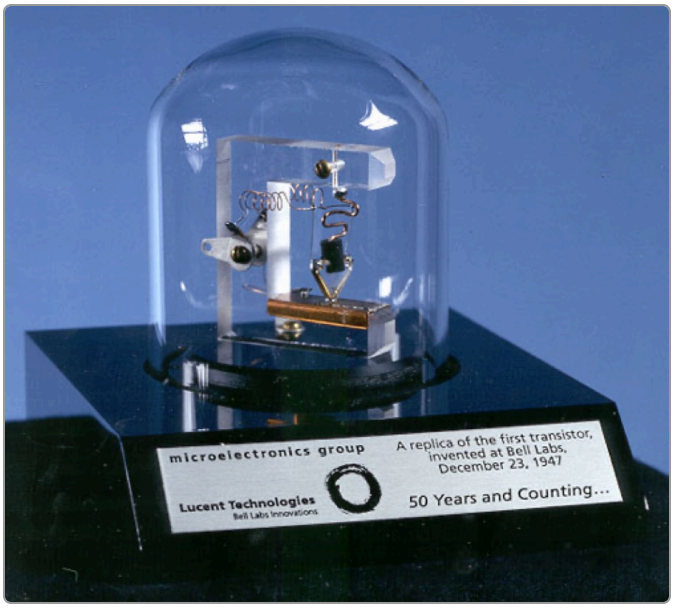
How they figured it out. Engineers learned that the key to a good switch is to avoid the in-between region. A transistor that is half on has a voltage across it *and* current through it, so it heats up ($P = V_{CE} I_C$). Fully off, the current is nearly zero; fully on (saturated), the voltage is nearly zero; either way, little power is wasted. So designers give the base enough current to saturate the transistor with margin, because β varies from part to part and with temperature.

The physics. In a low-side NPN switch, the load (an LED and resistor, a motor or a relay) connects from the supply to the collector, and the emitter goes to ground. A control signal, such as an Arduino pin at 5 V, drives the base through a base resistor. The load needs a current I_C. The minimum base current is $I_C/\beta_{\min}$; engineers supply about 5–10 times that, so $I_B = (5\text{–}10) I_C/\beta$, and $R_B = (V_{\text{control}} - 0.7\ \text{V})/I_B$. In saturation, $V_{CE} \approx 0.2$ V, so the transistor dissipates $P \approx 0.2 \times I_C$: just 20 mW at 100 mA. Inductive loads need a **flyback diode** across them (Lesson 3.3), or the turn-off spike will destroy the transistor.

The engineering. A microcontroller pin can safely supply about 20 mA; many loads need far more. A transistor switch is the standard bridge between logic and power: a 2N2222 can switch about 0.5 A (its datasheet maximum is higher, but it heats). Engineers check four numbers: the load current against the transistor's maximum I_C, the supply voltage against its maximum V_{CE}, the power $V_{CE(sat)} I_C$ against its rating, and the base current against what the pin can supply. For larger currents they use a MOSFET (Lesson 4.4).

Try it. You will design and build a switch that lets a few milliamperes control a cluster of LEDs and then a motor, and you will measure how close to an ideal switch a transistor really is.

PICTURE STUDY



A Replica of the First Transistor, U.S. federal government photograph, 1997 (replica of the 1947 device) · Photograph · Wikimedia Commons

Image: Wikimedia Commons, public domain

This replica shows the point-contact transistor Bardeen and Brattain made in December 1947. The original is kept by Nokia Bell Labs; replicas like this one help us see its parts.

Look closely

- Find the plastic triangle and the gold foil around its point.
- Find the slab of germanium underneath. Where do the two contacts touch it?
- Find the spring or clip that presses the point down.
- Find the three connections. Which one would be the base?

Talk about it

1. Why did the two gold contacts have to be so close together?
2. Why was this device too fragile for a factory to make in millions?
3. How is a modern transistor switch different from this one, and how is it the same?

> **Safety first.** Batteries and USB power only, never wall power. Build with the power disconnected and connect it last. Transistors can get hot if wired wrongly: if one is too hot to touch, disconnect at once. Put a 1N4001 flyback diode across the motor in this build (cathode to the + supply). Use the separate 4-AA pack for the motor, joined to the Arduino's ground.

BUILD

A Transistor Switch for LEDs and a Motor

You will design a transistor switch for a cluster of LEDs driven from a tiny control current, measure how close it comes to an ideal switch, and then switch the kit's motor safely with a flyback diode.

You will need

- NPN transistor (2N2222, PN2222 or similar), resistors (1 kΩ, 4.7 kΩ, 10 kΩ, 100 kΩ, six 180–220 Ω), six red LEDs, a push button
- A 1N4001 diode, the kit's small DC motor
- Arduino Uno on USB (used as a 5 V supply; no code yet), a 4-AA holder for the motor
- Breadboard, jumpers, multimeter

Steps

1. Design: six LED branches in parallel, each with its own resistor, from the 5 V pin, switched by the transistor. Calculate the resistor for 15 mA per LED, the total I_C, and R_B for 5× overdrive assuming β = 100. Draw the schematic.
2. Build it with the push button between 5 V and the base resistor, and a 100 kΩ resistor from the base to ground (so the base is held off when the button is open).
3. Press the button. Measure V_{BE}, V_{CE}, the base current (from the voltage across R_B) and the total collector current. Is the transistor saturated?
4. Calculate the transistor's power and the ratio I_C/I_B. Compare it with the β you measured in Lesson 4.1.
5. Swap R_B for 10 kΩ and then 100 kΩ. Measure V_{CE} and the LED current each time. At what point does the switch stop working well?
6. **Motor.** Disconnect. Build a second switch: 4-AA + → motor → collector; emitter → ground; the 4-AA − joined to the Arduino's GND. Put the 1N4001 across the motor with its band toward the + supply. Use R_B = 1 kΩ from the button.

7. Run the motor. Measure its running current and V_{CE}. Gently slow the motor with your fingers (do not stall it for long) and watch the current rise.
8. **Improve it.** Feel the transistor after one minute of running the motor (carefully, with one finger). If it is warm, calculate its power and decide whether to lower R_B, use a larger transistor, or move to a MOSFET in Lesson 4.4.

Tips

- Join the grounds: the motor battery's − and the Arduino's GND must be connected, or the base current has no return path.
- The 100 kΩ pull-down from base to ground keeps the transistor firmly off when the button is not pressed.
- A motor's current at stall can be three to five times its running current.

Check your work

☐ I designed a base resistor from the load current, β and an overdrive factor.

☐ My switch saturated with

V_{CE}below about 0.3 V, and I measured when it stopped saturating.

☐ I switched a motor safely with a flyback diode.

ENGINEER'S NOTEBOOK

1. Both schematics with all values and the design calculations.
2. A table of R_B, I_B, I_C, V_{CE} and transistor power for each base resistor.
3. A paragraph: Why is "fully on or fully off" the rule for transistor switches?

KEY FORMULAS

$$I_{B,\min} = \frac{I_C}{\beta}$$

$$R_B = \frac{V_{\text{control}} - 0.7\ \text{V}}{I_B}$$

$$P_Q \approx V_{CE(\text{sat})}\, I_C$$

From history. The Manchester Transistor Computer (1953) still used some vacuum tubes for its clock; the Harwell CADET (1955) in England and MIT's TX-0 (1956) were among the first computers built essentially from transistors. Within a decade, tube computers were obsolete.

Example 1. An Arduino pin (5.0 V) must switch a 100 mA load with an NPN transistor of minimum β = 100. Design the base resistor with 5× overdrive and find the transistor's power in saturation ($V_{CE} = 0.2$ V).

Show solution

1. Minimum base current: $I_B = 100\ \text{mA}/100 = 1.0\ \text{mA}$.
2. With 5× overdrive: $I_B = 5.0$ mA (safe for the pin).
3. $R_B = (5.0 - 0.7)/0.0050 = 860\ \Omega$; use the standard 820 Ω (a little more base current).
4. Power: $P = (0.2)(0.100) = 0.020$ W.

Answer: $R_B \approx 820\ \Omega$; 20 mW in the transistor

Example 2. A 9.0 V battery lights a red LED ($V_F = 2.0$ V) at 20 mA through a collector resistor, switched by an NPN transistor ($V_{CE(sat)} = 0.2$ V). Find the collector resistor.

Show solution

1. KVL around the load loop: $9.0 = V_R + 2.0 + 0.2$.
2. $V_R = 6.8$ V; $R = 6.8/0.020 = 340\ \Omega$; use 330 Ω or 390 Ω.

Answer: About 340 Ω (330 Ω or 390 Ω standard)

Example 3. A student drives the same 100 mA load with a 100 kΩ base resistor. What happens?

Show solution

1. $I_B = (5.0 - 0.7)/100{,}000 = 43\ \mu\text{A}$.
2. Maximum $I_C = \beta I_B = 100 \times 0.043\ \text{mA} = 4.3\ \text{mA}$, far less than 100 mA.
3. The transistor is not saturated: it limits the current, the load barely works, and V_{CE} is large, so the transistor heats instead of the load working.

Answer: Only about 4 mA flows; the transistor is not saturated

PRACTICE

1. **Easy** In cutoff, is the transistor like an open or a closed switch? In saturation?

   Show answer

   Cutoff: open. Saturation: closed.

2. **Easy** What is the minimum base current to switch 60 mA if β = 120?

   Show answer

   0.50 mA

3. **Easy** Why does a saturated transistor waste little power?

   Show answer

   Its voltage V_{CE} is very small, so $P = V_{CE} I_C$ is small even with a large current.

4. **Medium** Design R_B for a 3.3 V Raspberry Pi Pico pin to switch 100 mA, β = 100, with 5× overdrive.

   Show answer

   $I_B = 5$ mA; $R_B = (3.3 - 0.7)/0.005 = 520\ \Omega$; use 510 Ω (or 470 Ω).

5. **Medium** A relay coil needs 71 mA at 5 V. Design a 2N2222 switch from an Arduino pin (β ≥ 100, 5× overdrive). What else must you add?

   Show answer

   $I_B = 3.6$ mA; $R_B = 4.3/0.0036 \approx 1.2$ kΩ. Add a flyback diode across the coil.

6. **Medium** Find the power in a transistor switching 300 mA with $V_{CE(sat)} = 0.3$ V.

   Show answer

   0.09 W

7. **Medium** Why is the emitter of an NPN low-side switch connected to ground rather than the load?

   Show answer

   So the base can be driven from a ground-referenced logic signal: the base needs to be about 0.7 V above the emitter, which is easy when the emitter is at 0 V.

8. Hard A transistor is "half on": $V_{CE} = 3.0$ V with $I_C = 100$ mA. Find its power and compare with saturation at 0.2 V.

Show answer

0.30 W against 0.02 W: fifteen times as much heat.

9. Hard Your 2N2222 switch for a 6 V motor gets hot. Name three possible causes.

Show answer

Base current too low (not saturated); motor current higher than expected (stall current can be several times the running current); no flyback diode, so turn-off spikes stress the transistor; or the motor current exceeds what a 2N2222 handles comfortably.

10. Hard The TX-0 had about 3,600 transistors. If each dissipated an average of 20 mW, what was the total transistor power? Compare with a 1,000-tube computer whose tubes used 5 W each.

Show answer

72 W against 5,000 W

11. Challenge Design a switch so an Arduino pin can light 6 parallel LED branches, each a red LED with its own resistor at 15 mA from a 5 V supply. Choose the transistor's base resistor (β ≥ 100, 5×) and each LED resistor (allow $V_{CE} = 0.2$ V).

Show answer

Total $I_C = 90$ mA; $I_B = 4.5$ mA; $R_B = 4.3 / 0.0045 = 956\ \Omega \to 910\ \Omega$ or 1 kΩ (1 kΩ gives 4.3 mA, still 4.8×). Each LED: $R = (5.0 - 2.0 - 0.2) / 0.015 = 187\ \Omega \to$ 180 Ω or 200 Ω.

COMMON MISTAKES

- Forgetting to join the grounds of two power sources.
- Choosing R_B from the typical β instead of the minimum, so some transistors do not saturate.
- Leaving out the flyback diode on a motor or relay.

Make it a game · Base Resistor Challenge. Design duel. Your parent gives a supply voltage, load current and transistor gain. Choose a base resistor with overdrive, writing every step. Show your work, then explain cutoff and saturation in one sentence each. Compare with your parent's answer and settle differences. Three designs per player; lowest error wins.

Scripture. “Behold also the ships, which though they be so great, and are driven of fierce winds, yet are they turned about with a very small helm, whithersoever the governor listeth.” (James 3:4, KJV)

A few milliamperes at the base steer amperes through the collector, as a small helm turns a great ship. James uses the picture to warn how much a small thing, the tongue, can steer.

4.3 Amplifiers, Simply: The Transistor Radio

OBJECTIVES

- Explain what an amplifier does and define voltage gain, including in decibels.
- Describe the common-emitter amplifier and why it must be biased in the middle of its range.
- Calculate the bias point and the approximate gain $A_v \approx -R_C/R_E$ of a simple common-emitter stage.
- Build a one-transistor amplifier and measure its gain (with an Arduino tone or a microphone signal).

> **Warm-up.** Whisper a word to a friend across the room, then say it through a cardboard tube, then through cupped hands. Which made it louder? Did any of them add energy? An electronic amplifier does what the tube cannot: it adds energy from a battery.

WATCH

Bipolar Junction Transistors - Common Emitter Amplifier

The Organic Chemistry Tutor · 11:25

https://www.youtube.com/watch?v=ZUXG9eZfSlw

> **WHEN TO WATCH**
> After the physics paragraph. Focus on the common-emitter configuration and the gain formula; you may skip the other configurations.

KEY TERMS

amplifier

A circuit that makes a signal larger, using energy from a power supply.

bias

The steady DC voltages and currents that set a transistor's operating point, so that the signal can swing up and down without clipping.

voltage gain (A_v)

Output signal voltage divided by input signal voltage. In decibels, $20 \log_{10} A_v$.

common-emitter amplifier

The basic BJT amplifier: signal into the base, output from the collector, emitter (through a resistor) to ground. It inverts the signal.

coupling capacitor

A capacitor that passes the changing signal into or out of a stage while blocking the DC bias.

CORE IDEAS

The story. In October 1954, the Regency TR-1 went on sale in the United States for $49.95 (about a week's pay for many workers): the first transistor radio sold to the public. Texas Instruments made its four germanium transistors, and the Industrial Development Engineering Associates (IDEA) company of Indianapolis designed and built the set. It ran for many hours on a 22.5 V battery and fit in a shirt pocket. A small company in Tokyo, which soon renamed itself Sony, followed with its own transistor radios, and within a decade the pocket radio was everywhere. For the first time, a person could carry music, news and sports anywhere, all because a few transistors could **amplify** the faint signal from an antenna until it could drive an earphone.

How they figured it out. Early transistors were noisy, varied wildly from one to the next, and drifted with temperature; an amplifier designed for one transistor might not work with another. Engineers learned to make circuits that did not depend on the exact β: a voltage divider sets the base voltage, and a resistor in the emitter sets the current. Then the gain depends mostly on the ratio of two resistors, which engineers can choose precisely. That idea, using **negative feedback** to trade some gain for predictability, is one of the most important in all of electronics.

The physics. A **common-emitter amplifier** is biased so the transistor is halfway on: neither cut off nor saturated. A divider (say 10 kΩ and 2.2 kΩ on 9 V) holds the base at about 1.6 V; the emitter sits 0.7 V lower, about 0.9 V, so a 470 Ω emitter resistor sets $I_E \approx 0.9/470 = 1.96$ mA; with a 2.2 kΩ collector resistor the collector rests at about $9 - 2.2 \times 1.96 = 4.7$ V, near the middle of the supply. Now a small signal at the base wiggles the emitter voltage by the same amount, which wiggles the current, which wiggles the collector voltage by R_C/R_E times as much, upside down: $A_v \approx -R_C/R_E = -2200/470 \approx -4.7$. (Bypassing R_E with a capacitor gives much more gain, but less predictably.) Gains multiply in stages and are often given in **decibels**: $20 \log_{10}(4.7) \approx 13$ dB.

The engineering. Amplifiers are in every phone, radio, hearing aid, sensor and instrument. Engineers bias them in the middle so the output can swing equally up and down without **clipping**, use coupling capacitors to pass signals while blocking DC, and use negative feedback for stable, low-distortion gain. Today most amplifiers are integrated circuits called **operational amplifiers** (op-amps), with hundreds of transistors inside, but each still rests on the ideas of this one-transistor stage.

Try it. You will build a common-emitter amplifier, measure its bias voltages, and measure its gain with a small signal, then listen to it with a speaker or piezo buzzer.

PICTURE STUDY



An Advertisement for the Regency TR-1, Regency Division, I.D.E.A., Inc., December 19, 1954 · Newspaper advertisement · The San Bernardino County Sun

Image: Wikimedia Commons, public domain

This advertisement appeared in a California newspaper a few weeks after the TR-1 went on sale, in time for Christmas 1954. Look at how the makers explained the new technology to ordinary readers.

Look closely

- Find the radio. How big does the advertisement say it is?
- Find any words about transistors, batteries or tubes. What advantages does the advertisement claim?
- Find the price. How does it compare with what you might spend on a phone today, adjusted for wages?
- Look for anything that tells you who the advertisement is aimed at.

Talk about it

1. Which engineering facts from this lesson does the advertisement turn into selling points?
2. Why would a pocket radio change how people lived?
3. What does the advertisement leave out that an engineer would want to know?

Safety first. Batteries and USB power only, never wall power. Build with the power disconnected and connect it last. Transistors can get hot if wired wrongly: if one is too hot to touch, disconnect at once. Keep earphones and speakers at low volume; amplifiers can produce loud sounds.

BUILD

A One-Transistor Amplifier

You will build a common-emitter amplifier, check its bias voltages against your calculations, feed it a small test signal from the Arduino, and measure the gain with the multimeter's AC volts setting. Then you will hear the difference with a piezo buzzer.

You will need

- NPN transistor (2N3904 or 2N2222), resistors 10 kΩ, 2.2 kΩ (two), 470 Ω, 1 kΩ, 100 kΩ; capacitors 10 µF (two) and 100 µF
- 9 V battery with clip (or 4-AA pack), breadboard, jumpers
- Arduino Uno on USB for a test tone (one short sketch, given in the steps), piezo buzzer
- Digital multimeter with AC volts

Steps

1. Calculate the bias point for $R_1 = 10$ kΩ, $R_2 = 2.2$ kΩ, $R_E = 470$ Ω, $R_C = 2.2$ kΩ on your battery's measured voltage (Worked Example 1). Write the predicted V_B, V_E and V_C.
2. Build the stage. Measure V_B, V_E and V_C to ground with no signal. Compare with your predictions. If V_C is near 9 V or near 1 V, check your wiring before going on.
3. Make a test signal. In the Arduino IDE (installed in Unit 7; a parent can help now, or use Wokwi), type a short program: in setup(), write tone(9, 440);, which makes a 440 Hz square wave on pin 9. Upload it.
4. Make the signal small: connect pin 9 through a 100 kΩ resistor to a 1 kΩ resistor to ground (a divider of about 1/100). The middle point is your input, about 50 mV.
5. Connect the input through a 10 µF capacitor (+ toward the transistor) to the base. Connect the Arduino's GND to the amplifier's ground.
6. Measure the AC voltage at the input (after the capacitor, to ground) and at the collector (through a second 10 µF capacitor, to ground). Calculate the gain

and compare with R_C/R_E.

7. Put a 100 µF capacitor across R_E (+ to the emitter). Measure the gain again. Explain the change.
8. **Improve it.** Connect the piezo buzzer from the output capacitor to ground. Listen with and without the amplifier, and with and without the bypass capacitor. Write down what changed, and one reason a designer might give up gain for predictability.

Tips

- A meter's AC volts reading on a square wave is approximate; compare input and output with the same meter so the errors cancel.
- If the output is distorted or the gain is low, check the bias first: V_C should be near half the supply.
- In the free Falstad simulator you can open a "common-emitter amplifier" example and see the input and output waves side by side.

Check your work

☐ My measured bias voltages agree with my calculations within about 10%.

☐ I measured the gain and compared it with

R_C/R_E.

☐ I can explain bias, inversion, clipping and the effect of the bypass capacitor.

ENGINEER'S NOTEBOOK

1. The amplifier schematic with calculated and measured DC voltages written beside each node.
2. Your gain measurements with and without the bypass capacitor, in plain numbers and in dB.
3. A sketch of the input and output waveforms, showing the inversion and what clipping would look like.

KEY FORMULAS

$$A_v = \frac{v_{\text{out}}}{v_{\text{in}}} \approx -\frac{R_C}{R_E}$$

$$\text{gain (dB)} = 20 \log_{10} |A_v|$$

$$V_B = V_{CC}\,\frac{R_2}{R_1 + R_2}, \quad I_E \approx \frac{V_B - 0.7}{R_E}$$

From history. Harold Black, an engineer at Bell Labs, invented the negative-feedback amplifier in 1927 while riding the ferry to work, and sketched it on a page of the New York Times. The Patent Office at first doubted it could work. Negative feedback is now used in almost every amplifier made.

WORKED EXAMPLES

Example 1. Find the bias point of a common-emitter stage: $V_{CC} = 9.0$ V, $R_1 = 10$ kΩ, $R_2 = 2.2$ kΩ, $R_E = 470$ Ω, $R_C = 2.2$ kΩ. (Assume β is large, so the base draws little current.)

Show solution

1. Base: $V_B = 9.0 \times 2.2/12.2 = 1.62$ V.
2. Emitter: $V_E = 1.62 - 0.7 = 0.92$ V; $I_E = 0.92/470 = 1.96$ mA $\approx I_C$.
3. Collector: $V_C = 9.0 - (2200)(0.00196) = 4.68$ V, near mid-supply: a good bias point.

Answer: $V_B = 1.62$ V, $I_C \approx 1.96$ mA, $V_C \approx 4.7$ V

Example 2. For the same stage, estimate the voltage gain and the output for a 50 mV peak input signal. What is the gain in dB?

Show solution

1. $A_v \approx -R_C/R_E = -2200/470 = -4.68$.
2. Output: 4.68×50 mV $= 234$ mV peak, inverted.
3. In decibels: $20 \log_{10} 4.68 = 13.4$ dB.

Answer: Gain ≈ −4.7 (13 dB); about 0.23 V peak out

Example 3. Two amplifier stages with gains of 10 and 20 are connected one after the other. What is the overall gain, in plain numbers and in dB?

Show solution

1. Gains multiply: $10 \times 20 = 200$.
2. In dB they add: $20 + 26 = 46$ dB (check: $20 \log_{10} 200 = 46$ dB).

Answer: 200, or 46 dB

PRACTICE

1. **Easy** An amplifier turns a 20 mV input into a 2.0 V output. What is its gain? In dB?

   Show answer

   100; 40 dB

2. **Easy** Where does the extra energy in an amplified signal come from?

   Show answer

   From the power supply (battery); the transistor only controls it.

3. **Easy** What was the Regency TR-1, and when did it go on sale?

   Show answer

   The first commercial transistor radio, October 1954.

4. **Medium** Find A_v for $R_C = 4.7\ \text{k}\Omega$ and $R_E = 1.0\ \text{k}\Omega$.

   Show answer

   About −4.7

5. **Medium** Why is a common-emitter amplifier biased with the collector near half the supply voltage?

   Show answer

   So the output can swing equally up and down without hitting the supply (cutoff) or ground (saturation), which would clip the signal.

6. **Medium** Why does a common-emitter amplifier invert the signal?

   Show answer

   When the input rises, the transistor's current rises, so the voltage drop across R_C rises and the collector voltage falls.

7. **Medium** What is a gain of 1,000 in dB? Of 0.5?

   Show answer

   60 dB; −6 dB

8. Hard Using a divider of 47 kΩ and 10 kΩ on 12 V, an emitter resistor of 1.0 kΩ and a collector resistor of 3.3 kΩ, find V_B, I_C, V_C and A_v.

Show answer

$V_B = 12 \times 10/57 = 2.11$ V; $I_C \approx 1.41$ mA; $V_C = 12 - 4.64 = 7.4$ V; $A_v \approx -3.3$

9. Hard The emitter-resistor design makes the gain depend on R_C/R_E, not on β. Why was that so important to early transistor-radio makers?

Show answer

Early transistors' β varied widely and drifted with temperature; a gain set by resistor ratios was predictable and repeatable in production.

10. Hard An amplifier with gain 4.7 is fed a 1.5 V peak signal while biased at $V_C = 4.7$ V on a 9 V supply. What happens to the output?

Show answer

The output would need to swing ±7 V, but it can only go from about 1 V to 9 V around 4.7 V; it clips at both ends, distorting the signal.

11. Challenge The TR-1 ran on a 22.5 V battery. Suppose it drew about 4 mA. Estimate its power. If a tabletop tube radio of the same era used about 30 W, how many times less power would the TR-1 use?

Show answer

$22.5 \times 0.004 = 0.09$ W; about $30/0.09 \approx 330$ times less.

COMMON MISTAKES

- Putting the signal straight onto the base without a coupling capacitor, which upsets the bias.
- Forgetting that the output is inverted.
- Expecting β to set the gain. In this design, the resistor ratio sets it.

> **Make it a game · Gain in Decibels.** Drill. Your parent gives an input and an output voltage; you give the gain and its value in decibels within twenty seconds. Then explain why a common-emitter amplifier must be biased in the middle of its range, and what the coupling capacitor does. Five right answers in a row sets a record.

4.4 MOSFETs and Driving Loads

OBJECTIVES

- Tell the story of the MOSFET at Bell Labs and explain why it is the most manufactured device in history.
- Explain how a MOSFET's gate voltage controls its channel, and the meaning of threshold voltage and $R_{DS(on)}$.
- Choose between a BJT and a logic-level MOSFET for a load and calculate MOSFET power dissipation.
- Build a MOSFET low-side switch with gate resistor, pull-down and flyback diode, and drive a motor or LED strip.

> **Warm-up.** A water faucet opens with a twist of the handle; you do not have to keep pushing water through the handle to keep it open. How is that different from a BJT, which needs a continuous base current? Write one sentence.

WATCH

MOSFET Explained - How MOSFET Works

The Engineering Mindset · 20:14

https://www.youtube.com/watch?v=AwRJsze_9m4

> **WHEN TO WATCH**
> After the story. Watch the explanation of the gate, channel and threshold; the sections on MOSFET types can be skimmed.

KEY TERMS

MOSFET

Metal–oxide–semiconductor field-effect transistor. A voltage on the gate, insulated by a thin oxide, creates a conducting channel between the drain and source.

gate, drain, source

The MOSFET's terminals: the gate controls; current flows from drain to source in an N-channel device.

threshold voltage ($V_{GS(th)}$)

The gate-to-source voltage at which the MOSFET just begins to conduct. A logic-level MOSFET is fully on at 4.5–5 V or less.

pull-down resistor

A resistor (often 10–100 kΩ) from the gate to the source that holds the MOSFET off when the control pin is not driving it.

$R_{DS(on)}$

The MOSFET's resistance from drain to source when fully on, often milliohms. Its power is $P = I^2 R_{DS(on)}$.

CORE IDEAS

The story. Shockley had wanted a field-effect transistor from the start, a device in which a voltage on an insulated plate would control a current, but surface states defeated every early attempt (Lesson 4.1). In 1957 and 1958 Carl Frosch and Lincoln Derick at Bell Labs found that a layer of silicon dioxide grown on silicon protected its surface. In 1959 Mohamed Atalla, an Egyptian-born engineer at Bell Labs, and Dawon Kahng, a Korean-born engineer working with him, used that clean oxide to build the first working **MOSFET**. Bell Labs at first saw little use for it: it was slower than the bipolar transistors of the day. But it was simple and could be made very small and very densely. Today the MOSFET is the most manufactured device in human history, with far more than 10^{21} made; nearly every transistor in every chip is one.

How they figured it out. The key was the oxide. Atalla showed that thermally grown silicon dioxide "passivated" the surface, tying up the dangling bonds that trapped electrons. With a clean, insulating layer just a fraction of a micrometer thick, a metal gate on top could pull electrons toward the surface and form a thin conducting channel between two n-type regions. Because the gate is insulated, it draws essentially no steady current; only a tiny charge to set its voltage.

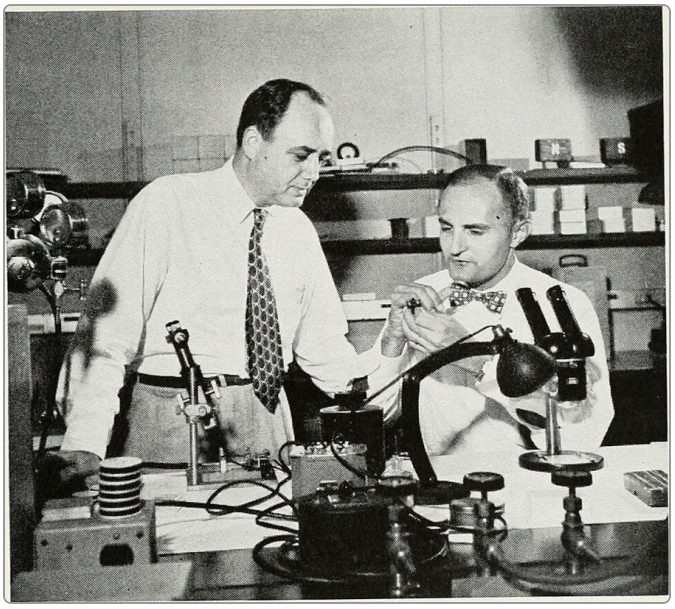
The physics. In an N-channel enhancement MOSFET, when the gate is at 0 V relative to the source, no channel exists and the drain–source path is open. Raise V_{GS} above the **threshold** (often 1–2 V), and electrons gather under the gate to form a channel; at 5–10 V the channel is fully formed and the drain–source path has a very small resistance, $R_{DS(on)}$, such as 0.025 Ω. The MOSFET then dissipates only $P = I^2 R_{DS(on)}$:

at 2.0 A, $4 \times 0.025 = 0.10$ W, compared with about 0.6 W for a BJT with 0.3 V across it. The gate is like a small capacitor: it draws a brief current spike when switched, then nothing.

The engineering. For switching loads above a few hundred milliamperes, engineers prefer MOSFETs. The rules: choose a **logic-level** MOSFET (rated $R_{DS(on)}$ at V_{GS} = 4.5 V or lower), because a standard MOSFET such as the IRF520 in some kits is only partly on at 5 V and gets hot; add a small gate resistor (100–220 Ω) to limit the switching current spike from the pin; add a pull-down (10–100 kΩ) from gate to source so the load stays off while the microcontroller starts; and add a flyback diode across any motor, relay or solenoid. Check the drain current, drain–source voltage and power ratings against the load. The same N-channel MOSFET low-side switch drives motors, LED strips, pumps and heaters in thousands of products.

Try it. You will build a MOSFET switch, measure its on-resistance, and compare it with the BJT switch from Lesson 4.2 on the same motor.

PICTURE STUDY



Researchers at Bell Telephone Laboratories, Bell Telephone Magazine, 1953 · Photograph · Bell Telephone Magazine (Internet Archive)

Image: Wikimedia Commons, public domain

This photograph from Bell Telephone Magazine shows researchers at work in the laboratories where the transistor, and six years later the MOSFET, were invented. Semiconductor research at Bell Labs combined physics, chemistry, metallurgy and careful measurement at the bench.

Look closely

- Find the microscope and the small device being examined. Why would semiconductor work need magnification?
- Look at the instruments and wiring on the bench. What might they measure?
- Look at what each person is doing. How does the picture show teamwork?

Talk about it

1. The MOSFET needed a clean, thin oxide layer only a fraction of a micrometer thick. What kinds of skills would a team need to make one?
2. Why might a research lab spend years on a device that had no obvious use yet?
3. What would you want to measure first on a new kind of transistor?

Safety first. Batteries and USB power only, never wall power. Build with the power disconnected and connect it last. Transistors can get hot if wired wrongly: if one is too hot to touch, disconnect at once. Put a 1N4001 flyback diode across the motor (band toward +). MOSFETs are sensitive to static: touch a grounded metal object before handling one, and hold it by the body.

BUILD

A MOSFET Motor Driver

You will build a logic-level MOSFET low-side switch for the kit's motor (or a strip of LEDs), measure its on-resistance and power, and compare it side by side with your BJT switch from Lesson 4.2.

You will need

- A logic-level N-channel MOSFET (IRLZ44N, IRLB8721 or similar; the IRF520 in some kits works poorly at 5 V, which you may test)
- Resistors 220 Ω and 10 kΩ; a 1N4001 diode; a push button
- The kit's DC motor; 4-AA holder; Arduino Uno on USB (as a 5 V control source)
- Breadboard, jumpers, multimeter; the BJT switch from Lesson 4.2

Steps

1. Find your MOSFET's datasheet and record: pinout (often gate, drain, source from the left, face forward), $V_{GS(th)}$, $R_{DS(on)}$ and the gate voltage at which it is specified.
2. Build: 4-AA + → motor → drain; source → ground; flyback diode across the motor (band to +). Gate → 220 Ω → push button → Arduino 5 V; 10 kΩ from gate to ground. Join the 4-AA − to the Arduino's GND.
3. Press the button. Measure V_{GS}, V_{DS} and the motor current. Calculate the MOSFET's effective resistance V_{DS}/I_D and its power.
4. Release the button. Measure V_{DS} (it should be near the battery voltage) and confirm the motor is off. Unplug the 10 kΩ pull-down and touch the gate wire: what happens? Plug it back in.
5. Compare: run the same motor with the Lesson 4.2 BJT switch. Measure V_{CE} and the base current. Fill a table comparing the two: voltage across the switch, power, control current.
6. If you have an IRF520 (non-logic-level), substitute it and repeat step 3. Compare its V_{DS} with the logic-level part's.

7. Try a variable gate voltage: use the potentiometer as a divider from 5 V to the gate (through the 220 Ω). Slowly raise the voltage and record V_{GS} when the motor first starts and when V_{DS} stops falling. Compare with the datasheet threshold.
8. **Improve it.** Write a one-page "driver-choice guide" for future projects: for a given load current, when you would choose a direct pin, a BJT, or a logic-level MOSFET, with the numbers that justify each.

Tips

- MOSFET pinouts differ from BJT pinouts. Check the datasheet: on most TO-220 parts, left to right facing the label, it is gate, drain, source.
- The metal tab of a TO-220 MOSFET is usually connected to the drain; do not let it touch other wires.
- A gate left floating can turn the MOSFET partly on; always use the pull-down.

Check your work

- ☐ My MOSFET switch has a much smaller voltage drop than my BJT switch at the same current.
- ☐ I measured $R_{DS(on)}$ and the threshold and compared them with the datasheet.
- ☐ I used a gate resistor, a pull-down and a flyback diode, and can explain each.

ENGINEER'S NOTEBOOK

1. The MOSFET driver schematic, with the gate resistor, pull-down and flyback diode labeled and explained.
2. The comparison table of BJT and MOSFET switches.
3. Your driver-choice guide.

KEY FORMULAS

$P = I_D^2 \, R_{DS(\text{on})}$

$I_{\text{gate,peak}} \approx \dfrac{V_{\text{pin}}}{R_G}$

$V_{GS} > V_{GS(\text{th})}$ to conduct

From history. Frank Wanlass at Fairchild invented CMOS logic in 1963, pairing N-channel and P-channel MOSFETs so that a logic gate draws almost no power except when it switches. CMOS is why a phone can hold billions of transistors and still run all day on a battery.

WORKED EXAMPLES

Example 1. A logic-level MOSFET with $R_{DS(on)} = 0.025\ \Omega$ switches a 2.0 A load. Find its power. Compare with a BJT with $V_{CE(sat)} = 0.30$ V.

Show solution

1. MOSFET: $P = I^2 R = (2.0)^2(0.025) = 0.10$ W.
2. BJT: $P = V_{CE} I_C = (0.30)(2.0) = 0.60$ W.
3. The MOSFET runs six times cooler, and needs no steady gate current.

Answer: 0.10 W against 0.60 W

Example 2. An Arduino pin drives a MOSFET gate through a 220 Ω resistor. What is the peak gate current at the instant of switching, and why is the resistor there?

Show solution

1. At the instant of switching, the gate capacitance is uncharged, so $I \approx 5.0/220 = 23$ mA.
2. Without the resistor, the gate capacitance could pull a large current spike from the pin; 23 mA is within the pin's limit for the brief moment it lasts.
3. Once the gate is charged, the current falls to essentially zero.

Answer: About 23 mA briefly; the resistor protects the pin

Example 3. A 6 V motor draws 0.50 A running and 2.0 A when stalled. Choose a switch: (a) 2N2222 BJT (maximum 0.6 A continuous in practice, β ≥ 100), or (b) IRLZ44N logic-level MOSFET ($R_{DS(on)} \approx 0.025\ \Omega$ at 5 V, 47 A rated). Justify.

Show solution

1. (a) The BJT needs $I_B \geq 5$ mA for 0.5 A with overdrive and would dissipate about 0.1–0.15 W running, but a stall current of 2.0 A is beyond what a small 2N2222 should carry.
2. (b) The MOSFET at stall: $P = (2.0)^2(0.025) = 0.10$ W; running: $(0.50)^2(0.025) = 0.006$ W. It barely warms, and needs no steady gate current.
3. Choose the MOSFET, with a gate resistor, a pull-down and a flyback diode.

Answer: The logic-level MOSFET

PRACTICE

1. Easy Name the three terminals of a MOSFET and say which one controls it.

   Show answer

   Gate, drain, source; the gate controls.

2. Easy Why does a MOSFET gate draw almost no steady current?

   Show answer

   The gate is insulated from the channel by a thin oxide layer; it is like a small capacitor.

3. Easy Who built the first working MOSFET, where and when?

   Show answer

   Mohamed Atalla and Dawon Kahng, at Bell Labs, in 1959.

4. Medium Find the power in a MOSFET with $R_{DS(on)} = 0.050\ \Omega$ carrying 3.0 A.

   Show answer

   0.45 W

5. **Medium** What is a logic-level MOSFET, and why does an Arduino project need one?

Show answer

A MOSFET whose $R_{DS(on)}$ is specified at a gate voltage of about 4.5 V or less, so a 5 V (or 3.3 V for some parts) pin turns it fully on; a standard MOSFET needs about 10 V and stays partly on and hot.

6. **Medium** What does the 10 kΩ resistor from gate to source do?

Show answer

It holds the gate at 0 V (off) when the control pin is floating, such as while the microcontroller is starting up.

7. **Medium** A 12 V LED strip draws 1.5 A. Find the MOSFET power with $R_{DS(on)} = 0.04\ \Omega$ and the power delivered to the strip.

Show answer

MOSFET: $(1.5)^2(0.04) = 0.09$ W; strip: about $12 \times 1.5 = 18$ W (minus 0.06 V lost).

8. **Hard** A standard MOSFET is only partly on at 5 V, with an effective resistance of 1.5 Ω, while switching 1.0 A. Find its power and explain the danger.

Show answer

$P = (1.0)^2(1.5) = 1.5$ W: enough to make a small package very hot without a heat sink, and it also starves the load of 1.5 V.

9. **Hard** Why did Bell Labs at first see little use for the MOSFET, and why did it later win?

Show answer

It was slower than bipolar transistors of 1959. It won because it is simple, draws no gate current, uses very little power in logic (CMOS) and can be shrunk and packed far more densely, which made large integrated circuits possible.

10. Hard A gate resistor of 100 Ω is used with a 3.3 V Pico pin. Find the peak gate current. Is it safe for a pin rated at 12 mA?

    Show answer

    33 mA peak, but only for nanoseconds while the gate charges; brief spikes are usually tolerated, though a 220–330 Ω resistor keeps the peak nearer the rating.

11. Challenge A heater element of 4.0 Ω is run from a 12 V battery pack through a MOSFET with $R_{DS(on)} = 0.030\ \Omega$. Find the current, the power in the heater, and the power in the MOSFET. What fraction of the power is lost in the switch?

    Show answer

    $I = 12/4.03 = 2.98$ A; heater $I^2R = 35.5$ W; MOSFET 0.27 W; fraction $0.27/35.8 = 0.74\%$.

COMMON MISTAKES

- Using a standard (non-logic-level) MOSFET with a 5 V or 3.3 V pin, so it is only partly on and gets hot.
- Leaving the gate floating with no pull-down resistor.
- Swapping drain and source. The MOSFET's built-in body diode then conducts and the switch cannot turn the load off.

> **Make it a game · MOSFET or BJT?.** Two-truths-and-a-tall-tale. State three claims about MOSFETs, covering gate voltage, threshold, R_DS(on) and pull-down resistors. Your parent guesses the false one. Swap. Then draw a MOSFET motor driver from memory and label gate, drain and source. Winner takes the round on fewest labeling errors.

4.5 The Integrated Circuit: Kilby and Noyce

OBJECTIVES

- Tell how Jack Kilby and Robert Noyce independently invented the integrated circuit in 1958–1959, and what each contributed.
- Explain the “tyranny of numbers” and why integration solved it.
- Describe in outline how chips are made by photolithography, and use Moore’s law to estimate growth.
- Identify chips in your kit, read their datasheets and pinouts, and build a circuit with a logic IC.

> **Warm-up.** Count the components on any old circuit board you can look at safely (an unpowered board from a broken toy with no batteries, or a picture). Imagine every one of them being hand-soldered, with two or three joints each. How many joints would a computer with 100,000 transistors need?

WATCH

Fairchild Briefing on Integrated Circuits

Computer History Museum · 29:51

https://www.youtube.com/watch?v=z47Gv2cdFtA

> **WHEN TO WATCH**
> After the story. This 1967 Fairchild film explains how integrated circuits are designed and made; watch the first 15 minutes, which cover the planar process and photolithography.

BACKUP VIDEO

Made in the USA | The History of the Integrated Circuit

Big Think · 10:28

https://www.youtube.com/watch?v=SYSJefKc7L4

A short summary of the history of the integrated circuit; optional review.

KEY TERMS

integrated circuit (IC, chip)

A complete circuit of transistors, resistors and connections made together on one piece of semiconductor.

tyranny of numbers

The problem of the late 1950s: circuits with thousands of separate parts and hand-made connections were too large, costly and unreliable to build.

planar process

Jean Hoerni's 1959 method of making transistors flat, under a protective oxide layer, so that metal connections could be laid on top.

photolithography

Printing a circuit pattern onto a silicon wafer with light through a mask, then etching or doping the exposed areas, layer by layer.

Moore's law

Gordon Moore's observation (1965, revised 1975) that the number of transistors on a chip doubles about every two years.

CORE IDEAS

The story. By the late 1950s engineers could design computers and guidance systems with hundreds of thousands of transistors, but they could not build them reliably: every part had to be wired and soldered by hand, and one bad joint could stop the machine. People called it the **tyranny of numbers**. In the summer of 1958, Jack Kilby, a new engineer at Texas Instruments in Dallas, stayed at work while most of his colleagues took vacation. He reasoned that resistors, capacitors and transistors could all be made of the same semiconductor, so why not make them all in one piece? On September 12, 1958, he showed a phase-shift oscillator made on a single sliver of germanium, its parts joined by fine gold wires. Six months later, at Fairchild Semiconductor in California, Robert Noyce described how to make a whole circuit in silicon with the connections printed flat on top, using his colleague Jean Hoerni's new planar process. Kilby received the Nobel Prize in Physics in 2000; Noyce, who had died in 1990, is honored as co-inventor. Noyce went on to co-found Intel in 1968.

How they figured it out. Kilby proved that every part could be made from one material. But his gold "flying wires" were still hand-made. Noyce's insight, building

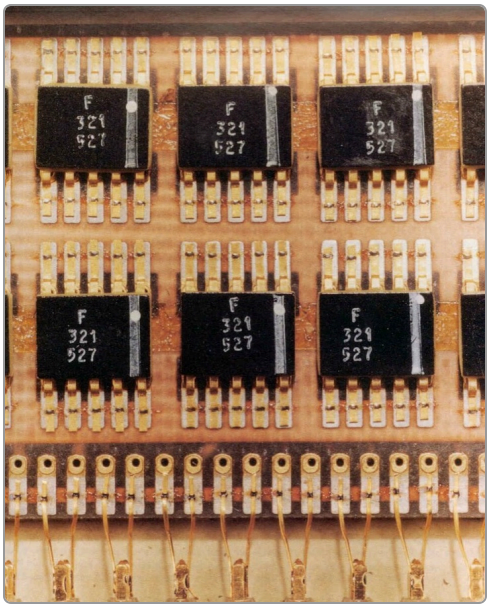
on Hoerni, solved the wiring: the planar process left the silicon covered by a smooth oxide, so a thin metal layer could be deposited on top and etched into connections by the same photographic process that made the transistors. Now the whole circuit, parts and wires, could be printed at once, many copies on one wafer. The U.S. space and defense programs were the first big customers: the Apollo Guidance Computer, flown to the Moon in 1969, used about 2,800 identical logic chips of a Fairchild design, each holding two simple NOR gates.

The physics and the process. A silicon wafer is coated with a light-sensitive resist, exposed to light through a patterned mask, and developed, so that the pattern is transferred to the resist. The exposed areas are etched, or doped with impurities by diffusion or ion implantation, to make the n- and p-regions of transistors. Oxide and metal layers are added and patterned the same way. Repeat for dozens of layers, and hundreds of identical chips are made on one wafer at once. That is why the cost per transistor has fallen so far: the cost of making a wafer is roughly the same whether its transistors are large or small. Gordon Moore noticed in 1965 that the number of components per chip was doubling every year; in 1975 he revised it to about every two years. From the Intel 4004 of 1971 (about 2,300 transistors) to chips of the 2020s with tens of billions, the doubling held for half a century.

The engineering. Engineers now design with ICs as building blocks: logic gates (the 74HC series), timers (the 555, Unit 5), voltage regulators, op-amps, motor drivers (the L293D in your kit), and whole microcontrollers (the ATmega328P on the Arduino, the RP2040 on the Pico). Each comes with a **datasheet** that gives the pinout, ratings and typical circuits; reading datasheets is one of an engineer’s daily skills. Pin 1 is marked by a notch or dot, and pins are numbered counterclockwise viewed from the top.

Try it. In the build you will find every IC in your kit, read its datasheet, and wire a 74HC00 chip, four NAND gates in one package, to light LEDs.

PICTURE STUDY



Integrated Circuits in the Apollo Guidance Computer, Unknown photographer, 1960s · Photograph · Wikimedia Commons

Image: Wikimedia Commons, public domain

These flat-pack chips are from the Apollo Guidance Computer. Each contains two NOR gates, and about 2,800 of them made the computer that helped guide astronauts to the Moon. NASA's large orders in the early 1960s helped make integrated circuits cheaper for everyone.

Look closely

- Count the leads on one chip. Which are power and which might be inputs and outputs?
- Find the markings on each chip. Why would every chip be identical?
- Look at how the leads are joined to the board. How is this different from a chip plugged into your breadboard?
- Estimate the size of one chip from the leads.

Talk about it

1. Why would engineers building a computer for the Moon trust one well-tested chip type rather than many types?
2. The AGC had about 5,600 gates. A phone chip today has billions of transistors. What made that growth possible?

3. What do you think happened to the price of chips as NASA and others bought them in large numbers?

Safety first. Batteries and USB power only, never wall power. Build with the power disconnected and connect it last. Transistors can get hot if wired wrongly: if one is too hot to touch, disconnect at once. Insert and remove ICs gently with a flat tool or by rocking them evenly, so the pins do not bend; never apply power with a chip in backward.

BUILD

Reading Datasheets and Wiring a NAND Chip

You will find every integrated circuit in your kit, read each datasheet for its pinout and ratings, and then wire a 74HC00 quad NAND chip to two push buttons and an LED, testing its truth table (a preview of Unit 6).

You will need

- The ICs in your kit (for example L293D, 74HC595, the ATmega328P on the Uno) and a 74HC00 quad NAND chip
- Two push buttons, two 10 kΩ resistors, a red LED and 220 Ω resistor
- Breadboard, jumpers, Arduino 5 V pin on USB (as a 5 V supply)
- A magnifier

Steps

1. With a magnifier, read the markings on each IC in your kit: maker's logo, part number and date code. Look up each datasheet and write a one-line description and its supply voltage range.
2. Draw the 74HC00's pinout from its datasheet: pins 1–14, which pins belong to each of the four gates, and pins 7 (GND) and 14 (VCC).
3. Place the 74HC00 across the breadboard's center gap with the notch to the left. Connect pin 14 to 5 V and pin 7 to GND. Add a 0.1 µF capacitor from pin 14 to pin 7 if you have one (decoupling).
4. Wire gate 1: input pins 1 and 2 each have a 10 kΩ pull-down to ground and a push button to 5 V. Output pin 3 → 220 Ω → LED → ground.
5. Test all four combinations of the buttons and write the truth table. Is the output high only when both buttons are pressed, or in every case except that?
6. Connect unused inputs of the other three gates to ground (CMOS inputs must never float). Explain why in one sentence.
7. Make a NOT gate from a NAND: tie both inputs of gate 2 together. Feed gate 1's output into it. What gate have you made from two NANDs?

8. **Improve it.** Count the transistors: a CMOS 2-input NAND gate uses 4 MOSFETs. How many are in your 74HC00? How many 74HC00 chips would a 1,000-gate design need, and why did engineers soon prefer a single larger chip?

Tips

- The notch marks pin 1's end; pin 1 is to the left of the notch, viewed from above, and the numbering runs counterclockwise.
- Unused CMOS inputs left floating can make the chip draw extra current or behave erratically; tie them to ground or VCC.
- If you have no 74HC00, use the free CircuitVerse simulator and build the same circuit there.

Check your work

- ☐ I read datasheets for the ICs in my kit and recorded their pinouts and supply voltages.
- ☐ I wired a 74HC00 correctly and recorded its truth table.
- ☐ I can explain the tyranny of numbers and how Kilby and Noyce solved it.

ENGINEER'S NOTEBOOK

1. A table of every IC in your kit with part number, maker, function, supply voltage and pin count.
2. The 74HC00 pinout drawing and your truth table.
3. A Moore's-law graph: plot $\log_{10}$ of transistor count against year for the 4004 (1971, 2,300), the 8086 (1978, about 29,000), the 80486 (1989, about 1.2 million), the Pentium 4 (2000, about 42 million) and a chip of about 2020 (about 10^{10}). Draw a best-fit line and find the doubling time.

KEY FORMULAS

$N(t) = N_0 \cdot 2^{t/T}$, with $T \approx 2$ years (Moore's law)
$\text{doublings} = \log_2(N/N_0)$

From history. Kilby also co-invented the handheld electronic calculator at Texas Instruments (the "Cal Tech" prototype of 1967), one of the first products to show ordinary people what integrated circuits could do.

WORKED EXAMPLES

Example 1. The Intel 4004 (1971) had about 2,300 transistors. If the count doubled every 2 years, estimate the count in 2021.

Show solution

1. Time: 50 years, so $50/2 = 25$ doublings.
2. $N = 2300 \times 2^{25} = 2300 \times 33{,}554{,}432 \approx 7.7 \times 10^{10}$.
3. Real chips of 2021 had roughly 10^{10} to 5×10^{10} transistors, so the estimate is close.

Answer: About 8×10^{10} transistors

Example 2. A computer of 1958 with 100,000 transistors, each with 3 hand-soldered joints, has joints that each fail with probability one in a million per year. About how many joint failures per year would you expect?

Show solution

1. Joints: $100{,}000 \times 3 = 300{,}000$.
2. Expected failures: $300{,}000 \times 10^{-6} = 0.3$ per year.
3. So roughly one failure every three years from joints alone, and finding the one bad joint among 300,000 is a nightmare. An IC has its connections made all at once in metal, not soldered.

Answer: About 0.3 per year (one every 3 years)

Example 3. A 74HC00 chip in a 14-pin package contains four 2-input NAND gates. It needs power on pins 14 (VCC) and 7 (GND). How many separate gate inputs and outputs are available, and how many pins does that use?

Show solution

1. Each gate: 2 inputs and 1 output = 3 pins; four gates use 12 pins.
2. Plus 2 power pins: $12 + 2 = 14$ pins, exactly the package.

Answer: 8 inputs and 4 outputs on 12 pins, plus 2 for power

PRACTICE

1. **Easy** What did Kilby show on September 12, 1958?

   Show answer

   The first integrated circuit, a phase-shift oscillator made on one piece of germanium.

2. **Easy** What was Noyce's key contribution?

   Show answer

   A practical way to make a whole circuit in silicon with flat connections deposited on top, using the planar process.

3. **Easy** How is pin 1 marked on an IC, and in which direction are pins numbered?

   Show answer

   By a notch or dot; counterclockwise viewed from the top.

4. **Medium** What was the "tyranny of numbers"?

   Show answer

   Circuits needed so many separate parts and hand-soldered connections that they became too big, costly and unreliable.

5. **Medium** How many doublings take 1,000 transistors to 1,000,000? At Moore's rate, how many years?

   Show answer

   $\log_2 1000 \approx 10$ doublings; about 20 years.

6. **Medium** Why does photolithography make each transistor cheaper as transistors get smaller?

   Show answer

   A wafer costs about the same to process however many transistors are printed on it; smaller transistors mean more per wafer, so each costs less.

7. **Medium** Name four ICs you will use in this course and what each does.

   Show answer

   For example: 74HC00 (NAND gates), 555 (timer), L293D (motor driver), ATmega328P (Arduino's microcontroller), RP2040 (Pico's microcontroller), voltage regulator.

8. Hard The Apollo Guidance Computer used about 2,800 chips, each with two 3-input NOR gates. How many gates is that? Why use only one type of chip?

Show answer

About 5,600 gates. One type could be tested thoroughly, bought in large numbers and trusted; NOR alone can build any logic function.

9. Hard If the first ICs of 1961 had about 4 transistors and Moore's doubling happened every year until 1975, how many would chips have in 1975? (Moore's 1965 paper predicted about 65,000 components by then.)

Show answer

$4 \times 2^{14} = 65{,}536$, matching Moore's prediction.

10. Hard Explain why the planar process was needed before Noyce's integrated circuit could work.

Show answer

It made transistors flat and covered by a protective oxide, so their surfaces were stable and a metal layer could be deposited on the oxide and patterned into connections without shorting the devices beneath.

11. Challenge A wafer 300 mm in diameter costs about $10,000 to process and holds chips of 100 mm^2 each. Estimate the number of chips (ignore the edges) and the cost per chip. If 80% work, what is the cost per working chip?

Show answer

Area $= \pi(150)^2 = 70{,}700\ \text{mm}^2$; about 700 chips; $14 each; with 80% yield, about 560 good chips at about $18 each.

COMMON MISTAKES

- Putting an IC in backward. Pin 1 is next to the notch or dot.
- Forgetting the power pins. A logic chip needs VCC and GND even though they are not drawn on the gate symbols.
- Leaving CMOS inputs floating.

Make it a game · Tyranny of Numbers. Role-play a debate. You are Kilby, your parent is Noyce. Each argues in thirty seconds how your approach solved the tyranny of numbers, one with a germanium chip, the other with the planar process. Then switch sides. Finally recite from memory what photolithography does and what Moore's law predicts.

Scripture. “For as the body is one, and hath many members, and all the members of that one body, being many, are one body: so also is Christ.” (1 Corinthians 12:12, KJV)

An integrated circuit is many parts made as one body, each doing its own work. Paul uses the same picture for the church: many members, one body.

UNIT 4

Transistors and Semiconductors

The transistor is the most important invention of the twentieth century: it is in every radio, phone, car and computer, and more of them have been made than any other manufactured thing. In this unit you will follow its story from the paper-clip prototype at Bell Labs in December 1947, through the pocket radio, the MOSFET and the integrated circuits of Kilby and Noyce, to the billions of transistors in your phone.

You will learn how doped silicon works, how a small current or voltage controls a large one, how to design transistor switches and a simple amplifier, how to choose between a BJT and a MOSFET for a real load, and how to read the datasheets that engineers use every day.

PREREQUISITES

- Unit 3: diodes, the p–n junction, LEDs, relays and flyback diodes
- Ohm's law and Kirchhoff's laws; voltage dividers
- Logarithms base 2 and 10 (introduced in this unit where needed)

MASTERY CHECKLIST

- ☐ I can explain doping, holes, the p–n junction and how an NPN transistor controls current, and use $I_C = \beta I_B$.
- ☐ I can design an NPN low-side switch with a base resistor and overdrive, and calculate its power.
- ☐ I can find the bias point and approximate gain of a common-emitter amplifier, in plain numbers and dB.
- ☐ I can design a logic-level MOSFET switch with gate resistor, pull-down and flyback diode, and choose between a BJT and a MOSFET.
- ☐ I can tell the story of the transistor and the integrated circuit, use Moore's law, and read an IC datasheet and pinout.

OPTIONAL KITS FOR THIS UNIT

- **A transistor and MOSFET assortment**: A small pack of 2N2222 or 2N3904 NPN transistors and a few logic-level MOSFETs (IRLZ44N or similar), plus a 74HC00, from any electronics supplier. Starter kits often include only one or two transistors and a non-logic-level MOSFET.
- **Wokwi (free online simulator)**: Free browser-based simulator for Arduino and Raspberry Pi Pico circuits with LEDs, buttons and many parts. Useful when a part is missing in Units 4–10.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

4.1	**Bell Labs, 1947: The First Transistor**	3 sessions of 50 minutes
4.2	**The Transistor as a Switch**	3 sessions of 50 minutes
4.3	**Amplifiers, Simply: The Transistor Radio**	3 sessions of 50 minutes
4.4	**MOSFETs and Driving Loads**	3 sessions of 50 minutes
4.5	**The Integrated Circuit: Kilby and Noyce**	3 sessions of 50 minutes

Unit 4 Test

Time: 50 minutes. A scientific calculator is allowed. Show the formula, the substitution with units and the answer with its unit for each calculation; correct setup earns partial credit. The test is worth 100 points.

1. **6 pts** **Lesson 4.1**

   A transistor has β = 120 and a base current of 0.25 mA. Find I_C and I_E.

2. **6 pts** **Lesson 4.1**

   Describe how Bardeen and Brattain made the first transistor work, including the problem Bardeen solved.

3. **6 pts** **Lesson 4.1**

   Explain n-type and p-type doping and why an NPN transistor's base is thin.

4. **8 pts** **Lesson 4.2**

   Design a base resistor so a 5 V Arduino pin can switch a 150 mA load with an NPN transistor of minimum β = 100, using 5× overdrive. What is the base current, and is it safe for the pin (20 mA)?

5. **6 pts** **Lesson 4.2**

   A transistor switch has $V_{CE} = 0.2$ V at 150 mA. Find its power. What would it be if it were only half on, with 2.5 V across it?

6. **6 pts** **Lesson 4.2**

   Why must a transistor switch be either fully off or fully on?

7. **8 pts** **Lesson 4.3**

   A common-emitter stage on 12 V has $R_1 = 33$ kΩ, $R_2 = 6.8$ kΩ, $R_E = 680$ Ω, $R_C = 3.3$ kΩ. Find V_B, I_C, V_C and the approximate gain in plain numbers and dB.

8. **6 pts** **Lesson 4.3**

   Explain why the gain of a common-emitter stage with an emitter resistor depends on R_C/R_E rather than on β, and why that matters.

9. **8 pts** **Lesson 4.4**

   A MOSFET with $R_{DS(on)} = 0.022$ Ω switches a 3.0 A load; a BJT with $V_{CE(sat)} = 0.4$ V could do the same. Compare their power dissipation.

10. **8 pts** **Lesson 4.4**

    Draw (describe) a complete logic-level MOSFET motor driver from an Arduino pin, naming and explaining each extra part.

11. **6 pts** **Lesson 4.4**

    Why is a non-logic-level MOSFET a poor choice with a 5 V microcontroller?

12. **8 pts** **Lesson 4.5**

    Using Moore's law (doubling every 2 years), how many transistors would you predict 20 years after a chip of 1.2 million? How many doublings take 2,300 to 2.3 billion?

13. **6 pts** **Lesson 4.5**

    State what Kilby and Noyce each contributed to the integrated circuit.

14. **4 pts** **Lesson 4.5**

    How is pin 1 identified on a DIP chip, and why must unused CMOS inputs be tied high or low?

15. **8 pts** **Lesson 4.1**

    Essay (one paragraph). Explain why the transistor replaced the vacuum tube and how that change led, within twenty years, to the integrated circuit and the pocket calculator.

ANSWER KEY

1. $I_C = 30$ mA; $I_E = 30.25$ mA
2. Shockley's field-effect idea failed because surface states trapped electrons; Bardeen explained this. Brattain pressed two gold contacts, made by slitting gold foil on a plastic wedge, very close together onto germanium; a small signal at one controlled a larger current at the other (December 1947).
3. n-type: added atoms with five outer electrons give free electrons; p-type: atoms with three leave holes. The thin base lets most electrons from the emitter cross to the collector before recombining, giving high gain.
4. $I_{B,\min} = 1.5$ mA; with 5×, 7.5 mA; $R_B = 4.3/0.0075 = 573\ \Omega \rightarrow 560\ \Omega$ (7.7 mA). Safe.
5. 0.03 W; 0.375 W
6. In between, it has both voltage across it and current through it, so it dissipates $V_{CE}I_C$ as heat; fully off ($I \approx 0$) or saturated ($V \approx 0$), it wastes little power.
7. $V_B = 12 \times 6.8/39.8 = 2.05$ V; $I_C \approx 1.35/680 = 1.99$ mA; $V_C = 12 - 6.56 = 5.4$ V; $A_v \approx -4.85$, about 13.7 dB
8. The emitter follows the base signal, so the signal current is v_{in}/R_E, and the output is that current times R_C; β cancels out. Transistors vary, so a gain set by resistors is predictable and repeatable.
9. MOSFET $= 9 \times 0.022 = 0.20$ W; BJT $= 1.2$ W
10. Pin → gate resistor (100–220 Ω, limits the switching spike) → gate; pull-down 10 kΩ gate to source (keeps it off at start-up); source to ground; motor from + supply to drain; flyback diode across the motor (absorbs turn-off spike); grounds joined.
11. Its $R_{DS(on)}$ is specified at about 10 V; at 5 V it is only partly on, so its resistance is high, it heats up and the load gets less voltage.
12. $1.2 \times 10^6 \times 2^{10} \approx 1.2 \times 10^9$; $\log_2(10^6) \approx 20$ doublings.
13. Kilby (Texas Instruments, 1958): all components can be made from one semiconductor, showed on germanium with wire connections. Noyce (Fairchild, 1959): a practical monolithic silicon IC with connections deposited on top of the oxide using the planar process.
14. By the notch or dot; floating CMOS inputs can drift, causing erratic behavior and extra current.

15. A strong answer: tubes were large, hot, power-hungry and short-lived; transistors were tiny, cool, reliable and cheap; transistor radios (1954) and computers followed; but hand-wired transistor circuits hit the tyranny of numbers; Kilby and Noyce integrated parts and wiring on one chip; space and defense orders lowered costs; by 1967–1971 chips held enough logic for handheld calculators and the first microprocessor.

PORTFOLIO PIECE: A TRANSISTOR-DRIVEN LOAD CONTROLLER

Design and build a controller that lets a push button and a light sensor (a photoresistor divider from Lesson 2.3) turn on a real load from the 4-AA pack: a motor-driven fan or a cluster of at least six LEDs. Use a transistor stage to turn the sensor's small voltage into a switching signal, and a logic-level MOSFET (or a properly designed BJT switch) to drive the load, with every protective part in place. Document the design calculations, the datasheet values you relied on, measured voltages and currents, the power in each switch, and one improvement.

LOOK FOR	WHAT IT MEANS
Design	Base or gate resistors, pull-downs, LED resistors and flyback diode chosen by calculation from datasheet values.
Working device	The load turns on and off reliably from the button and the light level; the switching transistor stays cool.
Measurements	Measured V_{CE} or V_{DS}, currents and power compared with the predictions.
Documentation	Schematic, datasheet notes, test table and a paragraph on one improvement made.

UNIT 5

Building Real Circuits

So far your circuits have lived on a breadboard. In this unit you will learn to build circuits that last: you will plan a perfboard layout, learn to solder safely and well, master the most famous chip of all, Hans Camenzind's 555 timer, learn how batteries and regulators really work (including the full rules for handling lithium batteries), and finish with a soldered, enclosed device of your own.

This is the most hands-on unit of the year, and the one with the most safety content. The soldering rules in Lesson 5.2 and the lithium rules in Lesson 5.4 are part of what you are learning: read them aloud, sign them, and follow them every time.

PREREQUISITES

- Units 1–4, especially RC timing (Lesson 3.2), LEDs (3.5) and integrated circuits (4.5)
- The course safety rules signed in Lesson 1.5
- A temperature-controlled soldering iron, stand, safety glasses and fan, and an adult present for Lessons 5.2 and 5.5

MASTERY CHECKLIST

- ☐ I can plan a perfboard layout from a schematic and check it connection by connection.
- ☐ I can solder good through-hole joints, fix bad ones, desolder, and state every soldering safety rule.
- ☐ I can design an astable or monostable 555 circuit and predict its timing.
- ☐ I can compare battery chemistries, calculate energy, run time and regulator efficiency, and state the lithium safety rules.
- ☐ I can build, test in stages, enclose and document a finished soldered device.

OPTIONAL KITS FOR THIS UNIT

- **A learn-to-solder kit**: Many electronics suppliers sell inexpensive beginner soldering kits (blinking-LED badges, 555 flashers or small sound makers) with a printed circuit board and parts. A good optional extra practice project after Lesson 5.2, and an excellent way to compare a PCB with perfboard.
- **Weller soldering tools**: Weller has made soldering irons since the 1940s; its temperature-controlled stations are a common choice for schools. Any temperature-controlled iron with a stand is fine.
- **Hakko soldering tools**: Another long-established maker of temperature-controlled soldering stations, tip cleaners and desoldering tools.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

5.1	**From Breadboard to Perfboard**	3 sessions of 50 minutes
5.2	**Soldering Safely**	3 sessions of 50 minutes
5.3	**The 555 Timer: Hans Camenzind's Chip**	3 sessions of 50 minutes
5.4	**Power Supplies, Batteries and Lithium Safety**	3 sessions of 50 minutes
5.5	**A Finished Soldered Project**	3 sessions of 50 minutes

Unit 5 test

Time: 50 minutes. A scientific calculator is allowed. Show the formula, the substitution with units and the answer with its unit for each calculation; correct setup earns partial credit. Safety answers must be complete. The test is worth 100 points.

1. **6 pts** **Lesson 5.1**
   Compare a solderless breadboard, perfboard and a PCB: when would you use each?

2. **6 pts** **Lesson 5.1**

   A layout has 40 connections and a 2% chance of error each. What is the chance of at least one error? What habit reduces it?

3. **10 pts** **Lesson 5.2**

   List eight soldering safety rules.

4. **6 pts** **Lesson 5.2**

   Describe how to make a good through-hole joint and what a cold joint looks like.

5. **6 pts** **Lesson 5.2**

   How much heat brings a 0.30 g copper joint from 20 °C to 250 °C? ($c = 0.385\ \text{J/(g·°C)}$.) How long with 6 W delivered?

6. **8 pts** **Lesson 5.3**

   An astable 555 has $R_1 = 2.2\ \text{k}\Omega$, $R_2 = 33\ \text{k}\Omega$, $C = 22\ \mu\text{F}$. Find t_{high}, t_{low}, f and duty cycle.

7. **6 pts** **Lesson 5.3**

   Design a 555 monostable for a 5.0 s pulse with a 47 µF capacitor.

8. **6 pts** **Lesson 5.3**

   Explain why a 555's timing is nearly independent of its supply voltage.

9. **8 pts** **Lesson 5.4**

   A 7805 supplies 5.0 V at 200 mA from 12 V. Find the regulator heat and efficiency, and the battery current. What would a 90% switching regulator draw from the 12 V battery?

10. **10 pts** **Lesson 5.4**

    List eight rules for handling lithium batteries safely.

11. **6 pts** **Lesson 5.4**

    Find the energy of a 5,000 mAh, 3.7 V pack, and the run time of a 0.50 W load through an 85% efficient converter.

12. **6 pts** **Lesson 5.4**

    Explain thermal runaway and why a lithium fire is dangerous.

13. **6 pts** **Lesson 5.5**

Describe the staged test you would do before and during the first power-up of a newly soldered board.

14. **6 pts** **Lesson 5.5**

A flasher draws 0.2 mA plus an LED of 10 mA at 50% duty from a 500 mAh battery. Predict its life.

15. **4 pts** **Lesson 5.5**

Why put a power switch in series with the battery of a finished device?

ANSWER KEY

1. Breadboard: quick prototypes and experiments. Perfboard: permanent one-off or few-off builds. PCB: compact, reliable, repeatable devices made in quantity or when the design is final.
2. $1 - 0.98^{40} = 55\%$. Checking every connection against the schematic (highlighter method) before soldering.
3. Any eight: adult present; safety glasses; fan blowing smoke away; ventilation; iron always in stand; never catch a falling iron; cord routed safely; hold parts with clips not fingers; never solder powered circuits; heat-proof mat; no eating or drinking, wash hands; unplug and cool in stand; cool water 10 minutes for a burn.
4. Clean, tinned tip on pad and lead together 1–2 s; feed solder into the joint until it flows; remove solder, then iron; 2–4 s total; do not move it while cooling. A good joint is a smooth concave cone. A cold joint is dull, lumpy or balled, not wetting the pad.
5. $Q = 0.30 \times 0.385 \times 230 = 26.6$ J; $t = 4.4$ s
6. $t_{\text{high}} = 0.693 \times 35{,}200 \times 22 \times 10^{-6} = 0.537$ s; $t_{\text{low}} = 0.503$ s; $f = 0.96$ Hz; duty 52%
7. $R = 5.0/(1.1 \times 47 \times 10^{-6}) = 96.7$ kΩ; use 100 kΩ (5.2 s).
8. Its comparator thresholds are 1/3 and 2/3 of the supply, and the capacitor charges toward the supply, so both scale together and the time between thresholds is unchanged.
9. Heat 1.4 W; efficiency 42%; 200 mA. Switching: $1.0/0.9 = 1.11$ W in, 93 mA.
10. Any eight: never cut, puncture, crush, bend or open; never short (no loose cells with keys or coins); never charge damaged, swollen, hot or wet cells; use only the proper charger; never charge unattended or overnight; charge on a hard non-flammable surface; stop using and move away any cell that is hot, swelling, hissing or smelling; no homemade packs or chargers; recycle with taped terminals; keep coin cells from small children, emergency help if swallowed.
11. 18.5 Wh; $0.85 \times 18.5/0.50 = 31$ h
12. Damage or abuse starts heat-releasing reactions that speed up as the cell heats, releasing more heat and gas; the cell can vent flammable gas, burn intensely, burst and ignite neighbors, and such fires are hard to put out.
13. Visual inspection with a magnifier; check part orientation; resistance between + and ground with chip out (no short); insert chip correctly; first power through the meter on mA and compare with the power budget; then connect directly.

14. Average 5.2 mA; 96 h (4 days)
15. So the device draws no current when off, saving the battery, and can be turned off safely.

PORTFOLIO PIECE: THE FINISHED DEVICE FILE

Present your soldered, enclosed project from Lesson 5.5 as a finished product with a complete documentation file: the schematic, the perfboard layout (both sides), a parts list with values, ratings and costs, the power budget and predicted battery life, the staged test record (inspection, short test, first power-up current, measured timing), photographs of both sides of the board and the enclosure, a user guide with safety notes, and a one-page reflection on what you would change in a second version.

LOOK FOR	WHAT IT MEANS
Workmanship	Clean, smooth joints with no bridges; parts straight and correctly oriented; strain relief and a secure enclosure.
Testing	Short test and first power-up current recorded before normal use; timing measured and compared with the design.
Safety	Soldering rules followed with an adult present; lithium and battery rules respected; device runs only on its battery.
Documentation	Schematic, layout, parts list, power budget, test record, photographs and user guide complete and neat.
Reflection	Thoughtful reflection naming at least one specific change for a second version, with a reason.

5.1 From Breadboard to Perfboard

OBJECTIVES

- Trace the history of circuit construction from wooden breadboards and point-to-point wiring to the printed circuit board.
- Explain how solderless breadboards, perfboard, stripboard and printed circuit boards differ, and when each is used.
- Plan a perfboard layout from a schematic, minimizing crossings and keeping power and ground tidy.
- Transfer a working breadboard circuit to a perfboard layout on paper and check it against the schematic.

> **Warm-up.** Look at your breadboard from earlier builds. Shake it gently. What would happen to it in a backpack? In a car for a year? Write three reasons a finished device should not stay on a breadboard.

WATCH

Circuit Skills: Perfboard Prototyping

Make: · 8:37

https://www.youtube.com/watch?v=3N3ApzmyjzE

> **WHEN TO WATCH**
> After the story. Watch how the presenter plans the board before soldering; pause and copy his layout ideas into your notebook.

BACKUP VIDEO

From Solderless Breadboard to Soldered Circuit - Electronics with Becky Stern | Digi-Key Electronics

DigiKey · 5:33

https://www.youtube.com/watch?v=F9Krq7seV1g

A short DigiKey overview of moving a project from a solderless breadboard to a soldered board.

KEY TERMS

solderless breadboard

A plastic board with spring clips under rows of holes, so parts and wires can be pushed in and moved without soldering. Ideal for prototypes, poor for finished devices.

perfboard

A board of insulating material with a grid of holes on 0.1-inch (2.54 mm) spacing, each with its own copper pad. Parts are soldered in and joined with wire.

stripboard (Veroboard)

Perfboard with long copper strips joining rows of holes; strips are cut where a break is needed.

printed circuit board (PCB)

A board with copper traces etched in a pattern to make all the connections, designed in software and made in a factory.

layout

The physical arrangement of parts and connections on a board, planned from the schematic.

CORE IDEAS

The story. The word *breadboard* is literal. In the early 1920s radio amateurs built their sets on wooden boards, sometimes their mothers' bread boards, screwing the parts down and running bare wires between them. A government publication of 1922 from the National Bureau of Standards showed a homemade receiver built just that way. Production radios moved to metal chassis wired by hand, "point to point." Then in 1936 Paul Eisler, an Austrian engineer living in London, made a radio with its wiring printed and etched in copper foil on an insulating board: the **printed circuit board.** The PCB was adopted widely in the late 1940s and 1950s. The plastic solderless breadboard that you have used all year came later, in the early 1970s: Ronald Portugal of E&L Instruments patented a design that became the standard.

How they figured it out. Every method trades flexibility against permanence. Point-to-point wiring is flexible but slow and error-prone. A PCB is fast to assemble, compact, repeatable and reliable, but each design must be laid out and ordered, so changes are slow. Engineers fill the gap with **perfboard** and **stripboard**: permanent,

soldered and sturdy, but made by hand for one or a few copies. Stripboard, sold as Veroboard from around 1960, made it faster by providing ready-made copper strips.

The physics. A board must do two things: connect what the schematic connects, and insulate everything else. A breadboard's spring clips have contact resistance of tens of milliohms that can grow as they wear, and they add a few picofarads of capacitance between rows, harmless for slow circuits but a problem for radio and fast logic. A soldered joint has a fraction of a milliohm of resistance and does not loosen with vibration. Copper traces and wires must be thick enough for their current: a typical thin perfboard wire carries an ampere easily; motor and power paths deserve thicker wire.

The engineering. Good layout follows rules: place parts in the same arrangement as the schematic where possible; run power and ground as straight "rails" along the edges; keep the pins of chips in sockets so a chip can be replaced; leave room for fingers and a soldering iron; keep wires short and flat; and label the board. Engineers draw the layout on graph paper (one square per hole) or in free software before they solder anything, then check every connection against the schematic with a highlighter. Professional boards today are designed in programs such as KiCad and made by factories in a few days, even for students.

Try it. In the build you will plan, on paper, the perfboard layout for the circuit you will solder in Lesson 5.5, and check it connection by connection.

PICTURE STUDY



A Breadboard Receiver on the Cover of QST, American Radio Relay League, August 1922 · Magazine cover · *QST* magazine

Image: Wikimedia Commons, public domain

In 1922 the radio amateurs' magazine QST showed on its cover a receiver built, like so many of the day, on a flat wooden board. Sets like this are why we still call a prototyping board a breadboard.

Look closely

- Find the parts mounted on the board. How do you think they are held down?
- Find the large loop or frame behind the set. What do you think it is for?
- Look at how the parts are spaced. Why leave so much room?
- Find anything that could come loose or short against something else.

Talk about it

1. What are the advantages of building on a flat board where every connection can be seen?
2. How is your plastic breadboard better than this one, and how is this one better than yours?
3. Why would a magazine for amateurs show a homemade set on its cover in 1922?

> **Safety first.** Batteries and USB power only, never wall power. Build with the power disconnected and connect it last. No soldering in this lesson; the layout is planned on paper.

BUILD

Planning a Perfboard Layout

You will take the 555 LED flasher you will build in Lessons 5.3 and 5.5 (or the fade-out night light from Unit 3), prototype it on the breadboard, then plan its perfboard layout on graph paper and check every connection, ready for soldering.

You will need

- Graph paper (0.1-inch or 5 mm squares), colored pencils, a highlighter
- A perfboard (about 5 × 7 cm) to measure and plan on (do not solder yet)
- Your breadboard with a working circuit (or build the 555 flasher of Lesson 5.3 early)
- A ruler and fine marker; optionally KiCad

Steps

1. Draw a clean schematic of the circuit, with every part labeled (designator and value) and every node given a name or number.
2. Make a parts list with each part's footprint: how many holes it spans and how its legs are spaced (resistor 4–5 holes, small capacitor 2 holes, 8-pin chip 4 × 2 rows 3 holes apart, LED 2 holes, battery clip wires).
3. On graph paper, mark the perfboard outline (count its holes). Draw the power rail (+) along the top edge and ground along the bottom edge.
4. Place the chip (in its socket) near the center. Place each part close to the pins it connects to, arranged as on the schematic.
5. Draw the wire connections in colors: red for +, black for ground, other colors for signals. Avoid crossing wires; where you must cross, use an insulated jumper.
6. Check: with a highlighter, mark each connection on the schematic as you find it on the layout. Every line on the schematic must be highlighted, and nothing on the layout may be left unhighlighted.
7. Mirror check: the layout is drawn from the component side. Draw a second, mirror-image copy for the solder side, which is what you will see when

soldering.

8. **Improve it.** Ask someone to compare your layout with your schematic without your help. Fix anything they question. Then place the real parts on the perfboard (unsoldered) to check that they fit.

Tips

- Leave at least one empty hole between parts so the iron can reach each joint.
- Put the battery wires and switch at one edge, where they can reach the enclosure.
- Number the chip's pins on your layout; pin 1 errors are the most common perfboard mistake.

Check your work

- ☐ My schematic and layout match connection for connection.
- ☐ My layout has clear power and ground rails and few crossings.
- ☐ I drew a mirror-image solder-side view.

ENGINEER'S NOTEBOOK

1. The schematic with every node named.
2. The component-side and solder-side layouts on graph paper.
3. A table comparing breadboard, perfboard, stripboard and PCB: cost, speed, permanence and when to use each.

KEY FORMULAS

$$\text{hole pitch} = 0.1\ \text{in} = 2.54\ \text{mm}$$

$$R_{\text{wire}} = \frac{\rho L}{A}$$

From history. Eisler's printed circuits were first used in large numbers during the Second World War in small radio devices, and after the war in hearing aids and radios. By the 1960s nearly all electronic equipment used PCBs, and today a phone's board has ten or more copper layers stacked inside it.

WORKED EXAMPLES

Example 1. A perfboard is 24 holes by 18 holes on 0.1-inch pitch. What are its usable dimensions in millimeters? Will an 8-pin chip (two rows of 4 pins, 0.3 inch apart) and ten resistors (each spanning 4 holes) fit with room to spare?

Show solution

1. Width: $24 \times 2.54 = 61$ mm; height: $18 \times 2.54 = 46$ mm.
2. The chip occupies 4 holes by 4 holes (including the 0.3-inch row spacing): 16 positions.
3. Ten resistors, each 4 holes long and 1 hole wide: about 40 positions.
4. The board has $24 \times 18 = 432$ holes, so even with wiring channels there is plenty of room.

Answer: About 61 mm × 46 mm; yes, easily

Example 2. A breadboard row's contact resistance is 0.05 Ω per connection. A motor current of 0.50 A passes through four breadboard connections on its way. How much voltage and power are lost? Compare with four soldered joints at 0.001 Ω each.

Show solution

1. Breadboard: $R = 4 \times 0.05 = 0.20\ \Omega$; $V = IR = 0.50 \times 0.20 = 0.10$ V; $P = I^2R = 0.05$ W.
2. Soldered: $R = 0.004\ \Omega$; $V = 0.002$ V; $P = 0.001$ W.

Answer: 0.10 V and 0.05 W on the breadboard against 0.002 V and 0.001 W soldered

Example 3. A layout needs 30 connections. You check each against the schematic, and you have a 2% chance of mis-wiring any one connection. Estimate the chance the board has at least one error. Why do engineers check every connection?

Show solution

1. Probability all 30 are right: $0.98^{30} = 0.545$.
2. Probability of at least one error: $1 - 0.545 = 0.455$, about 45%.
3. Small error rates add up quickly over many connections; checking each one with a highlighter on the schematic catches most errors before soldering.

Answer: About a 45% chance of at least one error

PRACTICE

1. Easy Why is a solderless breadboard called a “breadboard”?

   Show answer

   Early radio builders mounted their circuits on wooden boards, sometimes actual bread boards.

2. Easy Who invented the printed circuit board, and when?

   Show answer

   Paul Eisler, in 1936.

3. Easy What is the hole spacing of standard perfboard?

   Show answer

   0.1 inch (2.54 mm).

4. Medium Give two advantages and two disadvantages of perfboard compared with a PCB.

   Show answer

   Perfboard: no waiting or cost to order, easy to change. But it is slow to wire by hand, larger, and easier to make wiring mistakes in.

5. **Medium** On stripboard, why must you cut the copper strip under a chip?

   Show answer

   Each strip connects a whole row; without a cut, the chip's pins on opposite sides would be shorted together along the strip.

6. **Medium** A 40 mm × 30 mm perfboard: how many holes across and down?

   Show answer

   About 15 by 11 (40/2.54 = 15.7, 30/2.54 = 11.8)

7. **Medium** Why should a chip go into a socket on a perfboard?

   Show answer

   So the chip is not heated by soldering and can be replaced easily if it fails or is put in backward.

8. **Hard** A motor draws 1.0 A through 0.30 m of perfboard wire with $A = 0.20\ \text{mm}^2$, out and back. Find the wire's resistance and the voltage lost. ($\rho = 1.68 \times 10^{-8}\ \Omega \cdot \text{m}$.)

   Show answer

   $L = 0.60\ \text{m}$; $R = (1.68 \times 10^{-8})(0.60)/(0.20 \times 10^{-6}) = 0.050\ \Omega$; $V = 0.05\ \text{V}$

9. **Hard** Explain why a breadboard can cause trouble in a radio circuit at 100 MHz but not in an LED flasher at 1 Hz.

   Show answer

   Rows of breadboard clips have a few picofarads of capacitance and long wires add inductance; at 100 MHz these small values matter, coupling signals between rows. At 1 Hz they are negligible.

10. **Hard** Using the 2% error rate of Worked Example 3, how many connections can a layout have before the chance of an error exceeds 50%?

    Show answer

    $0.98^n < 0.5 \to n > \ln 0.5 / \ln 0.98 = 34.3$: about 35 connections.

11. **Challenge** A factory makes 1,000 PCBs at $2.00 each plus a $50 setup charge. Hand-wired perfboards take 45 minutes of labor at $20 per hour plus $3 of materials. Above how many boards is the PCB cheaper?

    Show answer

    PCB cost $= 50 + 2n$; perfboard $= 18n$. Equal when $50 + 2n = 18n$, so $n = 3.1$: for 4 or more boards, the PCB is cheaper.

COMMON MISTAKES

- Forgetting that the solder side is a mirror image of the component side.
- Placing parts so close together that the iron cannot reach a joint.
- Leaving a chip's orientation unmarked, so it is soldered in backward.

> **Make it a game · Board Matchup.** Sort cards: solderless breadboard, perfboard, stripboard, printed circuit board. Your parent names a situation, such as a quick test or a mass-produced device, and you pick the board and defend it. Then sketch a perfboard layout of a simple LED circuit in two minutes. Best defense scores a point.

5.2 Soldering Safely

OBJECTIVES

- State and follow the full set of soldering safety rules.
- Explain what solder is, how flux works and why a good joint needs both the pad and the lead to be heated.
- Make good through-hole solder joints on a practice board, and recognize and fix cold, bridged and dry joints.
- Desolder a part with wick or a solder sucker.

> **Warm-up.** Hold an ice cube against a cold spoon and a warm spoon. Which melts it faster? Now guess: will solder stick better to a cold wire or a hot one? Write your prediction and why.

WATCH

iFixit's Soldering 101: Beginners Guide

iFixit · 6:46

https://www.youtube.com/watch?v=rK38rpUy568

> **WHEN TO WATCH**
> Before the build, at the start of session 2. Watch the whole video once, then watch the joint-making section again with your iron cold and in its stand, copying the movements.

BACKUP VIDEO

Soldering Safety | Home-made robots | Electrical engineering | Khan Academy

Khan Academy - Projects · 2:53

https://www.youtube.com/watch?v=gW-7yeUW7-k

A short Khan Academy video on soldering safety; watch it with your parent before you turn the iron on for the first time.

KEY TERMS

solder

A metal alloy with a low melting point, used to join electrical parts. Lead-free solder (tin, silver, copper) melts near 217–220 °C; old 63/37 tin-lead solder at 183 °C.

flux

A chemical (usually rosin, inside the solder's core) that cleans oxide from metal surfaces as they heat, so the solder can wet them.

wetting

Molten solder flowing smoothly over and bonding to a clean, hot metal surface, forming a concave fillet.

cold joint

A dull, lumpy joint where the solder did not properly wet the pad or lead, usually because one was not hot enough. It may conduct poorly or crack.

solder bridge

Unwanted solder connecting two neighboring pads or pins, causing a short circuit.

CORE IDEAS

The story. Soldering is very old. Goldsmiths in the ancient world joined fine metalwork with soft solders, and Roman plumbers sealed lead water pipes with tin-lead solder; our word *plumber* comes from *plumbum*, Latin for lead. Scripture remembers Bezalel, filled with skill "to work in gold, and in silver, and in brass." Electrical soldering came with the telegraph and then radio. Early irons were heated in a flame; electric soldering irons appeared around 1900, and later in the century temperature-controlled irons made reliable electronics soldering much easier. In the 2000s much of the world moved to lead-free solders for health and environmental reasons, which melt at higher temperatures and need a little more care.

How they figured it out. Early electronic equipment failed most often at its joints. Engineers learned that the secret of a good joint is not the solder but the **heat** and the **flux**: both metal surfaces must be clean and hot enough to melt the solder themselves, so that the molten solder *wets* them and forms a metallic bond. Solder melted onto a cold lead just sits on it as a blob. NASA and the military wrote strict

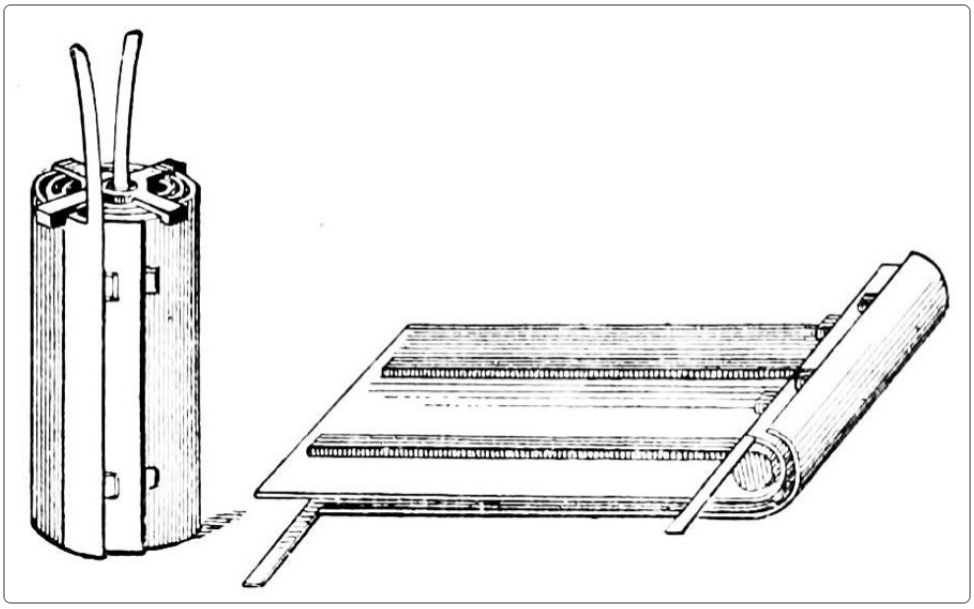
soldering standards in the 1960s for spacecraft and aircraft, and today's industry standard workmanship rules (IPC J-STD-001 and IPC-A-610) descend from them.

The physics. A solder joint is a small piece of metallurgy. When molten tin touches clean copper, a thin layer of tin–copper alloy (an intermetallic compound) forms at the boundary, bonding the two. Oxide on the copper prevents that, which is why flux, which dissolves oxide as it heats, is essential. The iron's tip (at about 330–370 °C) must transfer heat into both the pad and the lead; a thin layer of molten solder on the tip, called tinning, greatly improves heat transfer. Too little heat gives a cold joint; too much or too long lifts the pad off the board or damages the part. A good joint takes 2–4 seconds: heat, feed solder, remove solder, remove iron.

The engineering and safety. Soldering rules (read them aloud and follow every one): an adult is in the room whenever the iron is on. Wear safety glasses; solder and clipped leads can spit or fly. Work on a heat-proof mat in a ventilated room with a small fan blowing the rosin smoke away from your face (not toward it), and never breathe the smoke directly. The tip is about 350 °C: always return the iron to its stand, never set it on the bench, never catch a falling iron, and keep the cord where it cannot be snagged. Hold parts with pliers, clips or a helping hand, not your fingers. Never solder anything that is powered or connected to a battery. Lead-free solder is preferred; if you use leaded solder, never eat or drink at the bench and wash your hands afterward. Unplug the iron when you finish and let it cool in its stand. A burn goes under cool running water for at least 10 minutes; tell an adult.

Try it. In the build you will practice on a scrap perfboard with resistors and wire until your joints are shiny, smooth cones, and you will learn to fix your mistakes.

PICTURE STUDY



Planté's Accumulator, Popular Science Monthly, 1890–1891 · Engraving · Popular Science Monthly, vol. 38

Image: Wikimedia Commons, public domain

Gaston Planté's lead-acid battery of 1859 was made from two sheets of lead, separated and rolled up, in dilute acid. Its plates were joined to their terminals by lead burning and soldering, metalworking skills that electrical engineers borrowed from plumbers. You will study the battery itself in Lesson 5.4.

Look closely

- Find the two lead sheets and whatever keeps them apart.
- Why would the sheets be rolled into a spiral rather than left flat?
- Find where the terminals would be attached to each sheet.
- Look for anything that would have to be joined metal to metal, by soldering or welding.

Talk about it

1. Why must the two sheets never touch?
2. What makes a joint between a lead plate and a terminal good or bad, electrically and mechanically?
3. What do the separators in this battery and the insulation between solder pads have in common?

Safety first. Soldering rules (read them aloud and follow every one): an adult is in the room whenever the iron is on. Wear safety glasses; solder and clipped leads can spit or fly. Work on a heat-proof mat in a ventilated room with a small fan blowing the rosin smoke away from your face (not toward it), and never breathe the smoke directly. The tip is about 350 °C: always return the iron to its stand, never set it on the bench, never catch a falling iron, and keep the cord where it cannot be snagged. Hold parts with pliers, clips or a helping hand, not your fingers. Never solder anything that is powered or connected to a battery. Lead-free solder is preferred; if you use leaded solder, never eat or drink at the bench and wash your hands afterward. Unplug the iron when you finish and let it cool in its stand. A burn goes under cool running water for at least 10 minutes; tell an adult.

BUILD

The Soldering Practice Board

With an adult present, you will set up a safe soldering station, make at least 30 practice joints on scrap perfboard, inspect each one with a magnifier, fix the bad ones, and practice desoldering.

You will need

- Temperature-controlled soldering iron (set about 330–350 °C for tin-lead, 350–370 °C for lead-free) with stand and damp sponge or brass tip cleaner
- Rosin-core solder, 0.6–0.8 mm diameter; solder wick and a solder sucker
- Scrap perfboard, 20 old or spare resistors, a length of solid hookup wire
- Safety glasses, a small desk fan, a heat-proof mat, flush cutters, a helping hand or clip, a magnifier

Steps

1. Set up the station on the heat-proof mat: iron in its stand on your writing-hand side, cord routed behind the bench, fan placed to blow across the work and away from your face, glasses on. Read the safety rules aloud with your adult.
2. Turn on the iron and let it reach temperature. Wipe the tip on the sponge or brass and melt a little solder onto it to tin it. The tip should look shiny silver.
3. Insert a resistor into the perfboard, bend its leads slightly outward to hold it, and flip the board in the helping hand.
4. Make a joint: touch the tip to both the pad and the lead together for 1–2 seconds; feed solder into the joint (not onto the tip) until it flows around the lead; remove the solder; then remove the iron. Total 2–4 seconds. Do not move the part while the joint cools.
5. Make 30 joints. After every five, inspect them with the magnifier and sort them into good, cold, too much solder, too little solder, or bridged. Record the counts.
6. Fix every bad joint: reheat and add a little solder for cold or thin joints; use wick for blobs and bridges.

7. Clip the leads about 1–2 mm above the joints, holding the board so the cut ends fly downward, glasses on.
8. **Improve it.** Practice desoldering: remove three resistors with the wick and sucker without lifting a pad. Then solder two lengths of wire together end to end (twist, heat, flow) and test the joint with the meter's continuity mode. Compare your good-joint rate for the first ten and the last ten joints.

Tips

- Heat the joint, not the solder. Solder should melt because the pad and lead are hot.
- A dirty, black tip will not transfer heat. Clean and re-tin it often.
- If a joint will not flow in 5 seconds, stop, let it cool, add flux (fresh solder) and try again.

Check your work

- ☐ I followed every soldering safety rule, with an adult present.
- ☐ I made at least 30 joints and can recognize good, cold, bridged and blobbed joints.
- ☐ I fixed my bad joints and desoldered parts without lifting pads.

ENGINEER'S NOTEBOOK

1. The soldering safety rules, signed and dated by you and your adult.
2. Labeled sketches of a good joint and of each kind of bad joint, with its cause and fix.
3. Your inspection counts for each group of five joints, and a sentence on how your skill changed.

KEY FORMULAS

$Q = mc\,\Delta T$ (heat needed to warm a joint)

$$P = \frac{Q}{t}$$

From history. The Apollo spacecraft and the Space Shuttle were built by technicians trained and certified to NASA's soldering standards. Every joint was inspected, often under magnification, because one failed joint could end a mission.

WORKED EXAMPLES

Example 1. A copper pad and lead have a total mass of 0.20 g. How much heat warms them from 20 °C to 250 °C? ($c_{\text{copper}} = 0.385\ \text{J/(g·°C)}$.) If the iron delivers about 5 W into the joint, how long does it take?

Show solution

1. $Q = mc\Delta T = (0.20)(0.385)(230) = 17.7\ \text{J}$.
2. $t = Q/P = 17.7/5 = 3.5\ \text{s}$.
3. That is why a good joint takes 2–4 seconds of heating, and why a large pad or thick wire needs a larger tip or a hotter iron.

Answer: About 18 J, about 3.5 s

Example 2. Lead-free solder melts at about 217 °C and tin-lead at 183 °C. If the iron tip is set to 350 °C, how many degrees above the melting point is each? Why do lead-free joints need a slightly hotter iron or a little longer?

Show solution

1. Lead-free: $350 - 217 = 133\ ^\circ\text{C}$ margin.
2. Tin-lead: $350 - 183 = 167\ ^\circ\text{C}$ margin.
3. The smaller margin means heat flows into the joint more slowly once it nears the melting point, so lead-free joints need a well-tinned tip, good contact, and sometimes 20–30 °C more.

Answer: 133 °C against 167 °C of margin

Example 3. A student holds the iron on a pad for 15 seconds and the pad peels off the board. Explain what went wrong and how to fix the board.

Show solution

1. Too much heat for too long softened the adhesive that bonds the copper pad to the board, so the pad lifted.
2. Fix: do not try to resolder to the lifted pad; route a short wire from the part's lead to the next point on the same net, and solder it there.
3. Prevention: use a properly tinned tip, heat both the pad and the lead together, and finish each joint in 2–4 seconds; if it will not flow, stop, let it cool, add flux and try again.

Answer: Overheating lifted the pad; jump it with a wire

PRACTICE

1. Easy Why must the soldering iron always go back into its stand?

   Show answer

   The tip is about 350 °C; set down anywhere else it can burn you, the bench or its own cord, or roll off.

2. Easy What does flux do?

   Show answer

   It cleans oxide from the metal surfaces as they heat, so molten solder can wet them and bond.

3. Easy Describe a good through-hole joint.

   Show answer

   Shiny (for tin-lead; lead-free is a little duller), smooth, concave cone or "volcano" shape, covering the pad and climbing the lead, with no gaps or blobs.

4. Medium Name three safety rules for soldering besides using the stand.

Show answer

Any three: an adult present; safety glasses; fan to blow smoke away and ventilation; never solder powered circuits; hold parts with clips, not fingers; never catch a falling iron; wash hands after (especially with leaded solder); unplug when done; cool water for 10 minutes for a burn.

5. Medium What causes a cold joint, and how do you fix it?

Show answer

Not enough heat on the pad or lead (or dirty surfaces), so solder did not wet both. Reheat the joint with a clean tinned tip, add a little fresh solder (with its flux) and let it flow.

6. Medium How do you remove a solder bridge between two pins?

Show answer

Drag a clean, hot tip between them, or press solder wick (braid) over the bridge with the iron so the wick soaks up the excess solder.

7. Medium Why is the smoke from soldering mainly from flux, and why should you avoid breathing it?

Show answer

Rosin flux boils and burns as it heats; its fumes can irritate the eyes and lungs and can trigger asthma with repeated exposure, so a fan blows them away from the face.

8. Hard A thick wire and pad have mass 0.60 g. Using Worked Example 1, how long would a 5 W iron take to bring them to 250 °C? What should you do instead?

Show answer

$Q = 0.60 \times 0.385 \times 230 = 53$ J; $t = 10.6$ s, long enough to damage parts. Use a larger tip or more powerful iron, or a slightly higher temperature, so the joint heats quickly.

9. Hard Why do professional standards require the lead to be clipped after soldering, leaving about 1–2 mm?

Show answer

Long leads can bend over and short to neighbors; clipping to a short, consistent length keeps the board safe and neat. (Clip with the board pointed away and eyes protected; cut leads fly.)

10. Hard Explain the role of the intermetallic layer in a solder joint.

Show answer

Where tin meets clean copper, a thin layer of tin–copper alloy forms, metallurgically bonding the solder to the pad and lead; without it (oxide in the way) the solder only sits on the surface and the joint is weak.

11. Challenge A board has 60 joints. A beginner's first-try joint is good 90% of the time; after practice, 99%. Find the expected number of bad joints in each case and the chance of a board with no bad joints.

Show answer

Beginner: 6 expected bad joints; $0.90^{60} = 0.0018$ chance of none. Practiced: 0.6 expected; $0.99^{60} = 0.55$. Practice and inspection matter.

COMMON MISTAKES

- Melting solder on the tip and dabbing it onto a cold joint. Heat the pad and lead first.
- Moving the part before the solder solidifies, which leaves a grainy, weak joint.
- Using far too much solder; a good joint is a small cone, not a ball.

> **Make it a game · Safety Rules Recital.** Recital challenge, no soldering. Recite the full soldering safety rules from memory, in order, in under sixty seconds. Your parent checks the list and flags any missing one. Then explain flux, wetting and why both pad and lead must be heated. Draw a good joint and a cold joint. Perfect recall is the record.

> **Scripture.** “And I have filled him with the spirit of God, in wisdom, and in understanding, and in knowledge, and in all manner of workmanship, To devise cunning works, to work in gold, and in silver, and in brass, And in cutting of stones, to set them, and in carving of timber, to work in all manner of workmanship.” (Exodus 31:3-5, KJV)
>
> Bezalel’s skill with metal was called a gift of God. Careful, patient work with your hands, done well and safely, honors the Giver.

5.3 The 555 Timer: Hans Camenzind's Chip

OBJECTIVES

- Tell the story of the 555 timer and why it became one of the best-selling chips of all time.
- Explain the 555's inside: comparators at one-third and two-thirds of the supply, a flip-flop and a discharge transistor.
- Use the astable equations to find frequency, high and low times and duty cycle, and design for a given frequency.
- Build an astable 555 LED flasher and a tone generator and compare measured with calculated timing.

> **Warm-up.** Set a timer on a phone for 10 seconds and start it. What would you need to build a box that blinks a light every second forever, without a computer? List the parts you think it would need.

WATCH

Electronic Basics #26: 555 Timer IC

GreatScott! · 7:29

https://www.youtube.com/watch?v=fLaexx-NMj8

> **WHEN TO WATCH**
> After the story. Pause at the internal block diagram and label the comparators, flip-flop and discharge transistor in your notebook.

BACKUP VIDEO

Astable 555 timer - 8-bit computer clock - part 1

Ben Eater · 27:50

https://www.youtube.com/watch?v=kRlSFm519Bo

Ben Eater builds and explains an astable 555 in careful detail as the clock for his breadboard computer; watch the first 15 minutes for the charging and discharging explanation.

KEY TERMS

555 timer

An integrated circuit (8 pins) that produces accurate time delays or continuous pulses, set by external resistors and a capacitor.

astable

A mode with no stable state: the output switches high and low continuously, making a square wave.

monostable

A mode with one stable state: a trigger makes one output pulse of fixed length, $t = 1.1RC$.

comparator

A circuit that compares two voltages and gives a high or low output depending on which is larger.

duty cycle

The fraction of each cycle that the output is high, as a percent.

CORE IDEAS

The story. In 1970 Hans Camenzind, a Swiss-born engineer working under contract for Signetics in Sunnyvale, California, designed a general-purpose timer chip. He had worked on oscillator circuits and saw that many products needed a simple, reliable way to make delays and pulses. His first design used too many pins; he simplified it, cut the transistor count, and fit the whole timer into an eight-pin package. Signetics released it as the NE555 in 1971. Engineers loved it: it worked over a wide range of supply voltages, its timing was stable, and it cost very little. It has been made in enormous numbers ever since, by many companies, and is still sold today. Camenzind later wrote a book on the history of electronics for general readers.

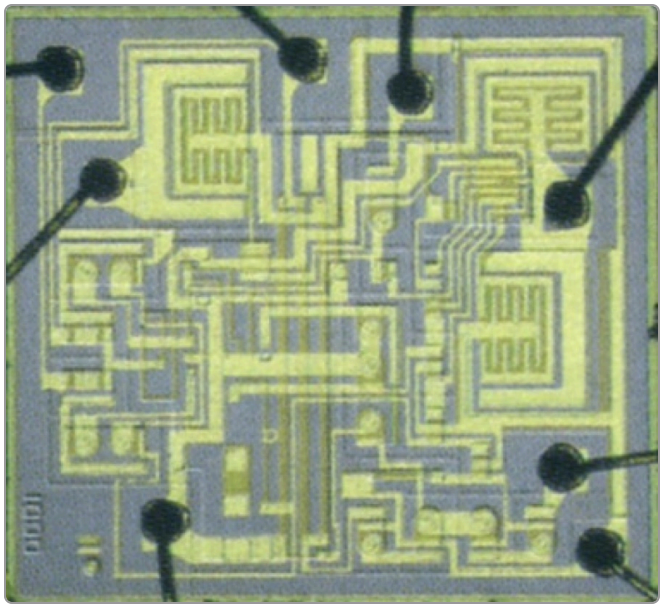
How they figured it out. Camenzind's insight was to time with a capacitor charging through resistors (Lesson 3.2), but to make the timing independent of the supply voltage. Inside the chip, three equal 5 kΩ resistors divide the supply into thirds. Two comparators watch the capacitor: when it charges past two-thirds of the supply, one comparator resets a flip-flop and the output goes low; when it discharges below one-third, the other sets it and the output goes high. Because both thresholds are fractions of the supply, a change in the supply voltage changes the thresholds and the charging speed in the same proportion, and the timing stays the same.

The physics. In the astable circuit, the capacitor C charges through $R_1 + R_2$ from one-third to two-thirds of the supply, and discharges through R_2 alone (through the chip's discharge pin, pin 7). Charging from 1/3 to 2/3 on an exponential curve takes $\ln 2 = 0.693$ time constants, so $t_{\text{high}} = 0.693(R_1 + R_2)C$ and $t_{\text{low}} = 0.693 R_2 C$. The period is $T = 0.693(R_1 + 2R_2)C$ and the frequency is $f = 1.44/[(R_1 + 2R_2)C]$. With $R_1 = 1\ \text{k}\Omega$, $R_2 = 68\ \text{k}\Omega$ and $C = 10\ \mu\text{F}$: $f = 1.44/(137{,}000 \times 0.00001) = 1.05\ \text{Hz}$, a blink about once a second. Because $R_1 + R_2 > R_2$, the output is always high a little longer than it is low.

The engineering. The 555 appears in toys, alarms, traffic-light controllers, metronomes, LED flashers, tone generators and motor-speed controllers. Engineers read its datasheet for the supply range (4.5–16 V for the NE555; CMOS versions such as the TLC555 work down to about 2 V and draw far less current), the output current (up to about 200 mA, enough for LEDs and small relays, with a flyback diode), and the need for a 0.01 µF capacitor on pin 5 and a 0.1 µF decoupling capacitor across the supply. For accurate timing they use film capacitors rather than electrolytics, which can be ±20%.

Try it. You will build an astable 555 flasher, measure its timing against the equations, and then change C to make it sing.

PICTURE STUDY



The Die of the First 555, CQ Publishing, about 1971 · Photomicrograph · Wikimedia Commons

Image: Wikimedia Commons, public domain

This is the silicon die of an early 555 timer, photographed through a microscope. The whole chip, with its two dozen or so transistors and its resistors, is smaller than a grain of rice.

Look closely

- Find the square pads around the edges where fine wires connect to the eight pins.
- Look for long, thin zigzag shapes. Which components might they be?
- Find the lighter lines that join the parts. What metal do you think they are?
- Look for three similar shapes in a row. Could they be the three resistors that divide the supply into thirds?

Talk about it

1. Why would Camenzind work hard to reduce the number of transistors and pins?
2. What makes a chip like this so cheap to make in millions, though it took months to design?
3. How does this die compare with the Apollo flat-packs of Lesson 4.5?

> **Safety first.** Batteries and USB power only, never wall power. Build with the power disconnected and connect it last. Use the 9 V battery or the 4-AA pack. If you add the speaker or piezo, keep the volume low and do not hold it against your ear.

BUILD

A 555 Flasher and Tone Generator

You will build an astable 555 that flashes an LED, measure its timing with a stopwatch and compare it with the equations, then switch capacitors to make it sing through a piezo buzzer, and tune it to a musical note.

You will need

- An NE555 (or TLC555) timer chip
- Resistors: 1 kΩ, 10 kΩ, 47 kΩ, 68 kΩ, 470 Ω; a 10 kΩ potentiometer
- Capacitors: 10 µF electrolytic, 0.1 µF and 0.01 µF ceramic
- Red LED, piezo buzzer, 9 V battery and clip (or 4-AA pack), breadboard, jumpers, multimeter, a stopwatch app (and optionally a free tuner app)

Steps

1. Draw the astable schematic: pin 8 (VCC) and pin 4 (reset) to +; pin 1 to ground; R_1 from + to pin 7; R_2 from pin 7 to pins 6 and 2 (joined); C from pins 6 and 2 to ground; 0.01 µF from pin 5 to ground; output pin 3 → 470 Ω → LED → ground; 0.1 µF across the supply.
2. With $R_1 = 1$ kΩ, $R_2 = 68$ kΩ, $C = 10\ \mu$F, calculate t_{high}, t_{low}, f and duty cycle.
3. Build it, check the chip's orientation (notch, pin 1), and connect the battery. The LED should blink about once a second.
4. Time 20 blinks with a stopwatch and calculate the measured period and frequency. Compare with your prediction and find the percent difference. (Remember the electrolytic's tolerance.)
5. Measure the capacitor voltage at pins 2/6 with the meter: it should swing between about 3 V and 6 V on a 9 V supply. Measure the battery voltage too and check the 1/3 and 2/3 fractions.
6. Change R_2 to 47 kΩ, then 10 kΩ. Predict and measure the frequency each time and make a table.
7. **Sound.** Replace C with 0.1 µF, R_2 with 10 kΩ in series with the 10 kΩ potentiometer (as a variable resistor), and connect the piezo from pin 3 to

ground. Calculate the frequency range, then tune to 440 Hz with a tuner app or by ear against a known A.

8. **Improve it.** Test the claim that the timing does not depend on the supply: run the flasher on the 9 V battery, then on 4.5 V (3 AA cells), timing 20 blinks each. Record the result and explain it.

Tips

- If the LED stays on or off, check pin 4 (reset must be at +) and that pins 2 and 6 are joined.
- Electrolytic capacitors are often 20% off their marked value; measure C with your meter if it has a capacitance range.
- A CMOS TLC555 runs on lower voltages and drains the battery more slowly; it is pin-compatible with the NE555.

Check your work

- ☐ My flasher's measured frequency is within the capacitor tolerance of the calculated value.
- ☐ I measured the 1/3 and 2/3 thresholds.
- ☐ I designed and tuned a tone generator and showed that timing is nearly independent of supply voltage.

ENGINEER'S NOTEBOOK

1. The astable schematic with pin numbers and part values.
2. A table of R_1, R_2, C, predicted and measured frequency, and percent difference.
3. A sketch of the capacitor voltage (sawtooth-like between 1/3 and 2/3) and the output square wave, lined up in time.

KEY FORMULAS

$$t_{\text{high}} = 0.693\,(R_1 + R_2)\,C$$
$$t_{\text{low}} = 0.693\,R_2\,C$$
$$f = \frac{1.44}{(R_1 + 2R_2)\,C}$$
$$\text{duty} = \frac{R_1 + R_2}{R_1 + 2R_2}$$
$$t_{\text{mono}} = 1.1\,RC$$

From history. Camenzind later designed other chips, including an early phase-locked loop, and wrote *Much Ado About Almost Nothing*, a history of electronics for general readers. He said the 555 succeeded because it was easy to use and forgiving of mistakes, a lesson in designing for the people who will use your work.

WORKED EXAMPLES

Example 1. An astable 555 has $R_1 = 10\ \text{k}\Omega$, $R_2 = 47\ \text{k}\Omega$ and $C = 10\ \mu\text{F}$. Find t_{high}, t_{low}, the frequency and the duty cycle.

Show solution

1. $t_{\text{high}} = 0.693(57{,}000)(10 \times 10^{-6}) = 0.395\ \text{s}$.
2. $t_{\text{low}} = 0.693(47{,}000)(10 \times 10^{-6}) = 0.326\ \text{s}$.
3. $T = 0.721\ \text{s}$; $f = 1/T = 1.39\ \text{Hz}$ (check: $1.44/(104{,}000 \times 10^{-5}) = 1.38\ \text{Hz}$).
4. Duty $= 0.395/0.721 = 55\%$.

Answer: 0.40 s high, 0.33 s low, 1.4 Hz, 55% duty

Example 2. Design a 555 tone generator at about 440 Hz (the note A) with $C = 0.10\ \mu\text{F}$ and $R_1 = 1.0\ \text{k}\Omega$. Find R_2.

Show solution

1. From $f = 1.44/[(R_1 + 2R_2)C]$:
   $R_1 + 2R_2 = 1.44/(fC) = 1.44/(440 \times 0.10 \times 10^{-6}) = 32{,}700\ \Omega$.
2. $2R_2 = 31{,}700$, so $R_2 = 15{,}900\ \Omega$.
3. Use a standard 15 kΩ (gives about 465 Hz) or a 10 kΩ resistor plus a 10 kΩ potentiometer to tune it.

Answer: $R_2 \approx 16\ \text{k}\Omega$ (15 kΩ standard, or tune with a pot)

Example 3. A 555 monostable must keep a light on for 11 s after a button press. With $C = 100\ \mu\text{F}$, what resistor is needed?

Show solution

1. $t = 1.1RC$, so $R = t/(1.1C) = 11/(1.1 \times 100 \times 10^{-6}) = 100{,}000\ \Omega$.

Answer: 100 kΩ

PRACTICE

1. Easy What are the 555's internal threshold voltages, as fractions of the supply?

Show answer

One-third and two-thirds.

2. Easy Find f for $R_1 = 1\ \text{k}\Omega$, $R_2 = 10\ \text{k}\Omega$, $C = 10\ \mu\text{F}$.

Show answer

$1.44/(21{,}000 \times 10^{-5}) = 6.9\ \text{Hz}$

3. Easy Who designed the 555, and for which company?

Show answer

Hans Camenzind, for Signetics (released 1971).

4. Medium Find the duty cycle for $R_1 = 1\ \text{k}\Omega$, $R_2 = 10\ \text{k}\Omega$.

Show answer

$11/21 = 52\%$

5. Medium Why does the 555's timing hardly change when the battery voltage drops?

Show answer

The thresholds are fixed fractions of the supply, and the capacitor's charging rate scales with the supply too, so the time to move between the thresholds stays the same.

6. Medium For a 1.0 Hz flasher with $C = 10\ \mu\text{F}$ and $R_1 = 1.0\ \text{k}\Omega$, find R_2.

Show answer

$R_1 + 2R_2 = 144\ \text{k}\Omega$; $R_2 = 71.5\ \text{k}\Omega$ (use 68 kΩ for 1.05 Hz)

7. Medium What does doubling C do to the frequency?

Show answer

Halves it.

8. Hard A 555 drives an LED through 470 Ω from 9 V; the output high is about 7.5 V. Find the LED current ($V_F = 2.0$ V). Is it within the 555's output rating?

Show answer

$(7.5 - 2.0)/470 = 11.7\ \text{mA}$; yes, far below about 200 mA.

9. Hard Show that charging from 1/3 to 2/3 of the supply takes $\ln 2$ time constants.

Show answer

Charging toward V_s: the gap to V_s falls from $\frac{2}{3}V_s$ to $\frac{1}{3}V_s$, a factor of 2; since the gap decays as $e^{-t/\tau}$, $e^{-t/\tau} = \frac{1}{2}$, so $t = \tau \ln 2 = 0.693\tau$.

10. Hard Why can a basic astable 555 never have a duty cycle below 50%, and how do engineers get one?

Show answer

t_{high} uses $R_1 + R_2$ and t_{low} only R_2, so high is always longer. A diode across R_2 lets charging bypass it, so $t_{\text{high}} = 0.693R_1C$ and $t_{\text{low}} = 0.693R_2C$ can be set independently.

11. Challenge A 555 flasher draws about 4 mA itself plus an LED at 12 mA for 55% of each cycle, from a 500 mAh 9 V battery. Estimate the battery life. How much longer would a CMOS TLC555 (about 0.2 mA itself) last?

Show answer

Average $= 4 + 0.55 \times 12 = 10.6$ mA; $500/10.6 = 47$ h. With TLC555: $0.2 + 6.6 = 6.8$ mA; 74 h, about 1.6 times as long.

COMMON MISTAKES

- Forgetting to connect pin 4 (reset) to the positive supply, so the 555 never runs.
- Not joining pins 2 and 6 in astable mode.
- Using the formula with kΩ and µF but forgetting the powers of ten: $k \times \mu = 10^{-3}$, so kΩ × µF gives milliseconds.

Make it a game · 555 Insides. Draw the inside of a 555 timer from memory in ninety seconds: two comparators, one-third and two-thirds thresholds, a flip-flop and a discharge transistor. Your parent checks it. Then calculate a duty cycle for two resistor values. Name astable versus monostable. Retell Camenzind's story in thirty seconds.

Scripture. “To every thing there is a season, and a time to every purpose under the heaven:” (Ecclesiastes 3:1, KJV)

A timer chip measures out seconds faithfully, on and off. The Preacher reminds us that our days, too, are measured, and each season has its purpose.

5.4 Power Supplies, Batteries and Lithium Safety

OBJECTIVES

- Compare battery chemistries (alkaline, NiMH, lead-acid and lithium-ion) by voltage, capacity, energy, rechargeability and hazards.
- Calculate capacity in Wh, run time, C-rate and regulator efficiency and heat.
- Explain linear and switching regulators and when each is used.
- State the lithium-battery safety rules in full, and build and test a regulated 5 V supply from a battery pack.

> **Warm-up.** List every device in your house that runs on a rechargeable battery. For each, guess what kind of battery it uses and how long it lasts between charges. Which would be most dangerous if its battery were damaged?

WATCH

How do Lithium-ion Batteries Work?

Branch Education · 9:30

https://www.youtube.com/watch?v=G5McJw4KkG8

> **WHEN TO WATCH**
> After the story and before the physics paragraph. Watch how lithium ions move between the electrodes during charging and discharging.

BACKUP VIDEO

The Power and Danger of Lithium-ion Batteries

NFPA Kids · 2:32

https://www.youtube.com/watch?v=Af27049X8Io

A short NFPA (National Fire Protection Association) video on how lithium-ion batteries work and how to handle them safely; watch it with your parent before the build.

KEY TERMS

primary / secondary cell

A primary cell (alkaline, lithium coin) is used once; a secondary cell (NiMH, lead-acid, lithium-ion) is rechargeable.

C-rate

Charge or discharge current relative to capacity: 1C for a 2,000 mAh cell is 2.0 A; 0.5C is 1.0 A.

thermal runaway

A dangerous chain reaction in a damaged, overcharged or overheated lithium cell: heat causes reactions that release more heat, leading to venting, fire or explosion of the cell.

switching regulator

A regulator (buck or boost converter) that switches rapidly and uses an inductor to convert voltage efficiently, often 85–95%.

linear regulator

A regulator (such as the 7805) that drops excess voltage as heat to give a steady output: simple and quiet, but wasteful when the input is much higher than the output.

CORE IDEAS

The story. In 1859 the French physicist Gaston Planté rolled two sheets of lead, separated by cloth, into a spiral, put them in dilute sulfuric acid, and made the first rechargeable battery. Lead-acid batteries still start most cars. In the 1970s, during worries about oil supplies, Stanley Whittingham at Exxon built a rechargeable lithium battery with a titanium disulfide electrode, but it could short and catch fire. In 1980 John Goodenough at Oxford found that lithium cobalt oxide made a far better, higher-voltage electrode, and in 1985 Akira Yoshino in Japan paired it with a carbon electrode that held lithium safely. Sony sold the first commercial lithium-ion cells in 1991. The three men shared the 2019 Nobel Prize in Chemistry. Goodenough, who came to faith as a young man, worked on batteries until he was nearly 100.

How they figured it out. Lithium is the lightest metal and gives up its electron very readily, so it promised batteries with high voltage and light weight. The danger was the same reactivity: pure lithium metal grows needle-like crystals as it is recharged, which can pierce the separator and short the cell. Yoshino's solution was never to use lithium metal: in a lithium-ion cell, lithium ions shuttle between two host materials (carbon and a metal oxide) through a liquid electrolyte, and a thin porous plastic separator keeps the electrodes apart. Protection circuits were added to stop overcharging, over-discharging and short circuits.

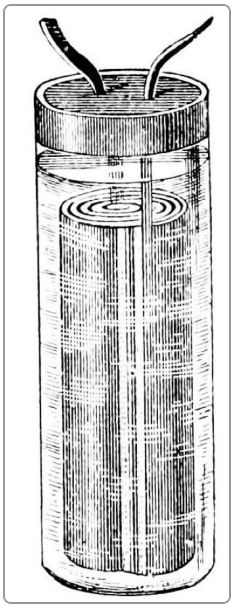
The physics. Each chemistry has its own cell voltage: alkaline 1.5 V, NiMH 1.2 V, lead-acid 2.0 V, lithium-ion about 3.6–3.7 V nominal (4.2 V full, about 3.0 V empty). Energy is capacity times voltage, $W = (\text{Ah})(V)$; an 18650 lithium cell of 3,000 mAh

at 3.6 V holds 10.8 Wh. Run time is capacity divided by current. Circuits usually need a steady voltage, so engineers add a **regulator**. A linear regulator such as the 7805 gives 5.0 V from 7–20 V but turns the difference into heat: $P = (V_{\text{in}} - V_{\text{out}})I$; from 9 V at 100 mA it wastes 0.4 W and is only 56% efficient. A switching regulator does the same job at about 90% efficiency by switching an inductor on and off thousands of times a second. The Arduino Uno has a linear regulator for its barrel jack; the Pico has a switching one.

Lithium safety (read carefully). Lithium cells store a great deal of energy in a small space, and a damaged or abused cell can enter thermal runaway, venting hot gas, catching fire, and even bursting; such fires are very hard to put out. Rules for this course and for life: (1) Never cut, puncture, crush, bend, drop hard, or open a lithium cell or pack. (2) Never short its terminals; carry spare cells in a case, never loose in a pocket with keys or coins. (3) Never charge a damaged, swollen, hot, dented or wet cell, and never charge with a charger not made for that cell or device. (4) Never leave lithium cells charging unattended or overnight, and charge on a hard, non-flammable surface, never on a bed or sofa. (5) Stop using any cell that gets hot, swells, hisses or smells; move it outdoors away from anything flammable if it is safe to do so, and call for help. (6) Do not build your own lithium packs or chargers in this course; use only sealed commercial power banks and products with built-in protection. (7) Recycle lithium cells at a battery drop-off point with tape over the terminals; never throw them in household trash. (8) Coin cells are lithium too and are very dangerous if swallowed: keep them away from small children, and if a child might have swallowed one, get emergency help immediately.

The engineering. Engineers choose a power source by the energy needed, the current, the size and weight, the cost, the temperature range and safety. Alkaline AA cells are cheap, safe and good for low-current projects; NiMH are rechargeable and safe; lithium-ion packs are light and powerful but need protection circuits and careful handling. For this course a USB power bank is the safest way to carry lithium power: its protection circuit and charger are built in and certified. A good design also includes a fuse or current limit, a reverse-polarity diode, and decoupling capacitors.

PICTURE STUDY



Planté's Rechargeable Battery, Popular Science Monthly, 1890–1891 · Engraving · Popular Science Monthly, vol. 38

Image: Wikimedia Commons, public domain

Planté's accumulator of 1859 was the first battery that could be recharged again and again. This engraving appeared in a popular science magazine about thirty years later, when such batteries were storing power for telegraphs and the first electric lights.

Look closely

- Find the jar and the rolled plates inside. What fills the jar?
- Find the two terminals. Which might be positive?
- Why would the jar be glass?
- Compare its size with the energy it might store. How does it compare with a phone battery?

Talk about it

1. Why is a liquid acid battery like this unsuitable for a phone?
2. Lead-acid batteries still start cars. What advantages might they have over lithium-ion?
3. What safety rules would apply to a battery full of acid?

> **Safety first.** Lithium rules for this lesson and the whole course: never cut, puncture, crush, short or open a lithium cell or pack; never charge a damaged, swollen, hot or wet cell; never leave lithium charging unattended; use only sealed commercial power banks with built-in protection; recycle cells with taped terminals; keep coin cells away from small children. Regulators can get hot: touch them only after disconnecting, and check temperature with a fingertip briefly. Batteries and USB power only, never wall power.

BUILD

A Regulated 5 V Supply and a Power Budget

You will build a 5 V regulated supply from a 6-AA or 9 V battery with a linear regulator, measure its efficiency and heat, compare it with a USB power bank, and write a power budget for the soldered project of Lesson 5.5.

You will need

- A 7805 or a low-dropout 5 V regulator (such as an LM2940 or MCP1702), with 0.33 µF (or 10 µF) input and 0.1 µF (or 10 µF) output capacitors as the datasheet requires
- A 9 V battery and clip or a 6-AA holder; a USB power bank (sealed, commercial) and a USB breakout or the Arduino as a load
- Load resistors: 100 Ω (1/2 W or larger) and 220 Ω; an LED with 330 Ω; a 1N4001 diode
- Breadboard, jumpers, multimeter

Steps

1. Read the regulator's datasheet: pinout (for the 7805 facing the label: input, ground, output), minimum dropout voltage, maximum current, and required capacitors. Draw the schematic, including a 1N4001 at the input for reverse-polarity protection.
2. Build it. With no load, measure the input and output voltages.
3. Add a 220 Ω load (about 23 mA), then a 100 Ω load (50 mA). For each, measure V_{in}, I_{in} (meter in series at the input), V_{out} and I_{out}.
4. Calculate input power, output power, efficiency and regulator heat for each load. After one minute at 50 mA, touch the regulator briefly with a fingertip (after disconnecting): is it warm?
5. Test regulation: replace the 9 V battery with 6 AA cells (or a partly used battery) and record whether V_{out} stays at 5.0 V. Find the lowest input at which it still regulates (the dropout).
6. Compare with the power bank: run the same 100 Ω load (5.0 V, 50 mA, 0.25 W) from the bank's USB output. Use the bank's Wh rating and an 85%

efficiency to estimate its run time, and compare with the 9 V battery and regulator.

7. Write the power budget for the Lesson 5.5 soldered project: each part's current, the total, and the predicted run time on your chosen battery.
8. **Improve it.** Write a one-page "lithium safety card" for your bench and a list of every lithium battery in your house with where it is charged. Discuss with your family whether any charging habits should change.

Tips

- Regulators can oscillate without their capacitors; put them right at the pins.
- A 9 V battery has a high internal resistance, so its voltage sags under load; measure it while loaded.
- Never connect the power bank and the battery to the same circuit at once.

Check your work

- ☐ I measured efficiency and heat for a linear regulator and explained the losses.
- ☐ I found the regulator's dropout voltage.
- ☐ I can state the lithium safety rules in full and made a safety card for my bench.

ENGINEER'S NOTEBOOK

1. The regulator schematic, measurements table and efficiency calculations.
2. A comparison table of battery chemistries: voltage, energy, rechargeable or not, hazards, uses.
3. Your lithium safety card and household battery list.
4. The power budget for Lesson 5.5.

KEY FORMULAS

$W = (\text{capacity in Ah}) \times V$

$t = \dfrac{\text{capacity}}{I}$

$P_{\text{reg}} = (V_{\text{in}} - V_{\text{out}})\, I$ (linear)

$\eta = \dfrac{P_{\text{out}}}{P_{\text{in}}}$

From history. Goodenough was 57 when he found the lithium cobalt oxide cathode and in his nineties when he was still publishing on new battery chemistries. He received the Nobel Prize at 97, the oldest person ever to receive it.

WORKED EXAMPLES

Example 1. An 18650 lithium-ion cell is rated 3,000 mAh at 3.6 V. Find its energy. What current is 1C, and what is 2C?

Show solution

1. $W = (3.0\ \text{Ah})(3.6\ \text{V}) = 10.8\ \text{Wh}$.
2. $1\text{C} = 3.0\ \text{A}$; $2\text{C} = 6.0\ \text{A}$.

Answer: 10.8 Wh; 3.0 A and 6.0 A

Example 2. A 7805 linear regulator supplies 5.0 V at 100 mA from a 9.0 V battery. Find the power wasted in the regulator and its efficiency. Compare with a 90%-efficient switching regulator: what current does each draw from the battery?

Show solution

1. Linear: $P = (9.0 - 5.0)(0.100) = 0.40\ \text{W}$ wasted; efficiency $= 0.50/0.90 = 56\%$; battery current 100 mA.
2. Switching: output power $0.50\ \text{W}$; input power $0.50/0.90 = 0.556\ \text{W}$; battery current $0.556/9.0 = 62\ \text{mA}$.
3. The switching regulator makes the battery last about 1.6 times as long.

Answer: 0.40 W wasted, 56%; 100 mA against 62 mA

Example 3. A project needs 5.0 V at 250 mA for 8 hours a day. Compare (a) four AA alkaline cells (6.0 V, 2.5 Ah) with a low-dropout linear regulator and (b) a 10,000 mAh, 3.7 V power bank with a 5 V output at 85% efficiency. How many days does each last?

Show solution

1. (a) Linear: battery current equals load current, 0.25 A; $2.5/0.25 = 10$ h, about 1.25 days.
2. (b) Energy $= 10 \times 3.7 = 37$ Wh; usable $0.85 \times 37 = 31.5$ Wh; load $= 5.0 \times 0.25 = 1.25$ W; $31.5/1.25 = 25$ h, about 3.1 days.
3. The power bank lasts longer and is rechargeable, with its protection built in.

Answer: (a) about 1.25 days; (b) about 3.1 days

PRACTICE

1. Easy Give the nominal cell voltage of alkaline, NiMH and lithium-ion cells.

   Show answer

   1.5 V, 1.2 V, about 3.6–3.7 V.

2. Easy Who shared the 2019 Nobel Prize in Chemistry, and for what?

   Show answer

   John Goodenough, Stanley Whittingham and Akira Yoshino, for developing lithium-ion batteries.

3. Easy State four of the lithium safety rules.

   Show answer

   Any four from the eight in the lesson, for example: never cut, puncture or crush; never short; never charge damaged or swollen cells; never charge unattended; stop using hot or swelling cells; no homemade packs; recycle properly; keep coin cells from children.

4. Medium A 2,000 mAh NiMH pack of four cells: find its voltage and energy.

   Show answer

   4.8 V; 9.6 Wh

5. **Medium** A 7805 regulator gives 5 V at 0.50 A from 12 V. How much heat does it produce? Would it need a heat sink?

Show answer

3.5 W; yes, a TO-220 regulator without a heat sink can shed only about 1–2 W safely.

6. **Medium** Why is pure lithium metal dangerous in a rechargeable cell, and how does a lithium-ion cell avoid it?

Show answer

Recharging lithium metal grows needle-like dendrites that can pierce the separator and short the cell. Lithium-ion cells keep lithium as ions stored in carbon and oxide host materials, never as metal.

7. **Medium** Why should spare lithium cells and coin cells never be carried loose in a pocket?

Show answer

Keys or coins can short their terminals, causing heating and possible fire.

8. **Hard** Find the run time of a 1.25 W load from a 2,500 mAh, 3.7 V cell through a boost converter that is 88% efficient.

Show answer

Energy $9.25\ \text{Wh}$; usable $8.14\ \text{Wh}$; $t = 6.5\ \text{h}$

9. **Hard** Airlines limit lithium packs in carry-on bags to 100 Wh without special approval. Is a 26,800 mAh, 3.7 V power bank allowed?

Show answer

$26.8 \times 3.7 = 99.2\ \text{Wh}$: just under 100 Wh, so yes.

10. **Hard** Explain thermal runaway in three sentences.

Show answer

Damage, overcharging or overheating starts chemical reactions inside the cell that release heat. Heat speeds up the reactions, which release more heat and gas, a runaway loop. The cell can vent, catch fire or burst, and can ignite neighboring cells.

11. **Challenge** A design must run 5.0 V at 150 mA for 30 hours. Which is the smallest of these that works: (a) a 9 V alkaline (0.5 Ah) with a 7805; (b) six AA alkalines (9 V, 2.5 Ah) with a 7805; (c) a 5,000 mAh 3.7 V power bank at 85%? Show calculations.

    Show answer

    Needed: 150 mA for 30 h = 4.5 Ah at 5 V (22.5 Wh). (a) 0.5/0.15 = 3.3 h: no. (b) 2.5/0.15 = 16.7 h: no. (c) $0.85 \times 18.5 = 15.7$ Wh; $15.7/0.75 = 21$ h: no. None works alone; use a 10,000 mAh bank ($31.5/0.75 = 42$ h) or reduce the current.

COMMON MISTAKES

- Comparing batteries by mAh when their voltages differ; compare Wh.
- Expecting a linear regulator to save energy. Its battery current equals its load current; the extra voltage becomes heat.
- Leaving off the regulator's input and output capacitors.

Make it a game · Battery Showdown. Cards for alkaline, NiMH, lead-acid and lithium-ion. Your parent calls a feature, such as highest energy, cheapest or most hazardous. Name the chemistry in five seconds. Then calculate run time from Wh and load, and explain thermal runaway in a sentence. Ten right answers beats the record. No batteries needed.

Scripture. "A prudent man foreseeth the evil, and hideth himself: but the simple pass on, and are punished." (Proverbs 22:3, KJV)

Battery fires are rare because prudent people follow simple rules. Foreseeing danger and acting on it is part of wisdom, at the bench and everywhere.

5.5 A Finished Soldered Project

OBJECTIVES

- Carry a project from schematic and layout through soldering, testing and enclosing, as kit builders have done since the 1920s.
- Inspect and test a soldered board systematically before and after applying power.
- Document a finished device with a schematic, layout, parts list, test data and user notes.
- Solder a working 555 flasher (or night light) on perfboard with a switch, battery and enclosure.

> **Warm-up.** Look at a finished electronic product (a remote, a toy, a flashlight). What makes it feel "finished" rather than a prototype? List five features, such as a case, a switch, labels or a battery door.

WATCH

Soldering Tutorial for Beginners: Five Easy Steps

oneTesla · 3:57

https://www.youtube.com/watch?v=Qps9woUGkvI

> **WHEN TO WATCH**
> Before you start soldering. Watch it once as a refresher, then keep these five steps beside your iron.

KEY TERMS

kit

A packaged set of parts, a board and instructions from which a builder assembles a working device.

smoke test

Engineers' joking name for the first time power is applied to a new board; done with a current-limited supply or a meter in series, so a fault shows up as a reading, not smoke.

visual inspection

Checking every joint, part orientation and value with a magnifier before power is applied.

enclosure

The case that protects a circuit and the user: it holds the board and battery and exposes only the switch, light or controls.

strain relief

A way of securing wires (a knot, a tie or glue) so that pulling on them does not pull on the solder joints.

CORE IDEAS

The story. In 1922 the U.S. National Bureau of Standards published Circular 120, telling ordinary families how to build a simple radio receiver from wire, a cardboard tube, a crystal detector and a pair of headphones. Thousands did. After the Second World War, the Heath Company of Benton Harbor, Michigan, began selling electronic kits, and for more than forty years, from 1947 until 1992, "Heathkits" let families build their own test equipment, radios, televisions and even computers at the kitchen table, following careful step-by-step manuals with a check box for every solder joint. Many engineers of the twentieth century said they learned their trade building Heathkits as teenagers.

How they figured it out. Heath's manuals were famous because they were designed for success. Every step said exactly which part went where, with its value and its orientation; every step had a check box; the manual told the builder how to test each section before going on; and there was a troubleshooting chart at the end. Those habits, small steps, check each one, test in stages, keep records, are exactly how professional engineers build and test prototypes today.

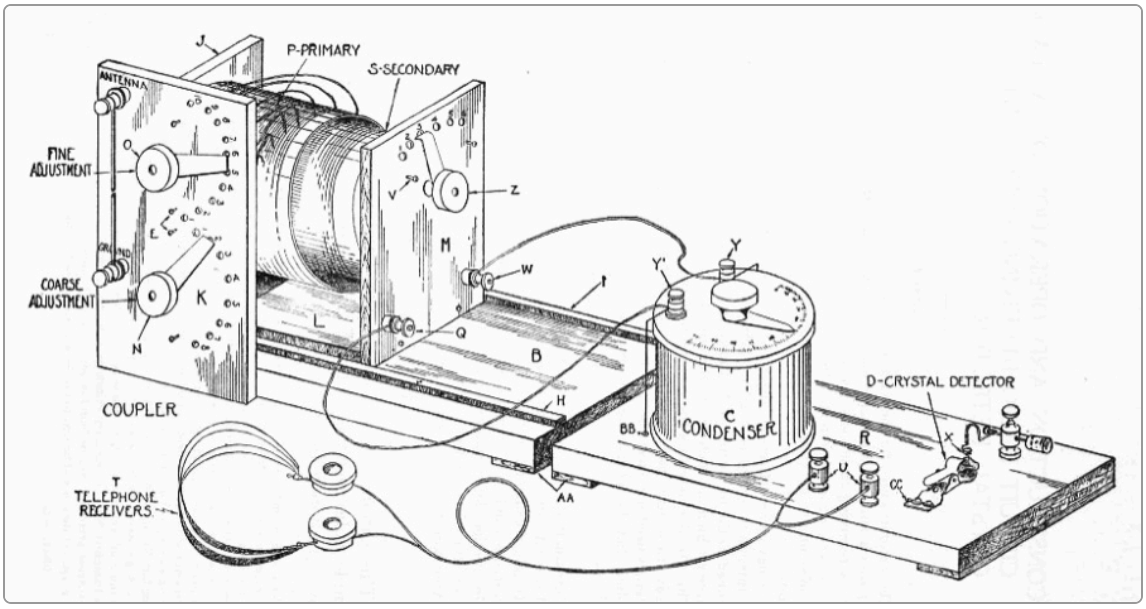
The physics. The finished project is the 555 astable of Lesson 5.3, now soldered: $f = 1.44/[(R_1 + 2R_2)C]$, an LED with its current-limiting resistor, a power switch and a battery. The new physics is reliability. A soldered joint holds where a breadboard clip loosens; a switch in series breaks the battery current, so the device draws nothing when off; an enclosure keeps fingers, coins and moisture from shorting the battery. The power budget from Lesson 5.4 predicts the battery life.

The engineering. Build in stages: (1) solder the low parts first (resistors, then the chip socket, then capacitors and the LED); (2) inspect every joint and part with a magnifier against your layout; (3) check for shorts between + and ground with the meter's resistance or continuity mode before any battery is connected; (4) insert the chip in its socket, the right way round; (5) connect the battery through the meter on its mA range for the first power-up, and check that the current matches the power budget; (6) only then connect directly. Add strain relief to the battery wires, mount

the board so nothing can short against it, label the switch and battery, and write a one-paragraph user guide.

Try it. This is your first finished, soldered electronic device. Build it carefully, test it in stages, and document it as a real product.

PICTURE STUDY



A Two-Circuit Crystal Radio, National Bureau of Standards, 1922 · Technical drawing · Bureau of Standards Circular 121

Image: Wikimedia Commons, public domain

In 1922 the National Bureau of Standards published simple, careful instructions for families to build their own radio receivers. This drawing from Circular 121 shows an improved two-circuit set. Instructions like these began a long tradition of learning electronics by building kits.

Look closely

- Find the coils and the crystal detector.
- Find the terminals for the antenna, ground and headphones.
- How does the drawing help a builder place each part correctly?
- Look for labels or letters that match the text of the instructions.

Talk about it

1. What makes instructions like these easy or hard to follow?
2. Why would a government agency want ordinary families to build radios?
3. What would you add to these instructions if you were writing them today?

Safety first. Soldering rules (read them aloud and follow every one): an adult is in the room whenever the iron is on. Wear safety glasses; solder and clipped leads can spit or fly. Work on a heat-proof mat in a ventilated room with a small fan blowing the rosin smoke away from your face (not toward it), and never breathe the smoke directly. The tip is about 350 °C: always return the iron to its stand, never set it on the bench, never catch a falling iron, and keep the cord where it cannot be snagged. Hold parts with pliers, clips or a helping hand, not your fingers. Never solder anything that is powered or connected to a battery. Lead-free solder is preferred; if you use leaded solder, never eat or drink at the bench and wash your hands afterward. Unplug the iron when you finish and let it cool in its stand. A burn goes under cool running water for at least 10 minutes; tell an adult. The finished device runs only on its battery; never connect it to any other power.

BUILD

A Soldered, Enclosed 555 Flasher

You will solder the 555 flasher you designed and laid out (Lessons 5.1 and 5.3) onto perfboard, with a chip socket, a power switch and a 9 V battery clip; test it in stages; enclose it; and document it as a finished product. (If you prefer, solder the Unit 3 fade-out night light instead, following the same steps.)

You will need

- Perfboard (about 5 × 7 cm), an 8-pin DIP socket, an NE555 or TLC555
- Resistors and capacitors from your Lesson 5.3 design (for example 1 kΩ, 68 kΩ, 10 µF, 0.01 µF, 0.1 µF), an LED and its resistor (470 Ω on 9 V)
- A slide or toggle switch, a 9 V battery clip, hookup wire
- An enclosure: a small plastic project box or a sturdy box you make, with a hole for the LED and switch; double-sided foam tape or standoffs
- Soldering station and safety gear (Lesson 5.2), multimeter, magnifier

Steps

1. Set up the soldering station and read the safety rules aloud with your adult. Lay out your schematic, layout and parts list where you can see them. Make a checklist with one box per part and per connection.
2. Solder the resistors first, then the chip socket (notch toward your marked pin 1), then the capacitors (electrolytic stripe to ground), then the LED (flat side to ground). Check off each part.
3. Make the wire connections on the solder side as drawn on your mirror-image layout. Check off each connection.
4. Inspect every joint with the magnifier. Fix cold joints and bridges. Compare the board with the layout part by part.
5. With no chip and no battery, measure resistance between the + and ground rails. It should be high (a capacitor may make it climb slowly). If it is low, find the short before going on.
6. Insert the 555 the right way round. Solder the switch in series with the battery's red wire, and the battery clip's black wire to ground. Tie a knot or

use a cable tie for strain relief.

7. First power-up: connect the battery through the meter on its mA range. Compare the current with your power budget (Worked Example 1). If it matches, connect directly. Time 20 blinks and compare the frequency with your design.
8. **Improve it and finish.** Mount the board in the enclosure, with the LED and switch reachable and nothing able to short against the battery. Label the switch. Write a one-paragraph user guide (what it does, how to change the battery, what not to do). Then add one improvement of your own choice: a second LED that alternates (pin 3 to a second LED through a resistor to +), a light sensor, or a different rate.

Tips

- Work in good light, and take a break if your hands get tired; most bad joints happen when you rush.
- Keep the iron in its stand whenever you are reading the layout.
- Photograph the board from both sides before you enclose it, for your documentation.

Check your work

- ☐ My board passed visual inspection and the short test before power was applied.
- ☐ The first power-up current matched my power budget.
- ☐ My finished, enclosed device works, and I documented it with schematic, layout, parts list, test data and user guide.

ENGINEER'S NOTEBOOK

1. The completed checklist with every box ticked.
2. Photographs or sketches of both sides of the finished board.
3. The test record: rail resistance, first power-up current, measured frequency and battery life prediction.
4. A short reflection: what went well, what you would change, and what you learned from any fault you fixed.

KEY FORMULAS

$$f = \frac{1.44}{(R_1 + 2R_2)\,C}$$

$$I_{\text{avg}} = I_{\text{chip}} + D \cdot I_{\text{LED}}$$

$$t_{\text{battery}} = \frac{\text{capacity}}{I_{\text{avg}}}$$

From history. Heathkit's customers built everything from oscilloscopes to the H8 computer of 1977. The company's manuals were so carefully written that some engineering schools used them to teach technical writing.

WORKED EXAMPLES

Example 1. Your soldered flasher draws 4.0 mA for the 555 and 13 mA for the LED, which is on 52% of the time, from a 9 V battery of 500 mAh. Predict its life. What current should the first power-up test show with the LED on, and with it off?

Show solution

1. Average: $I = 4.0 + 0.52 \times 13 = 10.8$ mA; life $= 500/10.8 = 46$ h.
2. First power-up: about 17 mA with the LED on and about 4 mA with it off. A reading of hundreds of milliamperes would mean a short: disconnect at once.

Answer: About 46 h; about 17 mA on and 4 mA off

Example 2. Before power-up, you measure 12 Ω between the + and ground rails of your board. What does this tell you, and what do you do?

Show solution

1. A healthy board with the chip out should read a high resistance (thousands of ohms or more, with capacitors charging slowly).
2. 12 Ω means a near-short: probably a solder bridge, a misplaced wire or a reversed part.
3. Do not connect the battery. Inspect with a magnifier, especially neighboring pads on the rails, and use continuity mode to half-split the board until you find it.

Answer: A short; find it before applying power

Example 3. The finished flasher blinks at 0.92 Hz instead of the designed 1.05 Hz. Is that a fault?

Show solution

1. Percent difference: $(0.92 - 1.05)/1.05 = -12\%$.
2. The 10 µF electrolytic may be ±20%, and the resistors ±5%; a 12% error is within the tolerances.
3. Not a fault. To make it exact, measure C and adjust R_2, or use a trimmer potentiometer.

Answer: −12%: within tolerance, not a fault

PRACTICE

1. Easy What did the Bureau of Standards' Circular 120 (1922) teach?

   Show answer

   How to build a simple homemade radio receiver.

2. Easy Why solder the shortest parts (resistors) first?

   Show answer

   The board then lies flat on the bench while you solder them; taller parts would hold it up unevenly.

3. Easy Why put the chip in a socket?

   Show answer

   So it is not heated during soldering and can be removed or replaced, and so it can be inserted only after the board is checked.

4. Medium What should you check with the meter before connecting the battery for the first time?

   Show answer

   The resistance (or continuity) between + and ground, to catch shorts; also that the chip is out of its socket or correctly oriented.

5. Medium Why connect the battery through the meter (mA range) for the first power-up?

Show answer

So you can see the current: a normal reading confirms the board, and a very high reading reveals a short before parts overheat.

6. Medium What is strain relief, and why do battery wires need it?

Show answer

Securing wires so that pulling on them does not stress the solder joints; battery clips get pulled often, and a broken joint stops the device.

7. Medium Name three features that make a device “finished” rather than a prototype.

Show answer

Any three: soldered board, enclosure, power switch, strain relief, labels, user guide, secure battery holder.

8. Hard Your board reads 4 mA with the LED off and 4 mA with it on: the LED never lights. Give two likely causes and how to test each.

Show answer

LED in backward (test: diode-test it in place or check its flat side against the layout) or an open joint in the LED path (test: measure voltage at pin 3 and across the resistor and LED while pin 3 is high).

9. Hard Heathkit manuals had a check box for every step. Explain why this reduces errors, using the probability idea from Lesson 5.1.

Show answer

Each step done without checking has a small chance of error, and over hundreds of steps those chances add up; checking each step as it is done catches errors immediately, when they are easy to fix, rather than leaving several to find at the end.

10. Hard An enclosure adds a power switch in series with the battery. When off, how much current flows, and how long would the battery last in storage?

Show answer

Essentially zero; the battery lasts its shelf life (years for alkaline), limited only by self-discharge.

11. Challenge You want your flasher to run for 7 days continuously on one 9 V battery (500 mAh). Using a TLC555 (0.2 mA) and a red LED, what is the largest average LED current you can allow, and what LED current (when on) and duty cycle would you design?

Show answer

7 days = 168 h; average current ≤ 500/168 = 2.98 mA; LED average ≤ 2.78 mA. For example, a 20% duty cycle (diode-steered 555) with 13 mA when on gives 2.6 mA average, or 50% duty at 5.5 mA.

COMMON MISTAKES

- Soldering the chip directly to the board, then finding it was in backward.
- Skipping the short test and connecting the battery straight away.
- Leaving battery wires without strain relief, so a joint breaks the first time the battery is changed.

Make it a game · Inspect Before Power. Role-play the final inspection. Your parent shows a drawing of a board with three planted faults: a solder bridge, a cold joint, a reversed part. You find them with the visual inspection checklist, then recite the test order before power. Swap with a new drawing. Most faults found wins.

Scripture. “And whatsoever ye do, do it heartily, as to the Lord, and not unto men;” (Colossians 3:23, KJV)

A finished device, built carefully, tested honestly and documented well, is work done heartily. That is the standard for every project in this course.

UNIT 5

Building Real Circuits

So far your circuits have lived on a breadboard. In this unit you will learn to build circuits that last: you will plan a perfboard layout, learn to solder safely and well, master the most famous chip of all, Hans Camenzind's 555 timer, learn how batteries and regulators really work (including the full rules for handling lithium batteries), and finish with a soldered, enclosed device of your own.

This is the most hands-on unit of the year, and the one with the most safety content. The soldering rules in Lesson 5.2 and the lithium rules in Lesson 5.4 are part of what you are learning: read them aloud, sign them, and follow them every time.

PREREQUISITES

- Units 1–4, especially RC timing (Lesson 3.2), LEDs (3.5) and integrated circuits (4.5)
- The course safety rules signed in Lesson 1.5
- A temperature-controlled soldering iron, stand, safety glasses and fan, and an adult present for Lessons 5.2 and 5.5

MASTERY CHECKLIST

- ☐ I can plan a perfboard layout from a schematic and check it connection by connection.
- ☐ I can solder good through-hole joints, fix bad ones, desolder, and state every soldering safety rule.
- ☐ I can design an astable or monostable 555 circuit and predict its timing.
- ☐ I can compare battery chemistries, calculate energy, run time and regulator efficiency, and state the lithium safety rules.
- ☐ I can build, test in stages, enclose and document a finished soldered device.

OPTIONAL KITS FOR THIS UNIT

- **A learn-to-solder kit**: Many electronics suppliers sell inexpensive beginner soldering kits (blinking-LED badges, 555 flashers or small sound makers) with a printed circuit board and parts. A good optional extra practice project after Lesson 5.2, and an excellent way to compare a PCB with perfboard.
- **Weller soldering tools**: Weller has made soldering irons since the 1940s; its temperature-controlled stations are a common choice for schools. Any temperature-controlled iron with a stand is fine.
- **Hakko soldering tools**: Another long-established maker of temperature-controlled soldering stations, tip cleaners and desoldering tools.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

5.1	**From Breadboard to Perfboard**	3 sessions of 50 minutes
5.2	**Soldering Safely**	3 sessions of 50 minutes
5.3	**The 555 Timer: Hans Camenzind's Chip**	3 sessions of 50 minutes
5.4	**Power Supplies, Batteries and Lithium Safety**	3 sessions of 50 minutes
5.5	**A Finished Soldered Project**	3 sessions of 50 minutes

Unit 5 test

Time: 50 minutes. A scientific calculator is allowed. Show the formula, the substitution with units and the answer with its unit for each calculation; correct setup earns partial credit. Safety answers must be complete. The test is worth 100 points.

1. **6 pts** **Lesson 5.1**
   Compare a solderless breadboard, perfboard and a PCB: when would you use each?

2. **6 pts** **Lesson 5.1**

   A layout has 40 connections and a 2% chance of error each. What is the chance of at least one error? What habit reduces it?

3. **10 pts** **Lesson 5.2**

   List eight soldering safety rules.

4. **6 pts** **Lesson 5.2**

   Describe how to make a good through-hole joint and what a cold joint looks like.

5. **6 pts** **Lesson 5.2**

   How much heat brings a 0.30 g copper joint from 20 °C to 250 °C? ($c = 0.385\ \text{J/(g·°C)}$.) How long with 6 W delivered?

6. **8 pts** **Lesson 5.3**

   An astable 555 has $R_1 = 2.2\ \text{k}\Omega$, $R_2 = 33\ \text{k}\Omega$, $C = 22\ \mu\text{F}$. Find t_{high}, t_{low}, f and duty cycle.

7. **6 pts** **Lesson 5.3**

   Design a 555 monostable for a 5.0 s pulse with a 47 µF capacitor.

8. **6 pts** **Lesson 5.3**

   Explain why a 555's timing is nearly independent of its supply voltage.

9. **8 pts** **Lesson 5.4**

   A 7805 supplies 5.0 V at 200 mA from 12 V. Find the regulator heat and efficiency, and the battery current. What would a 90% switching regulator draw from the 12 V battery?

10. **10 pts** **Lesson 5.4**

    List eight rules for handling lithium batteries safely.

11. **6 pts** **Lesson 5.4**

    Find the energy of a 5,000 mAh, 3.7 V pack, and the run time of a 0.50 W load through an 85% efficient converter.

12. **6 pts** **Lesson 5.4**

    Explain thermal runaway and why a lithium fire is dangerous.

13. **6 pts** **Lesson 5.5**

Describe the staged test you would do before and during the first power-up of a newly soldered board.

14. **6 pts** **Lesson 5.5**

A flasher draws 0.2 mA plus an LED of 10 mA at 50% duty from a 500 mAh battery. Predict its life.

15. **4 pts** **Lesson 5.5**

Why put a power switch in series with the battery of a finished device?

ANSWER KEY

1. Breadboard: quick prototypes and experiments. Perfboard: permanent one-off or few-off builds. PCB: compact, reliable, repeatable devices made in quantity or when the design is final.
2. $1 - 0.98^{40} = 55\%$. Checking every connection against the schematic (highlighter method) before soldering.
3. Any eight: adult present; safety glasses; fan blowing smoke away; ventilation; iron always in stand; never catch a falling iron; cord routed safely; hold parts with clips not fingers; never solder powered circuits; heat-proof mat; no eating or drinking, wash hands; unplug and cool in stand; cool water 10 minutes for a burn.
4. Clean, tinned tip on pad and lead together 1–2 s; feed solder into the joint until it flows; remove solder, then iron; 2–4 s total; do not move it while cooling. A good joint is a smooth concave cone. A cold joint is dull, lumpy or balled, not wetting the pad.
5. $Q = 0.30 \times 0.385 \times 230 = 26.6$ J; $t = 4.4$ s
6. $t_{\text{high}} = 0.693 \times 35{,}200 \times 22 \times 10^{-6} = 0.537$ s; $t_{\text{low}} = 0.503$ s; $f = 0.96$ Hz; duty 52%
7. $R = 5.0/(1.1 \times 47 \times 10^{-6}) = 96.7$ kΩ; use 100 kΩ (5.2 s).
8. Its comparator thresholds are 1/3 and 2/3 of the supply, and the capacitor charges toward the supply, so both scale together and the time between thresholds is unchanged.
9. Heat 1.4 W; efficiency 42%; 200 mA. Switching: $1.0/0.9 = 1.11$ W in, 93 mA.
10. Any eight: never cut, puncture, crush, bend or open; never short (no loose cells with keys or coins); never charge damaged, swollen, hot or wet cells; use only the proper charger; never charge unattended or overnight; charge on a hard non-flammable surface; stop using and move away any cell that is hot, swelling, hissing or smelling; no homemade packs or chargers; recycle with taped terminals; keep coin cells from small children, emergency help if swallowed.
11. 18.5 Wh; $0.85 \times 18.5/0.50 = 31$ h
12. Damage or abuse starts heat-releasing reactions that speed up as the cell heats, releasing more heat and gas; the cell can vent flammable gas, burn intensely, burst and ignite neighbors, and such fires are hard to put out.
13. Visual inspection with a magnifier; check part orientation; resistance between + and ground with chip out (no short); insert chip correctly; first power through the meter on mA and compare with the power budget; then connect directly.

14. Average 5.2 mA; 96 h (4 days)
15. So the device draws no current when off, saving the battery, and can be turned off safely.

PORTFOLIO PIECE: THE FINISHED DEVICE FILE

Present your soldered, enclosed project from Lesson 5.5 as a finished product with a complete documentation file: the schematic, the perfboard layout (both sides), a parts list with values, ratings and costs, the power budget and predicted battery life, the staged test record (inspection, short test, first power-up current, measured timing), photographs of both sides of the board and the enclosure, a user guide with safety notes, and a one-page reflection on what you would change in a second version.

LOOK FOR	WHAT IT MEANS
Workmanship	Clean, smooth joints with no bridges; parts straight and correctly oriented; strain relief and a secure enclosure.
Testing	Short test and first power-up current recorded before normal use; timing measured and compared with the design.
Safety	Soldering rules followed with an adult present; lithium and battery rules respected; device runs only on its battery.
Documentation	Schematic, layout, parts list, power budget, test record, photographs and user guide complete and neat.
Reflection	Thoughtful reflection naming at least one specific change for a second version, with a reason.

UNIT 6

Digital Logic

In this unit you will cross from analog electronics into the digital world. You will follow the ideas that made computers possible: George Boole's algebra of logic, Claude Shannon's discovery that switches obey it, Leibniz's binary numbers, the logic gates and flip-flops that store and process bits, and finally Babbage's and Lovelace's vision of a general-purpose computer, realized at last in transistors.

You will design with Boolean algebra and truth tables, convert among decimal, binary and hexadecimal, build logic gates from transistors and from NAND chips, store bits in latches and a shift register, and run a program by hand as a CPU does. By the end of the unit you will understand what is happening inside the microcontroller you begin programming in Unit 7.

PREREQUISITES

- Unit 4: transistors as switches, integrated circuits and datasheets
- Exponents and powers of 2; simple algebra
- Breadboard and chip-handling skills (Lessons 4.5 and 5.1)

MASTERY CHECKLIST

- ☐ I can write, simplify and test Boolean expressions, including with De Morgan's laws.
- ☐ I can convert among decimal, binary and hexadecimal, add in binary and use two's complement.
- ☐ I can give the truth table of every basic gate, build gates from NAND or NOR, and design from a truth table.
- ☐ I can explain latches, flip-flops, shift registers and counters, and why buttons need debouncing.
- ☐ I can explain the fetch–decode–execute cycle and how gates, adders and flip-flops make a CPU.

OPTIONAL KITS FOR THIS UNIT

- **CircuitVerse (free online logic simulator)**: A free, browser-based digital logic simulator with gates, flip-flops and displays. Used in Lessons 6.3 and 6.5; excellent for testing designs before building them.
- **A 74HC logic chip assortment**: A few 74HC00 (NAND), 74HC02 (NOR), 74HC86 (XOR), 74HC74 (D flip-flop) and 74HC595 (shift register) chips from any electronics supplier make this unit more hands-on. Optional.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

6.1	**Boole and Shannon: Logic in Switches**	3 sessions of 50 minutes
6.2	**Binary and Hexadecimal: Leibniz's Ones and Zeros**	3 sessions of 50 minutes
6.3	**Logic Gates and Truth Tables**	3 sessions of 50 minutes
6.4	**Flip-Flops and Counters: Memory from Gates**	3 sessions of 50 minutes
6.5	**From Gates to a Computer: Babbage, Lovelace and the CPU**	3 sessions of 50 minutes

Unit 6 test

Time: 50 minutes. A scientific calculator is allowed (but do conversions by hand, showing work). Show truth tables, algebra steps and calculations clearly; correct method earns partial credit. The test is worth 100 points.

1. **6 pts** **Lesson 6.1**

   Write the 8-row truth table for $Y = \overline{A}B + C$.

2. **6 pts** **Lesson 6.1**

   Simplify $AB + A\overline{B} + \overline{A}B$ with Boolean algebra, one step per line.

3. **6 pts** **Lesson 6.1**

   Explain what Shannon showed in 1937 and why it mattered.

4. **6 pts** **Lesson 6.2**

   Convert 182 to binary and hex; convert 0x2D and 11101_2 to decimal.

5. **6 pts** **Lesson 6.2**

   Add 0111 + 0101 in binary and check in decimal. Write −12 in 8-bit two’s complement.

6. **6 pts** **Lesson 6.2**

   An 8-bit DAC from 3.3 V: what is the step size and the output for input 128?

7. **6 pts** **Lesson 6.3**

   Give the truth tables of NAND, NOR and XOR, and show how to make an OR gate from NAND gates only.

8. **8 pts** **Lesson 6.3**

   Design a circuit with output 1 when the 2-bit number AB is 2 or 3 or when C is 1 and AB is 1. Write it as a sum of products and simplify.

9. **6 pts** **Lesson 6.3**

   Five gates each with 9 ns delay lie on the longest path. What is the fastest rate of new results?

10. **8 pts** **Lesson 6.4**

    A NAND SR latch starts at Q = 1. Inputs: $\overline{R}$ low, both high, $\overline{R}$ low again, $\overline{S}$ low, both high. Give Q after each step. What input is forbidden?

11. **6 pts** **Lesson 6.4**

    A 12-stage counter is driven by a 4.096 kHz clock. What frequency does the last stage give, and what is the counter’s range?

12. **6 pts** **Lesson 6.4**

    Explain switch bounce and two ways to fix it.

13. **6 pts** **Lesson 6.5**

    Use the method of differences to extend 3, 7, 13, 21 by two values.

14. **6 pts** **Lesson 6.5**

Trace this program: 0: LOAD A, [8]; 1: ADD A, [8]; 2: ADD A, [9]; 3: STORE A, [10]; 4: HALT, with memory 8 = 6 and 9 = 4. What is in address 10?

15. **4 pts** **Lesson 6.5**

Name the parts of a CPU and say what each does.

16. **8 pts** **Lesson 6.5**

Essay (one paragraph). Babbage designed a general-purpose computer in the 1830s, but working computers came only in the 1940s. Explain what was missing, and how the ideas of Boole, Shannon, Leibniz and the flip-flop supplied it.

ANSWER KEY

1. ABC: 000→0, 001→1, 010→1, 011→1, 100→0, 101→1, 110→0, 111→1
2. $A(B + \overline{B}) + \overline{A}B = A + \overline{A}B = (A + \overline{A})(A + B) = A + B$
3. That switch and relay circuits follow Boolean algebra (series = AND, parallel = OR), so they can be designed, simplified and checked mathematically and can do binary arithmetic: the basis of digital design.
4. 182 = 10110110_2 = 0xB6; 0x2D = 45; 11101_2 = 29
5. 1100_2 = 12 (7 + 5); 12 = 00001100 → 11110011 + 1 = 11110100
6. $3.3/256 = 12.9$ mV; $3.3 \times 128/256 = 1.65$ V
7. NAND 1,1,1,0; NOR 1,0,0,0; XOR 0,1,1,0. OR: invert A and B with NANDs (inputs joined), then NAND the results: $\overline{\overline{A}\,\overline{B}} = A + B$.
8. AB = 10 or 11 means A = 1; AB = 01 with C = 1 is $\overline{A}BC$. $Y = A + \overline{A}BC = A + BC$.
9. 45 ns; about 22 MHz
10. 0, 0, 0, 1, 1. Both $\overline{S}$ and $\overline{R}$ low together is forbidden.
11. $4096/4096 = 1.0$ Hz; 0 to 4095
12. Contacts bounce open and closed for a few ms, giving several pulses; fix with an SR latch (two-contact switch), an RC filter (often with a Schmitt trigger), or a delay in code.
13. Differences 4, 6, 8 (second difference 2): next 10, 12; values 31, 43
14. A = 6, then 12, then 16; memory 10 = 16
15. Control unit (fetches and decodes instructions, directs everything), program counter (address of next instruction), registers (fast storage of a few values), ALU (arithmetic and logic), bus (shared wires), clock (paces each step).
16. A strong answer: Babbage's concepts (store, mill, programs on cards) were right, but mechanical parts were too costly and slow; Leibniz's binary and Boole's algebra gave a simple two-state number system and logic; Shannon showed switches could implement them; flip-flops (1918) gave fast electronic memory; with tubes and later transistors, gates and flip-flops built ALUs and registers, and the stored-program idea completed the computer.

PORTFOLIO PIECE: A LOGIC-BASED GAME OR INTERLOCK

Design and build a digital logic device from gates and flip-flops (no microcontroller): for example, a two-player "who pressed first" quiz buzzer (two SR latches that lock each other out), a combination lock that lights a green LED only for the right button pattern, or a machine interlock with emergency stop. Write the requirements as a truth table or rule, derive and simplify the Boolean expression, build it from 74HC chips (or transistors), test every case, and document it with schematic, chip and pin numbers, truth table and test record.

LOOK FOR	WHAT IT MEANS
Logic design	Requirements written as a truth table or rule; Boolean expression derived and simplified with work shown.
Build	Chips correctly powered and decoupled, unused inputs tied, every gate traceable to the schematic.
Testing	Every input case tested and recorded, including any forbidden or tricky case (such as simultaneous presses).
Documentation	Schematic with chip and pin numbers, truth table, test record and a paragraph on how it could be improved.

6.1 Boole and Shannon: Logic in Switches

OBJECTIVES

- Tell how George Boole made logic into algebra and how Claude Shannon showed that switching circuits obey it.
- Use Boolean notation (AND, OR, NOT) and the basic laws, including De Morgan's laws, to simplify expressions.
- Translate between switch circuits, Boolean expressions and truth tables.
- Build AND, OR and more complex logic from push buttons and LEDs and verify each truth table.

> **Warm-up.** A car's interior light comes on if the driver's door is open OR the passenger's door is open. A rocket may launch only if fuel is ready AND weather is good AND the range is clear. Write two rules like these from your own house, using the words AND, OR and NOT.

WATCH

The Man Who Should Be As Famous As Einstein

Newsthink · 14:51

https://www.youtube.com/watch?v=0wlmzvf8_gI

> **WHEN TO WATCH**
> After the story. Watch for Shannon's 1937 master's thesis and how it joined Boole's algebra to relay circuits; the later parts on information theory are optional.

Note: A few seconds of archival wartime photographs appear while the narrator describes Shannon's work at Bell Labs in the 1940s; there is nothing graphic.

KEY TERMS

Boolean algebra

Algebra of true and false (1 and 0) with the operations AND (·), OR (+) and NOT (overbar or ′).

AND

$A \cdot B = 1$ only when both A and B are 1. Switches in series.

OR

$A + B = 1$ when A or B (or both) is 1. Switches in parallel.

NOT

$\overline{A}$ is 1 when A is 0, and 0 when A is 1. A normally closed contact, or an inverter.

De Morgan's laws

$\overline{A \cdot B} = \overline{A} + \overline{B}$ and $\overline{A + B} = \overline{A} \cdot \overline{B}$.

CORE IDEAS

The story. George Boole was the son of a shoemaker in Lincoln, England, who could not afford university and taught himself mathematics, Latin and Greek while working as a schoolteacher from the age of sixteen. In 1849 he became the first professor of mathematics at the new Queen's College in Cork, Ireland. In 1854 he published *An Investigation of the Laws of Thought*, in which statements that are true or false are combined by AND, OR and NOT and worked with like algebra. For eighty years it was admired as pure mathematics. Then in 1937 Claude Shannon, a 21-year-old graduate student at MIT who had studied Boole as an undergraduate and had worked on Vannevar Bush's huge mechanical analyzer, wrote a master's thesis showing that circuits of relays and switches obey exactly Boole's algebra.

How they figured it out. Telephone engineers designed relay circuits by trial, intuition and experience, and the circuits were hard to check or simplify. Shannon saw that a contact that is closed or open is just a 1 or 0: two contacts in series conduct only if both are closed (AND), two in parallel if either is (OR), and a normally closed contact is a NOT. So any switching circuit could be written as a Boolean expression, simplified on paper with Boole's laws, and built with fewer relays. He also showed that relays could add binary numbers. His thesis, "A Symbolic Analysis of Relay and Switching Circuits," has been called one of the most important master's theses ever written: it is the foundation of digital circuit design.

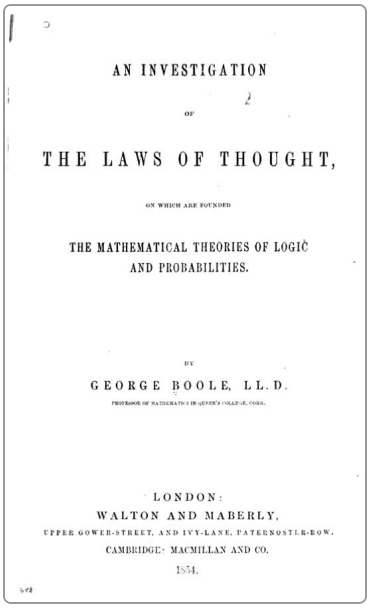
The physics. In a digital circuit, a voltage near 0 V is a 0 and a voltage near the supply is a 1. A wide gap between the two makes the circuit immune to noise, which is why digital systems are so reliable. Boolean algebra has its own laws: $A \cdot 1 = A$, $A + 0 = A$, $A \cdot 0 = 0$, $A + 1 = 1$, $A + \overline{A} = 1$, $A \cdot \overline{A} = 0$, and it is distributive in both directions: $A(B + C) = AB + AC$ and also $A + BC = (A + B)(A + C)$. The most

useful are **De Morgan's laws:** $\overline{AB} = \overline{A} + \overline{B}$ and $\overline{A + B} = \overline{A}\,\overline{B}$. A **truth table** lists every input combination: with n inputs there are 2^n rows.

The engineering. Every safety interlock is Boolean logic: a microwave runs only if the door is closed AND start is pressed; an elevator moves only if the doors are closed AND no emergency stop is pressed. Engineers write the rule, simplify it, and build it from the fewest parts, because fewer parts mean lower cost and fewer failures. Today the logic is usually in a microcontroller's code (Units 7–10) or in programmable logic chips, but the algebra is Boole's.

Try it. In the build you will wire Shannon's switch circuits with push buttons, then design and simplify an interlock and check it against its truth table.

PICTURE STUDY



AN INVESTIGATION

OF

THE LAWS OF THOUGHT,

ON WHICH ARE FOUNDED

THE MATHEMATICAL THEORIES OF LOGIC
AND PROBABILITIES.

BY

GEORGE BOOLE, LL.D.

LONDON:
WALTON AND MABERLY,
UPPER GOWER-STREET, AND IVY-LANE, PATERNOSTER-ROW.
CAMBRIDGE: MACMILLAN AND CO.
1854.

Title Page of The Laws of Thought, George Boole, 1854 · Printed book · Wikimedia Commons

Image: Wikimedia Commons, public domain

This is the title page of Boole's great book. He thought he was describing the laws of human reasoning; he could not know that his algebra would one day run inside every computer.

Look closely

- Read the full title. What two subjects did Boole say his laws were the foundation of?
- Find his name and his position. Where was he teaching?
- Find the date and publisher. What does the plain style of the page suggest about the book?

Talk about it

1. Why might a book about "thought" become the basis of electronic circuits?
2. Boole wrote that he hoped to understand the mind God gave us. How does studying logic connect with honoring truth?
3. What did it take, 83 years later, for Shannon to see the connection to switches?

> **Safety first.** Batteries and USB power only, never wall power. Insert chips the right way round (notch and pin 1) before connecting power, and tie unused CMOS inputs to ground or 5 V.

BUILD

Shannon's Switch Circuits

You will wire AND, OR and NOT from push buttons and an LED, check each truth table, then design, simplify and build a safety interlock and prove that your simplified circuit behaves exactly like the original expression.

You will need

- Four push buttons (or slide switches), a red LED and 220 Ω resistor, a 1 kΩ resistor
- Breadboard, jumpers, Arduino 5 V pin on USB (as a supply) or a 4-AA pack
- Multimeter (continuity mode)

Steps

1. **AND.** Wire 5 V → button A → button B → 220 Ω → LED → ground. Test all four combinations and record the truth table.
2. **OR.** Put buttons A and B in parallel instead. Test and record.
3. **NOT.** Wire 5 V → 220 Ω → LED → ground, with button A connected directly across the LED, so pressing it bypasses the LED. (The resistor protects the supply.) Record: is the LED on when A is 0 or when A is 1?
4. **A three-input rule.** Wire $Y = (A + B)C$: A and B in parallel, in series with C. Write the 8-row truth table first, then test every row.
5. **Design an interlock.** Use Worked Example 3: $M = G(S + R)\overline{E}$. You have no normally closed button, so let E be a button that, when pressed, shorts the LED (like the NOT above). Draw the circuit, predict all 16 rows, and test at least 8 of them.
6. **Simplify and prove.** Show by algebra that $AB + A\overline{B} + \overline{A}B = A + B$ (practice problem 8). Build both versions if you can (the long one needs two-way switches; otherwise compare truth tables) and show they match.
7. Use the meter's continuity mode on each switch network with the LED disconnected to confirm the switch logic directly.

8. **Improve it.** Design a circuit for a two-key safe that opens only if both keys are turned and no alarm button is pressed. Write its expression, simplify it if you can, draw it and build it.

Tips

- Kit push buttons have four legs; the legs on each side are joined in pairs. Use legs on diagonally opposite corners to be sure you get the switch.
- Write the truth table before testing; then testing becomes checking, not guessing.
- If a circuit behaves strangely, test each button alone with continuity mode.

Check your work

- ☐ My AND, OR and NOT circuits matched their truth tables.
- ☐ I translated an expression into a switch circuit and tested every row.
- ☐ I simplified an expression with Boolean algebra and showed the result is equivalent.

ENGINEER'S NOTEBOOK

1. Each circuit drawn as a switch diagram, its Boolean expression and its truth table.
2. Your algebraic simplification, one law per line, with the name of each law.
3. A paragraph: How did an 1854 book about logic become the basis of computers?

KEY FORMULAS

$\overline{A \cdot B} = \overline{A} + \overline{B}$
$\overline{A + B} = \overline{A} \cdot \overline{B}$
$A + AB = A$ (absorption)
rows $= 2^n$

From history. Shannon went on to found information theory in 1948 and defined the bit as the unit of information. He also built a mechanical mouse named Theseus that could learn its way through a maze, one of the first machines that learned.

WORKED EXAMPLES

Example 1. Write the truth table for $Y = A \cdot \overline{B} + C$ (three inputs).

Show solution

1. There are $2^3 = 8$ rows: ABC = 000, 001, 010, 011, 100, 101, 110, 111.
2. $A\overline{B}$ is 1 only when $A = 1$ and $B = 0$ (rows 100 and 101).
3. $Y = 1$ whenever $C = 1$ (rows 001, 011, 101, 111) or $A\overline{B} = 1$ (rows 100, 101).
4. So Y = 0, 1, 0, 1, 1, 1, 0, 1 for the eight rows in order.

Answer: Y = 0, 1, 0, 1, 1, 1, 0, 1

Example 2. Simplify $Y = AB + A\overline{B}$ and explain it with switches.

Show solution

1. Factor: $Y = A(B + \overline{B})$.
2. $B + \overline{B} = 1$, so $Y = A \cdot 1 = A$.
3. With switches: A in series with (B in parallel with not-B). One of B or not-B is always closed, so the circuit conducts exactly when A is closed. Four contacts reduce to one.

Answer: $Y = A$

Example 3. A machine may run (M = 1) only if the guard is closed (G = 1) AND either the start button (S) or the remote signal (R) is on, AND the emergency stop (E) is NOT pressed. Write the expression and its switch circuit.

Show solution

1. Expression: $M = G \cdot (S + R) \cdot \overline{E}$.
2. Circuit: guard switch in series with (start in parallel with remote) in series with the emergency stop's normally closed contact.
3. Check one row: $G = 1$, $S = 0$, $R = 1$, $E = 0$ gives $M = 1 \cdot 1 \cdot 1 = 1$: the machine runs.

Answer: $M = G(S + R)\overline{E}$

PRACTICE

1. Easy How many rows does a truth table with 4 inputs have?

   Show answer

   16

2. Easy Write the truth table for $A + B$.

   Show answer

   00→0, 01→1, 10→1, 11→1

3. Easy What did Shannon show in 1937?

   Show answer

   That relay and switch circuits obey Boolean algebra, so they can be designed and simplified mathematically, and can perform arithmetic.

4. Medium Simplify $A + AB$.

   Show answer

   $A(1 + B) = A$

5. Medium Use De Morgan to rewrite $\overline{A + B}$ and check with the row $A = 1$, $B = 0$.

   Show answer

   $\overline{A}\,\overline{B}$; row: $\overline{1 + 0} = 0$ and $0 \cdot 1 = 0$ ✓

6. Medium Draw (describe) a switch circuit for $Y = (A + B)C$.

   Show answer

   A and B in parallel, that pair in series with C.

7. Medium Why do digital circuits use only two levels instead of ten?

   Show answer

   Two widely separated levels are easy to tell apart even with noise, temperature changes and part variation, so digital signals can be copied and processed without errors.

8. Hard Simplify $Y = \overline{A}B + AB + A\overline{B}$.

   Show answer

   $B(\overline{A} + A) + A\overline{B} = B + A\overline{B} = (B + A)(B + \overline{B}) = A + B$

9. Hard A staircase light must change state when either of two switches is flipped. Write its truth table and Boolean expression. Which gate is this?

Show answer

Light on when the switches differ: 00→0, 01→1, 10→1, 11→0; $Y = A\overline{B} + \overline{A}B$: exclusive OR (XOR).

10. Hard Boole was largely self-taught and his work had no practical use for 80 years. What does that suggest about the value of careful thinking without an immediate use?

Show answer

Ideas pursued for their truth can later become essential; Boole's algebra became the basis of every digital device. Careful, honest work can serve people long after the worker is gone.

11. Challenge A vault opens (V = 1) if the manager (M) and one of two clerks (C_1 or C_2) both use their keys, or if both clerks and the guard (G) use theirs. Write V, give the number of rows in its truth table, and find V for $M = 0$, $C_1 = 1$, $C_2 = 1$, $G = 1$.

Show answer

$V = M(C_1 + C_2) + C_1C_2G$; 16 rows; $V = 0 + 1 \cdot 1 \cdot 1 = 1$.

COMMON MISTAKES

- Confusing OR with "one or the other but not both." Boolean OR includes both; "one but not both" is XOR.
- Writing too few rows: n inputs need 2^n rows.
- Applying ordinary algebra where it fails: in Boolean algebra $A + A = A$, not $2A$.

> **Make it a game · De Morgan Duel.** Simplify against the clock. Your parent writes Boolean expressions on slips of paper and you reduce them using De Morgan's laws and the basic laws in forty-five seconds each. Wrong simplification returns to the stack. Then tell the Boole and Shannon story in thirty seconds. Clear the stack for a record.

> **Scripture.** “But let your communication be, Yea, yea; Nay, nay: for whatsoever is more than these cometh of evil.” (Matthew 5:37, KJV)
>
> Our Lord asks for plain, honest speech: yes meaning yes and no meaning no. A digital signal has the same virtue; there is no doubt what it means.

6.2 Binary and Hexadecimal: Leibniz's Ones and Zeros

OBJECTIVES

- Convert between decimal, binary and hexadecimal, and explain place value in each base.
- Explain bits, bytes, the range of n-bit numbers and why engineers use hexadecimal.
- Add binary numbers and represent negative numbers with two's complement.
- Build a 4-bit binary-to-voltage converter (an R–2R ladder) and check it against $V = V_{\text{ref}} N / 16$.

> **Warm-up.** Count to 31 on one hand, with each finger worth twice the one beside it (thumb 1, index 2, middle 4, ring 8, little 16). Show 5, 12 and 31. What is the largest number on two hands?

WATCH

Understanding Binary, Hexadecimal, Decimal (Base-10), and more

Corey Schafer · 10:43

https://www.youtube.com/watch?v=ZL-LhaaMTTE

> **WHEN TO WATCH**
> After the physics paragraph. Pause after each conversion example and do the next one yourself before watching.

BACKUP VIDEO

Number Systems Introduction - Decimal, Binary, Octal & Hexadecimal

The Organic Chemistry Tutor · 10:57

https://www.youtube.com/watch?v=FFDMzbrEXaE

A full worked introduction to number systems with many examples; use it for review before the practice set.

KEY TERMS

bit

A binary digit, 0 or 1.

byte

Eight bits, which can represent $2^8 = 256$ values (0 to 255).

hexadecimal

Base 16, using digits 0–9 and A–F (A = 10 … F = 15). One hex digit is exactly four bits.

place value

Each position is worth the base raised to a power: in binary 1, 2, 4, 8, 16…; in hex 1, 16, 256, 4096…

two's complement

The standard way to store negative integers: invert every bit and add 1. In 8 bits it covers −128 to +127.

CORE IDEAS

The story. The German mathematician and philosopher Gottfried Wilhelm Leibniz, co-inventor of calculus, worked out binary arithmetic in a manuscript of 1679 and published it in 1703 in his *Explication de l'Arithmétique Binaire*. He was fascinated that every number could be written with only 1 and 0. In a letter of 1697 to Duke Rudolph August of Brunswick he even proposed a medal showing binary as an image of creation: all things made from one, God, and nothing. He also built a mechanical calculating machine. Binary waited 250 years for a use: in the 1930s and 1940s, Shannon, John Atanasoff, Konrad Zuse and others realized it was perfect for switches, relays and tubes, which have just two states.

How they figured it out. Early computers stored numbers in several ways. ENIAC (1945) used decimal counters; others used binary. Binary won because the hardware is simplest and most reliable: each element only needs to be on or off. But long strings of bits are hard for people to read, so engineers grouped them. Octal (base 8, three bits per digit) was common on early machines; IBM's System/360 of 1964, built around 8-bit bytes, made **hexadecimal** (four bits per digit) the standard. Today memory addresses, colors on web pages (#FF8800), error codes and microcontroller registers are all written in hex.

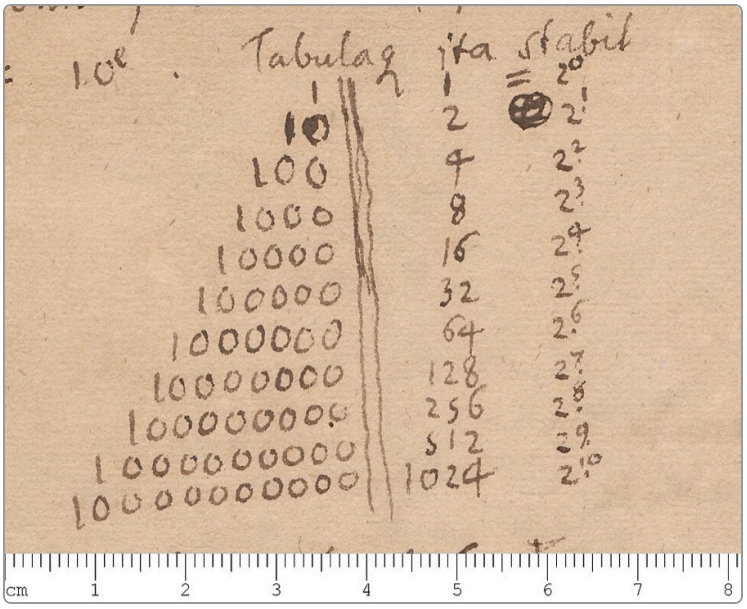
The physics and the mathematics. In decimal, 2026 means $2 \times 1000 + 0 \times 100 + 2 \times 10 + 6$. In binary each place is a power of 2: $101101_2 = 32 + 8 + 4 + 1 = 45$. To convert decimal to binary, subtract the largest powers of 2 (or divide by 2 repeatedly and read the remainders upward). Hex groups bits by four from the right: $10110110_2 = 1011\ 0110 = \mathrm{B6}_{16} = 11 \times 16 + 6 = 182$. An n-bit number holds 2^n values. Binary addition carries just as decimal does: $1 + 1 = 10_2$. Negative numbers in **two's complement**: to get −5 in 8 bits, write 5 =

00000101, invert to 11111010, add 1: 11111011. Adding it to 5 gives 1 00000000, and the ninth bit falls off, leaving 0.

The engineering. A microcontroller converts between the analog world and binary all the time. An Arduino's analog input (Lesson 7.4) turns 0–5 V into a 10-bit number, 0 to 1023; its PWM output (Lesson 7.5) uses an 8-bit number, 0 to 255. A **digital-to-analog converter** does the reverse: the R–2R resistor ladder you will build adds currents weighted 8, 4, 2, 1, so that its output voltage is proportional to the binary number set by its inputs. Engineers choose the number of bits by the precision needed: each extra bit doubles the resolution.

Try it. You will set binary numbers with jumper wires and read them out as voltages, turning ones and zeros into a measurable quantity.

PICTURE STUDY



Leibniz's Table of Binary Place Values, Gottfried Wilhelm Leibniz, about 1697–1703 · Manuscript · Wikimedia Commons

Image: Wikimedia Commons, public domain

This manuscript page in Leibniz's hand sets binary place values beside their decimal values and the powers of two. In the same years he wrote to the Duke of Brunswick suggesting a medal that would show binary as a picture of creation from nothing.

Look closely

- Find the column of binary numbers. How does each differ from the one above it?
- Find the decimal values beside them. Check three rows.
- Find the powers of two written as 2 with a small raised number. How do they match the binary column?
- Find the ruler along the bottom. Why would an archive photograph a page with a ruler?

Talk about it

1. Why might Leibniz think binary was beautiful even with no practical use?
2. What would the next three rows of Leibniz's table be?
3. How would Leibniz have reacted to a computer?

> **Safety first.** Batteries and USB power only, never wall power. Insert chips the right way round (notch and pin 1) before connecting power, and tie unused CMOS inputs to ground or 5 V.

BUILD

A 4-Bit Binary-to-Voltage Converter

You will build an R–2R resistor ladder, set 4-bit binary numbers with jumper wires, measure the output voltage for all 16 numbers, graph it, and see binary turned into a proportional analog voltage.

You will need

- Eight 10 kΩ resistors and one more (or use 20 kΩ resistors for the "2R" values: two 10 kΩ in series make 20 kΩ)
- Breadboard, jumpers, Arduino 5 V pin on USB (or a 4-AA pack with a 5 V regulator from Lesson 5.4)
- Digital multimeter
- Four LEDs with 1 kΩ resistors (optional, to display the bits)

Steps

1. Draw the 4-bit R–2R ladder: each bit input connects through a 2R (20 kΩ) resistor to a node on a chain of R (10 kΩ) resistors; the least significant end has a 2R to ground; the output is at the most significant node. (Look up "R–2R ladder" schematic to check your drawing.)
2. Build it. Each bit input is a jumper you can move to 5 V (bit = 1) or to ground (bit = 0).
3. Make a table of all 16 numbers (0000 to 1111) with decimal value, hex digit and predicted voltage $V = 5.0 \times N/16$.
4. Measure the output for every number and record it.
5. Graph measured voltage against N. Draw the best-fit line. Is it straight? What is the slope (volts per step)?
6. Find the step with the largest error and explain it (resistor tolerance, the supply voltage, the meter's loading).
7. Optional: add an LED with 1 kΩ to each bit input so the binary number shows as lights while you measure. Check whether the LEDs change the ladder's voltages (they load the inputs, not the output).

8. **Improve it.** Explain how many bits you would need to make steps smaller than 10 mV from 5 V, and how many resistors that ladder would use.

Tips

- Measure the actual 5 V supply and use it in your predictions.
- Use resistors from the same batch, and measure them; matched resistors make a straighter line.
- The order matters: the bit nearest the output is the most significant (worth 8).

Check your work

- ☐ I converted all 16 four-bit numbers to decimal and hex.
- ☐ My measured voltages fell on a straight line within a few percent.
- ☐ I can explain how an R–2R ladder turns binary into a voltage.

ENGINEER'S NOTEBOOK

1. The R–2R schematic and your 16-row table.
2. The graph of output voltage against N with the best-fit line and slope.
3. A conversion chart: decimal 0–31 in binary and hex, written from memory.

KEY FORMULAS

$N = \sum b_k \, 2^k$

range of n bits $= 0$ to $2^n - 1$

$V_{\text{out}} = V_{\text{ref}} \dfrac{N}{2^n}$ (R–2R ladder)

$-x = \overline{x} + 1$ (two's complement)

From history. Konrad Zuse in Berlin completed the Z3 in 1941, a programmable binary computer built from about 2,600 relays and using binary floating-point numbers. John Atanasoff and Clifford Berry at Iowa State built a binary electronic calculator around the same time.

WORKED EXAMPLES

Example 1. Convert 200 to binary and hexadecimal.

Show solution

1. Powers of 2: 128, 64, 32, 16, 8, 4, 2, 1. $200 - 128 = 72$; $72 - 64 = 8$; $8 - 8 = 0$.
2. So 200 = 128 + 64 + 8: bits 1100 1000.
3. Hex: 1100 = C, 1000 = 8, so C8. Check: $12 \times 16 + 8 = 200$.

Answer: $11001000_2 = \mathrm{C8}_{16}$

Example 2. Add $1011_2 + 0110_2$ in binary and check in decimal. Then write −6 in 8-bit two's complement.

Show solution

1. Right to left: 1 + 0 = 1; 1 + 1 = 10 (write 0, carry 1); 0 + 1 + 1 = 10 (write 0, carry 1); 1 + 0 + 1 = 10 (write 0, carry 1); carry 1.
2. Result: $10001_2 = 17$. Check: $11 + 6 = 17$.
3. −6: 6 = 00000110; invert: 11111001; add 1: 11111010.

Answer: $10001_2 = 17$; −6 = 11111010

Example 3. A 4-bit R–2R ladder runs from 5.0 V. What output voltage do the inputs 1011 give? What is the smallest step?

Show solution

1. $N = 1011_2 = 11$.
2. $V = 5.0 \times 11/16 = 3.44\ \mathrm{V}$.
3. Step: $5.0/16 = 0.3125\ \mathrm{V}$.

Answer: 3.44 V; steps of 0.31 V

PRACTICE

1. Easy Convert 11001_2 to decimal.

Show answer

25

2. **Easy** Convert 45 to binary.

   Show answer

   101101

3. **Easy** How many values can 16 bits represent?

   Show answer

   65,536

4. **Medium** Convert 0xA7 and 0x1F4 to decimal.

   Show answer

   167; 500

5. **Medium** Convert 1000 to hexadecimal.

   Show answer

   0x3E8

6. **Medium** A web color is #3F00FF. Give the red, green and blue values in decimal.

   Show answer

   Red 63, green 0, blue 255

7. **Medium** Add $1101_2 + 1011_2$.

   Show answer

   11000_2 (13 + 11 = 24)

8. **Hard** Write −1 and −128 in 8-bit two's complement. What is the range of 8-bit signed numbers?

   Show answer

   −1 = 11111111; −128 = 10000000; range −128 to +127.

9. **Hard** An 8-bit DAC runs from 5.0 V. What is its step size, and what input gives about 2.0 V?

   Show answer

   Step $5.0/256 = 19.5$ mV; $N = 2.0/0.0195 = 102$, binary 01100110 (102 gives 1.99 V).

10. Hard Leibniz saw binary as a picture of creation from nothing. Explain the picture in your own words, and why binary is a good fit for switches.

Show answer

Every number can be built from 1 and 0 alone, as Leibniz pictured all things made by God from nothing. Switches, relays and transistors naturally have two states, so binary needs only on and off and is reliable.

11. Challenge Convert 2026 to binary and to hex, and find how many bits are needed to store any year up to 9999.

Show answer

2026 = 11111101010₂ = 0x7EA; $2^{13} = 8192 < 9999 < 2^{14}$, so 14 bits.

COMMON MISTAKES

- Reading binary from the wrong end. The rightmost bit is worth 1.
- Grouping hex digits from the left instead of the right: group four bits starting at the right.
- Forgetting the carry in binary addition: $1 + 1 = 10_2$, write 0 and carry 1.

Make it a game · Hex and Binary Blitz. Conversion speed round. Your parent calls a decimal number from 0 to 255. You say it in binary and hexadecimal within fifteen seconds. Then call the range of an n-bit number for n = 8 and n = 12. Two's complement bonus: write minus five in four bits. Beat your streak.

Scripture. “He telleth the number of the stars; he calleth them all by their names. Great is our Lord, and of great power: his understanding is infinite.” (Psalm 147:4-5, KJV)

We need clever notations to count even to a billion. The Lord numbers the stars and names each one.

6.3 Logic Gates and Truth Tables

OBJECTIVES

- Draw the symbols and write the truth tables of NOT, AND, OR, NAND, NOR, XOR and XNOR.
- Explain how gates are built from transistors, and why NAND and NOR are universal.
- Design a combinational circuit from a truth table using sum-of-products.
- Build gates from transistors and with a 74HC00, and build a half adder from NAND gates.

> **Warm-up.** Write a rule for a game: “You score a point if exactly one of us says yes.” What should happen if both say yes? If neither does? Make a four-row table. You have just written a truth table for a gate.

WATCH

Making logic gates from transistors

Ben Eater · 13:01

https://www.youtube.com/watch?v=sTu3LwpF6XI

> **WHEN TO WATCH**
> After the physics paragraph, before the build. Ben Eater builds real gates from transistors on a breadboard; watch the NOT, AND and OR sections closely, since you will build them too.

BACKUP VIDEO

Understanding Logic Gates

Spanning Tree · 7:27

https://www.youtube.com/watch?v=INEtYZqtjTo

A clear animated review of every gate and its truth table.

KEY TERMS

logic gate

A circuit that produces a digital output from one or more digital inputs by a fixed rule.

NAND / NOR

NOT-AND and NOT-OR. Each is universal: every other gate can be built from NANDs alone, or from NORs alone.

XOR

Exclusive OR: 1 when the inputs differ. $A \oplus B = A\overline{B} + \overline{A}B$.

sum of products

A way to write any truth table: OR together one AND term for each row whose output is 1.

half adder

A circuit that adds two bits: sum $= A \oplus B$, carry $= AB$.

CORE IDEAS

The story. The Apollo Guidance Computer, which helped guide astronauts to the Moon in 1969, was built entirely from one kind of chip: a pair of three-input NOR gates, made of a few transistors and resistors each. MIT's Instrumentation Laboratory chose a single, simple gate so that every chip could be tested exhaustively and trusted, and because NOR alone can build any logic. A few years earlier, in the mid-1960s, Texas Instruments had introduced the 7400 family of logic chips, starting with the 7400 quad NAND gate. Engineers built computers, test instruments and industrial controls from boards full of these chips for decades, and their descendants, such as the 74HC00 in this lesson, are still made.

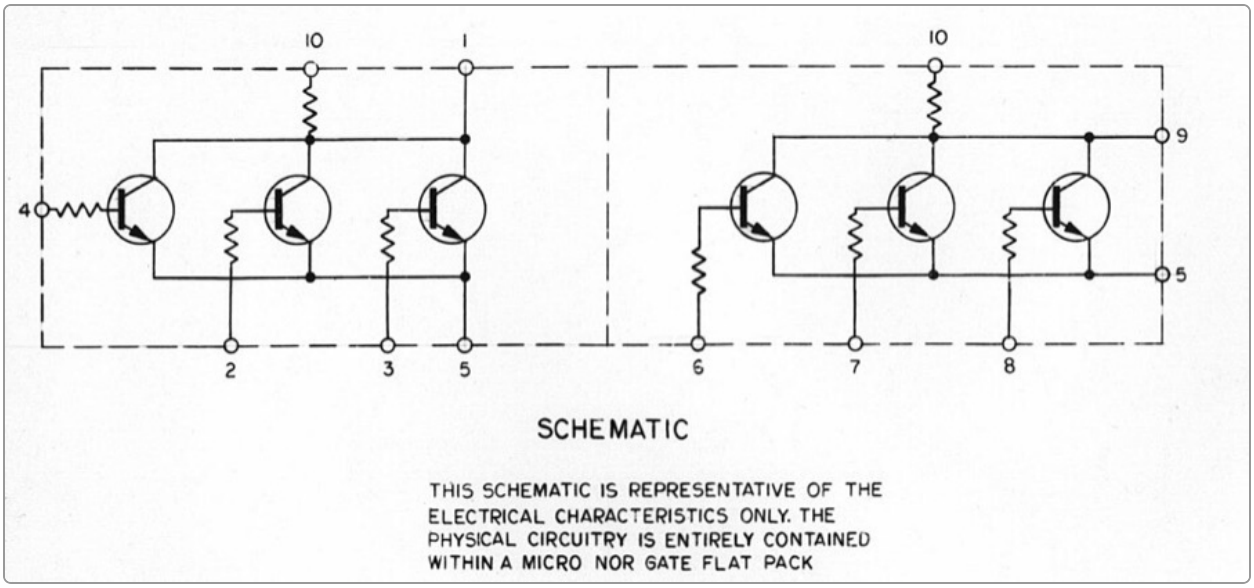
How they figured it out. Early gates were built from relays, then diodes and resistors, then transistors. Engineers found that the simplest transistor gate is an inverter: an NPN switch with a resistor to the supply. When the input is high, the transistor saturates and pulls the output low; when the input is low, the resistor pulls the output high. Put two transistors in parallel and you have NOR; in series, NAND. Because NAND and NOR are the simplest gates to build, designers built everything from them, using De Morgan's laws to convert any design. Modern CMOS gates use pairs of N- and P-channel MOSFETs, so they draw almost no current except while switching.

The physics. The gates: **NOT** inverts; **AND** is 1 only if all inputs are 1; **OR** is 1 if any input is 1; **NAND** is 0 only if all inputs are 1; **NOR** is 1 only if all inputs are 0; **XOR** is 1 if the inputs differ; **XNOR** is 1 if they are the same. Any truth table can be built as a **sum of products**: for each row with output 1, write an AND term of the inputs (inverting those that are 0), then OR the terms. XOR, for example, is 1 in rows 01 and 10: $Y = \overline{A}B + A\overline{B}$. Real gates take a few nanoseconds to respond (propagation delay), and those delays add up through a chain of gates, which limits how fast a circuit can run.

The engineering. Engineers choose a logic family by speed, power and voltage: 74HC (CMOS, 2–6 V, low power), 74HCT (works with older 5 V TTL levels), 74LVC (3.3 V and below). They check the output current (enough for an LED with a resistor, about 4–20 mA), tie unused inputs high or low, put a 0.1 µF decoupling capacitor at every chip, and count the gates in a design to choose the fewest chips. Today large logic designs go into programmable chips (FPGAs) or microcontroller code, but every one of them is built from the gates in this lesson.

Try it. You will build an inverter and a NOR gate from transistors, as Apollo's chips were built, and a half adder from a single 74HC00 chip.

PICTURE STUDY



Schematic of an Apollo NOR-Gate Chip, MIT Instrumentation Laboratory, 1960s · Engineering drawing · Wikimedia Commons

Image: Wikimedia Commons, public domain

This schematic shows what is inside each flat-pack chip of the Apollo Guidance Computer: two three-input NOR gates, each made of three transistors in parallel with a shared resistor to the supply. The note says the drawing shows the electrical behavior only; the parts themselves are inside one small package.

Look closely

- Find the two identical halves. Each half is one gate.
- In one half, find the three transistors. Are they in series or in parallel?
- Find the resistor that pulls the output up toward the supply.
- Find the numbered pins. Which ones are the inputs, and which is the output?

Talk about it

1. If any one input is high, what happens to the output? Why does that make this a NOR gate?
2. Why would NASA's engineers want every chip in the computer to be the same?
3. How would you build an inverter from this chip?

> **Safety first.** Batteries and USB power only, never wall power. Insert chips the right way round (notch and pin 1) before connecting power, and tie unused CMOS inputs to ground or 5 V.

BUILD

Gates from Transistors and a NAND Half Adder

You will build an inverter and a two-input NOR gate from NPN transistors and resistors, like the Apollo chips, check their truth tables and voltages, then build every basic gate and a half adder from 74HC00 NAND gates.

You will need

- Two NPN transistors (2N2222 or 2N3904), resistors 1 kΩ (two), 10 kΩ (four), 220 Ω (two), two red LEDs
- Two 74HC00 chips (or one, plus the CircuitVerse simulator), 0.1 µF capacitors
- Two push buttons with 10 kΩ pull-down resistors
- Breadboard, jumpers, Arduino 5 V on USB, multimeter

Steps

1. **Transistor inverter.** Input → 10 kΩ → base; emitter → ground; collector → 1 kΩ → 5 V; output at the collector. Drive the input with a button (and a 10 kΩ pull-down). Measure the output voltage for input 0 and 1 and record the truth table.
2. **Transistor NOR.** Add a second transistor with its own 10 kΩ base resistor and button, collector and emitter in parallel with the first. Test all four input combinations and record the output voltages.
3. Show the output with an LED: connect the output through 220 Ω to an LED to ground. Notice that the LED dims the high output, because the 1 kΩ pull-up is weak (practice problem 8).
4. **NAND chip.** Place the 74HC00 (notch left), power pin 14 and ground pin 7, 0.1 µF across them, and tie unused inputs to ground. Test gate 1 with the two buttons and an LED (through 220 Ω) on its output.
5. Build NOT, AND and OR from NAND gates (Worked Example 1), testing each truth table.
6. **Half adder.** Build XOR from four NANDs (look up the standard four-NAND XOR, or derive it) for the sum, and use one more NAND as an inverter on the

first NAND's output for the carry. Use two LEDs for sum and carry. Test all four input pairs.

7. Record each output voltage for a 1 and a 0. Compare with the 74HC datasheet's guaranteed output levels.
8. **Improve it.** In the CircuitVerse simulator, join two half adders and an OR gate into a full adder, then four full adders into a 4-bit adder. Test 1011 + 0110 and compare with your Lesson 6.2 answer.

Tips

- Label every gate on your schematic with its chip and pin numbers before wiring.
- If a NAND output is stuck, check that pin 14 has 5 V and pin 7 has ground.
- Build and test one gate at a time; then a fault is always in the newest part.

Check your work

- ☐ My transistor inverter and NOR gate matched their truth tables.
- ☐ I built NOT, AND, OR and XOR from NAND gates.
- ☐ My half adder adds two bits correctly, and I simulated a 4-bit adder.

ENGINEER'S NOTEBOOK

1. Truth tables and symbols for all seven gates.
2. The transistor gate schematics with measured output voltages.
3. The NAND-only half adder schematic with chip and pin numbers.
4. The sum-of-products design for the majority rule, drawn as gates.

KEY FORMULAS

$A \oplus B = A\overline{B} + \overline{A}B$

NOT $A = \overline{A \cdot A}$ (NAND with inputs joined)

$A \cdot B = \overline{\overline{A \cdot B}}$

$A + B = \overline{\overline{A} \cdot \overline{B}}$

From history. The 7400 quad NAND was so common that engineers still refer to the whole family of logic chips by the "74" prefix. The 74181 of 1970 put a complete 4-bit arithmetic logic unit on one chip and was used in many minicomputers of the 1970s.

Example 1. Show how to make AND, OR and NOT from NAND gates only.

Show solution

1. NOT: join a NAND's inputs: $\overline{A \cdot A} = \overline{A}$.
2. AND: a NAND followed by a NOT (a second NAND with joined inputs): $\overline{\overline{AB}} = AB$.
3. OR: invert each input with a NAND, then NAND them: $\overline{\overline{A}\,\overline{B}} = A + B$ by De Morgan.

Answer: NOT = 1 NAND; AND = 2 NANDs; OR = 3 NANDs

Example 2. Design a circuit for a three-input majority rule: Y = 1 when at least two of A, B, C are 1. Simplify.

Show solution

1. Rows with Y = 1: 011, 101, 110, 111.
2. Sum of products: $Y = \overline{A}BC + A\overline{B}C + AB\overline{C} + ABC$.
3. Simplify: $Y = AB + AC + BC$ (each pair; check row 111 is covered by all three terms, and each two-1 row by exactly one).

Answer: $Y = AB + BC + AC$

Example 3. Each 74HC gate has a propagation delay of about 10 ns. A signal passes through 4 gates. What is the total delay, and roughly the highest rate at which the circuit can produce new results?

Show solution

1. Total delay: $4 \times 10 = 40$ ns.
2. New results at most every 40 ns: $f = 1/(40 \times 10^{-9}) = 25$ MHz.

Answer: 40 ns; about 25 MHz

PRACTICE

1. **Easy** Write the truth table of NAND.

   Show answer

   00→1, 01→1, 10→1, 11→0

2. **Easy** Write the truth table of XOR.

   Show answer

   00→0, 01→1, 10→1, 11→0

3. **Easy** What single kind of gate was the Apollo Guidance Computer built from?

   Show answer

   Three-input NOR gates (two per chip).

4. **Medium** Show that NOR is universal by making NOT and OR from NORs.

   Show answer

   NOT: NOR with inputs joined. OR: NOR followed by a NOR-inverter.

5. **Medium** Write the sum of products for the truth table 00→1, 01→0, 10→0, 11→1. What gate is it?

   Show answer

   $\overline{A}\,\overline{B} + AB$: XNOR.

6. **Medium** A half adder adds A = 1 and B = 1. What are the sum and carry?

   Show answer

   Sum 0, carry 1 ($1 + 1 = 10_2$).

7. **Medium** Why must unused inputs on a CMOS chip be tied to ground or VCC?

   Show answer

   Floating inputs can drift to an in-between voltage, causing random switching, oscillation and extra current draw.

8. Hard A transistor inverter uses a 1 kΩ collector resistor on 5 V and drives an LED input of a following gate. When the output is high, what limits the current it can supply? When low?

   Show answer

   High: the 1 kΩ pull-up limits it to a few mA. Low: the saturated transistor can sink much more. That is why simple RTL outputs pull down strongly but up weakly.

9. Hard How many 74HC00 chips (4 NAND gates each) does a half adder need, if XOR takes 4 NANDs and the carry (AND) takes 2? Could one gate be shared?

   Show answer

   6 NANDs = 2 chips; but the first NAND of the XOR circuit already computes $\overline{AB}$, so the carry needs only one more NAND (an inverter): 5 NANDs, still 2 chips.

10. Hard Design a circuit with inputs A, B and C whose output is 1 only when exactly one input is 1. Write the sum of products.

    Show answer

    $Y = A\overline{B}\,\overline{C} + \overline{A}B\overline{C} + \overline{A}\,\overline{B}C$

11. Challenge The AGC had about 5,600 NOR gates. If each gate's delay was 20 ns and the longest path through its logic was about 12 gates, what was the fastest that path could settle? The AGC's clock was about 1 MHz (1 µs per step); was the logic fast enough?

    Show answer

    $12 \times 20 = 240$ ns, less than 1 µs, so yes, with margin.

COMMON MISTAKES

- Forgetting the chip's power pins.
- Confusing NAND with AND or NOR with OR: the small circle (bubble) on the output means NOT.
- Building the whole circuit before testing any part of it.

Make it a game · Truth Table Draw. Beat the clock. Draw the symbol and truth table for each gate: NOT, AND, OR, NAND, NOR, XOR, XNOR, from memory in two minutes. Your parent checks every row. Then explain why NAND is universal by building NOT from NAND on paper. Record your time and aim to cut it.

6.4 Flip-Flops and Counters: Memory from Gates

OBJECTIVES

- Explain how feedback lets two gates remember one bit, in an SR latch.
- Describe D flip-flops, clocks, edge triggering and shift registers.
- Explain how a chain of toggle flip-flops counts in binary and divides frequency by powers of 2.
- Build an SR latch from NAND gates and use a 74HC595 shift register to store and display bits.

> **Warm-up.** Press a light switch on and walk away: the light stays on. Press a doorbell and let go: the bell stops. One remembers and one does not. List two other things in your house that remember a setting and two that do not.

WATCH

SR latch

Ben Eater · 12:58

https://www.youtube.com/watch?v=KM0DdEaY5sY

> **WHEN TO WATCH**
> After the physics paragraph. Ben Eater builds an SR latch; pause after each input change and predict the output before he shows it.

BACKUP VIDEO

How Flip Flops Work - The Learning Circuit

element14 presents · 9:03

https://www.youtube.com/watch?v=Hi7rK0hZnfc

A short element14 overview of the main flip-flop types; good review for the test.

KEY TERMS

latch

A circuit with two stable states that remembers one bit. An SR latch has Set and Reset inputs.

flip-flop

A clocked memory element. A D flip-flop copies its D input to its output Q at the moment the clock rises (the rising edge) and holds it until the next edge.

clock

A steady square wave that tells the parts of a digital system when to change, so they change together.

shift register

A chain of flip-flops that passes bits along one place on each clock pulse, such as the 74HC595.

counter

A chain of flip-flops that counts clock pulses in binary; each stage divides the frequency by 2.

CORE IDEAS

The story. In 1918 two British physicists, William Eccles and F. W. Jordan, patented a "trigger relay" made of two vacuum tubes, each feeding its output to the other's input, so that the pair stayed in one state until a pulse flipped it to the other. They had invented the **flip-flop**. For twenty years it was a laboratory curiosity. Then in the 1940s it became the memory of the first electronic computers. ENIAC, completed at the University of Pennsylvania in 1945 for the U.S. Army, used about 18,000 vacuum tubes, a large share of them in flip-flop circuits wired into decimal counters, to add five thousand numbers a second, a thousand times faster than relay machines.

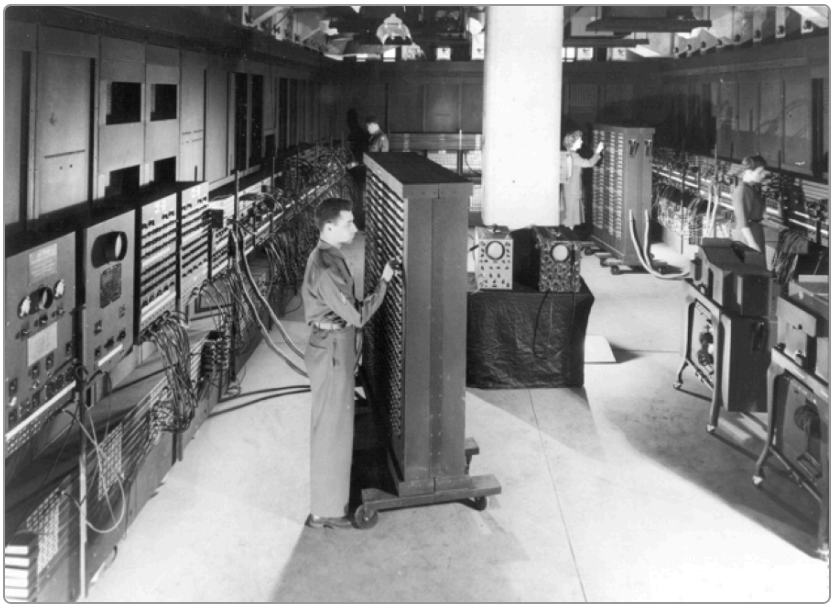
How they figured it out. The secret of memory is **feedback**. A gate by itself forgets: its output follows its inputs. But connect two inverting gates so that each one's output drives the other's input, and the pair has two stable states, like a light switch that rests in either position. A short pulse on one input knocks it into the other state, where it stays after the pulse ends. Later designers added a **clock**, so that thousands of flip-flops would all change at the same instant, avoiding the races and glitches that came from gates changing at slightly different times.

The physics. An **SR latch** made of two NAND gates has active-low inputs $\overline{S}$ and $\overline{R}$. Pulling $\overline{S}$ low makes Q = 1; pulling $\overline{R}$ low makes Q = 0; with both high, the latch holds its last state. (Both low is forbidden: both outputs go high, and the final state is unpredictable.) A **D flip-flop** samples its D input only at the rising edge of the clock. Chain D flip-flops output to input and you have a **shift register**: each clock pulse moves every bit one place along. Connect a flip-flop's inverted output back to its own D input and it **toggles** on every clock, dividing the frequency by 2; a chain of n toggles counts from 0 to $2^n - 1$ in binary and divides the clock by 2^n.

The engineering. Every register in a processor, every bit of fast cache memory, and every counter and timer inside a microcontroller is built from flip-flops. Engineers design synchronous systems in which all flip-flops share one clock, and they make sure signals settle (the gate delays of Lesson 6.3) before the next clock edge; that is what limits a chip's clock speed. Buttons need special care: a mechanical contact bounces open and closed several times in the first few milliseconds, which a flip-flop would count as several presses, so engineers **debounce** them with an SR latch, an RC filter or code.

Try it. You will build a one-bit memory from two NAND gates, then use a 74HC595 shift register to store a byte and display it on eight LEDs.

PICTURE STUDY



The ENIAC, U.S. Army photograph, about 1946 · Photograph · U.S. Army

Image: Wikimedia Commons, public domain

ENIAC filled a room about 30 by 50 feet, weighed about 30 tons and used about 18,000 vacuum tubes. Its counters were made of flip-flops, and its programs were set up by plugging cables and turning switches, a job done by a team of mathematicians, among them six women who became the first programmers of an electronic computer.

Look closely

- Find the cables plugged into the panels. What do you think they connect?
- Look for rows of small lights. What could they show about the flip-flops inside?
- Find the people in the picture. How big is the machine compared with them?
- Count how many panels you can see. What would happen if one tube failed?

Talk about it

1. ENIAC's flip-flops were pairs of vacuum tubes. How many transistors would a modern flip-flop use, and how small is it?
2. Why would setting up a program by plugging cables be slow? What idea replaced it?

3. Why would scientists and engineers in 1945 want a machine that could compute tables a thousand times faster than a person with a desk calculator?

Safety first. Batteries and USB power only, never wall power. Insert chips the right way round (notch and pin 1) before connecting power, and tie unused CMOS inputs to ground or 5 V.

BUILD

One-Bit Memory and a Shift Register Display

You will build an SR latch from two NAND gates and see it remember, use it to debounce a button, then load bytes into a 74HC595 shift register by hand, one clock pulse at a time, and watch the bits march across eight LEDs.

You will need

- A 74HC00 quad NAND chip and a 74HC595 shift register (in many starter kits), 0.1 µF capacitors
- Three push buttons, three 10 kΩ pull-up resistors, nine LEDs with 220 Ω (or 330 Ω) resistors
- Breadboard, jumpers, Arduino 5 V on USB, multimeter

Steps

1. **SR latch.** Use two NANDs of the 74HC00: gate A's output (Q) goes to one input of gate B; gate B's output ($\overline{Q}$) goes to one input of gate A. The other input of A is $\overline{S}$, and of B is $\overline{R}$. Each has a 10 kΩ pull-up to 5 V and a button to ground. Put LEDs (with resistors) on Q and $\overline{Q}$.
2. Test: press and release S, then R, then S twice, then R twice. Record Q after each. Show that a second press of S changes nothing (it already remembers 1).
3. Try pressing both together, then releasing them at slightly different times. Record what happens and explain why it is forbidden.
4. **74HC595.** From the datasheet, wire VCC (16) and GND (8), 0.1 µF across them, OE (13) to ground, SRCLR (10) to 5 V, and LEDs with resistors on outputs QA–QH (pins 15, 1–7).
5. Connect SER (14, the data input) to a jumper you can move between 5 V and ground. Connect SRCLK (11, shift clock) and RCLK (12, latch clock) each to a button with a 10 kΩ pull-down (button to 5 V).
6. Load a byte: set SER, press SRCLK once; repeat for eight bits; then press RCLK once to copy the shifted bits to the outputs. Load 10110010 and check the LEDs against Worked Example 3.

7. Notice bounce: sometimes one press of SRCLK shifts two places. Count how often in 20 presses. Then debounce the clock button with your SR latch (one button sets it, a second resets it) or with a 1 µF capacitor across the button, and count again.
8. **Improve it.** In Unit 7 an Arduino will do this loading in microseconds. For now, write out the exact sequence of SER values and clock presses that would make a single lit LED move from QA to QH, and test it.

Tips

- Pins on the 74HC595 are easy to misnumber; mark pin 1 on your layout and count counterclockwise.
- If no LEDs light, check OE (pin 13) is low and SRCLR (pin 10) is high.
- Shift-register outputs can supply about 6 mA each comfortably; use 330 Ω or higher if many LEDs are on.

Check your work

- ☐ My SR latch remembered set and reset, and I can explain the forbidden state.
- ☐ I loaded a chosen byte into a 74HC595 by hand and it displayed correctly.
- ☐ I observed switch bounce, measured how often it happened, and reduced it.

ENGINEER'S NOTEBOOK

1. The SR latch schematic and a table of inputs and Q for your test sequence.
2. The 74HC595 wiring diagram with pin numbers.
3. A timing diagram: clock pulses, the data bits and the eight outputs after each pulse.
4. Your bounce counts before and after debouncing.

KEY FORMULAS

$$f_{\text{out}} = \frac{f_{\text{clock}}}{2^n} \text{ (n toggle stages)}$$

$$\text{count range} = 0 \text{ to } 2^n - 1$$

$$f_{\max} \approx \frac{1}{t_{\text{delay, longest path}}}$$

From history. ENIAC's programmers, among them Kathleen McNulty, Jean Jennings, Betty Snyder, Marlyn Wescoff, Frances Bilas and Ruth Lichterman, set up its problems by working out the wiring from the machine's diagrams. Their work was little known for decades and is now remembered as the beginning of computer programming.

WORKED EXAMPLES

Example 1. A NAND SR latch starts with Q = 0. The inputs go: $\overline{S}$ low briefly, then both high, then $\overline{R}$ low briefly, then both high. Give Q after each step.

Show solution

1. $\overline{S}$ low: the latch is set, Q = 1.
2. Both high: hold, Q stays 1.
3. $\overline{R}$ low: reset, Q = 0.
4. Both high: hold, Q stays 0.

Answer: Q = 1, 1, 0, 0

Example 2. A 4-stage binary counter is clocked at 1.0 Hz. What is the frequency of the last stage, and what number does it show after 11 pulses (starting from 0)?

Show solution

1. Each stage halves: $1.0/2^4 = 0.0625$ Hz, one cycle every 16 s.
2. After 11 pulses the count is $11 = 1011_2$: Q3 = 1, Q2 = 0, Q1 = 1, Q0 = 1.

Answer: 0.0625 Hz; 1011

Example 3. A 74HC595 shift register receives the bits 1, 0, 1, 1, 0, 0, 1, 0 (first bit first), one per clock pulse. After eight pulses, which bit is in the last stage (QH), and which in the first (QA)?

Show solution

1. Each new bit enters QA and pushes the others along.
2. After eight pulses, the first bit sent (1) has moved all the way to QH, and the last bit sent (0) is in QA.
3. So QA…QH = 0, 1, 0, 0, 1, 1, 0, 1.

Answer: QH = 1 (the first bit), QA = 0 (the last bit)

PRACTICE

1. Easy What makes a latch able to remember?

   Show answer

   Feedback: each gate's output drives the other's input, giving two stable states.

2. Easy Who invented the flip-flop, and when?

   Show answer

   William Eccles and F. W. Jordan, 1918.

3. Easy How many states can an 8-bit counter count through?

   Show answer

   256 (0 to 255).

4. Medium A 1 MHz clock drives a 10-stage counter. What frequency comes out of the last stage?

   Show answer

   $10^6/1024 \approx 977$ Hz

5. Medium Why is $\overline{S} = \overline{R} = 0$ forbidden in a NAND latch?

   Show answer

   Both outputs are forced high, so Q and its complement are no longer opposite, and when the inputs are released the final state is unpredictable.

6. Medium What does a D flip-flop do at the rising edge of its clock?

Show answer

It copies the D input to Q and holds it until the next rising edge.

7. Medium Why do mechanical buttons need debouncing?

Show answer

Their contacts bounce open and closed several times in the first few milliseconds, which digital circuits would see as several presses.

8. Hard How many flip-flops are needed to count to at least 1,000? To divide a 32,768 Hz watch crystal down to 1 Hz?

Show answer

10 (counts 0–1023); 15, since $2^{15} = 32{,}768$.

9. Hard ENIAC added about 5,000 numbers a second. A modern core does about 10^{10} simple operations a second. How many times faster is that?

Show answer

$10^{10} / 5000 = 2 \times 10^6$: two million times.

10. Hard A design's longest gate path is 6 gates of 8 ns each, plus 5 ns for the flip-flop's setup. What is the fastest safe clock?

Show answer

$6 \times 8 + 5 = 53$ ns; $f \approx 1/53$ ns $= 19$ MHz

11. Challenge Two 74HC595s are chained to drive 16 LEDs. How many clock pulses load a new pattern? If the clock runs at 1 MHz, how long does that take, and could you update the display 1,000 times a second?

Show answer

16 pulses (plus one latch pulse); about 16 µs; yes, 1,000 updates need only 16 ms of every second.

COMMON MISTAKES

- Forgetting to pulse the latch clock (RCLK) after shifting, so the outputs never change.
- Misnumbering the shift register's pins.
- Counting a bounced button press as one press.

> **Make it a game · Latch Acting.** Two players act as the two gates of an SR latch, each looking at the other's output. Practice the set and reset commands and show how the bit is remembered. Then explain what a clock edge does in a D flip-flop. Your parent calls the inputs and you give the outputs. Longest streak wins.

6.5 From Gates to a Computer: Babbage, Lovelace and the CPU

OBJECTIVES

- Tell the story of Babbage's Difference and Analytical Engines and Ada Lovelace's notes.
- Use the method of differences, as Babbage's engine did, to compute a table.
- Describe a stored-program computer: memory, registers, ALU, control unit, bus and the fetch–decode–execute cycle.
- Run a short program by hand on a paper computer and build an adder-based ALU in a simulator.

> **Warm-up.** Write the squares 1, 4, 9, 16, 25, 36. Under them, write the differences between neighbors. Under those, write the differences again. What do you notice? Babbage built a machine on that pattern.

WATCH

False Dawn: The Babbage Engine

Computer History Museum · 5:38

https://www.youtube.com/watch?v=XSkGY6LchJs

> **WHEN TO WATCH**
> At the start, after the warm-up. Watch the Difference Engine at work and notice how it turns cranks into a table of numbers.

BACKUP VIDEO

The Engineering that Runs the Digital World 🛠️⚙️💻 How do CPUs Work?

Branch Education · 36:23

https://www.youtube.com/watch?v=16zrEPOsIcI

Branch Education's long, beautifully animated tour of how a modern processor and computer work; watch the CPU sections after the physics paragraph.

KEY TERMS

method of differences

Computing a polynomial table using only addition, because the nth differences of an nth-degree polynomial are constant.

Analytical Engine

Babbage's design (from 1834) for a general-purpose mechanical computer with a "store" (memory), a "mill" (processor) and programs on punched cards.

CPU

Central processing unit: the control unit, registers and arithmetic logic unit (ALU) that fetch and carry out instructions.

stored program

Keeping the program's instructions in the same memory as its data, so the computer can load and change programs easily.

fetch–decode–execute

The cycle every CPU repeats: fetch the next instruction from memory, decode what it means, execute it, and move on.

CORE IDEAS

The story. In the 1820s mathematical tables (logarithms, navigation and astronomy) were computed by hand and were full of errors that could wreck ships. Charles Babbage, a Cambridge mathematician, designed a machine to calculate and print tables automatically: the **Difference Engine**. Then he conceived something far greater, the **Analytical Engine** (from 1834): a general-purpose machine with a memory he called the "store," a processor he called the "mill," and programs on punched cards borrowed from Joseph Marie Jacquard's weaving loom. In 1843 Ada, Countess of Lovelace, translated an Italian paper on the Engine and added notes three times its length. Her Note G set out step by step how the Engine could compute the Bernoulli numbers, often called the first published computer program, and she saw that such a machine could work with any symbols, not only numbers. Babbage, a sincere believer, also wrote a book arguing that the order of nature shows the mind of its Creator.

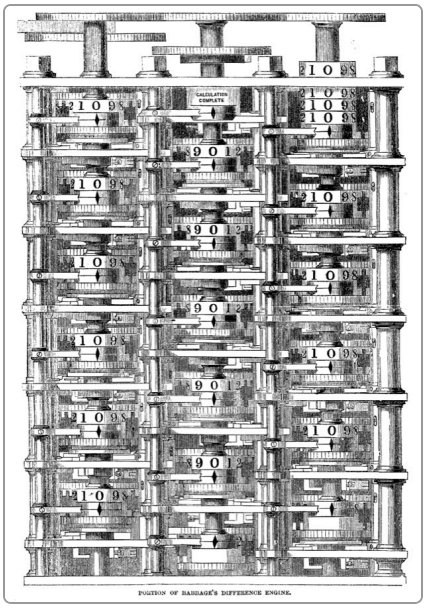
How they figured it out. Babbage's Difference Engine used a neat mathematical fact: for any polynomial of degree n, the nth differences between successive values are constant, so the whole table can be built by adding alone, and adding is easy for gears. But the precision machining of the 1820s and 1830s could not make his thousands of parts cheaply enough, his funding ended in disputes, and neither engine was finished in his lifetime. In 1991 London's Science Museum built his Difference Engine No. 2 from his own drawings of 1847–1849. It worked, calculating to 31 digits, proving his design had been right all along.

The physics and logic of a CPU. A modern computer is the Analytical Engine made of transistors. Memory holds numbers and, following the stored-program idea described by John von Neumann and the ENIAC team in 1945, the program itself. The **CPU** repeats a cycle: the control unit **fetches** the instruction whose address is in the program counter, **decodes** it, and **executes** it, perhaps using the ALU (adders built from the gates of Lesson 6.3) to add two registers (built from the flip-flops of Lesson 6.4), then moves on. Everything travels on shared wires called a **bus.** A clock paces the cycle. The Intel 4004 of 1971, the first microprocessor on one chip, ran at 740 kHz and did about 90,000 instructions a second; a modern processor core runs at about 3–5 GHz and can do several instructions each cycle.

The engineering. The microcontroller on your Arduino (the ATmega328P) is a whole computer on one chip: CPU, 32 KB of program memory, 2 KB of data memory, timers, counters, analog inputs and serial interfaces. It runs at 16 MHz, doing up to about 16 million simple instructions a second. In Unit 7 you will program it, and every line of your code will be turned into machine instructions that its CPU fetches, decodes and executes, using the gates, adders and flip-flops you have built by hand.

Try it. You will run Babbage's method of differences by hand, execute a short program on a paper computer exactly as a CPU would, and build an adder-based ALU in a simulator.

PICTURE STUDY



Babbage's Difference Engine, Engraver for Harper's New Monthly Magazine, December 1864 · Engraving · Wikimedia Commons

Image: Wikimedia Commons, public domain

In 1832 Babbage's engineer Joseph Clement assembled a small working section of the Difference Engine, about one-seventh of the whole. It worked perfectly. This engraving of it appeared in an American magazine in 1864.

Look closely

- Find the columns of number wheels. Each column holds one number, digit by digit.
- Look for the gears and levers between the columns. What operation do they perform?
- Find the crank or handle that drives it.
- Count the wheels in one column. How many digits could each number have?

Talk about it

1. Why could this machine compute a table using only addition?
2. What would a column of number wheels be called in a modern CPU?
3. Why would accurate tables matter so much to sailors and engineers in the 1800s?

> **Safety first.** Batteries and USB power only, never wall power. Insert chips the right way round (notch and pin 1) before connecting power, and tie unused CMOS inputs to ground or 5 V. This lesson is mostly paper and simulation; if you build adders on the breadboard, follow the chip rules above.

BUILD

A Difference Engine, a Paper Computer and an ALU

You will compute a table by Babbage's method, act as the CPU of a paper computer running programs, and build a 4-bit adder and a tiny ALU in the free CircuitVerse simulator, connecting this whole unit together.

You will need

- Graph paper, pencil, index cards
- A computer with the free CircuitVerse simulator (circuitverse.org)
- Optional: two 74HC00 chips and LEDs to build a 1-bit full adder on the breadboard

Steps

1. **Difference engine.** Choose $f(n) = n^2 + n + 41$ (a table Babbage himself liked to show). Compute f(0), f(1), f(2) directly. Find the differences and then use only addition to extend the table to f(15). Check three values directly.
2. **Paper computer.** Make 16 index cards for memory addresses 0–15 and one card each for the registers A and PC. Write the program of Worked Example 3 and its data on the cards.
3. Run it: act as the control unit, reading the card at the PC, decoding, executing, and updating the PC. Record each step in a table (PC, instruction, A, memory changes).
4. Add a jump: instruction JNZ A, n means "if A is not zero, set PC = n." Write and run a program that counts down from 5 to 0, subtracting 1 each time (add SUB A, [x] with memory x holding 1). Count how many instructions it executes.
5. **4-bit adder.** In CircuitVerse, build a full adder from gates (two XORs, two ANDs, one OR), test its 8-row truth table, then chain four into a 4-bit adder. Add 0111 + 0101 and 1111 + 0001 and record the results and carries.
6. **ALU.** Add a control input that chooses between A + B and A AND B (use a multiplexer, or AND gates with the control and its inverse). Test both operations.

7. Count the gates and estimate the transistor count (about 4–6 transistors per gate in CMOS). Compare with the 4004's 2,300.
8. **Improve it.** Optional on the breadboard: build one full adder from 74HC00 NAND gates and check it against your simulation. Or write a paper-computer program that multiplies 3 by 4 by repeated addition.

Tips

- In the paper computer, update the PC before executing a jump, or decide your rule and use it consistently; real CPUs follow one rule exactly.
- Label every input and output in the simulator.
- Test the full adder alone before chaining four.

Check your work

☐ I extended a table by Babbage's method and checked it.

☐ I executed a program by hand, step by step, as a CPU does.

☐ I built and tested a 4-bit adder and a simple ALU in a simulator.

ENGINEER'S NOTEBOOK

1. Your difference table for $n^2 + n + 41$ to n = 15.
2. The trace table of your paper-computer programs.
3. A block diagram of a CPU: memory, bus, control unit, PC, registers, ALU and clock, with arrows for the fetch–decode–execute cycle.
4. A paragraph: How do the gates, flip-flops and binary numbers of this unit come together in a computer?

KEY FORMULAS

$\Delta^n f = \text{constant for a polynomial of degree } n$

$\text{instructions per second} \approx f_{\text{clock}} \times \text{instructions per cycle}$

From history. Charles Babbage's son, Henry Prevost Babbage, built small parts of the Analytical Engine's mill from his father's drawings after his death. A piece of it, now in the Science Museum in London, could compute, showing again that the design was sound.

WORKED EXAMPLES

Example 1. Use the method of differences to extend the table of $f(n) = n^2$ from 1, 4, 9 to the next three values, using only addition.

Show solution

1. First differences of 1, 4, 9: 3, 5. Second difference: 2 (constant for a square).
2. Next first difference: $5 + 2 = 7$; next value: $9 + 7 = 16$.
3. Then $7 + 2 = 9$, value $16 + 9 = 25$; then $9 + 2 = 11$, value $25 + 11 = 36$.

Answer: 16, 25, 36

Example 2. Extend the table of cubes 1, 8, 27, 64 by two more values with the method of differences.

Show solution

1. First differences: 7, 19, 37. Second: 12, 18. Third: 6 (constant for a cube).
2. Next second difference: $18 + 6 = 24$; next first: $37 + 24 = 61$; next value: $64 + 61 = 125$.
3. Then $24 + 6 = 30$; $61 + 30 = 91$; $125 + 91 = 216$.

Answer: 125, 216

Example 3. A paper computer has these instructions in memory at addresses 0–4: 0: LOAD A, [10] (put the number at address 10 into register A); 1: ADD A, [11] (add the number at 11 to A); 2: STORE A, [12]; 3: HALT. Address 10 holds 7 and address 11 holds 5. Trace the fetch–decode–execute cycle.

Show solution

1. PC = 0: fetch LOAD; decode; execute: A = 7. PC = 1.
2. PC = 1: fetch ADD; the ALU adds 5: A = 12. PC = 2.
3. PC = 2: fetch STORE; memory[12] = 12. PC = 3.
4. PC = 3: fetch HALT; stop. Memory 12 now holds 12.

Answer: Address 12 ends up holding 12

PRACTICE

1. Easy What did Babbage call the memory and the processor of the Analytical Engine?

Show answer

The store and the mill.

2. Easy What is Ada Lovelace's Note G famous for?

Show answer

A step-by-step method for the Analytical Engine to compute the Bernoulli numbers, often called the first published computer program.

3. Easy Name the three steps of the CPU cycle.

Show answer

Fetch, decode, execute.

4. Medium Use differences to find the next two values of $2n + 3$: 5, 7, 9, ...

Show answer

First difference constant at 2: 11, 13.

5. Medium Use differences to extend $n^2 + n$: 2, 6, 12, 20, ... by two values.

Show answer

First differences 4, 6, 8; second difference 2: next first differences 10, 12; values 30, 42.

6. Medium Why did Babbage's engines fail to be completed in his lifetime, and what did the 1991 rebuild show?

Show answer

Manufacturing thousands of precise parts was too costly and slow for the period, and funding ended in disputes. The rebuild from his drawings worked, showing the design was sound.

7. Medium What does "stored program" mean, and why was it important?

Show answer

The program is kept in memory like data, so a new program can be loaded quickly instead of rewiring the machine.

8. Hard An Arduino's ATmega328P runs at 16 MHz and does about one simple instruction per cycle. How many instructions does it do in 1 ms? How does that compare with the 4004?

Show answer

About 16,000 in 1 ms; the 4004 did about 90 in 1 ms, so about 180 times fewer.

9. Hard Write a paper-computer program (using LOAD, ADD, STORE, HALT) that adds the numbers at addresses 20, 21 and 22 and stores the total at 23.

Show answer

LOAD A, [20]; ADD A, [21]; ADD A, [22]; STORE A, [23]; HALT.

10. Hard Lovelace wrote that the Engine could act on things other than number, such as musical notes, if their relations could be expressed. Why was that insight ahead of its time?

Show answer

She saw that a computer manipulates symbols by rules, not only numbers, anticipating word processing, music, graphics and every modern use of computers a century before electronic computers existed.

11. Challenge A table of $f(n) = n^3 - n$ begins 0, 6, 24, 60 for n = 1 to 4. Find the third difference and use the method to compute f(5) and f(6). Check by direct calculation.

Show answer

First differences 6, 18, 36; second 12, 18; third 6. Next second $= 24$, first $= 60$, f(5) = 120; next second 30, first 90, f(6) = 210. Check: $125 - 5 = 120$, $216 - 6 = 210$ ✓.

COMMON MISTAKES

- Mixing up addresses and the numbers stored at them. [10] means "the number stored at address 10."
- Forgetting to update the program counter.
- Assuming the method of differences works for any function; it works exactly for polynomials.

Make it a game · Difference Engine Paper Race. Method-of-differences race. Pick a polynomial like $n^2 + n$ and build a table by adding differences only, no multiplying. Your parent times you for ten rows. Then recite fetch, decode, execute with a made-up instruction. Retell Ada Lovelace's notes in thirty seconds. Cut your time on the second try.

Scripture. “Through wisdom is an house builded; and by understanding it is established: And by knowledge shall the chambers be filled with all precious and pleasant riches.” (Proverbs 24:3-4, KJV)

A computer is built up by wisdom, layer on layer: from switches to gates, gates to memory, memory to a machine. Each layer rests on understanding the one below.

UNIT 6

Digital Logic

In this unit you will cross from analog electronics into the digital world. You will follow the ideas that made computers possible: George Boole's algebra of logic, Claude Shannon's discovery that switches obey it, Leibniz's binary numbers, the logic gates and flip-flops that store and process bits, and finally Babbage's and Lovelace's vision of a general-purpose computer, realized at last in transistors.

You will design with Boolean algebra and truth tables, convert among decimal, binary and hexadecimal, build logic gates from transistors and from NAND chips, store bits in latches and a shift register, and run a program by hand as a CPU does. By the end of the unit you will understand what is happening inside the microcontroller you begin programming in Unit 7.

PREREQUISITES

- Unit 4: transistors as switches, integrated circuits and datasheets
- Exponents and powers of 2; simple algebra
- Breadboard and chip-handling skills (Lessons 4.5 and 5.1)

MASTERY CHECKLIST

- ☐ I can write, simplify and test Boolean expressions, including with De Morgan's laws.
- ☐ I can convert among decimal, binary and hexadecimal, add in binary and use two's complement.
- ☐ I can give the truth table of every basic gate, build gates from NAND or NOR, and design from a truth table.
- ☐ I can explain latches, flip-flops, shift registers and counters, and why buttons need debouncing.
- ☐ I can explain the fetch–decode–execute cycle and how gates, adders and flip-flops make a CPU.

OPTIONAL KITS FOR THIS UNIT

- **CircuitVerse (free online logic simulator)**: A free, browser-based digital logic simulator with gates, flip-flops and displays. Used in Lessons 6.3 and 6.5; excellent for testing designs before building them.
- **A 74HC logic chip assortment**: A few 74HC00 (NAND), 74HC02 (NOR), 74HC86 (XOR), 74HC74 (D flip-flop) and 74HC595 (shift register) chips from any electronics supplier make this unit more hands-on. Optional.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

6.1	**Boole and Shannon: Logic in Switches**	3 sessions of 50 minutes
6.2	**Binary and Hexadecimal: Leibniz's Ones and Zeros**	3 sessions of 50 minutes
6.3	**Logic Gates and Truth Tables**	3 sessions of 50 minutes
6.4	**Flip-Flops and Counters: Memory from Gates**	3 sessions of 50 minutes
6.5	**From Gates to a Computer: Babbage, Lovelace and the CPU**	3 sessions of 50 minutes

Unit 6 test

Time: 50 minutes. A scientific calculator is allowed (but do conversions by hand, showing work). Show truth tables, algebra steps and calculations clearly; correct method earns partial credit. The test is worth 100 points.

1. **6 pts** **Lesson 6.1**

   Write the 8-row truth table for $Y = \overline{A}B + C$.

2. **6 pts** **Lesson 6.1**

   Simplify $AB + A\overline{B} + \overline{A}B$ with Boolean algebra, one step per line.

3. **6 pts** **Lesson 6.1**

   Explain what Shannon showed in 1937 and why it mattered.

4. **6 pts** **Lesson 6.2**

   Convert 182 to binary and hex; convert 0x2D and 11101_2 to decimal.

5. **6 pts** **Lesson 6.2**

   Add 0111 + 0101 in binary and check in decimal. Write −12 in 8-bit two’s complement.

6. **6 pts** **Lesson 6.2**

   An 8-bit DAC from 3.3 V: what is the step size and the output for input 128?

7. **6 pts** **Lesson 6.3**

   Give the truth tables of NAND, NOR and XOR, and show how to make an OR gate from NAND gates only.

8. **8 pts** **Lesson 6.3**

   Design a circuit with output 1 when the 2-bit number AB is 2 or 3 or when C is 1 and AB is 1. Write it as a sum of products and simplify.

9. **6 pts** **Lesson 6.3**

   Five gates each with 9 ns delay lie on the longest path. What is the fastest rate of new results?

10. **8 pts** **Lesson 6.4**

    A NAND SR latch starts at Q = 1. Inputs: $\overline{R}$ low, both high, $\overline{R}$ low again, $\overline{S}$ low, both high. Give Q after each step. What input is forbidden?

11. **6 pts** **Lesson 6.4**

    A 12-stage counter is driven by a 4.096 kHz clock. What frequency does the last stage give, and what is the counter’s range?

12. **6 pts** **Lesson 6.4**

    Explain switch bounce and two ways to fix it.

13. **6 pts** **Lesson 6.5**

    Use the method of differences to extend 3, 7, 13, 21 by two values.

14. **6 pts** **Lesson 6.5**

Trace this program: 0: LOAD A, [8]; 1: ADD A, [8]; 2: ADD A, [9]; 3: STORE A, [10]; 4: HALT, with memory 8 = 6 and 9 = 4. What is in address 10?

15. **4 pts** **Lesson 6.5**

Name the parts of a CPU and say what each does.

16. **8 pts** **Lesson 6.5**

Essay (one paragraph). Babbage designed a general-purpose computer in the 1830s, but working computers came only in the 1940s. Explain what was missing, and how the ideas of Boole, Shannon, Leibniz and the flip-flop supplied it.

ANSWER KEY

1. ABC: 000→0, 001→1, 010→1, 011→1, 100→0, 101→1, 110→0, 111→1
2. $A(B + \overline{B}) + \overline{A}B = A + \overline{A}B = (A + \overline{A})(A + B) = A + B$
3. That switch and relay circuits follow Boolean algebra (series = AND, parallel = OR), so they can be designed, simplified and checked mathematically and can do binary arithmetic: the basis of digital design.
4. 182 = 10110110_2 = 0xB6; 0x2D = 45; 11101_2 = 29
5. 1100_2 = 12 (7 + 5); 12 = 00001100 → 11110011 + 1 = 11110100
6. $3.3/256 = 12.9$ mV; $3.3 \times 128/256 = 1.65$ V
7. NAND 1,1,1,0; NOR 1,0,0,0; XOR 0,1,1,0. OR: invert A and B with NANDs (inputs joined), then NAND the results: $\overline{\overline{A}\,\overline{B}} = A + B$.
8. AB = 10 or 11 means A = 1; AB = 01 with C = 1 is $\overline{A}BC$. $Y = A + \overline{A}BC = A + BC$.
9. 45 ns; about 22 MHz
10. 0, 0, 0, 1, 1. Both $\overline{S}$ and $\overline{R}$ low together is forbidden.
11. $4096/4096 = 1.0$ Hz; 0 to 4095
12. Contacts bounce open and closed for a few ms, giving several pulses; fix with an SR latch (two-contact switch), an RC filter (often with a Schmitt trigger), or a delay in code.
13. Differences 4, 6, 8 (second difference 2): next 10, 12; values 31, 43
14. A = 6, then 12, then 16; memory 10 = 16
15. Control unit (fetches and decodes instructions, directs everything), program counter (address of next instruction), registers (fast storage of a few values), ALU (arithmetic and logic), bus (shared wires), clock (paces each step).
16. A strong answer: Babbage's concepts (store, mill, programs on cards) were right, but mechanical parts were too costly and slow; Leibniz's binary and Boole's algebra gave a simple two-state number system and logic; Shannon showed switches could implement them; flip-flops (1918) gave fast electronic memory; with tubes and later transistors, gates and flip-flops built ALUs and registers, and the stored-program idea completed the computer.

PORTFOLIO PIECE: A LOGIC-BASED GAME OR INTERLOCK

Design and build a digital logic device from gates and flip-flops (no microcontroller): for example, a two-player "who pressed first" quiz buzzer (two SR latches that lock each other out), a combination lock that lights a green LED only for the right button pattern, or a machine interlock with emergency stop. Write the requirements as a truth table or rule, derive and simplify the Boolean expression, build it from 74HC chips (or transistors), test every case, and document it with schematic, chip and pin numbers, truth table and test record.

LOOK FOR	WHAT IT MEANS
Logic design	Requirements written as a truth table or rule; Boolean expression derived and simplified with work shown.
Build	Chips correctly powered and decoupled, unused inputs tied, every gate traceable to the schematic.
Testing	Every input case tested and recorded, including any forbidden or tricky case (such as simultaneous presses).
Documentation	Schematic with chip and pin numbers, truth table, test record and a paragraph on how it could be improved.

UNIT 7

Arduino I: Programming a Microcontroller

Now the circuits begin to think. In this unit you will program the Arduino Uno, the board created in Ivrea, Italy, in 2005 so that artists and students could build interactive devices. You will learn the structure of a sketch, control outputs with loops and functions, read buttons correctly with pull-up resistors and debouncing, measure analog voltages with the built-in analog-to-digital converter, and dim lights and mix colors with pulse-width modulation.

Each lesson's build is a real device: a Morse beacon, a traffic signal with a pedestrian light, a reaction-time game toy, a light meter and night light, and an RGB color mixer. You will also learn the engineer's habits for code: name things clearly, comment every block, change one thing at a time, and use the clock instead of waiting blindly.

PREREQUISITES

- Units 1–6, especially LEDs and current limiting (3.5), voltage dividers (2.3), transistor switches (4.2) and binary (6.2)
- A computer on which you may install the free Arduino IDE (or use the online editor)
- An Arduino Uno–compatible board and USB cable

MASTERY CHECKLIST

- ☐ I can explain the Uno's main parts and write, verify, upload and debug a sketch.
- ☐ I can use variables, constants, for loops, if statements and functions to control outputs.
- ☐ I can read buttons with pull-ups, debounce them, and measure time with millis().
- ☐ I can read analog sensors, convert readings to volts, calibrate, average and use thresholds with hysteresis.
- ☐ I can use PWM to dim LEDs and mix colors, and calculate duty cycle and average voltage.

OPTIONAL KITS FOR THIS UNIT

- **Arduino Starter Kit**: The official kit with project book; its first projects match this unit closely.
- **ELEGOO Uno starter kits**: Uno-compatible kits with tutorials covering LEDs, buttons, potentiometers, RGB LEDs and many sensors used in Units 7–8.
- **Wokwi (free online simulator)**: Runs Arduino sketches in a browser with simulated LEDs, buttons and sensors; useful for testing code away from the bench.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

7.1	**The Arduino: The Board and the IDE**	3 sessions of 50 minutes
7.2	**Digital Output and Loops: A Traffic Signal**	3 sessions of 50 minutes
7.3	**Digital Input and Buttons: A Reaction-Time Game**	3 sessions of 50 minutes
7.4	**Analog Input: From Kelvin's Tide Machine to the ADC**	3 sessions of 50 minutes
7.5	**PWM and Fading: Fooling the Eye**	3 sessions of 50 minutes

Unit 7 test

Time: 50 minutes. A scientific calculator is allowed. Write code neatly; small syntax slips lose little credit if the logic is right. Show calculations with units. The test is worth 100 points.

1. **6 pts** **Lesson 7.1**
   Describe the structure of an Arduino sketch and what setup() and loop() are for.

2. **6 pts** **Lesson 7.1**
   Choose a resistor for a yellow LED ($V_F = 2.1$ V) at 10 mA from an Arduino pin, and say whether eight such LEDs on at once are within the chip's 200 mA total.

3. **6 pts** **Lesson 7.1**

   Explain why the Arduino team made it open source and what that did.

4. **8 pts** **Lesson 7.2**

   Write code (or exact steps) for a for loop that flashes an LED on pin 6 eight times, 100 ms on and 400 ms off. How long does it take?

5. **6 pts** **Lesson 7.2**

   A signal's states last 20, 4, 2, 15, 4 and 2 s. Find the cycle time and cycles per hour.

6. **6 pts** **Lesson 7.2**

   Find the yellow time for 18 m/s, reaction 1.0 s, braking 3.0 m/s^2, with $t = t_r + v/(2a)$.

7. **6 pts** **Lesson 7.3**

   Explain floating inputs and how INPUT_PULLUP fixes them. With INPUT_PULLUP, what does a pressed button read?

8. **8 pts** **Lesson 7.3**

   Write the logic of a reaction game that catches false starts, using millis(). Why not use delay() for the random wait?

9. **6 pts** **Lesson 7.3**

   A ruler falls 18 cm before it is caught. Find the reaction time, and how far a car at 25 m/s travels in that time.

10. **8 pts** **Lesson 7.4**

    analogRead(A2) returns 307. Find the voltage. What reading would 4.2 V give? What is the resolution?

11. **6 pts** **Lesson 7.4**

    What is hysteresis, and why does a night light need it?

12. **6 pts** **Lesson 7.4**

    How would you measure a 9 V battery with an Uno safely? Give resistor values and the conversion.

13. **8 pts** **Lesson 7.5**

analogWrite(5, 77) on a 980 Hz pin: find duty cycle, average voltage, period and on-time.

14. **6 pts** **Lesson 7.5**

Explain why PWM dimming wastes little power and why the light looks steady.

15. **8 pts** **Lesson 7.3**

Essay (one paragraph). Explain why “use the clock, don’t wait blindly” is a key habit in embedded programming, with an example from your traffic signal or reaction game.

ANSWER KEY

1. setup() runs once at power-up or reset (configure pins, start serial); loop() then runs again and again forever (the main behavior).
2. $2.9 / 0.010 = 290\ \Omega \rightarrow 330\ \Omega$ (8.8 mA); 8 × 8.8 = 70 mA: within the limit.
3. So anyone could make and improve compatible boards; boards became cheap and widely available, a large community grew, and the platform spread worldwide.
4. for (int i = 0; i < 8; i++) { digitalWrite(6, HIGH); delay(100); digitalWrite(6, LOW); delay(400); }; 4.0 s
5. 47 s; 76.6 per hour
6. $1.0 + 3.0 = 4.0$ s
7. An unconnected input picks up noise and reads randomly; INPUT_PULLUP connects an internal resistor to 5 V so the pin reads HIGH when released. Pressed (connected to ground): LOW.
8. Wait for release; set goTime = millis() + random wait; while millis() < goTime, if pressed print “Too soon” and restart; then LED on, start = millis(); wait for press; t = millis() − start; print t. delay() stops the program, so early presses would be missed.
9. $t = \sqrt{0.36 / 9.8} = 0.19$ s; $d = 4.8$ m
10. $307 \times 5 / 1023 = 1.50$ V; 859; about 4.9 mV
11. Two thresholds (on and off) separated by a gap; without it, noise near a single threshold makes the light flicker on and off.
12. A divider such as 10 kΩ over 10 kΩ halves it (4.5 V max); volts = reading × 5/1023 × 2.
13. $D = 30.2\%$; 1.51 V; $T = 1.02$ ms; on 0.31 ms
14. The transistor or pin is fully on or fully off, so little power is lost in it; the switching (490 Hz) is faster than the eye can follow, so it blends into steady light (persistence of vision).
15. A strong answer: delay() stops the processor, so it cannot read inputs or run other tasks; checking millis() each pass through loop() lets a program time events and stay responsive. Example: the pedestrian button during a long green, or a false start during the random wait.

PORTFOLIO PIECE: AN INTERACTIVE ARDUINO TOY OR TOOL

Design, build and program an interactive device that uses at least one digital input, one analog input and one PWM output, and that uses millis() timing rather than long delays. Ideas: an improved reaction game with best scores and difficulty levels, a "Simon"-style memory game, a light-following night light that fades, an RGB color-guessing game, or a metronome with a tempo knob. Submit the schematic, a flowchart, commented code, a test log and a short user guide, and have someone else use it and record their feedback.

LOOK FOR	WHAT IT MEANS
Function	Reads a digital and an analog input and drives a PWM output reliably; responsive (uses millis(), no long blind delays).
Code quality	Clear names, constants for pins and timings, functions where repeated, a comment on every block.
Hardware	Correct resistors, pull-ups, current limits and a neat, documented schematic.
Testing and users	Test log of bugs found and fixed; feedback from another user and one change made because of it.

7.1 The Arduino: The Board and the IDE

OBJECTIVES

- Tell the story of the Arduino, from the Interaction Design Institute in Ivrea to millions of boards worldwide.
- Identify the parts of the Uno: microcontroller, USB interface, regulator, digital and analog pins, power pins and reset.
- Install the Arduino IDE, write, verify and upload a sketch, and use the Serial Monitor.
- Explain the structure of a sketch (setup() and loop()) and modify Blink to send Morse code.

> **Warm-up.** Look at your Arduino Uno with a magnifier. List every chip, connector and label you can find. Which part do you think is the “brain”? Which parts do you think handle power?

WATCH

Arduino Tutorial 1: Setting Up and Programming the Arduino for Absolute Beginners

Paul McWhorter · 23:50

https://www.youtube.com/watch?v=fJWR7dBuc18

> **WHEN TO WATCH**
> After the core ideas, before the build. Follow along with your own board: install the IDE, plug in the Uno, and upload Blink as Mr. McWhorter does.

BACKUP VIDEO

How to Use an Arduino (Lesson #1)

Science Buddies · 5:10

https://www.youtube.com/watch?v=cd04o5yqSAU

A short Science Buddies version of the same first steps, if you want a quick reminder.

KEY TERMS

microcontroller

A single chip with a CPU, program memory, data memory and input/output pins: a whole small computer. The Uno uses the ATmega328P.

sketch

An Arduino program, written in C++ with the Arduino library, made of a setup() function that runs once and a loop() function that repeats forever.

IDE

Integrated development environment: the program (the Arduino IDE) in which you write, verify (compile) and upload code.

compile / upload

Compiling turns your C++ into machine instructions; uploading sends them over USB into the microcontroller's flash memory.

Serial Monitor

A window in the IDE that shows text sent by the board with Serial.print(), and can send text back.

CORE IDEAS

The story. In 2005 at the Interaction Design Institute Ivrea, a small graduate school in northern Italy, teacher Massimo Banzi and his colleagues David Cuartielles, Tom Igoe, Gianluca Martino and David Mellis wanted design students, artists who had never studied electronics, to be able to build interactive projects in a few weeks. The microcontroller boards of the day were expensive and hard to program. Building on Wiring, a platform created at the school by Hernando Barragán, they designed a simple, cheap, open-source board and a friendly programming environment, and named it after the Bar di Re Arduino, where they met, itself named after Arduin of Ivrea, an eleventh-century king of Italy. Because the designs were open, anyone could make compatible boards. Millions of Arduinos are now in use in schools, laboratories and workshops.

How they figured it out. The team's rule was that a beginner should get an LED blinking within minutes. They hid the hard parts: a USB chip so the board could be programmed without special hardware; a bootloader, a small program in the microcontroller that receives new code over USB; a library of simple functions such

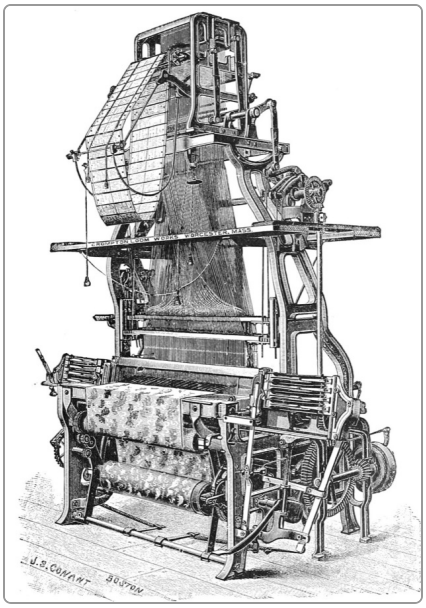
as digitalWrite() and delay(); and an IDE with one button to compile and one to upload. Open-source licensing let teachers and companies copy and improve the design, which is why your kit may be an official Arduino or a compatible board such as an Elegoo Uno, and both work the same way.

The physics. The Uno's ATmega328P runs at 16 MHz: its clock ticks every 62.5 ns. It has 32 KB of flash memory for programs (kept when power is off), 2 KB of SRAM for variables, and 1 KB of EEPROM for settings you want to keep. Its pins work at 5 V logic: a pin set HIGH is at about 5 V, LOW at about 0 V. Each pin can safely supply or sink about 20 mA (40 mA is the absolute maximum, and the whole chip about 200 mA). The board takes 5 V from USB; pin 13 has a small LED on the board. There are 14 digital pins (0–13; 0 and 1 are also used by USB serial), six of which can make PWM (marked ~), and six analog inputs (A0–A5).

The engineering. Every sketch has the same shape. setup() runs once at power-up or reset: configure pins with pinMode() and start serial with Serial.begin(9600). loop() then runs again and again, forever, as fast as it can. The classic first program, Blink, makes pin 13 HIGH, waits 1000 ms with delay(1000), makes it LOW, and waits again. Engineers write code in small steps: change one thing, verify, upload, test. The IDE's error messages give a line number; most beginner errors are a missing semicolon, a misspelled word (C++ is case-sensitive: digitalwrite is wrong) or a missing brace.

Try it. In the build you will install the IDE, upload Blink, print to the Serial Monitor, and then turn the LED into a Morse-code beacon.

PICTURE STUDY



A Carpet Loom with a Jacquard Attachment, Popular Science Monthly, 1891 · Engraving · Popular Science Monthly, vol. 39

Image: Wikimedia Commons, public domain

Joseph Marie Jacquard's loom of 1804 wove patterns from a chain of punched cards: each card told the loom which threads to lift for one row. It was one of the first machines controlled by a stored program, and Babbage borrowed its cards for the Analytical Engine. Your Arduino does the same thing with instructions stored in flash memory.

Look closely

- Find the chain of punched cards. Where does it enter the mechanism?
- Find the threads of the loom below. How does each card control them?
- Look for where the chain of cards loops back. What does that remind you of in an Arduino sketch?
- Find the weaver. What does he still have to do?

Talk about it

1. In what sense is a chain of cards a program?
2. Which part of the Jacquard loom is like setup(), and which like loop()?
3. How does changing the cards compare with uploading a new sketch?

> **Safety first.** The Arduino is powered only by its USB cable from a computer or a USB power bank, never by a wall adapter in this course. Unplug the USB cable before changing wiring. Never connect an Arduino pin straight to 5 V or ground with nothing in between, and never draw more than 20 mA from a pin: every LED needs its resistor.

BUILD

First Sketches: Blink, Hello and a Morse Beacon

You will install the IDE, upload the Blink example, change it, print messages to the Serial Monitor, and write your own Morse-code beacon with an external LED.

You will need

- Arduino Uno (or compatible) and USB cable, a computer
- Breadboard, a red LED, a 330 Ω resistor, jumper wires
- The free Arduino IDE (arduino.cc/en/software) or the online Arduino Cloud Editor

Steps

1. Install the Arduino IDE (a parent may need to approve the download). Plug in the Uno. In the IDE, choose Tools → Board → Arduino Uno and Tools → Port (the one that appears when you plug the board in).
2. Open File → Examples → 01.Basics → Blink. Read it line by line: pinMode(LED_BUILTIN, OUTPUT); in setup; in loop, digitalWrite(LED_BUILTIN, HIGH);, delay(1000);, digitalWrite(LED_BUILTIN, LOW);, delay(1000);. Click Verify (✓), then Upload (→). The board's LED should blink once a second.
3. Change both delays to 200 and upload. Then make the LED stay on for 100 ms and off for 900 ms. Record the period and duty cycle each time.
4. **Hello.** Start a new sketch. In setup() type Serial.begin(9600); and Serial.println("Hello from my Arduino");. In loop() type Serial.print("Seconds since start: ");, Serial.println(millis() / 1000); and delay(1000);. Upload and open the Serial Monitor (set to 9600 baud).
5. **External LED.** Unplug the USB. Wire pin 8 → 330 Ω → LED long leg; LED short leg → GND. Plug in and change your sketch to use pin 8 (and pinMode(8, OUTPUT);).
6. **Morse beacon.** Write two functions above setup(): void dot() { digitalWrite(8, HIGH); delay(200); digitalWrite(8, LOW); delay(200); } and void dash() { digitalWrite(8, HIGH); delay(600); digitalWrite(8, LOW); delay(200); }. In

loop(), call dot(); dot(); dot();, then delay(400); (making a 600 ms gap between letters), then three dash(); calls, delay(400);, three dot(); calls, and delay(1200); before repeating (with the 200 ms after the last dot, that makes the 1,400 ms gap between words). Upload and decode it.

7. Time ten repetitions of SOS with a stopwatch. Compare with your calculation (practice problem 9 with these timings) and explain any difference.
8. **Improve it.** Change the beacon to send your initials, using a unit-length variable int unit = 200; so that changing one number changes the speed of the whole message. Comment every line of your code with // notes.

Tips

- If upload fails, check the port, close other programs using the port, and try a different USB cable (some are power-only).
- Use Tools → Auto Format to tidy your code's indentation.
- Save each working version with a new name (beacon1, beacon2…), so you can always go back.

Check your work

☐ I uploaded Blink and changed its timing on purpose.

☐ I printed to the Serial Monitor.

☐ I wrote functions and used them to send Morse code from an external LED.

ENGINEER'S NOTEBOOK

1. A labeled drawing of the Uno: ATmega328P, USB chip, regulator, power pins, digital pins (with ~ marks), analog pins, reset button.
2. Your Morse sketch, printed or copied, with a comment on every line.
3. A short table: each delay setting you tried, the period, frequency and duty cycle.

KEY FORMULAS

$$T_{\text{clock}} = \frac{1}{f} = \frac{1}{16\ \text{MHz}} = 62.5\ \text{ns}$$

$$\text{duty} = \frac{t_{\text{on}}}{t_{\text{on}} + t_{\text{off}}}$$

$I_{\text{pin}} \leq 20\ \text{mA}$ (recommended)

From history. The Arduino team won an Honorary Mention at the Prix Ars Electronica in 2006, and the board quickly spread through universities and maker spaces. The Uno, introduced in 2010, became the standard model, and its layout of header pins became a standard that many other boards copy.

WORKED EXAMPLES

Example 1. Blink is changed to digitalWrite(13, HIGH); delay(200); digitalWrite(13, LOW); delay(800);. Find the period, frequency and duty cycle of the flashing.

Show solution

1. Period: $200 + 800 = 1000$ ms $= 1.0$ s.
2. Frequency: $f = 1/1.0 = 1.0$ Hz.
3. Duty cycle: $200/1000 = 20\%$.

Answer: 1.0 s, 1.0 Hz, 20% duty

Example 2. A red LED ($V_F = 2.0$ V) is connected from an Arduino pin through a resistor to ground. Choose a resistor for 10 mA, and check the pin current against the limit.

Show solution

1. $R = (5.0 - 2.0)/0.010 = 300\ \Omega$; use 330 Ω.
2. Then $I = 3.0/330 = 9.1$ mA, well under the 20 mA recommended limit.

Answer: 330 Ω, about 9 mA

Example 3. The ATmega328P has 32 KB of flash, of which the bootloader uses 0.5 KB. A sketch compiles to 1,924 bytes. What percentage of the available program memory does it use?

Show solution

1. Available: $32 \times 1024 - 512 = 32{,}256$ bytes.
2. Fraction: $1924/32{,}256 = 0.060 = 6.0\%$. (The IDE reports this number after each compile.)

Answer: About 6%

PRACTICE

1. Easy What are the two functions every Arduino sketch must have, and when does each run?

   Show answer

   setup() runs once at start-up or reset; loop() runs repeatedly forever after that.

2. Easy Where and when was the Arduino created?

   Show answer

   At the Interaction Design Institute Ivrea, Italy, in 2005.

3. Easy What does pinMode(13, OUTPUT); do?

   Show answer

   It sets pin 13 to be an output so the program can drive it HIGH or LOW.

4. Medium A sketch has delay(250) after HIGH and delay(250) after LOW. What is the blink frequency?

   Show answer

   Period 500 ms, frequency 2.0 Hz.

5. Medium The IDE reports an error at a line that looks fine. What is the most likely cause, and where should you look?

   Show answer

   A missing semicolon or brace on the line before; the compiler only notices the problem when it reaches the next line.

6. Medium Why is DigitalWrite an error while digitalWrite works?

   Show answer

   C++ is case-sensitive; the function's name is exactly digitalWrite.

7. Medium How long is one clock cycle of a 16 MHz microcontroller? How many cycles in 1 ms?

   Show answer

   62.5 ns; 16,000 cycles.

8. Hard An Uno drives eight LEDs, each at 15 mA. Is that within the chip's total limit of about 200 mA? What would happen with 15 LEDs at 15 mA?

Show answer

$8 \times 15 = 120$ mA: within the limit. 15 LEDs: 225 mA, over the limit; use transistors or lower currents.

9. Hard In Morse code a dot is 1 unit, a dash 3 units, the gap inside a letter 1 unit, between letters 3 units, between words 7 units. With a 200 ms unit, how long does "SOS" take?

Show answer

S: 3 dots + 2 gaps = 5 units; O: 3 dashes + 2 gaps = 11 units; plus two letter gaps of 3 units: $5 + 3 + 11 + 3 + 5 = 27$ units $= 5.4$ s.

10. Hard Why did the Arduino team make the hardware design open source?

Show answer

So that anyone could build, sell and improve compatible boards; this made boards cheap and widely available, built a large community and spread the platform worldwide.

11. Challenge Write (in words or code) a sketch that blinks the LED on pin 13 once, twice, three times... up to five times, with a 1 s pause between groups, and then starts over.

Show answer

In loop(), use a variable n from 1 to 5; for each n, a for loop blinks n times (HIGH, 200 ms, LOW, 200 ms), then delay(1000). (Any correct logic accepted.)

COMMON MISTAKES

- Forgetting the semicolon at the end of a statement.
- Choosing the wrong port or board in the Tools menu.
- Connecting an LED to a pin with no resistor.

> **Make it a game · Name the Uno Part.** Draw an Uno board from memory and label the microcontroller, USB interface, regulator, digital pins, analog pins, power pins and reset. Your parent checks. Then explain compile versus upload in one sentence. Score a point per correct label and one for the Ivrea story. Try to beat your count tomorrow.

7.2 Digital Output and Loops: A Traffic Signal

OBJECTIVES

- Tell the story of the electric traffic signal and its timing.
- Use variables, constants, for loops and functions to control several outputs.
- Calculate timing in sequences and loops.
- Build and program a traffic signal with a pedestrian light and a flashing mode.

> **Warm-up.** Stand at a corner (with an adult) or remember one near you. Time the green, yellow and red for one direction. Do the two directions ever both have green? What would happen if they did?

WATCH

How to Blink an LED with Arduino (Lesson #2)

Science Buddies · 15:57

https://www.youtube.com/watch?v=FKekzzj5844

> **WHEN TO WATCH**
> Before the build. Follow the wiring of an external LED and the changes to the code; pause at each “pause the video” prompt and do the task.

KEY TERMS

variable

A named place in memory that holds a value, such as int count = 0;. Its value can change.

constant

A named value that does not change, such as const int RED = 10;, which makes code easier to read and change.

for loop

Repeats a block of code a set number of times: for (int i = 0; i < 5; i++) { … } runs it 5 times.

function

A named block of code that can be called again and again, such as void flash() { … }.

state

The condition a system is in (for example, “north–south green”); a sequence of states makes a state machine.

CORE IDEAS

The story. As cars filled city streets, police officers in towers or on platforms directed traffic by hand. On August 5, 1914, Cleveland, Ohio, installed what is often called the first electric traffic signal, designed by James Hoge: red and green lights at each corner, with a buzzer to warn of a change, controlled by an operator in a booth. In 1920 William Potts, a Detroit police officer, added the amber (yellow) light and built signals that could be coordinated at several crossroads. Inventors added automatic timers in the 1920s, and today’s signals are run by microcontrollers that read sensors in the road and can be timed and linked across a whole city.

How they figured it out. The yellow light came from a simple engineering question: a car approaching a light that suddenly turns red cannot stop instantly. Engineers now calculate the yellow time from the approach speed, the driver’s reaction time and the braking rate, typically 3–6 seconds. They also add an “all red” interval when every direction is red for a second or two, to clear the crossing. Most important, the controller must make it impossible for crossing directions to be green at the same time; real signals have a separate hardware “conflict monitor” that forces all lights to flash red if the controller ever makes that mistake.

The physics and the code. A traffic signal is a sequence of states, each held for a set time. In code each state is a set of digitalWrite() calls followed by a delay(). Constants such as const int RED = 10; name the pins, so the code reads like the design. A for loop repeats a pattern a set number of times: for (int i = 0; i < 6; i++) runs with i = 0, 1, 2, 3, 4, 5 and then stops. Functions group repeated actions so that each is written once. The total cycle time is the sum of the state times, and the number of cycles per hour is 3,600 s divided by the cycle time.

The engineering. Good embedded code is readable and safe. Name things clearly, comment the purpose of each block, and put the timing numbers in constants at the top so they can be changed in one place. Think about failure: what should the outputs do if something goes wrong? A real controller defaults to flashing red. In this

lesson you will use delay(), which stops the program while it waits; in Lesson 7.3 you will see why engineers often avoid it and use the clock instead.

Try it. You will build a two-direction signal with three LEDs each, write it as a sequence of states, and add a pedestrian signal and a flashing night mode.

PICTURE STUDY



A Traffic Signal on Vasagatan, Stockholm, Unknown photographer, 1925 · Photograph · Wikimedia Commons

Image: Wikimedia Commons, public domain

Within a few years of Cleveland's 1914 signal, cities around the world were trying electric signals. This photograph shows an early one on Vasagatan in Stockholm in 1925.

Look closely

- Find the signal. How many lights or faces can you see?
- Look at the vehicles and people. Which kinds of traffic does the signal need to control?
- Look for anyone directing traffic by hand. Was the signal replacing a person, or helping one?
- Find where the signal would be visible from. Why does its position matter?

Talk about it

1. What would the controller of this 1925 signal have been: a person, a clock or a motor?
2. What problem would a signal solve on this street?
3. What would you have to add to this signal to make it safe for pedestrians?

> **Safety first.** The Arduino is powered only by its USB cable from a computer or a USB power bank, never by a wall adapter in this course. Unplug the USB cable before changing wiring. Never connect an Arduino pin straight to 5 V or ground with nothing in between, and never draw more than 20 mA from a pin: every LED needs its resistor.

BUILD

A Programmed Traffic Signal

You will build a two-direction traffic signal with six LEDs, program it as a sequence of states with constants and functions, then add a pedestrian light and a flashing night mode using for loops.

You will need

- Arduino Uno and USB cable, breadboard, jumpers
- Two red, two yellow and two green LEDs, plus one white or blue LED for the pedestrian signal; seven 330 Ω resistors
- Optional: cardboard and markers to make a model crossroads

Steps

1. Plan: draw a state table with columns for each LED (NS red, NS yellow, NS green, EW red, EW yellow, EW green) and a row for each state with its time (use Worked Example 1's times divided by 5 so testing is quick).
2. Wire the six LEDs, each through 330 Ω to ground, on pins 2–7. Draw the schematic.
3. At the top of the sketch, name the pins: const int NS_R = 2;, const int NS_Y = 3;, const int NS_G = 4;, const int EW_R = 5;, const int EW_Y = 6;, const int EW_G = 7;. Put the times in constants too: const int GREEN_MS = 5000; and so on.
4. In setup(), use a for loop to make pins 2 through 7 outputs: for (int p = 2; p <= 7; p++) { pinMode(p, OUTPUT); }.
5. Write a function void allOff() that turns all six LEDs off. In loop(), write each state: call allOff();, turn on the right two LEDs with digitalWrite(), then delay() for that state's time. Check your state table: there must never be two greens.
6. Upload and time each state with a stopwatch. Compare with your table.
7. **Pedestrian light.** Add the white LED on pin 8 with 330 Ω. During the NS red state, turn it on for most of the state, then flash it six times with a for loop before the state ends.

8. **Improve it.** Add a night mode: a for loop that flashes both yellows together 20 times, then returns to normal. Comment every block of your code. Then answer: if the code had a bug that turned on both greens, what hardware or code check would you add to catch it?

Tips

- Test one state at a time; comment out the others with // while you check each one.
- Use Tools → Serial Plotter or Serial.println() to print the state number as the signal runs, to debug the sequence.
- Keep the times short while testing, then set them to realistic values at the end.

Check your work

- ☐ My signal never shows two greens, and each state lasts its designed time.
- ☐ I used constants, a for loop and at least one function.
- ☐ I added a pedestrian light and a flashing night mode.

ENGINEER'S NOTEBOOK

1. The state table with times, and the cycle time and cycles per hour.
2. The schematic of the signal.
3. Your commented code (printed or copied).
4. A paragraph on how the yellow time is chosen, with your calculation for a 15 m/s approach.

KEY FORMULAS

$T_{\text{cycle}} = \sum t_{\text{state}}$

$\text{cycles per hour} = \dfrac{3600\ \text{s}}{T_{\text{cycle}}}$

$t_{\text{yellow}} \approx t_{\text{reaction}} + \dfrac{v}{2a}$ (simplified)

From history. Garrett Morgan, an inventor in Cleveland, patented a traffic signal in 1923 that added a position stopping all directions, an idea related to the all-red interval. He sold the rights to General Electric. Many inventors contributed pieces of the modern signal.

WORKED EXAMPLES

Example 1. A signal runs north–south green 25 s, yellow 4 s, all red 2 s, east–west green 20 s, yellow 4 s, all red 2 s. Find the cycle time and cycles per hour.

Show solution

1. $T = 25 + 4 + 2 + 20 + 4 + 2 = 57$ s.
2. Cycles per hour: $3600 / 57 = 63.2$.

Answer: 57 s; about 63 cycles per hour

Example 2. Find the yellow time for a car at 15 m/s (about 34 mph), a driver reaction time of 1.0 s and braking at 3.0 m/s², using $t = t_r + v/(2a)$.

Show solution

1. $v/(2a) = 15/(2 \times 3.0) = 2.5$ s.
2. $t = 1.0 + 2.5 = 3.5$ s.

Answer: About 3.5 s

Example 3. How many times does this loop flash the LED, and how long does it take? for (int i = 0; i < 6; i++) { digitalWrite(9, HIGH); delay(250); digitalWrite(9, LOW); delay(250); }

Show solution

1. i takes the values 0, 1, 2, 3, 4, 5: six passes.
2. Each pass: $250 + 250 = 500$ ms.
3. Total: $6 \times 0.5 = 3.0$ s.

Answer: 6 flashes, 3.0 s

PRACTICE

1. Easy How many times does for (int i = 0; i < 10; i++) repeat?

   Show answer

   10

2. Easy Who added the yellow light to traffic signals, and when?

Show answer

William Potts, Detroit, 1920.

3. Easy Why use const int GREEN = 8; instead of writing 8 everywhere?

Show answer

The name makes the code readable, and the pin can be changed in one place.

4. Medium How many times does for (int i = 2; i <= 10; i += 2) repeat, and with which values of i?

Show answer

5 times: 2, 4, 6, 8, 10

5. Medium A signal cycle has states of 30, 3, 1, 30, 3 and 1 s. How many cycles per hour?

Show answer

$3600/68 = 52.9$

6. Medium What does a real traffic controller's conflict monitor do?

Show answer

It independently watches the outputs and, if conflicting greens ever appear, forces the signal into flashing red.

7. Medium Find the yellow time for 20 m/s, reaction 1.0 s and braking 3.0 m/s^2.

Show answer

$1.0 + 20/6 = 4.3$ s

8. Hard In your sketch, the pedestrian "walk" light should stay on 8 s and then flash 6 times (300 ms on, 300 ms off) before turning off. Write the code for the flashing part in words or code, and find its time.

Show answer

A for loop of 6 passes: walk LED HIGH, 300 ms, LOW, 300 ms; total $6 \times 0.6 = 3.6$ s.

9. Hard Why do traffic engineers include an all-red interval?

Show answer

To let vehicles that entered on yellow clear the crossing before the cross traffic gets green.

10. Hard While delay(25000) is running, can the Arduino notice a pedestrian pressing a button? What does that suggest?

Show answer

No: delay() stops the program, so the button is missed. Long delays should be replaced by checking the time with millis() while also checking inputs (Lesson 7.3).

11. Challenge Write a function void showState(bool nsR, bool nsY, bool nsG, bool ewR, bool ewY, bool ewG, int ms) in words: what would it do, and how would it shorten the signal program? Then write the north–south yellow state as a single call.

Show answer

It sets each of the six LEDs from its argument with digitalWrite() and then waits ms milliseconds. Each state becomes one line, so the whole cycle is six calls. NS yellow: showState(false, true, false, true, false, false, 4000);

COMMON MISTAKES

- Using = (assignment) where == (comparison) is needed, or <= where < was meant in a for loop, so the loop runs one time too many.
- Forgetting to turn off the previous state's LEDs.
- Hard-coding times throughout the program so they are hard to change.

> **Make it a game · Traffic Light Timing.** Write on paper a program with a for loop and a function that runs a traffic signal. Your parent plays the controller, reading it out loud line by line, and you play the lights with colored paper. Find the bug together. Swap. Then explain the history of the signal in two sentences. Fewest bugs wins.

7.3 Digital Input and Buttons: A Reaction-Time Game

OBJECTIVES

- Read a button with digitalRead(), and explain floating inputs, pull-up and pull-down resistors and INPUT_PULLUP.
- Use if statements, comparison operators and millis() to measure time without delay().
- Explain switch bounce and debounce a button in code.
- Build a reaction-time game toy that catches early presses, and analyze reaction-time data.

> **Warm-up.** Have someone hold a ruler vertically above your open fingers and drop it without warning; catch it and read how far it fell. Do it five times. (You will turn that distance into a time in the practice set.)

WATCH

Floating Pins, Pull-Up Resistors and Arduino

Programming Electronics Academy · 10:29

https://www.youtube.com/watch?v=G_i1ZhadTa0

> **WHEN TO WATCH**
> Before the build. Watch the floating-pin demo closely: you will see the same random readings on your own board.

KEY TERMS

digitalRead()

Reads a pin set as an input and returns HIGH (about 5 V) or LOW (about 0 V).

floating input

An input connected to nothing; it picks up stray charge and reads randomly.

pull-up / pull-down resistor

A resistor (often 10 kΩ) that holds an input HIGH (to 5 V) or LOW (to ground) when the button is not pressed.

INPUT_PULLUP

A pin mode that turns on a resistor of about 20–50 kΩ inside the chip from the pin to 5 V. The button then connects the pin to ground, so pressed reads LOW.

millis()

Returns the number of milliseconds since the board started, used to measure time while the program keeps running.

CORE IDEAS

The story. In 1978 the toy company Milton Bradley released Simon, a round electronic game with four colored buttons that lit up in a sequence the player had to repeat. It was designed by Ralph Baer, an engineer and inventor of early home video-game hardware, with Howard Morrison, and it ran on a single tiny microcontroller reading four buttons. Simon became one of the best-selling toys of its era. Reaction and memory games like it are perfect first microcontroller projects, because they combine the two basic jobs of every embedded system: sensing an input and responding with an output, at the right time.

How they figured it out. A button seems simple, but engineers had to solve two problems before electronic games and keyboards could work. First, an input pin connected only to a button is connected to nothing when the button is up; it **floats** and picks up noise like an antenna, reading HIGH and LOW at random. The cure is a pull-up or pull-down resistor that holds the pin at a known level. Second, metal contacts **bounce**: for a few milliseconds after a press they open and close many times. A microcontroller is fast enough to see every bounce as a separate press, so engineers wait for the signal to settle, in hardware (Lesson 6.4) or in code.

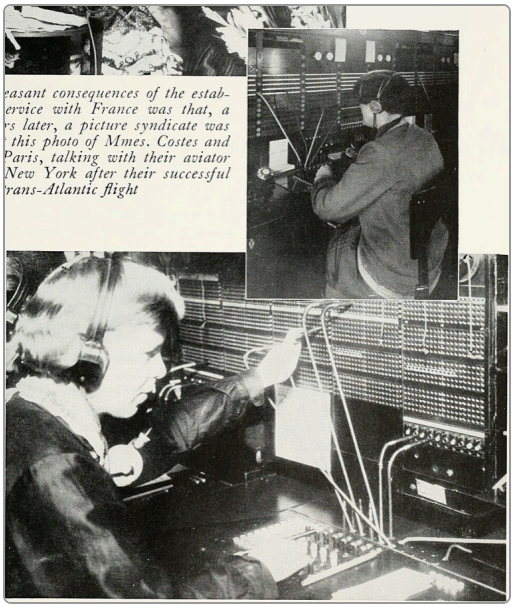
The physics and the code. With pinMode(2, INPUT_PULLUP); the chip's internal resistor (about 35 kΩ) connects pin 2 to 5 V, so a released button reads HIGH. The button connects the pin to ground when pressed, so pressed reads LOW, and only about $5\ \text{V} / 35\ \text{k}\Omega \approx 0.14\ \text{mA}$ flows. Code decides with an if statement: if (digitalRead(2) == LOW) { … }. To time something, read the clock twice: unsigned

long start = millis(); … later unsigned long elapsed = millis() - start;. Because millis() keeps counting while your loop runs, you can wait for a time and watch a button at once, which delay() cannot do. Human reaction to a light is typically 0.2–0.3 s.

The engineering. Reading the clock instead of waiting is the most important habit in embedded programming. A program that calls delay(3000) is deaf for three seconds; a program that checks millis() each time through loop() can watch several inputs, run several timers and stay responsive. Debouncing in code is simple: after detecting a change, ignore the button for about 20–50 ms. Toys must also be safe and fair: a reaction game must not reward a player who presses before the light (a “false start”), and its random wait must really be unpredictable.

Try it. You will build a reaction-time game: after a random wait the LED lights, and the program measures how fast you press the button, catches any early press, and reports your time in milliseconds.

PICTURE STUDY



A Telephone Exchange, Bell Telephone Magazine, late 1920s · Photograph · Bell Telephone Magazine (Internet Archive)

Image: Wikimedia Commons, public domain

Telephone exchanges of the 1920s, like the one on this magazine page, were full of inputs: keys, jacks and switches, each read by a person or a relay, and lamps that responded. Every press had to be noticed reliably and quickly. Your reaction game does the same job with one button and a microcontroller.

Look closely

- Find the keys, switches or jacks that are inputs.
- Find the lamps or indicators that are outputs.
- Look at how many inputs one person or panel had to watch. How would you design a system to watch them all?
- Look for anything that tells you how the equipment was labeled or organized.

Talk about it

1. How is an operator answering a lamp like your reaction game?
2. What would happen if a key “bounced” and rang a line twice?
3. How did relays and later microcontrollers replace this kind of human work?

> **Safety first.** The Arduino is powered only by its USB cable from a computer or a USB power bank, never by a wall adapter in this course. Unplug the USB cable before changing wiring. Never connect an Arduino pin straight to 5 V or ground with nothing in between, and never draw more than 20 mA from a pin: every LED needs its resistor. The game is played with a fingertip press; never strike the breadboard hard.

BUILD

The Reaction-Time Game (a Toy Build)

You will build a reaction-time game toy with a button, an LED and an optional buzzer. After a random wait the LED lights; the program times your press in milliseconds, catches early presses, and reports results to the Serial Monitor. Then you will collect data and analyze it.

You will need

- Arduino Uno and USB cable, breadboard, jumpers
- A push button, a red LED with 330 Ω, a green LED with 330 Ω (optional), a piezo buzzer (optional)
- A small box or cardboard case to make it a finished toy (optional)

Steps

1. **Floating test.** Connect a jumper to pin 2 and leave its other end loose. Upload a sketch with pinMode(2, INPUT); and, in loop(), Serial.println(digitalRead(2)); delay(100);. Watch the Serial Monitor as you move your hand near the wire. Then change to INPUT_PULLUP and see the readings settle.
2. Wire the button from pin 2 to GND (no resistor needed with INPUT_PULLUP). Wire the red LED with 330 Ω on pin 8.
3. Write the game. In setup(): Serial.begin(9600);, pinMode(2, INPUT_PULLUP);, pinMode(8, OUTPUT);, randomSeed(analogRead(A0));.
4. In loop(), first wait for the button to be released: while (digitalRead(2) == LOW) { }. Then print Get ready..., and set unsigned long goTime = millis() + random(2000, 5000);.
5. Wait for the go time while watching for a false start: while (millis() < goTime) { if (digitalRead(2) == LOW) { Serial.println("Too soon!"); delay(1000); return; } }. (The return ends this pass of loop(), which then starts over.)
6. Light the LED and time the press: digitalWrite(8, HIGH); unsigned long start = millis(); while (digitalRead(2) == HIGH) { } unsigned long t = millis() - start; digitalWrite(8, LOW);. Print it: Serial.print("Reaction time: "); Serial.print(t); Serial.println(" ms");. Then delay(1500);.

7. Play 20 rounds each for two or three people. Record every time and every false start in a table. Calculate each person's mean and range, and compare with your ruler-drop results.
8. **Improve it.** Make it a real toy: add the buzzer (a short tone(9, 1000, 100); when the LED lights, so you can test reaction to sound against reaction to light), keep a best-score variable that the game announces when beaten, and build a cardboard case with the button on top. Test it with a younger sibling or friend and write down one thing to change.

Tips

- If every round says "Too soon!", check that your button is wired to GND and the pin mode is INPUT_PULLUP.
- Use unsigned long for anything that stores millis(), because the values get large.

Check your work

- ☐ I showed a floating input and fixed it with INPUT_PULLUP.
- ☐ My game times presses with millis() and catches early presses.
- ☐ I collected at least 40 times and calculated means and ranges.

ENGINEER'S NOTEBOOK

1. The schematic and a flowchart of the game: wait for release, random wait with false-start check, light, time, report.
2. Your commented code.
3. A data table and a bar chart of each player's mean reaction time, with ruler-drop times for comparison.
4. The safety and fairness features of your toy, and one change after testing it with someone else.

KEY FORMULAS

$t_{\text{elapsed}} = \texttt{millis()}_{\text{end}} - \texttt{millis()}_{\text{start}}$
$d = \frac{1}{2} g t^2 \Rightarrow t = \sqrt{2d/g}$ (ruler drop)
$\bar{t} = \dfrac{\sum t_i}{n}$

> **From history.** Ralph Baer, who fled Germany as a teenager in 1938 and became an American engineer, also built the first home video-game console prototype in the 1960s. He received the National Medal of Technology in 2006.

WORKED EXAMPLES

Example 1. In the ruler-drop test, a ruler falls 22 cm before you catch it. What is your reaction time? ($g = 9.8\ \text{m/s}^2$.)

Show solution

1. $t = \sqrt{2d/g} = \sqrt{2(0.22)/9.8} = \sqrt{0.0449} = 0.212\ \text{s}$.

Answer: About 0.21 s (212 ms)

Example 2. Five reaction times are 231, 198, 254, 210 and 187 ms. Find the mean and the range.

Show solution

1. Mean: $(231 + 198 + 254 + 210 + 187)/5 = 1080/5 = 216\ \text{ms}$.
2. Range: $254 - 187 = 67\ \text{ms}$.

Answer: Mean 216 ms; range 67 ms

Example 3. A driver at 30 m/s (about 67 mph) has a reaction time of 0.25 s. How far does the car travel before the brakes are even touched? What if the driver is distracted and takes 1.5 s?

Show solution

1. $d = vt = (30)(0.25) = 7.5\ \text{m}$.
2. Distracted: $d = (30)(1.5) = 45\ \text{m}$, about ten car lengths.

Answer: 7.5 m; 45 m

PRACTICE

1. `Easy` With INPUT_PULLUP, what does a pressed button read? A released one?

   Show answer

   Pressed: LOW. Released: HIGH.

2. Easy Why does an unconnected input pin read randomly?

Show answer

It is floating: connected to nothing, it picks up stray charge and noise.

3. Easy Who designed the Simon game, and when was it released?

Show answer

Ralph Baer and Howard Morrison; Milton Bradley released it in 1978.

4. Medium A ruler falls 15 cm. Find the reaction time.

Show answer

$\sqrt{0.30/9.8} = 0.175$ s

5. Medium How much current flows through a 10 kΩ external pull-down when a button connects the pin to 5 V?

Show answer

0.5 mA

6. Medium What is wrong with this code for the game: delay(3000); if (digitalRead(2) == LOW) { Serial.println("Too soon"); }?

Show answer

It checks the button only once, after the 3 s delay, so presses during the wait are missed; the check must happen repeatedly during the wait, using millis().

7. Medium After unsigned long start = millis(); the board does other work, and later millis() returns a value 2,450 larger. How much time has passed?

Show answer

2,450 ms = 2.45 s

8. Hard A button bounces for 5 ms, closing and opening 8 times. A loop reads the button every 0.1 ms and counts every change from HIGH to LOW as a press. How many presses might it count? How do you fix it?

Show answer

Up to 8 presses for one real press. Fix: after detecting a press, ignore the button for about 20–50 ms (or wait until it has been steady for that long).

9. Hard Why must the random wait in a reaction game be unpredictable, and how does randomSeed(analogRead(A0)) help?

   Show answer

   If the wait were predictable, players could anticipate the light. random() gives the same sequence after every reset unless seeded; reading a floating analog pin gives a noisy value that starts the sequence differently each time.

10. Hard Your game records 20 times with a mean of 240 ms. One reading is 12 ms. What probably happened, and should it count?

    Show answer

    12 ms is far faster than human reaction (about 100 ms is the practical minimum): it was a lucky early press or a bounce slipping past the check. It should be rejected as a false start.

11. Challenge Convert your game into a two-player contest: two buttons on pins 2 and 3, one LED. Describe the logic, including false starts by either player and ties.

    Show answer

    Wait a random time while checking both buttons (either pressed early loses). Light the LED and record the start. Loop until either button is LOW; the first one read is the winner; record its time. If both read LOW in the same pass, call a tie. Then wait for both to be released before the next round. (Any correct logic accepted.)

COMMON MISTAKES

- Forgetting the pull-up, so the input floats.
- Using delay() for the random wait, so early presses are never seen.
- Storing millis() in an int, which overflows after about 32 seconds.

> **Make it a game · Pull-Up Pantomime.** Act out floating inputs. One player is the pin, the other the resistor. Show what happens with no resistor, with a pull-up and with INPUT_PULLUP. Then write an if statement that uses millis() to time a button press. Your parent tries to find a bug. Bonus point for stating a floating input in one sentence.

> **Scripture.** “Whatsoever thy hand findeth to do, do it with thy might;” (Ecclesiastes 9:10, KJV)
>
> Even a game is worth building well: fair to every player, safe for small hands, and honest in what it measures.

7.4 Analog Input: From Kelvin's Tide Machine to the ADC

OBJECTIVES

- Explain analog and digital quantities and how an analog-to-digital converter (ADC) works.
- Use analogRead(), convert readings to volts, and calculate resolution.
- Use map(), thresholds and averaging to turn sensor readings into decisions.
- Build a potentiometer voltmeter, a light meter with the Serial Plotter, and an automatic night light.

> **Warm-up.** Look at a thermometer with a liquid column (or an analog clock). Can it show any value at all between two marks? Now look at a digital thermometer or clock. How is what it can show different? Write two sentences.

WATCH

How to Use a Potentiometer with Arduino analogRead (Lesson #7)

Science Buddies · 11:51

https://www.youtube.com/watch?v=Wa8CjGsOFzY

> **WHEN TO WATCH**
> Before the build. Follow the potentiometer wiring and the Serial Monitor readings; pause at the prompt and calculate the voltage from a reading yourself.

KEY TERMS

analog

Continuously variable, able to take any value in a range, like a voltage from 0 to 5 V.

analog-to-digital converter (ADC)

A circuit that measures a voltage and gives it as a number. The Uno's ADC is 10-bit: 0 to 1023 for 0 to 5 V.

resolution

The smallest change an ADC can tell apart: $V_{\text{ref}}/2^n$. For the Uno, $5\ \text{V}/1024 \approx 4.9\ \text{mV}$.

map()

An Arduino function that rescales a number from one range to another, such as map(value, 0, 1023, 0, 100) for percent.

threshold and hysteresis

A threshold is a value at which a decision changes. Hysteresis uses two thresholds (on and off) so a reading near the boundary does not make the output flicker.

CORE IDEAS

The story. In 1872 William Thomson, later Lord Kelvin, built a machine to predict the tides. Tides are the sum of many regular cycles driven by the Moon and Sun; Kelvin's machine added them mechanically, with pulleys riding on cranks that turned at the right speeds, and a wire over the pulleys drew the predicted tide curve for a whole year in a few hours. It was an **analog computer**: it represented quantities by continuously varying positions, not by digits. Tide-predicting machines were used for harbors around the world for nearly a century. Kelvin, a devout Christian, was one of the great physicists of his age. Today we do the opposite: we turn the continuous world into numbers, with an analog-to-digital converter in every phone, camera and microcontroller.

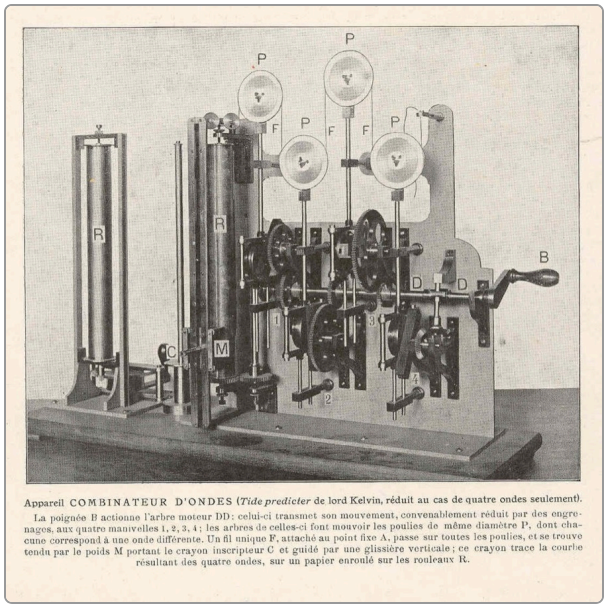
How they figured it out. Analog machines are fast and elegant but drift, wear and cannot be copied exactly. Digital numbers can be stored, copied and calculated perfectly. The bridge between them, the ADC, was worked out in the twentieth century: Alec Reeves at the International Telephone and Telegraph laboratories in Paris patented pulse-code modulation in 1938, sampling a voice signal many times a second and sending each sample as a binary number. The Uno's ADC uses a method called successive approximation: it compares the input with a voltage from an internal DAC (like your R–2R ladder of Lesson 6.2), deciding one bit at a time from the most significant down, like a game of "higher or lower."

The physics. analogRead(A0) returns a number N from 0 to 1023. Since 10 bits give 1024 levels, $V \approx N \times 5.0/1023$ (some engineers use 1024; the difference is one step). The **resolution** is about 4.9 mV. A reading takes about 0.1 ms, so the Uno can take roughly 10,000 readings a second. Any sensor that makes a voltage can be read: a potentiometer (Lesson 2.3), a photoresistor divider, a temperature sensor. Readings are noisy by a step or two; averaging several readings reduces the noise. To make decisions, compare with a **threshold**; to stop flicker near the threshold, use two thresholds (hysteresis), for example on below 300 and off above 350.

The engineering. Engineers check three things before reading a sensor: the voltage range (never above 5 V on an Uno input, or 3.3 V on a Pico, or the pin is damaged; use a divider if needed), the resolution needed, and the sampling rate. They calibrate: measure the real output at known conditions and fit a line. And they design for noise: short wires, a 0.1 µF capacitor at the sensor, averaging in code. The Serial Plotter in the Arduino IDE draws readings as a live graph, one of the best debugging tools you have.

Try it. You will turn your Arduino into a voltmeter, a light meter and an automatic night light, and graph the readings live.

PICTURE STUDY



Appareil COMBINATEUR D'ONDES (*Tide predicter* de lord Kelvin, réduit au cas de quatre ondes seulement).

La poignée B actionne l'arbre moteur DD; celui-ci transmet son mouvement, convenablement réduit par des engrenages, aux quatre manivelles 1, 2, 3, 4; les arbres de celles-ci font mouvoir les poulies de même diamètre P, dont chacune correspond à une onde différente. Un fil unique F, attaché au point fixe A, passe sur toutes les poulies, et se trouve tendu par le poids M portant le crayon inscripteur C et guidé par une glissière verticale; ce crayon trace la courbe résultant des quatre ondes, sur un papier enroulé sur les rouleaux R.

Lord Kelvin's Tide Predictor, Unknown illustrator, 1913 · Illustration · Wikimedia Commons

Image: Wikimedia Commons, public domain

This French illustration of 1913 shows Kelvin's tide-predicting machine reduced to just four wave components. The real machines combined ten or more. Each crank turns at the speed of one tidal cycle, and the wire running over all the pulleys adds them together.

Look closely

- Find the cranks. How many are there, and why would they turn at different speeds?
- Follow the wire over the pulleys to the pen. What does the pen draw?
- Find the gears that connect the cranks. How do they set each crank's speed?
- Find the paper roll. What does its motion represent?

Talk about it

1. Why is this an analog computer and not a digital one?
2. How would you represent the same tide curve in a microcontroller?
3. What are the advantages and weaknesses of each approach?

> **Safety first.** The Arduino is powered only by its USB cable from a computer or a USB power bank, never by a wall adapter in this course. Unplug the USB cable before changing wiring. Never connect an Arduino pin straight to 5 V or ground with nothing in between, and never draw more than 20 mA from a pin: every LED needs its resistor. Analog input pins must never see more than 5 V (or less than 0 V); use dividers for anything else.

BUILD

A Voltmeter, a Light Meter and an Automatic Night Light

You will read a potentiometer and turn the Arduino into a voltmeter, graph a light sensor live with the Serial Plotter, calibrate it, and build a night light with hysteresis.

You will need

- Arduino Uno and USB cable, breadboard, jumpers
- 10 kΩ potentiometer, photoresistor and a 10 kΩ resistor
- Red LED and 330 Ω resistor (or a row of 5 LEDs for a bar meter)
- Multimeter

Steps

1. **Voltmeter.** Wire the pot's outer pins to 5V and GND and its wiper to A0. In loop(): int raw = analogRead(A0); float volts = raw * 5.0 / 1023.0; Serial.print(raw); Serial.print(" "); Serial.println(volts); delay(200);.
2. Compare with your multimeter at five positions. Record raw, Arduino volts and meter volts, and the difference.
3. **Light meter.** Replace the pot with a divider: 5V → 10 kΩ → A0 → photoresistor → GND. Print only the raw reading. Open Tools → Serial Plotter and wave your hand over the sensor; sketch the graph.
4. Calibrate: record the reading in a dark closet, in room light and under a lamp. Compare with your predictions from Worked Example 2.
5. Add averaging: read 10 times in a for loop, add them in a long sum, and print sum / 10. Compare the plotter trace before and after.
6. **Night light.** Add the LED on pin 8. Use a variable bool lightOn = false;. If the reading is above 600 (dark) and the light is off, turn it on; if the reading is below 500 (bright) and the light is on, turn it off. (Adjust the numbers to your calibration.) Test at dusk or with your hand.
7. Try it without hysteresis (one threshold) and watch for flicker. Record what you see.

8. **Improve it.** Make a bar-graph light meter: five LEDs on pins 3–7, and use int bars = map(reading, darkValue, brightValue, 0, 5); with a for loop to light that many LEDs.

Tips

- Use float for volts, but int for raw readings.
- The Serial Plotter needs one number per line (or several separated by spaces).
- If readings jump wildly, check that the divider's ground and the Arduino's ground are the same.

Check your work

- ☐ My Arduino voltmeter agrees with my multimeter within a few hundredths of a volt.
- ☐ I graphed and calibrated a light sensor.
- ☐ My night light uses hysteresis and does not flicker.

ENGINEER'S NOTEBOOK

1. The table of raw, Arduino volts and meter volts, with differences.
2. Your sketch of the Serial Plotter graph and the calibration readings.
3. A graph showing the two thresholds of your night light and what the LED does as light rises and falls.
4. Your commented code.

KEY FORMULAS

$$V = N \times \frac{V_{\text{ref}}}{1023}$$

$$\text{resolution} = \frac{V_{\text{ref}}}{2^n}$$

$$\texttt{map}(x, a, b, c, d) = c + \frac{(x - a)(d - c)}{b - a}$$

From history. Kelvin also helped lay the first successful transatlantic telegraph cable (1866), designing the sensitive mirror galvanometer that detected its faint signals. He was knighted for the work and later made Baron Kelvin; the Kelvin temperature scale is named for him.

WORKED EXAMPLES

Example 1. analogRead(A0) returns 512. What voltage is on A0? What reading would 2.0 V and 3.3 V give?

Show solution

1. $V = 512 \times 5.0/1023 = 2.50$ V.
2. 2.0 V: $N = 2.0 \times 1023/5.0 = 409$.
3. 3.3 V: $N = 3.3 \times 1023/5.0 = 675$.

Answer: 2.50 V; 409 and 675

Example 2. A photoresistor is the bottom of a divider under a 10 kΩ resistor on 5.0 V. Its resistance is 1 kΩ in bright light and 100 kΩ in the dark. Predict the readings.

Show solution

1. Bright: $V = 5.0 \times 1/11 = 0.455$ V; $N = 0.455 \times 1023/5 = 93$.
2. Dark: $V = 5.0 \times 100/110 = 4.55$ V; $N = 930$.

Answer: About 93 bright and 930 dark

Example 3. What does map(700, 0, 1023, 0, 9) return (integer arithmetic)? How many bars of a 10-bar meter would light?

Show solution

1. $0 + (700 - 0)(9 - 0)/(1023 - 0) = 6300/1023 = 6.16$.
2. Integer arithmetic drops the fraction: 6.
3. So 6 bars (if bars 0–9 light up to the value, 7 LEDs counting bar 0).

Answer: 6

PRACTICE

1. Easy What is the range of analogRead() on an Uno?

   Show answer

   0 to 1023

2. Easy Find the voltage for a reading of 205.

Show answer

$205 \times 5/1023 = 1.00$ V

3. Easy What kind of computer was Kelvin's tide predictor?

Show answer

An analog computer.

4. Medium What is the resolution of a 12-bit ADC with a 3.3 V reference (as on the Pico)?

Show answer

$3.3/4096 = 0.81$ mV

5. Medium Convert a reading of 768 to a percent of full scale with map(), and in volts.

Show answer

map(768, 0, 1023, 0, 100) = 75; about 3.75 V

6. Medium Why should you never connect a 9 V battery directly to A0? How could you measure it safely?

Show answer

The input must stay between 0 and 5 V or the pin can be damaged. Use a divider, such as two 10 kΩ resistors, to halve it, and multiply the reading by 2.

7. Medium Why average several readings?

Show answer

Each reading has random noise of a step or two; averaging n readings reduces random noise (by about $\sqrt{n}$) and gives a steadier value.

8. Hard A night light turns on when the reading is below 300 and off when above 300. Near dusk it flickers. Explain and fix it.

Show answer

Noise makes the reading cross 300 back and forth. Use hysteresis: turn on below 300 and off only above 350.

9. Hard Using successive approximation on 3.1 V with a 5 V reference, give the first three decisions (most significant bits).

   Show answer

   Compare with 2.5 V: higher, bit 9 = 1. Compare with 3.75 V: lower, bit 8 = 0. Compare with 3.125 V: lower, bit 7 = 0. (The answer starts 100…)

10. Hard A 10-bit ADC samples a signal 10,000 times a second and stores 2 bytes each. How much memory does one second use? Could the Uno's 2 KB of SRAM hold it?

    Show answer

    20,000 bytes; no, far more than 2,048 bytes, so data must be sent out or reduced.

11. Challenge Calibrate a light meter: in a dark closet the reading is 920, in room light 410, under a lamp 150. You want "brightness" from 0 (dark) to 100 (lamp). Write the map() call and find the brightness in room light.

    Show answer

    map(reading, 920, 150, 0, 100); room light:
    $(410 - 920)(100)/(150 - 920) = 66.2$, so 66 with integer arithmetic.

COMMON MISTAKES

- Integer division: raw * 5 / 1023 gives whole volts only; use 5.0 and 1023.0 for decimals.
- Feeding more than 5 V into an analog pin.
- Using a single threshold for an on/off decision, which flickers near the boundary.

> **Make it a game · ADC Math Duel.** Calculation drill. Your parent gives a 10-bit reading from 0 to 1023 and a 5 V reference. Convert it to volts within fifteen seconds, then state the resolution per step. Explain hysteresis with a thermostat example. Eight correct answers in a row beats the record.

7.5 PWM and Fading: Fooling the Eye

OBJECTIVES

- Explain pulse-width modulation (PWM): frequency, duty cycle and average voltage.
- Use analogWrite() to dim LEDs and mix colors on an RGB LED.
- Explain persistence of vision and why PWM looks smooth to the eye.
- Build a breathing light and an RGB color mixer controlled by a potentiometer.

> **Warm-up.** Wave a lit flashlight or phone light in a circle in a dark room. What do you see? Now flick a light switch on and off as fast as you can. At what speed does it stop looking like flashing? Write your guess for how many flashes per second the eye can follow.

WATCH

How to Fade an LED with Arduino analogWrite (Lesson #6)

Science Buddies · 11:12

https://www.youtube.com/watch?v=QCZISwDi_Qo

> **WHEN TO WATCH**
> After the physics paragraph. Pause at the prompt and change the fade speed yourself before continuing.

KEY TERMS

PWM (pulse-width modulation)
Switching an output fully on and off rapidly, and varying the fraction of time it is on, so that the average power is controlled.

duty cycle
The fraction of each period that the signal is HIGH. With analogWrite(pin, x), duty $= x/255$.

analogWrite()
Sets a PWM output on a pin marked ~ (3, 5, 6, 9, 10, 11 on the Uno) with a value from 0 (always off) to 255 (always on).

persistence of vision
The eye and brain blend flashes faster than about 50–90 per second into steady light.

RGB LED

Three LEDs (red, green and blue) in one package; mixing their brightness makes any color.

CORE IDEAS

The story. In 1834 William Horner, an English mathematician, made the "daedaleum," a slotted drum with pictures inside; spun and viewed through the slots, the pictures seemed to move. Renamed the zoetrope by an American seller in 1867, it became a popular toy and an ancestor of motion pictures. It worked because the eye blends images and flashes that come faster than it can separate. A century later engineers used the same fact in reverse to control power: switch a light or motor fully on and off very fast, change how long it stays on in each cycle, and the eye sees steady dimming and the motor feels a steady push. This is **pulse-width modulation**, and it is how nearly every LED dimmer, motor speed control, phone screen backlight and efficient power supply works today.

How they figured it out. The old way to dim a light was a variable resistor in series, which wasted power as heat ($P = I^2R$). Engineers realized that a switch wastes almost no power, because it is either fully off (no current) or fully on (almost no voltage across it), exactly the lesson of the transistor switch in Lesson 4.2. If the switching is fast enough, the load only notices the average. So the problem became one of timing, and microcontrollers are very good at timing.

The physics. A PWM signal has a fixed frequency (about 490 Hz on most Uno pins, 980 Hz on pins 5 and 6) and a variable duty cycle. With analogWrite(9, 64) the pin is HIGH for $64/255 = 25\%$ of each 2.04 ms period, about 0.51 ms, and LOW for the rest. The average voltage is $5.0 \times 0.25 = 1.25$ V, and an LED glows at about a quarter of its full brightness (the eye's response is not linear, so it looks brighter than a quarter). A meter on DC volts shows the average. Because the eye blends flashes faster than about 50–90 per second, 490 Hz looks perfectly steady, though a quickly moving LED or a phone camera can reveal the flicker.

The engineering. PWM is efficient, simple and digital. Engineers choose the frequency to suit the load: hundreds of hertz for LEDs, a few kilohertz to tens of kilohertz for motors (above about 20 kHz they stop whining audibly), and hundreds of kilohertz for switching power supplies. Because the eye senses brightness roughly

logarithmically, smooth-looking fades use a curve rather than a straight line. With a transistor or MOSFET (Unit 4), the same 5 V PWM signal can dim a high-power LED strip or control a motor's speed. RGB LEDs mix three PWM channels to make any color, which is how every pixel of a screen works.

Try it. You will make an LED breathe, measure the average voltage, catch the flicker with a phone camera, and build a color mixer.

PICTURE STUDY



A Zoetrope Strip, Unknown printmaker, about 1860 · Print · Cooper Hewitt, Smithsonian Design Museum

Image: Wikimedia Commons, public domain

Strips like this were placed inside a spinning zoetrope drum. Seen through the slots, the separate pictures blend into one moving dog. The same property of the eye makes a flickering PWM light look steady.

Look closely

- Count the pictures in one cycle. How does each differ from the one before?
- Find where the cycle starts again. Why must the last picture lead smoothly into the first?
- Imagine the drum spinning once a second. How many pictures per second would the eye see?
- Compare this strip with a PWM signal: what plays the part of the slots?

Talk about it

1. About how fast must the pictures pass for the motion to look smooth?
2. Why does a 490 Hz PWM LED look steady but a 10 Hz one flicker?
3. Where do you see persistence of vision used in technology today?

> **Safety first.** The Arduino is powered only by its USB cable from a computer or a USB power bank, never by a wall adapter in this course. Unplug the USB cable before changing wiring. Never connect an Arduino pin straight to 5 V or ground with nothing in between, and never draw more than 20 mA from a pin: every LED needs its resistor. Do not stare into a bright LED at close range. Flickering lights can be uncomfortable for some people; keep flash rates low and warn anyone sensitive to flashing lights before running fast blink tests.

BUILD

A Breathing Light and an RGB Color Mixer

You will fade an LED with PWM, measure the average voltage, see the hidden flicker with a phone camera, then mix colors on an RGB LED, controlled by a potentiometer and by code.

You will need

- Arduino Uno and USB cable, breadboard, jumpers
- A red LED with 330 Ω; an RGB LED with three resistors (220 Ω for red, 150 Ω for green and blue, or as in Lesson 3.5)
- 10 kΩ potentiometer, multimeter, a phone camera (slow-motion video helps)

Steps

1. **Fade.** LED on pin 9 with 330 Ω. In loop(): for (int b = 0; b <= 255; b++) { analogWrite(9, b); delay(5); } then for (int b = 255; b >= 0; b--) { analogWrite(9, b); delay(5); }. Upload and time one breath.
2. **Average voltage.** Replace the fade with analogWrite(9, 64);, then 128, 191 and 255. Measure the pin's DC voltage with the meter each time and compare with $5.0 \times x/255$.
3. **See the flicker.** At analogWrite(9, 30), wave the LED quickly in the dark, or film it in slow motion with a phone. Describe the dashes you see and estimate their rate.
4. **Smooth fade.** Make a fade that looks even to the eye: inside the loop, use int level = (long)b * b / 255; (the long stops the multiplication from overflowing a 16-bit int) and analogWrite(9, level); (a squared curve). Compare the two fades side by side.
5. **RGB.** Wire the RGB LED: common lead to GND (common cathode) or 5V (common anode); red, green and blue leads through their resistors to pins 9, 10 and 11. Test each color alone with analogWrite(). (For common anode, 0 is full on and 255 is off.)
6. **Mixer.** Connect the pot's wiper to A0. Write code that reads it and sets a color: for example, int v = analogRead(A0) / 4;, then analogWrite(9, v);

analogWrite(11, 255 - v);, so the color slides from blue to red. Print the values.

7. Make a table of five colors you like with their red, green and blue values.
8. **Improve it.** Make a “mood lamp” that drifts slowly through colors using three variables that change at different rates, or a candle that flickers randomly using analogWrite(9, random(120, 255)); delay(random(30, 120));. Diffuse the light with a paper cup or ping-pong ball.

Tips

- Only pins marked ~ can do PWM; analogWrite() on other pins just turns them fully on or off.
- If the RGB colors seem backward, you probably have a common-anode LED.

Check your work

☐ I made a breathing light and measured average voltages that match $5.0 \times x/255$.

☐ I saw PWM flicker with a moving LED or camera and can explain persistence of vision.

☐ I mixed colors on an RGB LED and controlled them with a potentiometer.

ENGINEER’S NOTEBOOK

1. A sketch of PWM waveforms at 25%, 50% and 75% duty, with the average voltage marked.
2. The table of analogWrite() values, predicted and measured voltages.
3. Your color table and your mood-lamp or candle code, commented.

KEY FORMULAS

$D = \dfrac{x}{255}$ (for analogWrite(pin, x))

$V_{\text{avg}} = D \times 5.0\ \text{V}$

$t_{\text{on}} = D \times T, \quad T = \dfrac{1}{f}$

From history. Eadweard Muybridge’s 1878 photographs of a galloping horse, viewed in his zoopraxiscope, showed the motion of a horse’s legs for the first time and led toward motion pictures. Every movie and video since relies on the eye blending separate frames, just as your LED relies on it blending pulses.

WORKED EXAMPLES

Example 1. analogWrite(9, 191) on a 490 Hz pin. Find the duty cycle, average voltage, period and on-time.

Show solution

1. $D = 191/255 = 0.749 = 74.9\%$.
2. $V_{\text{avg}} = 0.749 \times 5.0 = 3.75\ \text{V}$.
3. $T = 1/490 = 2.04\ \text{ms}$; $t_{\text{on}} = 0.749 \times 2.04 = 1.53\ \text{ms}$.

Answer: 75%, 3.75 V, 2.04 ms period, 1.53 ms on

Example 2. A fade loop raises the value from 0 to 255 in steps of 1 with delay(5) each, then lowers it back. How long does one full breath take?

Show solution

1. Up: 256 values × 5 ms = 1,280 ms.
2. Down: about the same, 1,280 ms.
3. Total ≈ 2.56 s per breath.

Answer: About 2.6 s

Example 3. An LED draws 13 mA when fully on. At analogWrite(pin, 64), what is its average current? How much longer would a battery last than at full brightness (ignoring the board's own current)?

Show solution

1. Average current $= 0.251 \times 13 = 3.3\ \text{mA}$.
2. Battery life is about $1/0.251 \approx 4$ times as long.

Answer: About 3.3 mA; about 4 times as long

PRACTICE

1. Easy Which Uno pins can do PWM?

   Show answer

   3, 5, 6, 9, 10 and 11 (marked ~).

2. Easy What duty cycle does analogWrite(10, 128) give?

Show answer

About 50%

3. Easy What does a DC voltmeter show when connected to a PWM pin?

Show answer

The average voltage.

4. Medium What analogWrite() value gives an average of 2.0 V?

Show answer

$2.0/5.0 \times 255 = 102$

5. Medium Why does dimming with PWM waste less power than dimming with a series resistor?

Show answer

The switch is either fully off or fully on, so almost no power is lost in it; a resistor wastes I^2R continuously.

6. Medium Find the period and on-time for 30% duty at 980 Hz.

Show answer

$T = 1.02$ ms; on-time 0.31 ms

7. Medium Who invented the toy that became the zoetrope, and what does it show about vision?

Show answer

William Horner (1834); the eye blends rapid images or flashes into smooth motion or steady light.

8. Hard An RGB LED is set to red 255, green 128, blue 0. What color do you expect? What values would give a dim white?

Show answer

Orange. Dim white: roughly equal low values, such as 40, 40, 40 (adjusted for each color's brightness).

9. Hard A motor driven by PWM at 490 Hz whines. Why, and what would engineers change?

Show answer

The motor's coil and parts vibrate at the switching frequency, which is audible; raise the PWM frequency above about 20 kHz (using a timer setting or a dedicated driver).

10. Hard Why does a fade with equal steps of analogWrite() value look fast at the dim end and slow at the bright end?

Show answer

The eye responds roughly logarithmically: a change from 5 to 10 doubles the light and looks large, while 200 to 205 looks tiny. Fades look smoother with steps that grow in proportion (an exponential or squared curve).

11. Challenge A 12 V LED strip draws 1.5 A at full brightness, switched by a MOSFET from an Arduino PWM pin. At analogWrite(9, 51), find the duty cycle, average current and average power, and the power saved compared with full brightness.

Show answer

$D = 51/255 = 20\%$; average current 0.30 A; power $12 \times 0.30 = 3.6$ W against 18 W, saving 14.4 W.

COMMON MISTAKES

- Using analogWrite() on a pin without PWM.
- Expecting analogWrite() to make a true analog voltage. It makes a fast square wave whose average is the value.
- Writing values above 255.

> **Make it a game · Duty Cycle Drill.** Quick-fire. Your parent calls a duty cycle percentage and supply voltage; you give the average voltage. Then give the analogWrite value from 0 to 255. Explain persistence of vision in one sentence. Mix three LED colors on paper as red, green and blue values for a color your parent names. Personal record: ten correct.

UNIT 7

Arduino I: Programming a Microcontroller

Now the circuits begin to think. In this unit you will program the Arduino Uno, the board created in Ivrea, Italy, in 2005 so that artists and students could build interactive devices. You will learn the structure of a sketch, control outputs with loops and functions, read buttons correctly with pull-up resistors and debouncing, measure analog voltages with the built-in analog-to-digital converter, and dim lights and mix colors with pulse-width modulation.

Each lesson's build is a real device: a Morse beacon, a traffic signal with a pedestrian light, a reaction-time game toy, a light meter and night light, and an RGB color mixer. You will also learn the engineer's habits for code: name things clearly, comment every block, change one thing at a time, and use the clock instead of waiting blindly.

PREREQUISITES

- Units 1–6, especially LEDs and current limiting (3.5), voltage dividers (2.3), transistor switches (4.2) and binary (6.2)
- A computer on which you may install the free Arduino IDE (or use the online editor)
- An Arduino Uno–compatible board and USB cable

MASTERY CHECKLIST

- ☐ I can explain the Uno's main parts and write, verify, upload and debug a sketch.
- ☐ I can use variables, constants, for loops, if statements and functions to control outputs.
- ☐ I can read buttons with pull-ups, debounce them, and measure time with millis().
- ☐ I can read analog sensors, convert readings to volts, calibrate, average and use thresholds with hysteresis.
- ☐ I can use PWM to dim LEDs and mix colors, and calculate duty cycle and average voltage.

OPTIONAL KITS FOR THIS UNIT

- **Arduino Starter Kit**: The official kit with project book; its first projects match this unit closely.
- **ELEGOO Uno starter kits**: Uno-compatible kits with tutorials covering LEDs, buttons, potentiometers, RGB LEDs and many sensors used in Units 7–8.
- **Wokwi (free online simulator)**: Runs Arduino sketches in a browser with simulated LEDs, buttons and sensors; useful for testing code away from the bench.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

7.1	**The Arduino: The Board and the IDE**	3 sessions of 50 minutes
7.2	**Digital Output and Loops: A Traffic Signal**	3 sessions of 50 minutes
7.3	**Digital Input and Buttons: A Reaction-Time Game**	3 sessions of 50 minutes
7.4	**Analog Input: From Kelvin's Tide Machine to the ADC**	3 sessions of 50 minutes
7.5	**PWM and Fading: Fooling the Eye**	3 sessions of 50 minutes

Unit 7 test

Time: 50 minutes. A scientific calculator is allowed. Write code neatly; small syntax slips lose little credit if the logic is right. Show calculations with units. The test is worth 100 points.

1. **6 pts** **Lesson 7.1**
   Describe the structure of an Arduino sketch and what setup() and loop() are for.

2. **6 pts** **Lesson 7.1**
   Choose a resistor for a yellow LED ($V_F = 2.1$ V) at 10 mA from an Arduino pin, and say whether eight such LEDs on at once are within the chip's 200 mA total.

3. **6 pts** **Lesson 7.1**

   Explain why the Arduino team made it open source and what that did.

4. **8 pts** **Lesson 7.2**

   Write code (or exact steps) for a for loop that flashes an LED on pin 6 eight times, 100 ms on and 400 ms off. How long does it take?

5. **6 pts** **Lesson 7.2**

   A signal's states last 20, 4, 2, 15, 4 and 2 s. Find the cycle time and cycles per hour.

6. **6 pts** **Lesson 7.2**

   Find the yellow time for 18 m/s, reaction 1.0 s, braking 3.0 m/s^2, with $t = t_r + v/(2a)$.

7. **6 pts** **Lesson 7.3**

   Explain floating inputs and how INPUT_PULLUP fixes them. With INPUT_PULLUP, what does a pressed button read?

8. **8 pts** **Lesson 7.3**

   Write the logic of a reaction game that catches false starts, using millis(). Why not use delay() for the random wait?

9. **6 pts** **Lesson 7.3**

   A ruler falls 18 cm before it is caught. Find the reaction time, and how far a car at 25 m/s travels in that time.

10. **8 pts** **Lesson 7.4**

    analogRead(A2) returns 307. Find the voltage. What reading would 4.2 V give? What is the resolution?

11. **6 pts** **Lesson 7.4**

    What is hysteresis, and why does a night light need it?

12. **6 pts** **Lesson 7.4**

    How would you measure a 9 V battery with an Uno safely? Give resistor values and the conversion.

13. **8 pts** **Lesson 7.5**

analogWrite(5, 77) on a 980 Hz pin: find duty cycle, average voltage, period and on-time.

14. **6 pts** **Lesson 7.5**

Explain why PWM dimming wastes little power and why the light looks steady.

15. **8 pts** **Lesson 7.3**

Essay (one paragraph). Explain why “use the clock, don’t wait blindly” is a key habit in embedded programming, with an example from your traffic signal or reaction game.

ANSWER KEY

1. setup() runs once at power-up or reset (configure pins, start serial); loop() then runs again and again forever (the main behavior).
2. $2.9 / 0.010 = 290\ \Omega \rightarrow 330\ \Omega$ (8.8 mA); 8 × 8.8 = 70 mA: within the limit.
3. So anyone could make and improve compatible boards; boards became cheap and widely available, a large community grew, and the platform spread worldwide.
4. for (int i = 0; i < 8; i++) { digitalWrite(6, HIGH); delay(100); digitalWrite(6, LOW); delay(400); }; 4.0 s
5. 47 s; 76.6 per hour
6. $1.0 + 3.0 = 4.0$ s
7. An unconnected input picks up noise and reads randomly; INPUT_PULLUP connects an internal resistor to 5 V so the pin reads HIGH when released. Pressed (connected to ground): LOW.
8. Wait for release; set goTime = millis() + random wait; while millis() < goTime, if pressed print “Too soon” and restart; then LED on, start = millis(); wait for press; t = millis() − start; print t. delay() stops the program, so early presses would be missed.
9. $t = \sqrt{0.36 / 9.8} = 0.19$ s; $d = 4.8$ m
10. $307 \times 5 / 1023 = 1.50$ V; 859; about 4.9 mV
11. Two thresholds (on and off) separated by a gap; without it, noise near a single threshold makes the light flicker on and off.
12. A divider such as 10 kΩ over 10 kΩ halves it (4.5 V max); volts = reading × 5/1023 × 2.
13. $D = 30.2\%$; 1.51 V; $T = 1.02$ ms; on 0.31 ms
14. The transistor or pin is fully on or fully off, so little power is lost in it; the switching (490 Hz) is faster than the eye can follow, so it blends into steady light (persistence of vision).
15. A strong answer: delay() stops the processor, so it cannot read inputs or run other tasks; checking millis() each pass through loop() lets a program time events and stay responsive. Example: the pedestrian button during a long green, or a false start during the random wait.

PORTFOLIO PIECE: AN INTERACTIVE ARDUINO TOY OR TOOL

Design, build and program an interactive device that uses at least one digital input, one analog input and one PWM output, and that uses millis() timing rather than long delays. Ideas: an improved reaction game with best scores and difficulty levels, a "Simon"-style memory game, a light-following night light that fades, an RGB color-guessing game, or a metronome with a tempo knob. Submit the schematic, a flowchart, commented code, a test log and a short user guide, and have someone else use it and record their feedback.

LOOK FOR	WHAT IT MEANS
Function	Reads a digital and an analog input and drives a PWM output reliably; responsive (uses millis(), no long blind delays).
Code quality	Clear names, constants for pins and timings, functions where repeated, a comment on every block.
Hardware	Correct resistors, pull-ups, current limits and a neat, documented schematic.
Testing and users	Test log of bugs found and fixed; feedback from another user and one change made because of it.

UNIT 8

Arduino II: Sensors and Actuators

A microcontroller becomes useful when it can sense the world and act on it. In this unit you will connect the Arduino to sensors for temperature, light and distance, to actuators that move (servos and DC motors), and to a display, and you will finish by building a data logger that records a real experiment.

Each lesson begins with a story: Fessenden hearing an iceberg's echo after the *Titanic*, Maillardet's automaton that wrote its maker's name, Davenport selling a horse to buy an electromagnet, Heilmeier's first liquid-crystal displays, and Maury reading the winds from thousands of ships' logs. The builds include the second toy of the course, a servo-driven automaton, and an instrument you can leave running for a day.

PREREQUISITES

- Unit 7: sketches, digital and analog input, PWM and millis() timing
- Unit 4: transistor and MOSFET switches and flyback diodes
- Exponential curves from Lesson 3.2

MASTERY CHECKLIST

- ☐ I can read ultrasonic and temperature sensors, convert their outputs to units, and calibrate them.
- ☐ I can control a servo by angle, explain its feedback loop, and design for torque and toy safety.
- ☐ I can drive a DC motor in both directions at variable speed with an H-bridge and calculate driver losses.
- ☐ I can wire and program a character LCD and design a clear, flicker-free screen.
- ☐ I can plan, log, graph and analyze time-stamped sensor data, including fitting a cooling curve.

OPTIONAL KITS FOR THIS UNIT

- **ELEGOO Uno starter kits**: The larger kits include the HC-SR04, DHT11, servo, L293D or motor module, LCD and, in some, an SD-card or real-time-clock module used in this unit.
- **Arduino Starter Kit**: Includes the TMP36, servo, DC motor with L293D H-bridge and LCD used in this unit (add an HC-SR04 separately).
- **Adafruit (sensors and displays)**: A source of well-documented sensors, OLED displays and SD-card modules with free tutorials, if you want to extend the Unit 8 builds.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

8.1	**Sensors: Temperature, Light and Distance**	3 sessions of 50 minutes
8.2	**Servos and a Mechanical Automaton**	3 sessions of 50 minutes
8.3	**DC Motors and the H-Bridge**	3 sessions of 50 minutes
8.4	**Displays: From Segments to the LCD**	3 sessions of 50 minutes
8.5	**A Data Logger: Maury's Paths of the Seas**	3 sessions of 50 minutes

Unit 8 test

Time: 50 minutes. A scientific calculator is allowed. Show formulas, substitutions with units and answers with units; write code or logic clearly. The test is worth 100 points.

1. **6 pts** **Lesson 8.1**

   An ultrasonic echo lasts 3,500 µs at 20 °C. Find the distance. What would it be at 0 °C?

2. **6 pts** **Lesson 8.1**

   A TMP36 reads 0.68 V. Find the temperature. What analogRead() value would that be on a 5 V Uno?

3. **6 pts** **Lesson 8.1**

   Give two reasons an ultrasonic sensor might give a wrong reading and how to handle each.

4. **8 pts** **Lesson 8.2**

   What pulse width sets a servo to 60° (1.0 ms = 0°, 2.0 ms = 180°)? A servo of 2.5 kg·cm lifts a 50 g part on a 10 cm arm: find the safety factor.

5. **6 pts** **Lesson 8.2**

   Explain how a servo uses feedback, and why automata with cams are open loop.

6. **6 pts** **Lesson 8.2**

   Why should servos have a separate supply with a shared ground?

7. **8 pts** **Lesson 8.3**

   A 9.0 V pack drives a motor through an L293D with a 2.2 V drop at 0.40 A. Find the motor voltage, motor power, driver heat and driver efficiency.

8. **6 pts** **Lesson 8.3**

   Draw (describe) an H-bridge with four switches and say which are closed for each direction. What must never happen?

9. **6 pts** **Lesson 8.3**

   A motor with 4.0 Ω coil resistance runs at 0.35 A on 5.0 V. Find the back EMF and the stall current.

10. **6 pts** **Lesson 8.4**

    Why do LCDs use far less power than LED displays, and what part of an LCD module does use significant current?

11. **6 pts** **Lesson 8.4**

    Plan a 16 × 2 screen for a weather station showing temperature (one decimal), light level (0–100%) and a 3-character status (LOW, OK, HI). Write each row.

12. **6 pts** **Lesson 8.4**

    Your display flickers and shows leftover digits. Give the cause of each and the fix.

13. **8 pts** **Lesson 8.5**

    Plan a log of a greenhouse for 3 days at one reading every 2 minutes, with 24-byte CSV lines. Find the number of readings and the data size. Why must the data leave the Uno?

14. **6 pts** **Lesson 8.5**

    A sensor cools from 35 °C toward a 20 °C room; after 100 s it reads 25.5 °C. Find τ.

15. **10 pts** **Lesson 8.5**

    Essay (one paragraph). Explain how Matthew Maury's work with ships' logbooks is like a modern data logger, and what both teach about honest, standard records.

ANSWER KEY

1. $0.0343 \times 3500/2 = 60.0$ cm; at 0 °C, $v = 331$ m/s: 57.9 cm
2. 18 °C; $0.68 \times 1023/5 = 139$
3. Soft or angled targets (absorb or deflect sound): aim straight, use hard targets; stray echoes or noise (outliers): reject impossible values, take the median of several readings; also temperature (correct the speed of sound).
4. 1.33 ms; needed 0.5 kg·cm; safety factor 5
5. The servo measures its output angle with a potentiometer and drives the motor to reduce the difference from the command (closed loop). Cams drive a fixed motion with no measurement of the result (open loop).
6. Servos draw large currents when starting or stalled, which can sag the Arduino's supply and reset it; a shared ground lets the control signal be read correctly.
7. 6.8 V; 2.72 W; 0.88 W; 76%
8. Switches top-left, top-right, bottom-left, bottom-right around the motor. Forward: top-left and bottom-right; reverse: top-right and bottom-left. Never close both switches on one side (shoot-through short).
9. $5.0 - 1.4 = 3.6$ V; stall 1.25 A
10. LCDs switch light rather than making it, using microamps; the backlight LED uses most of the current (about 20 mA).
11. For example row 0: "T: 21.4 C OK" and row 1: "Light: 64 %"; any clear layout under 16 characters per row with units.
12. Flicker: clearing the whole screen too often; overwrite only changed fields. Leftover digits: shorter new values do not erase longer old ones; pad with spaces.
13. $3 \times 1440/2 = 2160$ readings; 51,840 bytes (about 52 KB); far more than the Uno's 2 KB RAM or 1 KB EEPROM.
14. $5.5 = 15e^{-100/\tau} \rightarrow \tau = 100/\ln(15/5.5) = 99.7$ s ≈ 100 s
15. A strong answer: many standard, time-stamped observations (wind, current, position) collected over time; analysis of the whole set reveals patterns invisible in single readings; standard formats (Brussels 1853, CSV today) let data be combined; accuracy and honesty matter, since false or selected data would mislead captains or engineers; outliers are noted and explained, not hidden.

PORTFOLIO PIECE: A SENSE-DECIDE-ACT INSTRUMENT

Design and build a stand-alone device that senses at least two quantities, shows them on the LCD, acts on them with a servo or motor, and logs its data. Examples: an automatic fan that turns on and speeds up with temperature and logs the room; a model “smart blind” that a servo opens with daylight; a parking assistant with an LCD bar, a beeper and a servo gate; a desk-top weather station with a moving pointer. Submit the design requirements, schematic, commented code, calibration records, a logged data set with graphs and a short report, and show it working.

LOOK FOR	WHAT IT MEANS
Sensing and calibration	Two sensors read correctly, converted to units, and calibrated against references.
Acting safely	Servo or motor driven correctly from a separate supply with a shared ground, protected, with safe limits.
Display and logging	Clear, flicker-free LCD screen with units; time-stamped CSV log graphed and analyzed.
Code and documentation	Readable, commented code using millis() timing; schematic and report complete.

8.1 Sensors: Temperature, Light and Distance

OBJECTIVES

- Tell how echo ranging began with Fessenden's oscillator after the *Titanic*, and how an ultrasonic sensor measures distance.
- Calculate distance from echo time and correct for the speed of sound at different temperatures.
- Read a temperature sensor (TMP36, DHT11 or thermistor) and convert its output to degrees Celsius.
- Build a parking-distance sensor and a thermometer, and test their accuracy against a ruler and a reference thermometer.

> **Warm-up.** Stand facing a large wall about 50 m away (with an adult, somewhere safe) and clap. Do you hear an echo? If you can time it, how long does it take? If not, imagine it: how long would sound take to go 50 m there and back at 343 m/s?

WATCH

HC-SR04 Ultrasonic Distance Sensor and Arduino (Lesson #9)

Science Buddies · 5:28

https://www.youtube.com/watch?v=n-gJ00GTsNg

> **WHEN TO WATCH**
> Before the distance build. Watch the wiring and the code for the trigger and echo pins; note the formula the presenter uses for distance.

BACKUP VIDEO

How to Use a TMP36 Temperature Sensor with Arduino (Lesson #39)

Science Buddies · 13:29

https://www.youtube.com/watch?v=5nF5R4CGZG4

For the temperature part: how a TMP36 works and how to convert its voltage to degrees. (If your kit has a DHT11 or a thermistor instead, the idea is the same.)

KEY TERMS

sensor

A device that turns a physical quantity (temperature, light, distance, pressure) into an electrical signal.

ultrasonic ranging

Measuring distance by sending a short burst of sound above human hearing (40 kHz for the HC-SR04) and timing its echo: $d = vt/2$.

speed of sound

About 343 m/s in air at 20 °C, rising about 0.6 m/s for each degree: $v \approx 331 + 0.6T$.

TMP36

An analog temperature sensor whose output is 0.50 V at 0 °C and rises 10 mV per °C: $T = (V - 0.50)/0.010$.

calibration

Comparing a sensor with a trusted reference at known points and correcting its readings.

CORE IDEAS

The story. After the *Titanic* struck an iceberg in April 1912, engineers looked for a way to detect obstacles that could not be seen. Reginald Fessenden, a Canadian-born inventor and the son of an Anglican minister, built a powerful underwater sound transmitter, the Fessenden oscillator. On April 27, 1914, off the Grand Banks of Newfoundland, he used it to send sound through the water and heard the echo from an iceberg about two miles away. It was one of the first successful tests of echo ranging. In 1917 the French physicist Paul Langevin used vibrating quartz crystals to make high-frequency sound beams, the ancestor of the ultrasonic sensors in car bumpers, robot vacuums and the HC-SR04 in your kit.

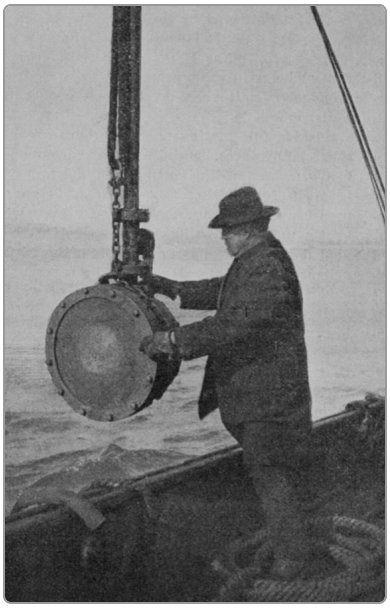
How they figured it out. The principle is simple: sound travels at a known speed, so the time for an echo to return tells the distance. The hard parts were making a short, strong pulse, hearing a faint echo, and timing it precisely. Higher frequencies make narrower beams and resolve smaller objects, but fade faster; ships use kilohertz sonar for long range, while the HC-SR04 uses 40 kHz for a few meters. Engineers also learned that the speed of sound changes with temperature, so precise instruments measure the temperature and correct for it.

The physics. The HC-SR04 sends eight 40 kHz pulses when its trigger pin is held HIGH for 10 µs, then holds its echo pin HIGH for as long as the sound takes to return. The distance is half the round trip: $d = vt/2$. With $v = 343\ \text{m/s} = 0.0343\ \text{cm}/\mu\text{s}$, an echo of 1,166 µs means $d = 0.0343 \times 1166/2 = 20.0\ \text{cm}$. Its range is about 2–400 cm. The wavelength at 40 kHz is $\lambda = v/f = 8.6\ \text{mm}$, which limits how small an object it can detect. A TMP36 temperature sensor outputs a voltage proportional to temperature: 0.50 V at 0 °C, plus 10 mV per degree, so 0.748 V means $(0.748 - 0.500)/0.010 = 24.8\ ^\circ\text{C}$. Light sensors (the photoresistor of Lesson 7.4) and thermistors are read as voltage dividers.

The engineering. Every sensor has a range, resolution, accuracy, response time and failure modes, and engineers read the datasheet for each. Ultrasonic sensors miss soft or angled objects (sound is absorbed or reflected away) and get confused by echoes from nearby walls; they work best on hard, flat targets facing them. Temperature sensors measure their own temperature, so they must be in good contact with what they measure and away from heat sources such as a warm regulator. Good designs average readings, reject impossible values (a 2,000 cm distance from a 400 cm sensor), and are calibrated against a reference.

Try it. You will build a parking-distance sensor that beeps faster as you get closer, and a thermometer, and test both against trusted references.

PICTURE STUDY



Reginald Fessenden and His Oscillator, Unknown photographer, about 1914 · Photograph · Wikimedia Commons

Image: Wikimedia Commons, public domain

Fessenden stands beside the oscillator he designed to send powerful sound through water. In 1914 it detected an iceberg by its echo and was later used for signaling between ships and for measuring the depth of the sea.

Look closely

- Look at the size of the oscillator compared with Fessenden. Why would an underwater transmitter need to be so heavy?
- Find where the sound would come out. Which way would it face when installed on a ship?
- Find any cables or connections. How was it powered and controlled?

Talk about it

1. How is this device like the small silver cylinders on your HC-SR04, and how is it different?
2. Why does sound work better than light for finding things under water?
3. What could an echo-ranging device have done for the *Titanic*?

Safety first. The Arduino runs only from its USB cable (computer or USB power bank). Motors and servos run from a separate 4-AA pack whose negative terminal is joined to the Arduino's GND; never power motors from an Arduino pin. Unplug power before rewiring. Do not point the ultrasonic sensor at pets for long; some animals can hear 40 kHz. When testing the thermometer, never heat the sensor with a flame or a hot iron; warm it with your fingers or cool it with a sealed bag of ice.

BUILD

A Parking-Distance Sensor and a Calibrated Thermometer

You will build an ultrasonic distance meter, test it against a ruler, add a beeper that speeds up as objects get closer, and build a thermometer whose readings you calibrate against a reference.

You will need

- Arduino Uno and USB cable, breadboard, jumpers
- HC-SR04 ultrasonic sensor, piezo buzzer, an LED with 330 Ω
- TMP36 temperature sensor (or the kit's DHT11 or thermistor), a kitchen or household thermometer as a reference
- Tape measure, a large book or board as a target, a sealed plastic bag of ice

Steps

1. Wire the HC-SR04: VCC → 5V, GND → GND, Trig → pin 9, Echo → pin 10. In setup(): Serial.begin(9600); pinMode(9, OUTPUT); pinMode(10, INPUT);.
2. In loop(), send a trigger pulse: digitalWrite(9, LOW); delayMicroseconds(2); digitalWrite(9, HIGH); delayMicroseconds(10); digitalWrite(9, LOW);. Then time the echo with long t = pulseIn(10, HIGH); and compute float cm = t * 0.0343 / 2;. Print t and cm, then delay(100);.
3. **Accuracy test.** Place the target at 10, 20, 50, 100 and 200 cm (measured with the tape) and record five readings at each. Make a table of true distance, mean reading and error. Graph measured against true distance.
4. Test the sensor's limits: a soft target (a pillow), a target at 45°, a thin pole. Record what happens.
5. **Parking beeper.** Add the buzzer on pin 8. Using millis(), beep for 30 ms every 10 * cm milliseconds when the target is between 10 and 100 cm, continuously below 10 cm, and not at all beyond 100 cm. Test it by walking a book toward the sensor.
6. **Thermometer.** Wire the TMP36 (flat face toward you: left pin to 5V, middle to A0, right to GND). Compute float v = analogRead(A0) * 5.0 / 1023.0; float c = (v

- 0.5) * 100.0; and print it every second. (For a DHT11, use its library from the IDE's Library Manager instead.)

7. **Calibrate.** Compare with the reference thermometer at room temperature, after holding the sensor between your fingers for a minute, and after holding it against the bag of ice. Record the errors and decide whether a simple offset correction is enough.
8. **Improve it.** Use your thermometer to correct the speed of sound in the distance sketch: float v = 331.0 + 0.6 * c; and float cm = t * (v / 10000.0) / 2;. Does the correction make a measurable difference indoors? Explain.

Tips

- If the TMP36 gets very hot, it is in backward: unplug at once and turn it around.
- pulseIn() waits up to one second for an echo; if nothing returns it gives 0, which your code should treat as "no reading."
- Point the HC-SR04 straight at the target and keep the space between clear.

Check your work

- ☐ My distance sensor is accurate to within about 1–2 cm from 10 to 200 cm, and I measured its errors.
- ☐ My parking beeper speeds up as the target approaches.
- ☐ My thermometer is calibrated against a reference, and I can convert TMP36 voltage to temperature.

ENGINEER'S NOTEBOOK

1. Schematics for both sensors.
2. The accuracy table and the graph of measured against true distance.
3. The thermometer calibration table with errors and your correction.
4. A paragraph on the limits of ultrasonic sensing you found, and where in a car each limit would matter.

KEY FORMULAS

$$d = \frac{vt}{2}$$

$$v \approx 331 + 0.6\,T \ \ (\text{m/s}, T \text{ in } ^\circ\text{C})$$

$$T_{\text{TMP36}} = \frac{V - 0.50\ \text{V}}{0.010\ \text{V}/^\circ\text{C}}$$

$$\lambda = \frac{v}{f}$$

From history. Fessenden is also remembered for what is often called the first radio broadcast of voice and music, on Christmas Eve 1906 from Brant Rock, Massachusetts, when, by his own later account, ship operators heard him play “O Holy Night” on the violin and read from the Gospel of Luke.

WORKED EXAMPLES

Example 1. An HC-SR04 echo lasts 1,166 µs at 20 °C. Find the distance. What echo time would 10 cm and 4.0 m give?

Show solution

1. $d = (0.0343\ \text{cm}/\mu\text{s})(1166\ \mu\text{s})/2 = 20.0\ \text{cm}$.
2. 10 cm: $t = 2d/v = 20/0.0343 = 583\ \mu\text{s}$.
3. 4.0 m: $t = 800/0.0343 = 23{,}300\ \mu\text{s} = 23.3\ \text{ms}$.

Answer: 20.0 cm; 583 µs; 23.3 ms

Example 2. The same 1,166 µs echo is measured in a hot garage at 30 °C. What is the true distance, and what error does assuming 343 m/s cause?

Show solution

1. $v = 331 + 0.6(30) = 349\ \text{m/s} = 0.0349\ \text{cm}/\mu\text{s}$.
2. $d = 0.0349 \times 1166/2 = 20.3\ \text{cm}$.
3. Assuming 343 m/s gives 20.0 cm: an error of 0.3 cm, about 1.7%.

Answer: 20.3 cm; 1.7% error

Example 3. A TMP36 on A0 gives analogRead() = 153 on a 5.0 V Uno. Find the temperature. What reading would 30 °C give?

Show solution

1. $V = 153 \times 5.0/1023 = 0.748$ V.
2. $T = (0.748 - 0.500)/0.010 = 24.8$ °C.
3. 30 °C: $V = 0.500 + 0.30 = 0.800$ V; reading $= 0.800 \times 1023/5.0 = 164$.

Answer: 24.8 °C; 164

Example 4. Fessenden heard an iceberg echo from about 3.2 km away in seawater, where sound travels about 1,500 m/s. How long did the echo take?

Show solution

1. $t = 2d/v = 2(3200)/1500 = 4.3$ s.

Answer: About 4.3 s

PRACTICE

1. Easy An echo takes 2,000 µs at 20 °C. How far away is the object?

   Show answer

   $0.0343 \times 2000/2 = 34.3$ cm

2. Easy Why is the distance formula divided by 2?

   Show answer

   The sound travels to the object and back; the time is for the round trip.

3. Easy What does a TMP36 output at 0 °C and at 25 °C?

   Show answer

   0.50 V; 0.75 V

4. Medium Find the speed of sound at 0 °C and at 35 °C.

   Show answer

   331 m/s; 352 m/s

5. **Medium** Find the wavelength of 40 kHz sound in air at 20 °C. Why can the sensor miss a thin wire?

Show answer

8.6 mm; an object much smaller than the wavelength reflects very little sound.

6. **Medium** A TMP36 reads 0.95 V. What is the temperature in °C and °F?

Show answer

45 °C; 113 °F

7. **Medium** Why might an ultrasonic sensor fail to see a pillow or a wall at a steep angle?

Show answer

Soft materials absorb sound; an angled hard surface reflects the echo away from the sensor.

8. **Hard** A TMP36 mounted next to the Arduino's voltage regulator reads 4 °C higher than a reference thermometer. Explain and give two fixes.

Show answer

It measures its own temperature, and the regulator warms it. Move it away on longer wires, or subtract a calibrated offset (better to move it).

9. **Hard** Your sensor gives readings of 52, 51, 53, 210 and 52 cm in five tries at a fixed object. How would you process them, and what is the result?

Show answer

Reject the impossible outlier (210, probably a stray echo) and average the rest, or take the median: about 52 cm.

10. **Hard** The HC-SR04 can range up to about 4 m. If you trigger it every 30 ms, is there time for the echo from 4 m to return before the next pulse?

Show answer

The echo from 4 m returns after about 23 ms, so yes, a 30 ms interval leaves time (the datasheet recommends at least about 60 ms to let stray echoes die out).

11. **Challenge** Design a parking sensor that beeps once per second at 100 cm and continuously at 10 cm or closer. Give a formula for the time between beeps as a function of distance and check two points.

    Show answer

    For example, interval (ms) = $10d$ for d in cm between 10 and 100: 100 cm → 1000 ms; 50 cm → 500 ms; at 10 cm or less, sound continuously. (Any reasonable design accepted.)

COMMON MISTAKES

- Forgetting to divide the echo time by 2.
- Mixing units: 0.0343 is in centimeters per microsecond.
- Wiring the TMP36 backward, which makes it hot.

> **Make it a game · Echo Estimate.** Estimation duel. Your parent names a round-trip echo time. You calculate the distance using the speed of sound at room temperature and correct for a hot day. Closest answer wins. Then tell the Fessenden and Titanic story in thirty seconds. Explain what calibration of a thermometer means. First to four points wins.

8.2 Servos and a Mechanical Automaton

OBJECTIVES

- Tell the story of eighteenth-century automata and how they stored motion in cams.
- Explain how a hobby servo uses a potentiometer and feedback to hold a position, and how pulse width sets its angle.
- Calculate servo pulse timing, torque at a lever and power needs.
- Build a servo-driven automaton toy with a linkage, triggered by a button or a sensor.

> **Warm-up.** Hold your arm straight out and close your eyes. Have someone gently push your hand down; you push back to keep it level. How do you know where your arm is without looking? Write a sentence. A servo does the same thing with a sensor and a feedback loop.

WATCH

Arduino Tutorial 30: Understanding and Using Servos in Projects

Paul McWhorter · 18:05

https://www.youtube.com/watch?v=aFHu65LiFok

> **WHEN TO WATCH**
> Before the build. Watch the wiring (three wires: power, ground, signal) and the Servo library code; pause and write down the range of angles the presenter uses.

BACKUP VIDEO

How to Control a Servo With an Arduino

The Engineering Mindset · 3:45

https://www.youtube.com/watch?v=QbgTl6VSA9Y

A short Engineering Mindset video on connecting and controlling a servo, with a potentiometer.

KEY TERMS

servo

A motor with a gearbox, a position sensor (potentiometer) and a control circuit that drives the output shaft to a commanded angle and holds it there.

feedback (closed loop)

Measuring the result and correcting toward the goal: the servo compares its actual angle with the commanded one and drives the motor to reduce the difference.

pulse width

The servo signal is a pulse every 20 ms (50 Hz); its width, about 1.0 ms to 2.0 ms, sets the angle from 0° to 180°.

cam and linkage

A cam is a shaped wheel that pushes a follower in a set pattern; a linkage is a set of bars and pivots that turns one motion into another.

torque

Turning force: force times lever arm. Servo torque is often given in kg·cm.

CORE IDEAS

The story. In the eighteenth century Swiss and French clockmakers built astonishing **automata**: mechanical figures that wrote, drew and played music. Around 1800 Henri Maillardet, a Swiss mechanician working in London, built a "Draughtsman-Writer," a kneeling boy at a desk who could draw four detailed pictures and write three poems, two in French and one in English. In 1928 its battered pieces were given to the Franklin Institute in Philadelphia, which did not know who had made it. When restorers got it working, the figure wrote a line at the end of its last poem saying that it had been made by the automaton of Maillardet, and so it told its own story. Its motions are stored in 96 brass cams, the largest mechanical memory of any automaton of its time.

How they figured it out. An automaton stores each motion as the shape of a cam. As the cam turns, a follower rides its edge and moves a lever by the right amount at the right moment; three sets of cams drive the hand in three directions. The mechanician had to work backward from the drawing to the cam shapes, filing each by hand. The weakness is that cam motion is **open loop**: if something slips, the hand

does not know. A modern servo solves this with feedback, and a microcontroller replaces the cams: the motions are numbers in code, easy to change.

The physics. A hobby servo contains a small DC motor, a gear train that trades speed for torque, a potentiometer on the output shaft that measures its angle, and a control chip. Every 20 ms the controller receives a pulse. A 1.0 ms pulse means 0°, 1.5 ms means 90°, 2.0 ms means 180° (the Arduino Servo library uses about 0.54–2.4 ms to reach the full range of most servos). The chip compares the commanded angle with the potentiometer's reading and drives the motor until they match: **closed-loop feedback**. Torque is force times lever arm, $\tau = Fr$: a small SG90 servo rated 1.8 kg·cm can hold 0.6 kg (about 5.9 N) at the end of a 3 cm arm, but only 0.18 kg at 10 cm.

The engineering. Servos are everywhere in robots, model aircraft, camera gimbals and toys. Engineers choose a servo by torque, speed (seconds per 60°), size and voltage, and they design linkages so the servo works well within its torque. They power servos from a separate supply, because a servo can draw several hundred milliamperes when it starts or stalls, enough to reset a microcontroller on USB power; the supplies share a ground. They avoid driving a servo against its end stops, which stalls it and heats it. And a toy must be safe: no pinch points where small fingers can be caught, no small parts that can come loose, and smooth, rounded edges.

Try it. You will program a servo, measure its angles, then build a cardboard automaton toy whose motion is stored in code instead of cams.

PICTURE STUDY



Maillardet's Automaton, Henri Maillardet (maker); photograph Daderot, about 1800 (photographed 2011) · Brass, steel and wood automaton · The Franklin Institute, Philadelphia

Image: Wikimedia Commons, public domain

Maillardet's Draughtsman-Writer sits on a cabinet that holds its "memory": stacks of brass cams. As the cams turn, followers move the figure's hand in three directions, so that it draws and writes. It is a program made of metal.

Look closely

- Find the figure's hand and pen. In how many directions must the hand move to write?
- Find the stack of cams in the cabinet. Why would each cam have a different shape?
- Look for the levers that connect the cams to the figure. Which parts act like a servo's output arm?
- Look for the spring motor or winding mechanism that powers it.

Talk about it

1. How is changing a drawing on this automaton different from changing the angles in your servo code?
2. The automaton has no feedback. What would happen if its pen slipped?

3. Why do you think automata like this were made, and what did they teach engineers?

Safety first. The Arduino runs only from its USB cable (computer or USB power bank). Motors and servos run from a separate 4-AA pack whose negative terminal is joined to the Arduino's GND; never power motors from an Arduino pin. Unplug power before rewiring. Keep fingers out of the linkage while the servo is powered; servos are strong enough to pinch. Use a craft knife only with an adult, cutting away from yourself on a cutting mat, and a low-temperature glue gun with care.

BUILD

A Servo-Driven Automaton (a Toy Build)

You will measure a servo's range and speed, then design and build a cardboard automaton, such as a blacksmith hammering an anvil, a bird flapping its wings or a figure waving hello, whose motion is stored in code. It moves when someone presses a button or approaches the ultrasonic sensor.

You will need

- Arduino Uno and USB cable, an SG90 (or similar) micro servo with horns, a push button (and optionally the HC-SR04)
- A 4-AA holder for the servo, jumpers, breadboard
- Cardboard, wooden skewers or craft sticks, paper fasteners (brads), tape, a low-temperature glue gun, markers
- Protractor, ruler, a stopwatch

Steps

1. Wire the servo: brown (or black) to the 4-AA pack's − and to the Arduino's GND; red to the 4-AA pack's +; orange (or yellow) signal to pin 9.
2. Test it: #include <Servo.h> at the top, Servo arm; before setup(), and in setup() arm.attach(9);. In loop(), arm.write(0); delay(1000); arm.write(90); delay(1000); arm.write(180); delay(1000);.
3. Measure: tape a paper protractor behind the horn and record the real angle for commands 0, 45, 90, 135 and 180. Time a 0-to-180 move with a slow-motion video. Note any buzzing at the ends (the servo pushing against its stop) and choose safe limits, such as 10 to 170.
4. Design your automaton on paper: the figure, the pivot points, and a linkage (a bar connecting the servo horn to the moving part, like a crank and rod). Estimate the torque needed (Worked Example 2).
5. Build it from cardboard and skewers, with brads as pivots. Mount the servo firmly with glue or tape. Check by hand (power off) that the linkage moves freely without binding.

6. Program the motion: a function void performShow() that moves the servo through a sequence (for example, ten hammer blows with for loops of small steps for smooth motion). Trigger it when the button on pin 2 (INPUT_PULLUP) is pressed, or when the ultrasonic sensor sees someone closer than 50 cm.
7. Test with a family member. Watch for binding, wobbling and pinch points; fix them.
8. **Improve it.** Make the motion lifelike: slow down near the ends of each stroke (smaller steps), add a pause, or add a second servo for a second motion. Then do a toy-safety check: list every pinch point and small part, and add a cardboard guard over the linkage.

Tips

- The Servo library uses the timer for pins 9 and 10, so analogWrite() on those pins will not work while it is attached.
- If the Arduino resets whenever the servo moves, its power is sagging: use the separate battery pack.
- Cardboard linkages last longer with a dab of glue on each end of a skewer pivot.

Check your work

- ☐ I measured my servo's real angles and speed and chose safe limits.
- ☐ My automaton moves smoothly, triggered by a button or sensor, without binding.
- ☐ I designed for torque and for toy safety, with guards over pinch points.

ENGINEER'S NOTEBOOK

1. The servo test table: commanded and measured angles, and the timed sweep.
2. Your automaton design sketch with pivots, linkage lengths and the torque estimate.
3. The commented code of your show.
4. A toy-safety checklist and the changes you made.

KEY FORMULAS

$$\text{angle} \approx 180^\circ \times \frac{t_{\text{pulse}} - 1.0\ \text{ms}}{1.0\ \text{ms}} \ \text{(typical)}$$

$$\tau = Fr$$

$$f = \frac{1}{20\ \text{ms}} = 50\ \text{Hz}$$

From history. Pierre Jaquet-Droz and his son built three famous automata in the 1770s, the Writer, the Draughtsman and the Musician, still working today in the museum of Neuchâtel, Switzerland. The Writer can be set to write any text of up to 40 letters by changing a wheel of interchangeable cams: an early programmable machine.

WORKED EXAMPLES

Example 1. A servo maps 1.0 ms to 0° and 2.0 ms to 180°. What pulse width gives 45°? What duty cycle is a 1.5 ms pulse every 20 ms?

Show solution

1. $t = 1.0 + (45/180)(1.0) = 1.25$ ms.
2. Duty: $1.5/20 = 7.5\%$.

Answer: 1.25 ms; 7.5%

Example 2. An SG90 servo is rated 1.8 kg·cm. Your automaton arm lifts a 40 g cardboard hammer at the end of an 8 cm arm. Is the servo strong enough, and with what safety factor?

Show solution

1. Needed torque: $0.040\ \text{kg} \times 8\ \text{cm} = 0.32$ kg·cm (plus the arm's own weight).
2. Safety factor: $1.8/0.32 = 5.6$.
3. Yes, with plenty of margin, even if the arm itself adds a little.

Answer: Yes; about 5.6 times the torque needed

Example 3. Two servos each draw 150 mA moving and up to 650 mA when stalled. Can they run from the Uno's 5 V pin on USB (about 500 mA available)?

Show solution

1. Moving: $2 \times 150 = 300$ mA, plus the Uno's own 50 mA: 350 mA, close to the limit.
2. Stalled: up to 1.3 A, far over 500 mA; the voltage would sag and the Uno could reset.
3. Use a separate 4-AA pack for the servos, with its ground joined to the Uno's GND.

Answer: No; use a separate supply with a shared ground

PRACTICE

1. Easy Name the four main parts inside a hobby servo.

   Show answer

   A DC motor, a gearbox, a potentiometer (position sensor) and a control circuit.

2. Easy How often does a servo receive a control pulse, and how wide is the pulse for the middle position?

   Show answer

   Every 20 ms (50 Hz); about 1.5 ms.

3. Easy What did Maillardet's automaton write that revealed its maker?

   Show answer

   A line at the end of its last poem saying it was made by the automaton of Maillardet.

4. Medium What pulse width gives 120° (1.0 ms = 0°, 2.0 ms = 180°)?

   Show answer

   1.67 ms

5. Medium An SG90 (1.8 kg·cm) moves a lever. What is the largest mass it can hold at 6 cm?

   Show answer

   0.30 kg

6. Medium Explain the difference between open-loop and closed-loop control, using a cam automaton and a servo.

Show answer

A cam drives a fixed motion without checking the result (open loop). A servo measures its actual angle and corrects toward the command (closed loop).

7. Medium Why should a servo and an Arduino share a ground when powered separately?

Show answer

The control pulse is measured relative to ground; without a common ground the servo cannot read the signal reliably.

8. Hard A servo turns 60° in 0.12 s (no load). How long does a full 180° sweep take? What is its average angular speed in degrees per second and in turns per minute (rpm)?

Show answer

0.36 s; 500 °/s; about 83 rpm

9. Hard Maillardet's automaton stored seven pieces (four drawings and three poems) in 96 cams. About how many cams is that per piece? Compare its memory with an Arduino's.

Show answer

About 14 cams per piece (96/7). An Arduino's 32 KB of flash could store the coordinates of thousands of drawings; the automaton's memory was brass, the Arduino's is silicon, but both store a program of motions.

10. Hard List three safety features a servo toy for young children should have.

Show answer

Any three: no pinch points (guard the linkage), no small detachable parts, rounded edges, a sealed battery compartment with a screw (especially for coin cells), low speed and force, a power switch.

11. **Challenge** An automaton's arm moves from 30° to 150° and back once every 2.0 s in steps of 2°. In code, what delay between steps gives that timing? Write the loop in words.

    Show answer

    Each sweep is 120°/2° = 60 steps; there and back is 120 steps in 2.0 s, so about 16.7 ms per step (use 17 ms). Loop: for angle from 30 to 150 in steps of 2, write the angle and wait 17 ms; then from 150 down to 30 the same.

COMMON MISTAKES

- Powering a servo from the Arduino's 5 V pin and getting random resets.
- Commanding angles beyond the servo's physical stops, so it buzzes and heats.
- Forgetting to join the grounds of the two supplies.

> **Make it a game · Servo Acting.** Act as a hobby servo. Your parent sets a pulse width in milliseconds and you point your arm to the angle it commands, using feedback from your own sense of position. Then explain the cam in an eighteenth-century automaton. Draw a cam that makes a bird bob. Personal record: eight correct angles in a row.

8.3 DC Motors and the H-Bridge

OBJECTIVES

- Tell the story of Thomas Davenport's motor and explain how a DC motor turns.
- Explain how an H-bridge reverses a motor and how PWM controls its speed.
- Wire an L293D motor driver, calculate its voltage drop and power, and choose a motor supply.
- Build a motor controller with direction, speed, a potentiometer and a stop, and measure the motor's speed and current.

> **Warm-up.** Spin the kit's small motor's shaft between your fingers while its two wires touch an LED's legs. Does the LED flicker? Now turn it the other way. A motor can be a generator too. Write what you think is happening.

WATCH

DC Motor Control with an H-Bridge and Arduino (Lesson #17)

Science Buddies · 19:16

https://www.youtube.com/watch?v=YU17L650k3s

> **WHEN TO WATCH**
> Before the build. Follow how the L293D connects to the Arduino and motor; pause on the pinout diagram and copy it into your notebook.

KEY TERMS

DC motor

A motor in which current in a coil, in the field of a magnet, makes a turning force. A commutator reverses the coil current each half turn so the rotation continues.

H-bridge

Four switches arranged like the letter H around a motor. Closing one diagonal pair drives current one way; the other pair reverses it.

L293D

A chip with two H-bridges (up to about 600 mA each) and built-in protection diodes, with separate supplies for logic (5 V) and motors.

back EMF

The voltage a spinning motor generates, which opposes the supply; it is why a motor draws much more current when stalled than when running.

stall current

The current a motor draws when it is prevented from turning; much higher than its running current.

CORE IDEAS

The story. In 1833 Thomas Davenport, a blacksmith in Brandon, Vermont, saw one of Joseph Henry's electromagnets lifting iron and was so taken with it that he sold his brother's horse to buy one. He took it apart to see how it worked, and by 1834 he had built a rotating electric motor. On February 25, 1837, he received the first United States patent for an electric motor. Davenport used his motors to run a small printing press and a model electric train, but the batteries of the day were too expensive to compete with steam, and he died poor in 1851. Only after generators made cheap electricity possible, decades later, did his idea power the world: today electric motors use a large share of all the electricity generated.

How they figured it out. The key was to keep the turning force always in the same direction. A current-carrying coil in a magnetic field feels a force, but as the coil turns past halfway, the force would pull it back. Davenport and others used a **commutator**, a split ring with brushes that reverses the coil current every half turn, so that the coil keeps turning. To run a motor backward, reverse the supply. Engineers later built the **H-bridge** so that electronic switches could reverse the motor on command without moving any wires.

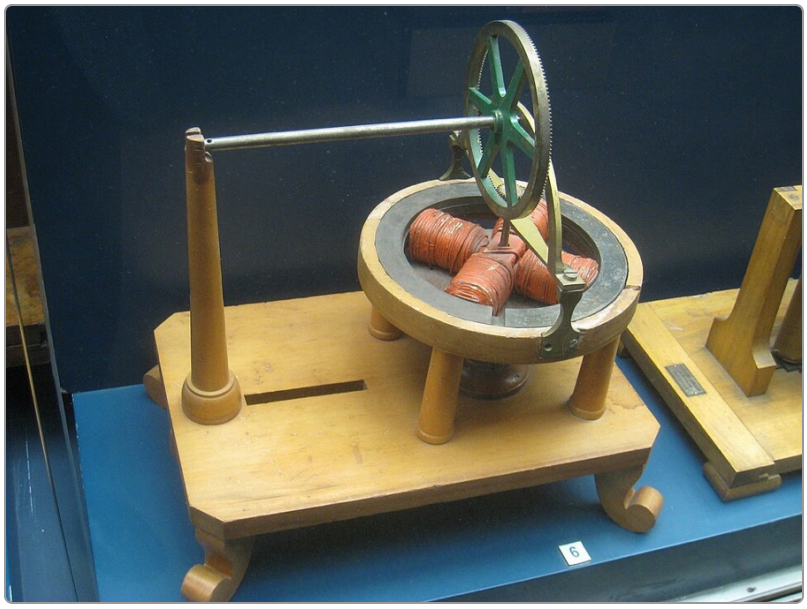
The physics. A DC motor's speed rises with voltage and its torque rises with current. As it spins faster, it generates a back EMF that opposes the supply, so the current falls; at stall there is no back EMF, and the current is limited only by the coil's resistance, often several times the running current. An H-bridge has four switches: closing the top-left and bottom-right sends current one way; top-right and bottom-left the other. Never close both switches on one side at once, or the supply is shorted

("shoot-through"). The L293D makes the H-bridge from transistors, with logic inputs: IN1 HIGH and IN2 LOW turns the motor forward, IN1 LOW and IN2 HIGH reverses it, both LOW stops it; PWM on the enable pin sets the speed. Its transistors drop about 1.5–2.5 V in total, so a 6 V supply gives the motor about 4 V, and the chip turns the rest into heat: at 0.30 A and 2 V, 0.6 W.

The engineering. Engineers choose a driver by the motor's voltage, its running and stall current, and efficiency. The L293D is simple and protected but inefficient; MOSFET-based drivers (such as the TB6612FNG or DRV8833) waste far less. They power motors from a separate supply, add capacitors across the motor terminals to reduce electrical noise, include flyback diodes (built into the L293D), and limit current so a stalled motor cannot overheat. Many products also measure the motor current to detect a jam and stop safely.

Try it. You will drive the kit's motor forward and backward at different speeds with an L293D and a potentiometer, and measure its current and speed.

PICTURE STUDY



An Electric Motor of 1837, Unknown maker; museum photograph, 1837 · Photograph of an early motor · Wikimedia Commons

Image: Wikimedia Commons, public domain

This early electric motor dates from 1837, the year of Davenport's patent. Motors of this period used electromagnets wound like Henry's, a rotating part, and contacts that switched the current as it turned, the first commutators.

Look closely

- Find the electromagnets. Which parts are fixed and which turn?
- Find the contacts that switch the current. When in each turn would they need to switch?
- Find where the battery wires would connect.
- Compare it with the kit's small motor. What has stayed the same?

Talk about it

1. Why must the current be switched as the motor turns?
2. Why were motors like this a curiosity rather than a business in 1837?
3. What does an H-bridge add that this motor did not have?

> **Safety first.** The Arduino runs only from its USB cable (computer or USB power bank). Motors and servos run from a separate 4-AA pack whose negative terminal is joined to the Arduino's GND; never power motors from an Arduino pin. Unplug power before rewiring. Hold the motor or fix it to the bench so it cannot jump around. Do not stall the motor for more than a second or two. Keep hair and loose clothing away from a spinning shaft or wheel, and wear safety glasses if anything is attached to the shaft.

BUILD

A Two-Way Speed-Controlled Motor

You will wire an L293D to drive the kit's DC motor forward and backward, control its speed with PWM from a potentiometer, measure the voltage drop and current, and estimate the motor's speed.

You will need

- Arduino Uno and USB cable, the kit's L293D chip (or a motor-driver module), the small DC motor, the 10 kΩ potentiometer, a push button
- 4-AA holder (6 V) for the motor; jumpers, breadboard
- Multimeter; a small paper flag or tape on the motor shaft; a phone with slow-motion video

Steps

1. Wire the L293D across the center gap (notch left): pins 4, 5, 12 and 13 to GND; pin 16 (logic VCC) to Arduino 5V; pin 8 (motor VCC) to the 4-AA pack's +; the pack's − to GND. Pin 1 (enable) to Arduino pin 9; pin 2 (IN1) to pin 4; pin 7 (IN2) to pin 5; pins 3 and 6 to the motor.
2. Test: in setup(), set pins 4, 5 and 9 as outputs. In loop(): forward (digitalWrite(4, HIGH); digitalWrite(5, LOW); analogWrite(9, 200);) for 2 s; stop (both LOW) 1 s; reverse (swap) 2 s; stop 1 s.
3. Measure the battery voltage, the voltage across the motor and the motor current while running forward at full speed (analogWrite(9, 255)). Calculate the L293D's drop and power.
4. Speed control: connect the pot's wiper to A0 and set analogWrite(9, analogRead(A0) / 4);. Measure the average motor voltage at five settings, and find the lowest value at which the motor starts from rest.
5. Estimate speed: tape a small paper flag to the shaft and film it in slow motion (240 frames per second) at full speed. Count frames per turn and calculate rpm. (Or listen to its pitch with a tuner app.)
6. Gently pinch the shaft to slow it (briefly, with care) and watch the current rise. Record the current near stall. Do not hold it stalled.

7. Combine: write the two-way pot control of practice problem 11, with a dead zone. Add a push button that stops the motor instantly when pressed, whatever the pot says.
8. **Improve it.** Add a soft start: when the motor starts or changes direction, ramp the speed up over half a second instead of jumping. Explain how this reduces the current surge and wear.

Tips

- If the motor only hums, the PWM value is too low to overcome friction; start higher and then slow down.
- The L293D gets warm at high currents; that is its voltage drop turning into heat.
- Some kits include an L298N module instead; it works the same way with its IN and EN pins.

Check your work

- ☐ My motor runs forward, backward and at variable speed under program control.
- ☐ I measured the driver's voltage drop and power and the motor's current, including near stall.
- ☐ I added an emergency stop and a soft start.

ENGINEER'S NOTEBOOK

1. The L293D wiring diagram with pin numbers, and a schematic of the H-bridge idea with four switches.
2. Measurements: supply, motor voltage, driver drop, current, power and efficiency.
3. A table of PWM value, average voltage and estimated speed, with a graph.
4. A paragraph on Davenport and why the electric motor had to wait for the generator.

KEY FORMULAS

$V_{\text{motor}} \approx V_{\text{supply}} - V_{\text{drop}}$
$P_{\text{driver}} = V_{\text{drop}}\, I$
$V_{\text{avg}} = D \times V_{\text{motor}}$ (PWM)
$P_{\text{mech}} = \tau\omega$

From history. Moritz Jacobi in St. Petersburg built a large battery-powered motor in 1838 that drove a boat carrying passengers on the Neva River at about walking pace. Like Davenport's, it worked but could not compete with steam until electricity became cheap.

WORKED EXAMPLES

Example 1. A 6.0 V battery pack drives a motor through an L293D that drops about 2.0 V. The motor draws 0.30 A. Find the motor voltage, motor power, driver power and efficiency of the driver.

Show solution

1. Motor voltage: $6.0 - 2.0 = 4.0\ \text{V}$.
2. Motor power: $4.0 \times 0.30 = 1.2\ \text{W}$.
3. Driver loss: $2.0 \times 0.30 = 0.60\ \text{W}$.
4. Efficiency: $1.2 / 1.8 = 67\%$.

Answer: 4.0 V; 1.2 W; 0.6 W lost; 67%

Example 2. With analogWrite(enablePin, 180), what average voltage does the motor see in Example 1?

Show solution

1. Duty: $180 / 255 = 0.706$.
2. Average: $0.706 \times 4.0 = 2.8\ \text{V}$.

Answer: About 2.8 V

Example 3. A motor has a coil resistance of 5.0 Ω and runs at 0.30 A on 4.0 V. Find its stall current and the back EMF while running.

Show solution

1. Stall: no back EMF, so $I = 4.0 / 5.0 = 0.80\ \text{A}$.
2. Running: $V = IR + E_{\text{back}}$, so $E_{\text{back}} = 4.0 - (0.30)(5.0) = 2.5\ \text{V}$.

Answer: 0.80 A at stall; 2.5 V back EMF

PRACTICE

1. Easy What does a commutator do?

Show answer

It reverses the current in the motor's coil every half turn so the torque keeps turning the rotor the same way.

2. Easy For an L293D, give IN1 and IN2 for forward, reverse and stop.

Show answer

Forward: HIGH, LOW. Reverse: LOW, HIGH. Stop: LOW, LOW (or both HIGH, a brake).

3. Easy Who received the first U.S. patent for an electric motor, and when?

Show answer

Thomas Davenport, February 25, 1837.

4. Medium Why must the two switches on the same side of an H-bridge never be closed together?

Show answer

They would connect the supply directly to ground (shoot-through), a short circuit that can destroy the switches.

5. Medium A motor on 4.5 V draws 0.25 A running. What is its electrical power? If it is 60% efficient, what is its mechanical power?

Show answer

1.125 W; 0.675 W

6. Medium Why does a stalled motor draw more current than a running one?

Show answer

A running motor generates back EMF opposing the supply; stalled, there is no back EMF, so only the coil resistance limits the current.

7. Medium With a 4.0 V motor voltage, what analogWrite() value gives an average of 2.0 V?

Show answer

About 128

8. Hard A driver drops 2.4 V at 0.5 A from a 9 V battery. Find the motor voltage, driver heat, and how a MOSFET driver with 0.3 Ω total resistance would compare.

Show answer

6.6 V; 1.2 W. MOSFET: drop $0.5 \times 0.3 = 0.15$ V, loss 0.075 W, motor gets 8.85 V.

9. Hard Davenport's motors worked, but he could not sell them. Explain why, in engineering terms.

Show answer

They ran on expensive, short-lived batteries, while steam engines ran on cheap fuel; without a cheap source of electricity (generators came decades later), electric motors could not compete on cost.

10. Hard A small motor spins at 9,000 rpm with a torque of 0.0012 N·m. Find its mechanical power. ($\omega = 2\pi \times \text{rpm}/60$.)

Show answer

$\omega = 942$ rad/s; $P = 1.13$ W

11. Challenge Write the logic (words or code) for a motor controller with a potentiometer: center position stops the motor; turning right speeds it forward; turning left speeds it in reverse. Include a dead zone around center.

Show answer

Read pot (0–1023). If between 462 and 562, stop (IN1 = IN2 = LOW, speed 0). If above 562, forward with speed map(pot, 562, 1023, 0, 255). If below 462, reverse with speed map(pot, 462, 0, 0, 255). Write the speed to the enable pin with analogWrite().

COMMON MISTAKES

- Powering the motor from pin 16 (logic) instead of pin 8 (motor supply), or from the Arduino's 5 V pin.
- Forgetting to connect the enable pin, so the motor never runs.
- Changing direction instantly at full speed, which causes current surges.

> **Make it a game · H-Bridge Switch Game.** Draw an H-bridge on paper. Your parent calls forward, reverse, brake and stop, and you mark which four switches are closed. Wrong marks cost a point. Never close both switches on one side: say why. Then explain back EMF and stall current in one sentence each. Ten correct calls wins.

> **Scripture.** “O LORD, how manifold are thy works! in wisdom hast thou made them all: the earth is full of thy riches.” (Psalm 104:24, KJV)
>
> Magnetism and current, the forces that turn every motor, were waiting in creation for Davenport to put them to work. The earth is full of such riches for engineers to find.

8.4 Displays: From Segments to the LCD

OBJECTIVES

- Trace the history of electronic displays from segmented lamps to the liquid-crystal display.
- Explain how a character LCD works and how it is driven in 4-bit mode.
- Format numbers and text for a 16 × 2 display, and calculate display data and timing.
- Build an LCD thermometer and distance display, and design a readable screen layout.

> **Warm-up.** Look at a digital clock, a microwave or a calculator. Draw the shape of the number 8 on its display. How many separate segments make it? Which segments are lit for 4? For 7?

WATCH

How to Use an LCD Screen with an Arduino (Lesson #21)

Science Buddies · 10:00

https://www.youtube.com/watch?v=s_-nIgo71_w

> **WHEN TO WATCH**
> Before the build. Follow the wiring of the 16-pin LCD and the contrast potentiometer; pause at the pin list and check it against your own display.

KEY TERMS

seven-segment display

A numeral made of seven bars (a–g) that are lit in patterns to show 0–9.

character LCD (16 × 2)

A display of 2 rows of 16 characters, each a 5 × 8 dot matrix, controlled by an HD44780-compatible chip.

LCD (liquid-crystal display)

A display in which liquid crystals between polarizing filters twist light so that each segment or pixel appears dark or clear when a voltage is applied.

4-bit mode

Sending each 8-bit character as two 4-bit halves over four data wires (D4–D7), saving pins.

contrast

The voltage on the LCD's V0 pin, set by a potentiometer, that makes the characters visible.

CORE IDEAS

The story. In 1908 Frank W. Wood filed a patent for a numeral display made of segments of lamps, the ancestor of the seven-segment "8" on every clock. Displays of glowing gas-filled "Nixie" tubes, introduced in the 1950s, showed bright orange numerals, and red LED segments filled calculators and watches in the early 1970s, though they drained batteries quickly. The breakthrough for low power came from liquid crystals, materials that flow like liquids but order their molecules like crystals. In 1964–1968 George Heilmeier and his team at RCA Laboratories in Princeton, New Jersey, showed that liquid crystals could make electronic displays. In 1973 Sharp sold a pocket calculator with an LCD that ran for about a hundred hours on a single battery, and the LCD soon took over watches, calculators and, decades later, computer and phone screens.

How they figured it out. The first LCDs scattered light and needed high voltages and careful conditions. The twisted nematic (TN) design of the early 1970s, developed by researchers in Switzerland and the United States, solved this: a thin layer of liquid crystal twists polarized light by 90°, so that it passes through a second, crossed polarizer. A small voltage untwists the molecules, the light is blocked, and that segment turns dark. Because an LCD only switches light rather than making it, it uses microwatts, a tiny fraction of the power of LEDs or tubes. Character LCDs added a dot matrix and a controller chip; Hitachi's HD44780, introduced in the 1980s, became a standard so universal that nearly every 16 × 2 display today still speaks its language.

The physics. Each character on a 16 × 2 display is a 5 × 8 grid of dots, so the whole display has $32 \times 40 = 1{,}280$ dots, but you never control them one by one: you send character codes (ASCII, such as 65 for "A"), and the controller draws them from its built-in font. In 4-bit mode the Arduino uses six wires: RS (command or character), E (the strobe that says "read now") and D4–D7. The LiquidCrystal library hides the details: lcd.setCursor(col, row) chooses a position and lcd.print() writes text or numbers. LCD segments must be driven with alternating voltage, or they slowly

break down; the controller chip does that for you. The backlight is a separate LED that needs its own resistor.

The engineering. A good display is designed for its reader: the most important number large or first, units always shown, no flicker, and enough contrast in the room where it will be used. Engineers plan the screen on graph paper, 16 squares by 2, and update only what changes, because clearing and rewriting the whole display causes visible flicker. They also budget power: the LCD itself uses less than a milliamp, but its backlight may use 20 mA or more. Many projects now use small OLED or e-paper displays, but the planning is the same.

Try it. You will wire a 16 × 2 LCD, display your own text, and turn your sensors of Lesson 8.1 into a stand-alone instrument with a readable screen.

PICTURE STUDY



The Apollo Display and Keyboard (DSKY), NASA, 1960s · Photograph · Wikimedia Commons

Image: Wikimedia Commons, public domain

Apollo astronauts read the guidance computer's numbers on these seven-segment electroluminescent displays, glowing green, and typed commands as two-digit "verb" and "noun" codes. It is the same segmented idea as Wood's 1908 patent and your microwave's clock.

Look closely

- Find the seven-segment digits. How many digits can the panel show at once?
- Which segments would light to show 5?
- Find the warning lights at the left. Why use labeled lamps instead of words on a screen?
- Find the VERB and NOUN keys. Why would short number codes suit a small numeric display?

Talk about it

1. Why is a segmented display easier to build and drive than a full picture, especially in a spacecraft?
2. What are its limits? Which letters can a seven-segment display not show well?
3. How does your 16 × 2 LCD solve those limits?

> **Safety first.** The Arduino runs only from its USB cable (computer or USB power bank). Motors and servos run from a separate 4-AA pack whose negative terminal is joined to the Arduino's GND; never power motors from an Arduino pin. Unplug power before rewiring. LCD modules have glass panels; handle them by the edges and do not press on the glass.

BUILD

An LCD Instrument

You will wire a 16 × 2 character LCD, display text and live numbers, and combine it with your Lesson 8.1 sensors to make a stand-alone thermometer and distance meter with a clear, flicker-free screen.

You will need

- Arduino Uno and USB cable, a 16 × 2 LCD (HD44780-compatible; some kits supply it with an I^2C adapter on the back)
- A 10 kΩ potentiometer for contrast, a 220 Ω resistor for the backlight if needed
- The TMP36 and HC-SR04 from Lesson 8.1, a push button
- Breadboard, jumpers, graph paper

Steps

1. Wire the LCD (if it has no I^2C adapter): VSS → GND, VDD → 5V, V0 → pot wiper (pot ends to 5V and GND), RS → pin 12, RW → GND, E → pin 11, D4 → 5, D5 → 4, D6 → 3, D7 → 2, A (backlight +) → 220 Ω → 5V, K → GND. (For an I^2C display, use its four wires and the LiquidCrystal_I2C library instead.)
2. Test: #include <LiquidCrystal.h>, then LiquidCrystal lcd(12, 11, 5, 4, 3, 2); before setup(). In setup(), lcd.begin(16, 2); lcd.print("Hello, engineer");. Upload and turn the contrast pot until the text is sharp.
3. Show a counter: in loop(), lcd.setCursor(0, 1); lcd.print(millis() / 1000); lcd.print(" s "); and delay(200);. Notice why the trailing spaces matter.
4. Plan your instrument screen on graph paper, 16 × 2 squares, with units on every value.
5. Combine: read the TMP36 and the HC-SR04 (Lesson 8.1 code), and display “Temp: 24.8 C” on row 0 and “Dist: 152 cm” on row 1, updating three times a second without lcd.clear().
6. Add a button that switches row 1 between distance in centimeters and in inches (1 in = 2.54 cm).

7. Add the parking bar of practice problem 11 as a third screen mode, using lcd.write(255) (a solid block on most displays) for each block.
8. **Improve it.** Show it to someone who has not seen it and ask them to read the values aloud. Note anything they misread or found confusing, and change your layout. Measure the display's current with and without the backlight.

Tips

- If the screen shows a row of solid blocks, the contrast is set but the code is not reaching it: check RS, E and D4–D7.
- If the screen is blank, turn the contrast pot; the right setting is often near one end.
- Use lcd.print(value, 1) to print a float with one decimal place.

Check your work

☐ My LCD shows text and live sensor values with units, without flicker.

☐ I planned the screen layout and improved it after a user test.

☐ I can explain how an LCD makes characters and why it uses little power.

ENGINEER'S NOTEBOOK

1. The LCD wiring table with pin numbers.
2. Your screen layouts on 16 × 2 graph paper, before and after the user test.
3. A labeled diagram of a twisted-nematic LCD cell: polarizers, liquid crystal, electrodes, on and off states.
4. Your commented code.

KEY FORMULAS

$$\text{dots} = (\text{columns} \times \text{rows}) \times (5 \times 8)$$

$$R_{\text{backlight}} = \frac{V_s - V_F}{I}$$

$$\text{ASCII: “0”} = 48, \text{“A”} = 65$$

From history. Heilmeier later directed DARPA, the U.S. research agency, and received the Kyoto Prize in 2005 for his work on liquid-crystal displays. He is remembered for a short list of questions he asked of every research project: what are you trying to do, how is it done today, what is new in your approach, and why do you think it will succeed.

WORKED EXAMPLES

Example 1. Which segments (a–g) light for the digits 4 and 7 on a seven-segment display? (a top, b upper right, c lower right, d bottom, e lower left, f upper left, g middle.)

Show solution

1. 4: f, g, b and c (upper left, middle, both right): four segments.
2. 7: a, b, c: three segments.

Answer: 4: b, c, f, g; 7: a, b, c

Example 2. Plan a 16 × 2 screen showing a temperature of 24.8 °C and a distance of 152 cm. Write exactly what goes on each row, and count the characters.

Show solution

1. Row 0: “Temp: 24.8 C” = 12 characters (the degree sign can be made with lcd.print((char)223); on most displays).
2. Row 1: “Dist: 152 cm” = 12 characters.
3. Both fit in 16; leave the last columns blank so changing values (such as 1,000 cm) still fit, and print spaces to erase old digits.

Answer: “Temp: 24.8 C” and “Dist: 152 cm”, 12 characters each

Example 3. The LCD backlight LED takes 3.2 V at 20 mA from 5.0 V. Find its resistor and power. How much current does the whole display use?

Show solution

1. $R = (5.0 - 3.2)/0.020 = 90\ \Omega$; use 100 Ω (18 mA).
2. Resistor power: $(0.018)^2(100) = 0.032\ \text{W}$.
3. Total: about 18 mA for the backlight plus about 1 mA for the LCD and controller: about 19 mA. (Many modules already include a backlight resistor; check the datasheet.)

Answer: 100 Ω, about 19 mA total

PRACTICE

1. Easy How many characters does a 16 × 2 LCD show? How many dots?

Show answer

32 characters; 1,280 dots

2. Easy What does lcd.setCursor(4, 1) do?

Show answer

Moves the cursor to column 4 (the fifth column) of row 1 (the second row).

3. Easy Who led the work at RCA that first showed working liquid-crystal displays?

Show answer

George Heilmeier.

4. Medium Which segments light for 2 and for 9?

Show answer

2: a, b, g, e, d. 9: a, b, c, d, f, g.

5. Medium Why do LCDs use so much less power than LED displays?

Show answer

They do not make light; they only switch light passing through or reflecting, using a tiny current to set the crystal's orientation.

6. Medium Why use 4-bit mode instead of 8-bit mode?

Show answer

It needs only four data wires instead of eight, saving Arduino pins, at the cost of sending each byte in two halves (slightly slower, which does not matter for a display).

7. Medium Your display shows "Dist: 152 cm" and then "Dist: 9 cmm". What went wrong, and how do you fix it?

Show answer

The old, longer text was not erased; print the value followed by spaces (or clear only that field) before writing the unit.

8. Hard The display is updated with lcd.clear() 20 times a second and flickers. Explain and fix.

Show answer

Clearing blanks the whole screen each time; overwrite only the changing characters (with setCursor() and padding spaces) and update a few times a second.

9. Hard Sharp's 1973 LCD calculator ran about 100 hours on one battery. If a red LED calculator drew 50 mA and the LCD one 0.5 mA, how many times longer would the same battery last?

Show answer

100 times longer (50/0.5).

10. Hard What ASCII codes are "7" and "a"? How would you print the character for code 67?

Show answer

"7" is 55 (48 + 7); "a" is 97; lcd.print((char)67); prints "C".

11. Challenge Design a two-row "parking assistant" screen: row 0 shows distance, row 1 shows a bar of up to 16 blocks that gets longer as the object gets closer (16 blocks at 10 cm or less, none at 100 cm or more). Give the formula for the number of blocks and check 55 cm.

Show answer

blocks = map(d, 100, 10, 0, 16), limited to 0–16 with constrain(). At 55 cm: $(55 - 100)(16)/(10 - 100) = 8$ blocks.

COMMON MISTAKES

- Forgetting the contrast potentiometer, so nothing is visible.
- Calling lcd.clear() on every loop, causing flicker.
- Not padding with spaces, so leftover characters remain.

> **Make it a game · Segment Code Challenge.** Draw a seven-segment display. Your parent calls a digit and you shade the lit segments in ten seconds. Then write the order of the pins for the LCD in 4-bit mode as you remember them. Tell the history of displays in one minute. Highest streak of correct digits wins.

8.5 A Data Logger: Maury's Paths of the Seas

OBJECTIVES

- Tell how Matthew Fontaine Maury turned thousands of ships' logbooks into charts that shortened voyages.
- Plan a data-logging experiment: what to measure, how often, for how long, and how much memory it needs.
- Log time-stamped sensor data from an Arduino in CSV format, import it into a spreadsheet and graph it.
- Run a cooling experiment and a 24-hour room log, and analyze them, including Newton's law of cooling.

> **Warm-up.** Think of a question about your house that you could answer only by measuring for a whole day: When is the kitchen warmest? How bright is your room at 7 a.m.? Write one question and guess the answer.

WATCH

Arduino SD Card and Data Logging to Excel Tutorial

How To Mechatronics · 6:22

https://www.youtube.com/watch?v=5Dp-XatLySM

> **WHEN TO WATCH**
> Before the build. You may not have an SD card module, but watch how data is written as comma-separated lines and opened in a spreadsheet; you will do the same through the Serial Monitor.

KEY TERMS

data logger
A device that records measurements automatically at set times, with a time stamp for each.

sampling interval
The time between measurements. It must be short enough to catch the changes you care about.

CSV

Comma-separated values: a plain-text format with one record per line, such as 120,24.8,512, that any spreadsheet can open.

time stamp

The time at which each measurement was made, such as seconds since the start from millis().

Newton's law of cooling

An object cools at a rate proportional to its temperature difference from its surroundings, giving an exponential approach:
$T(t) = T_{\text{room}} + (T_0 - T_{\text{room}})e^{-t/\tau}$.

CORE IDEAS

The story. In the 1840s Matthew Fontaine Maury, a U.S. Navy officer injured in a stagecoach accident and put in charge of the Navy's Depot of Charts and Instruments, found a storeroom of old ships' logbooks. Each recorded, day after day, the ship's position, wind, currents and weather. Maury and his staff extracted the data from thousands of logs and plotted it, and in 1847 began publishing his Wind and Current Charts. Captains who followed his recommended routes, and sent in their own logs in return, cut many voyages by days or weeks. In 1853 Maury helped organize an international conference in Brussels that agreed on a standard log format for ships of many nations. Maury was a devout Christian, and according to a well-known story, the words of Psalm 8 about the "paths of the seas" set him looking for them.

How they figured it out. No single log told Maury much: one ship saw one day's wind in one place. But thousands of logs, organized by location and month, revealed the patterns of the winds and currents. The secret was standard, careful, time-stamped records, collected over a long time and analyzed together. That is exactly what a data logger does: it records the same quantities at regular intervals, so that patterns and trends invisible in a single reading appear in the whole set.

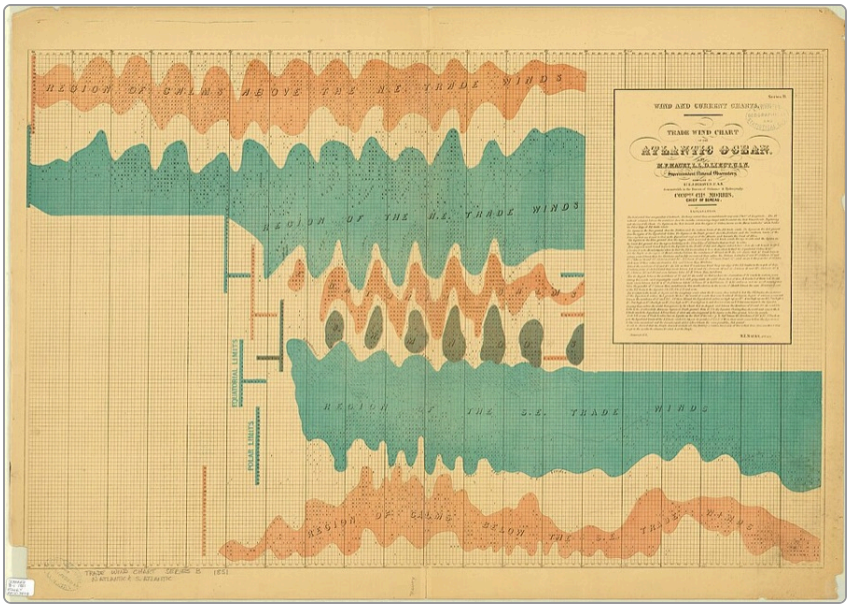
The physics and the planning. Before logging, decide what to measure, the **sampling interval** and the duration. To follow a cup of water cooling over an hour, a reading every 10 s is plenty (360 readings). To follow a room through a day, every minute is enough (1,440 readings). Memory matters: the Uno has only 2 KB of RAM and 1 KB of

EEPROM, so long logs are sent out as they are made, over USB to the computer (or written to an SD card). A line like 120,24.8,512 is 11 characters, so a day of one-minute lines of about 20 characters is about 29 KB, tiny for a computer. Cooling follows **Newton's law**: the temperature difference from the room falls exponentially, just like a capacitor discharging (Lesson 3.2), with its own time constant.

The engineering. Engineers log data everywhere: aircraft flight-data recorders, weather stations, bridges and dams monitored for strain, factories, spacecraft. Good loggers time-stamp every reading, write data in a simple standard format, check that values are sensible, and record their own conditions (sensor, location, calibration) in a header. The analysis is as important as the logging: graph the data, look for trends and outliers, fit a model, and compare it with theory. Honest data is the point: a logger that records only what we hoped to see is worthless.

Try it. You will build a temperature and light logger, record a cooling experiment and a full day in your house, and analyze the data in a spreadsheet.

PICTURE STUDY



Maury's Trade Winds Chart of the Atlantic, Matthew Fontaine Maury, U.S. Naval Observatory, 1851 · Engraved chart · U.S. Naval Observatory; Wikimedia Commons

Image: Wikimedia Commons, public domain

This chart, published by Maury in 1851, summarizes thousands of observations from ships' logbooks. Each small mark stands for many readings of the wind in one square of ocean in one season.

Look closely

- Find the coastlines. Which part of the Atlantic does the chart cover?
- Look closely at the small marks. What do you think they show about the wind?
- Find regions where the marks all point the same way. Those are the steady trade winds.
- Look for any regions with few marks. What would that tell you about the data?

Talk about it

1. How many logbook entries might lie behind one square of this chart?
2. How would a captain use this chart to choose a route?
3. What does Maury's work teach about the value of patient, standard, honest records?

Safety first. The Arduino runs only from its USB cable (computer or USB power bank). Motors and servos run from a separate 4-AA pack whose negative terminal is joined to the Arduino's GND; never power motors from an Arduino pin. Unplug power before rewiring. For the 24-hour log, power the Arduino from a computer or from a USB power bank that is not itself charging, on a hard, non-flammable surface. Never leave a power bank charging unattended. To warm the sensor, use your hands, never a flame, iron or hot water on bare electronics.

BUILD

A Temperature and Light Data Logger

You will build a logger that records time, temperature and light every few seconds as CSV, run a short cooling experiment and a 24-hour room log, and analyze both in a spreadsheet, as Maury analyzed his logbooks.

You will need

- Arduino Uno and USB cable; a computer with the Arduino IDE (and optionally a USB power bank)
- TMP36 (or DHT11) and the photoresistor with a 10 kΩ resistor; optional LCD from Lesson 8.4; optional SD card module
- A spreadsheet program (free ones are fine), a reference thermometer

Steps

1. Plan both experiments in your notebook: question, quantities, interval, duration, number of readings, and memory needed.
2. Wire the TMP36 to A0 and the photoresistor divider to A1.
3. Write the logger. In setup(), Serial.begin(9600); and print a header line: Serial.println("time_s,temp_C,light");. Keep unsigned long lastLog = 0; and const unsigned long INTERVAL = 5000; (5 s).
4. In loop(): if (millis() - lastLog >= INTERVAL) { lastLog = millis(); … }. Inside, read and average 10 readings of each sensor, compute the temperature, and print one line: Serial.print(millis() / 1000); Serial.print(","); Serial.print(tempC, 1); Serial.print(","); Serial.println(light);.
5. **Cooling experiment.** Warm the TMP36 between your fingers for two minutes, let go, and log for 10 minutes while it cools in still air. Copy the Serial Monitor text into a file named cooling.csv (or use the IDE's save option), and open it in a spreadsheet.
6. Graph temperature against time. Find τ from your data (Worked Example 2 or practice problem 8), and plot the Newton's-law model on the same graph. How well does it fit?

7. **24-hour log.** Change INTERVAL to 60000 (one minute). Place the logger near a window, away from heaters, and log for 24 hours (computer left on, or a power bank following the safety rules). Graph temperature and light against time of day.
8. **Improve it.** Find sunrise and sunset in your light data and compare them with published times for your town. Find the warmest and coolest times of the day. Write a one-page report as Maury might have: the question, the method, the data, the patterns, and what you would measure next.

Tips

- Close the Serial Plotter before copying text from the Serial Monitor; both cannot use the port at once.
- If your computer might sleep during the 24-hour log, change its power settings or use a power bank with an SD module.
- Keep the raw file unchanged; do your analysis in a copy.

Check your work

- ☐ My logger records time-stamped CSV data at a set interval using millis().
- ☐ I measured a cooling curve, found τ and compared it with Newton's law.
- ☐ I logged and analyzed a full day and wrote a report.

ENGINEER'S NOTEBOOK

1. The experiment plans with intervals, durations and memory estimates.
2. The cooling graph with the model curve and your value of τ.
3. The 24-hour graph with sunrise, sunset, warmest and coolest times marked.
4. Your Maury-style report.

KEY FORMULAS

$$N = \frac{\text{duration}}{\text{interval}}$$

$$\text{memory} = N \times \text{bytes per record}$$

$$T(t) = T_{\text{room}} + (T_0 - T_{\text{room}})\, e^{-t/\tau}$$

From history. Maury is remembered as the "Pathfinder of the Seas." His soundings of the North Atlantic also helped plan the route of the first transatlantic telegraph cable.

WORKED EXAMPLES

Example 1. You log every 10 s for 8 hours, 2 bytes per reading. How many readings, and how much memory? Could it fit in the Uno's 1 KB EEPROM? How long would the EEPROM last?

Show solution

1. $N = 8 \times 3600/10 = 2880$ readings.
2. Memory: $2880 \times 2 = 5760$ bytes, about 5.6 KB: too big for 1 KB.
3. EEPROM holds $1024/2 = 512$ readings: $512 \times 10\ \text{s} = 5120\ \text{s} \approx 1.4\ \text{h}$.

Answer: 2,880 readings, 5.8 KB; no; about 1.4 h

Example 2. A sensor warmed in your hand to 33.0 °C cools in a 21.0 °C room. After 120 s it reads 25.4 °C. Find the time constant τ, and predict the reading at 240 s.

Show solution

1. Difference: starts at 12.0 °C; after 120 s, $25.4 - 21.0 = 4.4\ ^\circ\text{C}$.
2. $4.4 = 12.0\, e^{-120/\tau}$, so $e^{-120/\tau} = 0.367$ and $120/\tau = 1.003$; $\tau = 120$ s.
3. At 240 s: difference $= 12.0 e^{-2} = 1.62\ ^\circ\text{C}$; reading $\approx 22.6\ ^\circ\text{C}$.

Answer: τ ≈ 120 s; about 22.6 °C at 240 s

Example 3. A day-long log of light readings has values every 60 s. The reading rises above 300 at 6:42 a.m. and falls below 300 at 7:18 p.m. How many hours of "daylight" did your window record, and how many readings is that?

Show solution

1. From 6:42 a.m. to 7:18 p.m. is 12 h 36 min = 12.6 h.
2. Readings: $12.6 \times 60 = 756$.

Answer: 12.6 h, 756 readings

PRACTICE

1. Easy How many readings does a logger make in 24 hours at one per minute?

Show answer

1,440

2. Easy What does CSV stand for, and why is it useful?

Show answer

Comma-separated values: plain text that any spreadsheet or program can read.

3. Easy What did Maury use to make his wind and current charts?

Show answer

Data from thousands of ships' logbooks, organized by place and month.

4. Medium Each CSV line is about 20 characters. How much data is a week of one-minute readings?

Show answer

$7 \times 1440 \times 20 = 201{,}600$ bytes, about 200 KB

5. Medium Why must every reading have a time stamp?

Show answer

So readings can be placed in time, graphed against time, compared with events, and missing or delayed readings can be detected.

6. Medium A cup of water cools from 60 °C toward a 20 °C room with τ = 900 s. What is it after 900 s and after 1,800 s?

Show answer

$20 + 40e^{-1} = 34.7\ ^\circ\text{C}$; $20 + 40e^{-2} = 25.4\ ^\circ\text{C}$

7. Medium Why is logging every 0.1 s a poor choice for a 24-hour room log?

Show answer

It makes 864,000 readings, far more than needed for slow changes, wasting memory and making analysis harder; the room changes over minutes, not tenths of a second.

8. Hard In your cooling data, the temperature difference falls from 10.0 to 5.0 °C in 85 s. Find τ.

Show answer

$5 = 10e^{-85/\tau} \rightarrow \tau = 85/\ln 2 = 123$ s

9. Hard Your room log shows a sudden 6 °C jump for one reading at 3:00 a.m. and then normal values. What might cause this, and what should you do with the reading?

Show answer

A glitch: electrical noise, a loose wire, or the sensor touched or heated. Note it, check for a cause, and exclude it from averages (but keep it in the raw data and say why it was excluded).

10. Hard Maury's charts improved as more captains sent in logs. Explain why more data made the charts more reliable.

Show answer

Each log has errors and unusual weather; averaging many logs for each place and month reduces random errors and reveals the true typical pattern.

11. Challenge A flight-data recorder stores 256 parameters, each 2 bytes, 8 times a second, for 25 hours. How much memory is needed?

Show answer

$256 \times 2 \times 8 \times 25 \times 3600 = 368{,}640{,}000$ bytes, about 369 MB

COMMON MISTAKES

- Using delay() for long intervals, so the timing drifts as the code itself takes time.
- Forgetting the header line, so columns are unlabeled.
- Deleting outliers from the raw data instead of noting and explaining them.

> **Make it a game · Plan the Logger.** Design duel. Your parent names a thing to measure, like a cooling cup of water over an hour. You decide the sampling interval, the length and the memory needed, defending every number. Draw a rough data table with timestamps. Then retell Maury's logbooks in thirty seconds. Best defended plan wins.

> **Scripture.** “The fowl of the air, and the fish of the sea, and whatsoever passeth through the paths of the seas.” (Psalm 8:8, KJV)
>
> Maury took these words to mean that the sea has paths, and patient records revealed them. Careful measurement is one way of reading the order God has written into His world.

UNIT 8

Arduino II: Sensors and Actuators

A microcontroller becomes useful when it can sense the world and act on it. In this unit you will connect the Arduino to sensors for temperature, light and distance, to actuators that move (servos and DC motors), and to a display, and you will finish by building a data logger that records a real experiment.

Each lesson begins with a story: Fessenden hearing an iceberg's echo after the *Titanic*, Maillardet's automaton that wrote its maker's name, Davenport selling a horse to buy an electromagnet, Heilmeier's first liquid-crystal displays, and Maury reading the winds from thousands of ships' logs. The builds include the second toy of the course, a servo-driven automaton, and an instrument you can leave running for a day.

PREREQUISITES

- Unit 7: sketches, digital and analog input, PWM and millis() timing
- Unit 4: transistor and MOSFET switches and flyback diodes
- Exponential curves from Lesson 3.2

MASTERY CHECKLIST

- ☐ I can read ultrasonic and temperature sensors, convert their outputs to units, and calibrate them.
- ☐ I can control a servo by angle, explain its feedback loop, and design for torque and toy safety.
- ☐ I can drive a DC motor in both directions at variable speed with an H-bridge and calculate driver losses.
- ☐ I can wire and program a character LCD and design a clear, flicker-free screen.
- ☐ I can plan, log, graph and analyze time-stamped sensor data, including fitting a cooling curve.

OPTIONAL KITS FOR THIS UNIT

- **ELEGOO Uno starter kits**: The larger kits include the HC-SR04, DHT11, servo, L293D or motor module, LCD and, in some, an SD-card or real-time-clock module used in this unit.
- **Arduino Starter Kit**: Includes the TMP36, servo, DC motor with L293D H-bridge and LCD used in this unit (add an HC-SR04 separately).
- **Adafruit (sensors and displays)**: A source of well-documented sensors, OLED displays and SD-card modules with free tutorials, if you want to extend the Unit 8 builds.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

8.1	**Sensors: Temperature, Light and Distance**	3 sessions of 50 minutes
8.2	**Servos and a Mechanical Automaton**	3 sessions of 50 minutes
8.3	**DC Motors and the H-Bridge**	3 sessions of 50 minutes
8.4	**Displays: From Segments to the LCD**	3 sessions of 50 minutes
8.5	**A Data Logger: Maury's Paths of the Seas**	3 sessions of 50 minutes

Unit 8 test

Time: 50 minutes. A scientific calculator is allowed. Show formulas, substitutions with units and answers with units; write code or logic clearly. The test is worth 100 points.

1. **6 pts** **Lesson 8.1**

   An ultrasonic echo lasts 3,500 µs at 20 °C. Find the distance. What would it be at 0 °C?

2. **6 pts** **Lesson 8.1**

   A TMP36 reads 0.68 V. Find the temperature. What analogRead() value would that be on a 5 V Uno?

3. **6 pts** **Lesson 8.1**

   Give two reasons an ultrasonic sensor might give a wrong reading and how to handle each.

4. **8 pts** **Lesson 8.2**

   What pulse width sets a servo to 60° (1.0 ms = 0°, 2.0 ms = 180°)? A servo of 2.5 kg·cm lifts a 50 g part on a 10 cm arm: find the safety factor.

5. **6 pts** **Lesson 8.2**

   Explain how a servo uses feedback, and why automata with cams are open loop.

6. **6 pts** **Lesson 8.2**

   Why should servos have a separate supply with a shared ground?

7. **8 pts** **Lesson 8.3**

   A 9.0 V pack drives a motor through an L293D with a 2.2 V drop at 0.40 A. Find the motor voltage, motor power, driver heat and driver efficiency.

8. **6 pts** **Lesson 8.3**

   Draw (describe) an H-bridge with four switches and say which are closed for each direction. What must never happen?

9. **6 pts** **Lesson 8.3**

   A motor with 4.0 Ω coil resistance runs at 0.35 A on 5.0 V. Find the back EMF and the stall current.

10. **6 pts** **Lesson 8.4**

    Why do LCDs use far less power than LED displays, and what part of an LCD module does use significant current?

11. **6 pts** **Lesson 8.4**

    Plan a 16 × 2 screen for a weather station showing temperature (one decimal), light level (0–100%) and a 3-character status (LOW, OK, HI). Write each row.

12. **6 pts** **Lesson 8.4**

    Your display flickers and shows leftover digits. Give the cause of each and the fix.

13. **8 pts** **Lesson 8.5**

    Plan a log of a greenhouse for 3 days at one reading every 2 minutes, with 24-byte CSV lines. Find the number of readings and the data size. Why must the data leave the Uno?

14. **6 pts** **Lesson 8.5**

    A sensor cools from 35 °C toward a 20 °C room; after 100 s it reads 25.5 °C. Find τ.

15. **10 pts** **Lesson 8.5**

    Essay (one paragraph). Explain how Matthew Maury's work with ships' logbooks is like a modern data logger, and what both teach about honest, standard records.

ANSWER KEY

1. $0.0343 \times 3500/2 = 60.0$ cm; at 0 °C, $v = 331$ m/s: 57.9 cm
2. 18 °C; $0.68 \times 1023/5 = 139$
3. Soft or angled targets (absorb or deflect sound): aim straight, use hard targets; stray echoes or noise (outliers): reject impossible values, take the median of several readings; also temperature (correct the speed of sound).
4. 1.33 ms; needed 0.5 kg·cm; safety factor 5
5. The servo measures its output angle with a potentiometer and drives the motor to reduce the difference from the command (closed loop). Cams drive a fixed motion with no measurement of the result (open loop).
6. Servos draw large currents when starting or stalled, which can sag the Arduino's supply and reset it; a shared ground lets the control signal be read correctly.
7. 6.8 V; 2.72 W; 0.88 W; 76%
8. Switches top-left, top-right, bottom-left, bottom-right around the motor. Forward: top-left and bottom-right; reverse: top-right and bottom-left. Never close both switches on one side (shoot-through short).
9. $5.0 - 1.4 = 3.6$ V; stall 1.25 A
10. LCDs switch light rather than making it, using microamps; the backlight LED uses most of the current (about 20 mA).
11. For example row 0: "T: 21.4 C OK" and row 1: "Light: 64 %"; any clear layout under 16 characters per row with units.
12. Flicker: clearing the whole screen too often; overwrite only changed fields. Leftover digits: shorter new values do not erase longer old ones; pad with spaces.
13. $3 \times 1440/2 = 2160$ readings; 51,840 bytes (about 52 KB); far more than the Uno's 2 KB RAM or 1 KB EEPROM.
14. $5.5 = 15e^{-100/\tau} \rightarrow \tau = 100/\ln(15/5.5) = 99.7$ s ≈ 100 s
15. A strong answer: many standard, time-stamped observations (wind, current, position) collected over time; analysis of the whole set reveals patterns invisible in single readings; standard formats (Brussels 1853, CSV today) let data be combined; accuracy and honesty matter, since false or selected data would mislead captains or engineers; outliers are noted and explained, not hidden.

PORTFOLIO PIECE: A SENSE-DECIDE-ACT INSTRUMENT

Design and build a stand-alone device that senses at least two quantities, shows them on the LCD, acts on them with a servo or motor, and logs its data. Examples: an automatic fan that turns on and speeds up with temperature and logs the room; a model “smart blind” that a servo opens with daylight; a parking assistant with an LCD bar, a beeper and a servo gate; a desk-top weather station with a moving pointer. Submit the design requirements, schematic, commented code, calibration records, a logged data set with graphs and a short report, and show it working.

LOOK FOR	WHAT IT MEANS
Sensing and calibration	Two sensors read correctly, converted to units, and calibrated against references.
Acting safely	Servo or motor driven correctly from a separate supply with a shared ground, protected, with safe limits.
Display and logging	Clear, flicker-free LCD screen with units; time-stamped CSV log graphed and analyzed.
Code and documentation	Readable, commented code using millis() timing; schematic and report complete.

UNIT 9

Raspberry Pi and Python

In this unit you will meet the Raspberry Pi family and the Python language. You will hear how a worry about students in Cambridge became tens of millions of low-cost computers; learn the Linux command line that grew from Unix at Bell Labs; write Python programs that calculate the electronics you have learned all year; and then program the Raspberry Pi Pico microcontroller in MicroPython, controlling LEDs, buttons, PWM and its analog-to-digital converter.

Everything you learned on the Arduino carries over: inputs and outputs, pull-ups and debouncing, PWM and analog readings, timing without blind delays. What changes is the language and the voltage: the Pico works at 3.3 V, and you must protect it from 5 V signals. A Raspberry Pi 4 or 5 is optional; every lesson can be done with your computer and a Pico.

PREREQUISITES

- Units 6–8: binary, logic, Arduino programming, sensors and PWM
- A computer on which you may install Thonny; a Raspberry Pi Pico (about $4–6) with headers and a micro-USB data cable
- Optional: a Raspberry Pi 4 or 5 set up by an adult

MASTERY CHECKLIST

- ☐ I can explain the Raspberry Pi story and the difference between a single-board computer and a microcontroller.
- ☐ I can navigate and organize files from the command line, read permissions, and follow the command-line safety rules.
- ☐ I can write Python with variables, lists, if, loops and functions, and test my code against hand calculations.
- ☐ I can install MicroPython on a Pico, use the REPL and main.py, and design for 3.3 V logic.
- ☐ I can read buttons with pull-ups and debouncing, use PWM and the ADC on the Pico, and log data with time stamps.

OPTIONAL KITS FOR THIS UNIT

- **Raspberry Pi Pico and Pico W**: Required for Units 9–10 (the Pico costs about $4; the Pico W, with Wi-Fi, a little more and is recommended for Lesson 10.3). Buy one with pre-soldered headers, or solder them yourself following Lesson 5.2.
- **Raspberry Pi 4 or 5**: Optional. A full Linux computer for Lessons 9.1–9.2 and the gpiozero extension in 9.5; needs its own power supply (connected by an adult), a microSD card, screen, keyboard and mouse.
- **Thonny (free Python editor)**: A free, beginner-friendly Python editor for Windows, macOS and Linux that also programs the Pico in MicroPython.
- **MicroPython**: The free MicroPython firmware and documentation, including the RP2040 quick reference used in Lessons 9.4–9.5.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

9.1	**The Raspberry Pi Story: Eben Upton and Cambridge**	3 sessions of 50 minutes
9.2	**Linux and the Command Line**	3 sessions of 50 minutes
9.3	**Python Basics**	3 sessions of 50 minutes
9.4	**The Pico and MicroPython**	3 sessions of 50 minutes
9.5	**GPIO with Python: Buttons, PWM and the ADC**	3 sessions of 50 minutes

Unit 9 test

Time: 50 minutes. A scientific calculator is allowed. Write code neatly with correct indentation; small syntax slips lose little credit if the logic is right. Show calculations with units. The test is worth 100 points.

1. **6 pts** **Lesson 9.1**

   Explain why Eben Upton and his colleagues built the Raspberry Pi and how they made it so cheap.

2. **6 pts** **Lesson 9.1**

   Give two differences between a Raspberry Pi 5 and a Pico, and one job for each.

3. **6 pts** **Lesson 9.1**

   A Pico draws 25 mA at 5 V. How long would a 5,000 mAh, 3.7 V power bank (85% efficient) run it?

4. **6 pts** **Lesson 9.2**

   You are in /home/pi/electronics/unit9. Where are you after cd ../data? What does pwd print?

5. **6 pts** **Lesson 9.2**

   Write rwxr--r-- in octal and binary. Who can do what?

6. **6 pts** **Lesson 9.2**

   State three command-line safety rules.

7. **8 pts** **Lesson 9.3**

   What does this print? r = [100, 220, 470], total = 0, for x in r: with indented total = total + x, then print(total, len(r), total / len(r)).

8. **8 pts** **Lesson 9.3**

   Write a Python function divider(vin, r1, r2) that returns the voltage-divider output, and the result of divider(9.0, 10000, 4700).

9. **6 pts** **Lesson 9.3**

   Give 19 // 4, 19 % 4, 19 / 4 and 3 ** 4.

10. **8 pts** **Lesson 9.4**

    Design a resistor for a green LED ($V_F = 2.2$ V) at 6 mA from a Pico pin. Why must a 5 V Arduino output not connect directly to a Pico input, and how would you fix it?

11. **6 pts** **Lesson 9.4**

    What is the difference between the REPL and main.py? How do you recover a Pico whose main.py misbehaves?

12. **8 pts** **Lesson 9.5**

pot.read_u16() returns 39,321. Find the voltage and the PWM duty cycle if this value is passed to duty_u16(). What average voltage does the PWM pin give?

13. **6 pts** **Lesson 9.5**

The RP2040 sensor reads 0.690 V. Find the chip temperature.

14. **6 pts** **Lesson 9.5**

Explain how to debounce a button in MicroPython with time.ticks_ms().

15. **8 pts** **Lesson 9.2**

Essay (one paragraph). Unix was designed in 1969 around small tools that each do one job and can be combined; Linux was built from 1991 by giving its code away openly. Explain how these two ideas help engineers build large, reliable systems, using an example from your own work this year.

ANSWER KEY

1. Cambridge applicants had little hands-on programming experience compared with earlier students raised on cheap home computers; they aimed for a computer a child could own and break. They used a mass-produced, inexpensive processor from set-top boxes and phones, free Linux and free software.
2. Pi 5: runs an operating system, much more memory and speed, networking and video (job: web server or camera). Pico: no operating system, runs one program instantly, very low power and cost, 3.3 V GPIO (job: sensor or motor control).
3. Power 0.125 W; energy $0.85 \times 18.5 = 15.7$ Wh; about 126 h
4. In /home/pi/electronics/data; pwd prints that path.
5. 744; 111 100 100. Owner: read, write, execute; group and others: read only.
6. Never run a command you do not understand (especially from the internet); check pwd before deleting; rm has no recycle bin, so name single files; use sudo only with a parent for a known task; work in your own project folder.
7. 790 3 263.3333333333333
8. def divider(vin, r1, r2): with indented return vin * r2 / (r1 + r2); result about 2.878 (V).
9. 4, 3, 4.75, 81
10. $1.1/0.006 = 183\ \Omega \rightarrow 180\ \Omega$ (6.1 mA). Pico inputs are rated for 3.3 V; 5 V can damage them. Use a divider (10 kΩ over 20 kΩ gives 3.33 V) with grounds joined, or a level shifter.
11. REPL runs lines interactively while connected; main.py runs automatically at power-up. Stop it from Thonny (Ctrl+C) and fix or rename main.py, or hold BOOTSEL and reinstall firmware.
12. 1.98 V; 60%; about 1.98 V
13. $27 - (0.690 - 0.706)/0.001721 = 27 + 9.3 = 36.3\ ^\circ\mathrm{C}$
14. When the reading changes, record the time; accept the new state only if it stays the same for about 20–50 ms (compare ticks_diff of now and the recorded time); ignore changes during that window.
15. A strong answer: small, single-purpose tools (or functions) are easy to understand, test and reuse; combining them builds complex behavior; openly published code with review catches errors and lets many contribute; examples:

your Python calculator's small tested functions, reusable dot()/dash() functions, publishing schematics for others to check.

PORTFOLIO PIECE: A STAND-ALONE PICO INSTRUMENT

Build a Pico project that runs by itself from a USB power bank (saved as main.py), with at least one button, one analog input and one PWM output, using debounced input and ticks_ms() timing. Examples: a night light with a brightness knob and an on/off button; a temperature-warning lamp that brightens as the chip or a sensor warms; a reaction game ported from Lesson 7.3; a metronome with a tempo knob and an LED and piezo beat. Submit the wiring diagram with GP numbers and resistor values, commented MicroPython code, a short Python program on your computer that analyzes a log from the device, and a demo.

LOOK FOR	WHAT IT MEANS
Hardware at 3.3 V	Correct resistors and pull-ups, no 5 V on any input, neat wiring diagram with GP numbers.
MicroPython code	Readable, commented, with functions; debounced input; ticks_ms() timing; runs as main.py.
Data and analysis	A time-stamped log from the device analyzed with a Python program on the computer, with a graph.
Demo	Runs from a power bank without a computer and does what the requirements say.

9.1 The Raspberry Pi Story: Eben Upton and Cambridge

OBJECTIVES

- Tell the story of the Raspberry Pi, from a worry about Cambridge applicants to tens of millions of computers.
- Distinguish a single-board computer (Raspberry Pi 4/5) from a microcontroller (Arduino Uno, Raspberry Pi Pico).
- Compare computing power and cost across sixty years, with numbers.
- Plan the Pico and Python tools for this unit and set up the Thonny editor on your computer.

> **Warm-up.** Ask an older relative what their first computer was, how much it cost and what they did with it. Write their answer. Then list what the cheapest computer in your house can do.

WATCH

10 years of Raspberry Pi

Raspberry Pi · 6:47

https://www.youtube.com/watch?v=eiwm5TMHIy8

> **WHEN TO WATCH**
> At the start of the lesson. This short film from Raspberry Pi itself tells the first ten years of the story.

BACKUP VIDEO

An Interview with Eben Upton- Creator and CEO of Raspberry Pi

Micro Center · 8:55

https://www.youtube.com/watch?v=EiWov2GWgDc

A short interview with Eben Upton about the mission of the Raspberry Pi; optional.

KEY TERMS

single-board computer

A complete general-purpose computer on one small board, with a processor, memory, video, USB and networking, running an operating system such as Linux. The Raspberry Pi 4 and 5 are examples.

microcontroller board

A small board built around a microcontroller that runs one program directly, with no operating system. The Arduino Uno and Raspberry Pi Pico are examples.

ARM processor

A family of efficient processor designs that began at Acorn Computers in Cambridge in 1985; they power most phones, the Raspberry Pi and the Pico.

operating system

Software, such as Linux, that manages a computer's hardware and lets many programs run and share it.

open hardware / education charity

The Raspberry Pi Foundation is an educational charity; its aim is to put affordable, programmable computers into the hands of learners.

CORE IDEAS

The story. In 2006 Eben Upton was a director of studies in computer science at St John's College, Cambridge. He and his colleagues noticed that the students applying to read computer science knew far less about how computers worked than applicants had in the 1990s. Those earlier students had grown up with cheap home computers such as the BBC Micro (1981), which started up ready to program. By the 2000s, families had expensive computers that children were not encouraged to tinker with, and game consoles that could not be programmed at all. Upton set out to make a computer so cheap that a child could own one and break it without worry. With colleagues including Rob Mullins, Jack Lang, Alan Mycroft, Pete Lomas and David Braben, he founded the Raspberry Pi Foundation, a charity, in 2009. On February 29, 2012, the first Raspberry Pi went on sale for $35. So many people tried to order it that the suppliers' websites crashed.

How they figured it out. The challenge was cost. Upton, who worked for the chip company Broadcom, saw that the processors made for set-top boxes and phones were powerful, cheap and made in huge numbers. Building around one of them, with the board designed by Pete Lomas and manufactured, from 2012, partly in Wales, the team hit the price. They chose the free Linux operating system and free tools such as Python and Scratch, so there was nothing else to buy. The Pi's processor uses the ARM design, which began at Acorn Computers in Cambridge, the same company that built the BBC Micro. In 2021 the Foundation released the Raspberry Pi Pico, a $4 microcontroller board built on its own chip, the RP2040.

The physics and the numbers. The IBM 704 of the 1950s, a room-sized computer used by NASA and its predecessors, could do roughly 40,000 instructions a second and rented for thousands of dollars a month. The first Raspberry Pi ran at 700 MHz, about 17,500 times the 704's instruction rate, on a board the size of a credit card using a few watts. Today's Raspberry Pi 5 is many times faster again. The Pico's RP2040 has two ARM Cortex-M0+ cores at 133 MHz, 264 KB of memory and 26 usable input/output pins at 3.3 V.

The engineering. Engineers choose between a single-board computer and a microcontroller by the job. A Raspberry Pi 4 or 5 runs Linux, a desktop, a web browser and many programs at once, with Wi-Fi, cameras and screens: good for a home server, a weather station with a web page, or a camera. A microcontroller such as the Pico runs one program from the instant it is powered, uses far less power, responds in microseconds, and costs a few dollars: good for reading sensors and controlling motors. Many products use both. In this unit you will use your computer for Linux and Python, and the Pico for MicroPython and hardware; a Raspberry Pi 4 or 5 is optional.

Today. Tens of millions of Raspberry Pi computers have been sold, used in classrooms and also in factories, laboratories and space: Raspberry Pi computers on the International Space Station run code written by students in the Astro Pi challenge. A worry about students in Cambridge became a tool for learners everywhere.

PICTURE STUDY



The IBM 704 at NACA, NASA, March 21, 1957 · Photograph · NASA

Image: Wikimedia Commons, public domain

This photograph shows an IBM 704 at a laboratory of NACA, the agency that became NASA in 1958. Machines like it computed aircraft designs and, soon, spacecraft orbits. It filled a room and cost a fortune; a Raspberry Pi in your hand is vastly more powerful.

Look closely

- Find the tape drives. What do you think they stored?
- Find the control console with its switches and lights.
- Count the people in the picture. Why would a computer need so many?
- Compare the size of the room with the size of a Raspberry Pi.

Talk about it

1. What do you think it cost to use this computer for an hour in 1957? Who could afford it?
2. How did cheap computers change who could learn to program?
3. What might engineers in 1957 have done with a computer as powerful as a Raspberry Pi?

Safety first. The Pico runs only from a USB data cable to a computer or a USB power bank. Its pins are 3.3 V: never connect 5 V (including the Arduino's 5 V pin) to a Pico input. Keep each pin's current below about 10 mA. If you use an optional Raspberry Pi 4 or 5, its power supply plugs into the wall: an adult connects it, and you never open it or touch its plug.

BUILD

Setting Up the Pico Bench and a Computer-History Timeline

You will set up your tools for Units 9–10 (Thonny on your computer, the Pico, and optionally a Raspberry Pi 4 or 5), and build a computing timeline with real numbers, from the IBM 704 to the Pico, to see the change for yourself.

You will need

- A computer with internet access; the free Thonny editor (thonny.org)
- A Raspberry Pi Pico or Pico W with header pins and a micro-USB data cable, a breadboard, an LED and a 150 Ω resistor
- Optional: a Raspberry Pi 4 or 5 with its supply, microSD card, keyboard, mouse and screen (adult sets up power)
- Graph paper or a spreadsheet

Steps

1. Install Thonny on your computer (a parent may approve the download). Open it, type print("Hello, Pi") in the Shell at the bottom, and press Enter. You have just run Python.
2. Inspect the Pico with a magnifier. Find the RP2040 chip, the flash memory chip, the micro-USB connector, the BOOTSEL button and the pin labels. Read the pinout card from the Raspberry Pi website and mark GP0–GP28, 3V3, VSYS, VBUS and the GND pins on a sketch.
3. Fit the Pico into the breadboard across the center gap (if its headers are soldered; otherwise, solder them using Lesson 5.2's rules). Do not connect it yet; we will install MicroPython in Lesson 9.4.
4. If you have a Raspberry Pi 4 or 5: with an adult, flash Raspberry Pi OS to the microSD card with the free Raspberry Pi Imager, and boot it. Record what you see.
5. Build a timeline table with at least six machines: IBM 704 (1954), the Apollo Guidance Computer (1966), the Intel 4004 (1971), the BBC Micro (1981), the first Raspberry Pi (2012) and the Pico (2021). For each, record its clock speed, memory, size, power and price, from reliable sources (museum websites, manufacturers' documents).

6. Graph clock speed (or instructions per second) on a logarithmic scale against year. Draw a best-fit line and estimate the doubling time.
7. Compute the cost per million instructions per second for each, ignoring inflation, and add it to the table.
8. **Improve it.** Write a one-page plan for what you would like to build with the Pico by the end of Unit 10, with the inputs and outputs it needs. This begins your capstone thinking.

Tips

- Use sources that give their references: museum pages (the Computer History Museum, the Centre for Computing History), manufacturers' datasheets and NASA history pages.
- Use powers of ten on your graph: 10^4, 10^6, 10^8 instructions per second.
- Keep the Pico in its antistatic bag until you use it, and handle it by the edges.

Check your work

- ☐ Thonny runs on my computer and I know the Pico's main parts and pins.
- ☐ My timeline table has real numbers with sources, and my graph shows the trend.
- ☐ I can explain the difference between a single-board computer and a microcontroller.

ENGINEER'S NOTEBOOK

1. A labeled sketch of the Pico with its pins.
2. The timeline table and logarithmic graph.
3. A paragraph: Why did Eben Upton think a cheap computer would help students, and do you agree?

KEY FORMULAS

$$\text{speed ratio} = \frac{\text{instructions/s (new)}}{\text{instructions/s (old)}}$$

$$\text{cost per instruction rate} = \frac{\text{price}}{\text{instructions/s}}$$

From history. The BBC Micro of 1981 was made for the BBC's Computer Literacy Project, which put computers into nearly every school in Britain. Its makers, Acorn, then designed their own processor, the ARM, whose descendants now run billions of devices, including the Raspberry Pi.

WORKED EXAMPLES

Example 1. The IBM 704 did about 40,000 instructions per second. The first Raspberry Pi ran at 700 MHz, doing roughly one simple instruction per clock cycle. Estimate how many times faster the Pi was.

Show solution

1. Pi: about 7×10^8 instructions per second.
2. Ratio: $7 \times 10^8 / 4 \times 10^4 = 17{,}500$.

Answer: About 17,500 times faster

Example 2. From the 704 (1957) to the Raspberry Pi (2012), how many years passed? If computing power per dollar doubled every 2 years, by what factor would it grow?

Show solution

1. Years: $2012 - 1957 = 55$.
2. Doublings: $55 / 2 = 27.5$.
3. Factor: $2^{27.5} \approx 1.9 \times 10^8$, nearly two hundred million.

Answer: About 2×10^8

Example 3. A Pico draws about 25 mA at 5 V from USB while running a program. How long could a 10,000 mAh, 3.7 V power bank run it, at 85% conversion efficiency?

Show solution

1. Pico power: $P = 5.0 \times 0.025 = 0.125$ W.
2. Usable energy: $0.85 \times 10 \times 3.7 = 31.5$ Wh.
3. Time: $31.5 / 0.125 = 252$ h, about 10 days.

Answer: About 250 h (10 days)

PRACTICE

1. Easy When did the first Raspberry Pi go on sale, and at what price?

Show answer

February 29, 2012, for $35.

2. Easy Is the Raspberry Pi Pico a single-board computer or a microcontroller board?

Show answer

A microcontroller board.

3. Easy What problem first made Eben Upton want to build the Raspberry Pi?

Show answer

Applicants to Cambridge computer science had much less hands-on programming experience than earlier students who had grown up with cheap programmable home computers.

4. Medium Give two jobs better suited to a Raspberry Pi 5 and two better suited to a Pico, with reasons.

Show answer

Pi 5: a web server or a camera recorder (needs an operating system, networking and lots of memory); a desktop for programming. Pico: reading a sensor and driving a motor (fast, simple, low power, cheap); a battery-powered data logger.

5. Medium The Pico's RP2040 runs at 133 MHz. What is one clock period?

Show answer

About 7.5 ns

6. Medium Why did the Raspberry Pi team use Linux and free software?

Show answer

To keep the total cost low (nothing else to buy) and because free, open tools let learners see and change how everything works.

7. Medium What company and city does the ARM processor design come from?

Show answer

Acorn Computers, Cambridge, England (1985).

8. Hard A Raspberry Pi 4 uses about 4 W and a Pico about 0.1 W. Over a year of running continuously, how much energy does each use in kWh?

   Show answer

   Pi: $4 \times 8760 = 35$ kWh; Pico: $0.1 \times 8760 = 0.88$ kWh

9. Hard Suppose the IBM 704 rented for about $30,000 a month in its day. Ignoring inflation, compare the cost per million instructions per second of the 704 for one month with buying a $35 Raspberry Pi outright.

   Show answer

   704: 0.04 MIPS for $30,000, about $750,000 per MIPS per month. Pi: about 700 MIPS for $35, about 5 cents per MIPS, once. Roughly ten million times cheaper (or more).

10. Hard Why might the Raspberry Pi's cheapness itself help people learn?

    Show answer

    Learners can experiment, make mistakes and even break it without fear, and every student can have one.

11. Challenge Using Worked Example 3, how many days would the Pico run if you made it sleep 90% of the time, drawing 2 mA while asleep and 25 mA while awake?

    Show answer

    Average $= 0.9(2) + 0.1(25) = 4.3$ mA; power 0.0215 W; $31.5 / 0.0215 = 1465$ h ≈ 61 days.

COMMON MISTAKES

- Confusing the Raspberry Pi (a Linux computer) with the Pico (a microcontroller board).
- Using a charge-only USB cable that carries power but no data.
- Connecting 5 V signals to the Pico's 3.3 V pins.

> **Make it a game · Computer or Controller?.** Sorting game. Write devices on cards: Raspberry Pi 5, Pico, Arduino Uno, laptop. Your parent calls a feature, such as runs an operating system or boots instantly, and you point to the right card. Then tell Eben Upton's story in forty-five seconds. Ten correct answers in a row sets the record.

9.2 Linux and the Command Line

OBJECTIVES

- Tell the story of Unix at Bell Labs and of Linux, and why the command line still matters.
- Navigate the file system with pwd, ls, cd and paths, and create, copy, move and view files.
- Read file permissions as binary numbers, and use commands safely (no unknown commands, care with rm and sudo).
- Organize a project folder from the terminal and run a Python script from it.

> **Warm-up.** Open your computer's file manager and find where your Arduino sketches from Unit 7 are saved. Write the full "path" of folders from the top of the disk to one sketch. How many folders deep is it?

WATCH

Raspberry Pi - Getting Started with Terminal

Core Electronics · 11:08

https://www.youtube.com/watch?v=UW3UxK4Tiqg

> **WHEN TO WATCH**
> Before the build. The commands work in the Raspberry Pi terminal, in macOS Terminal and (most of them) in Windows PowerShell; type each one along with the presenter.

BACKUP VIDEO

Introduction to Linux and Basic Linux Commands for Beginners

sakitech · 18:46

https://www.youtube.com/watch?v=IVquJh3DXUA

A longer introduction to Linux and its basic commands, with a clear explanation of the file system.

KEY TERMS

command line (shell)

A text interface where you type commands and the computer replies. The program that reads your commands is the shell (such as bash or zsh).

directory

Another word for folder. ~ means your home directory, . the current one and .. the one above.

sudo

A command that runs another command with administrator power. Use it only when you understand the command, and with a parent's approval.

path

The location of a file, written as folders separated by slashes: /home/pi/projects/blink.py. A relative path starts from the current folder.

permissions

Rules for who may read (r), write (w) and execute (x) a file, often written as three octal digits such as 755.

CORE IDEAS

The story. In 1969, at Bell Labs in New Jersey, Ken Thompson and Dennis Ritchie began writing a small, elegant operating system on a little-used minicomputer. They called it Unix. In 1972–73 Ritchie created the C language, and they rewrote Unix in C, so it could be moved to other computers. Unix was designed around simple tools that each do one job well and can be combined, controlled by typed commands, often at a Teletype terminal; Linux still calls a terminal a "tty." In 1991 Linus Torvalds, a 21-year-old student at the University of Helsinki, began writing a free Unix-like kernel as a hobby and posted it online, inviting others to help. Combined with free tools from the GNU project, Linux became the system that runs most of the world's web servers, all of the fastest supercomputers, every Android phone and the Raspberry Pi.

How they figured it out. Thompson and Ritchie's great idea was simplicity: everything is a file, small programs read text and write text, and the output of one can be "piped" into the next. A few dozen short commands could be combined to do

almost anything. Torvalds's great idea was to share the source code freely and let thousands of volunteers and companies improve it. Each change is reviewed, tested and recorded, so a project of millions of lines of code stays reliable: careful engineering by a very large team.

The physics of files (and the binary behind it). A file system is a tree: the root / at the top, folders inside folders, files at the leaves. pwd prints your current location; ls lists what is there; cd projects moves into a folder, cd .. moves up one. mkdir makes a folder, cp copies, mv moves or renames, cat shows a file, and nano edits one. Permissions show Unit 6's binary at work: each of owner, group and others has three bits, read (4), write (2) and execute (1). The permission 755 is binary 111 101 101: the owner may read, write and run; others may read and run. Storage is counted in powers of 2: a kibibyte is 1,024 bytes and a mebibyte $2^{20} = 1{,}048{,}576$ bytes.

The engineering and safety. Engineers use the command line because it is fast, precise, repeatable and scriptable, and because servers, robots and embedded Linux systems often have no screen at all. It is also powerful enough to do damage: rm deletes files without a recycle bin, and sudo runs commands with full power over the system. The rules: never type or paste a command you do not understand, especially one found on the internet; check your current folder with pwd before deleting; use rm on single named files, never with wildcards across folders; and use sudo only with a parent's approval for a known task, such as installing software.

Try it. You will set up a tidy project folder for this unit entirely from the terminal and run a Python program from it.

PICTURE STUDY



An Advertisement for the Teletype Model 33, Teletype Corporation, April 1974 · Magazine advertisement · Wikimedia Commons

Image: Wikimedia Commons, public domain

This 1974 advertisement sold the Teletype Model 33, the kind of terminal on which early Unix users typed their commands. Every command and every reply was printed on a roll of paper, which is why commands were short: ls is quicker to type than "list."

Look closely

- Find the terminal in the picture. What parts can you recognize?
- Read the advertisement's claims. What does it say the Model 33 is good for?
- ASR means "automatic send-receive": it had a paper-tape punch and reader. What could paper tape store?
- Look for any screen. Did this terminal have one, or did it print?

Talk about it

1. Why would short command names like ls, cp and mv make sense on this machine?
2. What would be the advantages of having every command printed on paper?
3. How is your terminal window today like this machine, and how is it different?

Safety first. The Pico runs only from a USB data cable to a computer or a USB power bank. Its pins are 3.3 V: never connect 5 V (including the Arduino's 5 V pin) to a Pico input. Keep each pin's current below about 10 mA. If you use an optional Raspberry Pi 4 or 5, its power supply plugs into the wall: an adult connects it, and you never open it or touch its plug. On any computer, never type or paste a command you do not understand, and use sudo or administrator mode only with a parent for a known task. Work only in your own project folder.

BUILD

A Project Folder Built from the Terminal

Using only the terminal (Raspberry Pi OS, macOS Terminal, Linux, or Windows PowerShell), you will build an organized folder for Units 9–10, create and edit files, check permissions, and run a Python script from the command line.

You will need

- A computer with a terminal (macOS Terminal, Linux, Windows PowerShell or the optional Raspberry Pi)
- Python 3 installed (Thonny includes it; on Windows you can run Python from Thonny's menu Tools → Open system shell)
- A notebook page for a command log

Steps

1. Open the terminal. Type pwd and write down where you are. Type ls and compare with what your file manager shows in the same place.
2. Make the project tree: mkdir electronics, cd electronics, then mkdir unit9 unit10 data notes. Check it with ls.
3. Create a file: cd notes, then nano readme.txt (on Windows PowerShell, use notepad readme.txt). Type three lines describing the project, save and exit (in nano: Ctrl+O, Enter, Ctrl+X). Show it with cat readme.txt (or type readme.txt in PowerShell).
4. Copy and rename: cp readme.txt readme_backup.txt, then mv readme_backup.txt old_readme.txt. List the folder after each command.
5. Write a Python script from the terminal: cd ../unit9, nano hello.py, type print("Hello from the command line") and a second line print(2 ** 10), save, then run it with python3 hello.py (or python hello.py on Windows).
6. On macOS, Linux or the Pi, view permissions with ls -l and write the permission string of hello.py as octal and as binary. (PowerShell shows different information; note what it shows instead.)
7. Keep a command log in your notebook: every command, what you expected and what happened. Mark any error and how you fixed it.

8. **Improve it.** Find out what three more commands do, safely, using the built-in help (man ls on Linux and macOS, or Get-Help ls in PowerShell): for example mkdir -p, ls -a and wc. Try each in your project folder only.

Tips

- Press Tab to complete a file or folder name; press the up arrow to recall your last command.
- If you get lost, cd ~ returns you to your home folder.
- Names with spaces need quotes; engineers avoid spaces in file names.

Check your work

- ☐ I can navigate with pwd, ls and cd, and create, copy, move and view files from the terminal.
- ☐ I can read permissions as octal and binary.
- ☐ I ran a Python script from the command line and kept a command log.

ENGINEER'S NOTEBOOK

1. A tree diagram of your project folders with full paths.
2. Your command log with expected and actual results.
3. A table of permission strings, octal and binary, for three files.
4. The safety rules for the command line in your own words.

KEY FORMULAS

$r = 4, \quad w = 2, \quad x = 1$

$755_8 = 111\,101\,101_2$

$1\ \text{MiB} = 2^{20}\ \text{bytes} = 1{,}048{,}576\ \text{bytes}$

From history. Thompson and Ritchie received the Turing Award in 1983 and the U.S. National Medal of Technology in 1998 for Unix and C. Much of the software on your phone and computer still traces its design to the choices they made in 1969–1973.

WORKED EXAMPLES

Example 1. What do the permissions 644 and 700 mean? Write each in binary.

Show solution

1. 644: owner 6 = 110 (read, write), group 4 = 100 (read), others 4 = 100 (read). Binary 110 100 100.
2. 700: owner 7 = 111 (read, write, execute); group and others 0 (nothing). Binary 111 000 000.

Answer: 644: owner rw, others read; 700: owner only, full access

Example 2. You are in /home/pi. You type mkdir projects, cd projects, mkdir pico, cd pico, then cd ../... Where are you, and what is the full path of the last folder you made?

Show solution

1. After cd pico you are in /home/pi/projects/pico.
2. cd ../.. goes up two levels, to /home/pi.
3. The folder made last is /home/pi/projects/pico.

Answer: Back in /home/pi; the folder is /home/pi/projects/pico

Example 3. A data log file is 3,145,728 bytes. How many MiB is it, and how many 512-byte blocks does it fill?

Show solution

1. MiB: $3{,}145{,}728 / 1{,}048{,}576 = 3.0$.
2. Blocks: $3{,}145{,}728 / 512 = 6144$.

Answer: 3.0 MiB; 6,144 blocks

PRACTICE

1. Easy What do pwd, ls and cd do?

   Show answer

   Print the current directory; list its contents; change directory.

2. Easy Who wrote the first Linux kernel, and when?

Show answer

Linus Torvalds, in 1991, as a student in Helsinki.

3. Easy What does cd .. do?

Show answer

Moves up one folder (to the parent directory).

4. Medium Write the permissions rwxr-x--- as three octal digits.

Show answer

750

5. Medium What is the difference between mv notes.txt old.txt and cp notes.txt old.txt?

Show answer

mv renames (moves) the file, leaving only old.txt; cp makes a copy, leaving both.

6. Medium Why is rm more dangerous than deleting a file in a file manager?

Show answer

It deletes immediately, with no recycle bin to recover from.

7. Medium Why do Linux systems still call a terminal a “tty”?

Show answer

Unix was first used from Teletype terminals; the abbreviation for teletypewriter stuck.

8. Hard You find a website that tells you to paste sudo rm -rf / to fix a problem. What would it do, and what is the rule?

Show answer

It would try to delete every file on the system with administrator power. Never run a command you do not understand, especially with sudo, and never from an untrusted source.

9. Hard Explain the Unix idea of small tools connected by pipes, with an example.

Show answer

Each tool does one job on text and passes its output to the next: for example, ls | wc -l lists files and counts the lines, giving the number of files.

10. Hard How many bytes are 2 GiB? How many 4 KiB pages is that?

Show answer

$2 \times 2^{30} = 2{,}147{,}483{,}648$ bytes; $2^{31} / 2^{12} = 2^{19} = 524{,}288$ pages.

11. Challenge Linux runs on servers, phones and the Pi, and is developed by thousands of people. Name two engineering practices that keep such a huge shared project reliable.

Show answer

Any two: every change reviewed by others before acceptance; version control recording every change and who made it; automatic testing; clear maintainers responsible for each part; releases tested before use.

COMMON MISTAKES

- Running a command in the wrong folder; check with pwd first.
- Typing spaces in file names, which the shell treats as separators.
- Copying commands from the internet without understanding them.

> **Make it a game · Command Line Charades.** Act out file commands without speaking. Your parent plays the shell. Mime pwd, ls, cd, cp, mv, mkdir and cat using gestures, and your parent writes the command. Swap roles. Then draw a path from the home folder to a project folder and write the cd commands needed. Most correct commands wins.

9.3 Python Basics

OBJECTIVES

- Trace programming languages from FORTRAN to Python, and explain what a high-level language is.
- Use Python variables, numbers, strings, lists, if statements, for and while loops, and functions, with correct indentation.
- Write programs that calculate electronics quantities (Ohm's law, LED resistors, RC time constants) and check them.
- Build an electronics calculator program with input checking and test it against your hand calculations.

> **Warm-up.** Write, in plain English, the steps to choose an LED resistor: what you need to know and what you do with it. Number the steps. You have just written an algorithm; today you will turn it into Python.

WATCH

Python Tutorial for Beginners - Learn the basics in 20 Min

Tech With Tim · 19:39

https://www.youtube.com/watch?v=Js05B8Z1ivE

> **WHEN TO WATCH**
> Before the build. Type every example along with the presenter in Thonny; pause after each section and change one thing to see what happens.

Note: The video includes a brief sponsor segment; skip it. Use Thonny (from Lesson 9.1) rather than the editor shown; the Python is the same.

BACKUP VIDEO

Learn Python in Less than 10 Minutes for Beginners (Fast & Easy)

Indently · 10:30

https://www.youtube.com/watch?v=fWjsdhR3z3c

A fast ten-minute tour of Python basics; good review after the lesson.

KEY TERMS

high-level language

A programming language written in words and symbols people can read, translated into machine instructions by a compiler or interpreter.

interpreter

A program that reads and runs code line by line. Python is usually interpreted, so you can type a line and see its result at once.

indentation

In Python, the spaces at the start of a line show which lines belong inside an if, loop or function. Four spaces per level is the standard.

list

An ordered collection, such as resistors = [220, 330, 1000], reached by position: resistors[0] is 220.

function

A named, reusable block of code defined with def, which can take inputs and return a result.

CORE IDEAS

The story. The first computers were programmed in machine code, long strings of numbers. In 1957 John Backus and his team at IBM released FORTRAN for the IBM 704, the first widely used high-level language: engineers could write a formula almost as in algebra, and a compiler turned it into machine code that ran nearly as fast as hand-written code. Grace Hopper (Lesson 2.5) championed English-like languages and led the work behind COBOL. In 1989, over his Christmas holiday, Guido van Rossum, a Dutch programmer at the national research institute for mathematics and computer science in Amsterdam, began writing a new language he wanted to be easy to read and fun to use. He named it Python, after a British comedy television program. Released in 1991, Python is now one of the most used programming languages in the world, in science, engineering, data analysis and teaching.

How they figured it out. Backus's team had to prove that a compiler could produce fast code, or engineers would not use it; they spent three years optimizing it. Van Rossum's goal was different: readability. Python uses indentation instead of braces to show structure, so a program's shape on the page matches its logic, and it has a large

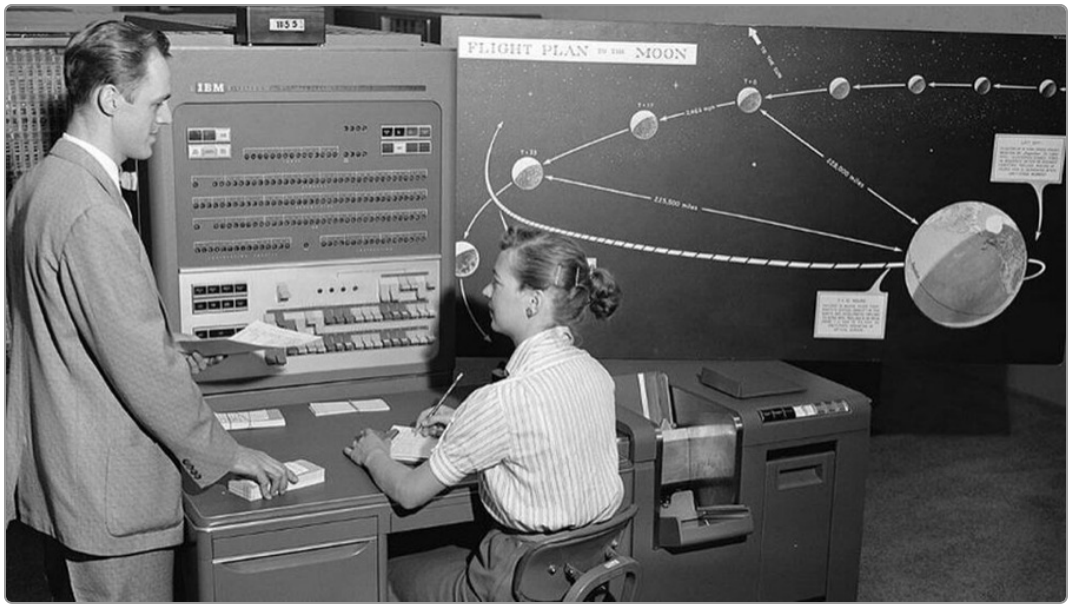
standard library so that common tasks need little code. Its rule of thumb, from the "Zen of Python," is that readability counts. Programs are read far more often than they are written.

The physics and the code. Python works like a calculator that remembers. V = 9.0, R = 470, I = V / R stores the current, and print(I * 1000, "mA") shows 19.1 mA. Arithmetic: + - * /, ** for powers, // for whole-number division and % for the remainder: 7 // 2 is 3 and 7 % 2 is 1. A list holds many values: for R in [220, 330, 470]: runs the indented lines once for each. An if chooses: if I > 0.020: followed by an indented print("Too much current!"). A function packages a calculation: def led_resistor(vs, vf, i): with an indented return (vs - vf) / i. A while loop repeats until a condition is false. Python cares about exact spelling, colons and indentation.

The engineering. Engineers use Python to calculate, automate and analyze: computing tables of values, processing logged data (as in Lesson 8.5), controlling instruments and, with MicroPython, programming microcontrollers. Good engineering code has clear names, small functions that each do one job, comments that explain why, and tests: you check a function against a case you have worked by hand before you trust it with new numbers. And it checks its inputs, because a program that divides by a zero current or accepts a negative resistance will give nonsense.

Try it. You will write an electronics calculator in Python that computes LED resistors, picks the nearest standard value, and checks power, and you will test it against your answers from Unit 3.

PICTURE STUDY



A Programmer at the IBM 704, NASA, 1959 · Photograph · NASA

Image: Wikimedia Commons, public domain

At NASA and its predecessor, many mathematicians, often called “human computers,” moved from calculating by hand to programming electronic computers such as the IBM 704. FORTRAN, the first widely used high-level language, was created for this machine.

Look closely

- Find the console’s lights and switches. What do you think they showed and controlled?
- Look at what the programmer is doing. Is she entering a program, reading a result or checking the machine?
- Look for any paper, cards or printouts. How were programs and data brought to the machine?

Talk about it

1. How would a high-level language like FORTRAN change her work compared with writing machine code?
2. What does Python make easier still?
3. Why would careful checking of every result matter for spaceflight calculations?

Safety first. The Pico runs only from a USB data cable to a computer or a USB power bank. Its pins are 3.3 V: never connect 5 V (including the Arduino's 5 V pin) to a Pico input. Keep each pin's current below about 10 mA. If you use an optional Raspberry Pi 4 or 5, its power supply plugs into the wall: an adult connects it, and you never open it or touch its plug. This lesson is done on your computer; no wiring is needed.

BUILD

An Electronics Calculator in Python

You will write a Python program, in Thonny, that calculates LED resistors, picks a standard value, checks resistor power and battery life, and tests itself against answers you worked by hand in Unit 3.

You will need

- A computer with Thonny
- Your Unit 3 notebook with hand-worked LED and RC answers

Steps

1. In Thonny's Shell, try arithmetic: 9.0 / 470, 2 ** 10, 7 // 2, 7 % 2, 0.1 + 0.2. Record each result and explain any surprise.
2. Open a new file, save it as calc.py in your unit9 folder. Write the function def led_resistor(vs, vf, i): returning (vs - vf) / i, and below it print(led_resistor(5.0, 2.0, 0.015)). Run it (green arrow) and compare with 200 Ω.
3. Add a list of E12 base values: E12 = [1.0, 1.2, 1.5, 1.8, 2.2, 2.7, 3.3, 3.9, 4.7, 5.6, 6.8, 8.2]. Write nearest_e12(r) (practice problem 11) that returns the smallest standard value at or above r. Test it: 200 → 220, 250 → 270, 1600 → 1800, 47 → 47.
4. Write def power(i, r): returning i ** 2 * r, and print the actual current and power for the standard resistor.
5. Make it interactive: vs = float(input("Supply voltage: ")), and the same for the LED voltage and the current in mA. Use an if to refuse impossible inputs (a current of zero or less, or $V_F \geq V_s$) with a clear message.
6. Add a battery-life function: given capacity in mAh and current in mA, return hours. Print it for a 2,500 mAh pack.
7. Test the whole program against at least five LED designs from Lesson 3.5 (worked examples and practice). Record each test: inputs, program output, hand answer, match or not.

8. **Improve it.** Add a menu with a while True: loop: choose 1 for LED resistor, 2 for RC time constant, 3 for voltage divider, 0 to quit. Comment every function with a line explaining what it does and its units.

Tips

- An IndentationError means the spaces at the start of a line are wrong; use four spaces per level.
- Use round(x, 1) to show one decimal place.
- Test each function alone before combining them.

Check your work

- ☐ My program computes LED resistors, standard values, power and battery life correctly.
- ☐ It refuses impossible inputs with a clear message.
- ☐ I tested it against at least five hand-worked answers and recorded the results.

ENGINEER'S NOTEBOOK

1. A flowchart of your calculator's menu and the LED-resistor calculation.
2. Your test table: inputs, outputs, hand answers.
3. A list of every error message you met and what caused it.

KEY FORMULAS

$R = \dfrac{V_s - V_F}{I}$ (as (vs - vf) / i)
$\tau = RC$ (as r * c)
$7 // 2 = 3, \quad 7 \% 2 = 1, \quad 2 * *10 = 1024$

From history. MicroPython, which you will use on the Pico, was written by Damien George, a physicist and programmer in Cambridge, and launched with a crowd-funding campaign in 2013. It squeezes much of Python into a few hundred kilobytes, so the same language runs on a computer and on a four-dollar chip.

WORKED EXAMPLES

Example 1. What does this program print? Line 1: total = 0. Line 2: for n in range(1, 101):. Line 3 (indented): total = total + n. Line 4 (not indented): print(total).

Show solution

1. range(1, 101) gives 1, 2, ..., 100 (it stops before 101).
2. The loop adds each number to total: $1 + 2 + \cdots + 100$.
3. That sum is $100 \times 101/2 = 5050$, printed once after the loop.

Answer: 5050

Example 2. Write a function for the LED resistor and test it with $V_s = 5.0$, $V_F = 2.0$, $I = 0.015$.

Show solution

1. Line 1: def led_resistor(vs, vf, i):; line 2 (indented): return (vs - vf) / i.
2. Test: print(led_resistor(5.0, 2.0, 0.015)).
3. By hand: $(5.0 - 2.0)/0.015 = 200\ \Omega$. Python prints 200.0 (perhaps 199.99999999999997, because computers store decimals in binary).

Answer: 200 Ω (prints about 200.0)

Example 3. What do 17 / 5, 17 // 5, 17 % 5 and 2 ** 8 give in Python?

Show solution

1. 17 / 5 = 3.4 (true division gives a decimal).
2. 17 // 5 = 3 (whole-number division).
3. 17 % 5 = 2 (the remainder).
4. 2 ** 8 = 256.

Answer: 3.4, 3, 2, 256

PRACTICE

1. Easy What does print(3 * 4 + 2) print?

   Show answer

   14

2. Easy Who created Python, and when was it first released?

   Show answer

   Guido van Rossum; 1991.

3. Easy Why does Python care about indentation?

   Show answer

   Indentation shows which lines belong inside an if, loop or function; it is part of the language's structure.

4. Medium What values does range(0, 10, 3) produce?

   Show answer

   0, 3, 6, 9

5. Medium Given r = [220, 330, 470, 1000], what are r[0], r[-1] and len(r)?

   Show answer

   220, 1000 and 4

6. Medium Write (in words or code) an if statement that prints "OK" if a current i is at most 0.020 A and "Too high" otherwise.

   Show answer

   if i <= 0.020: then indented print("OK"); else: then indented print("Too high").

7. Medium Why might print(0.1 + 0.2) show 0.30000000000000004?

   Show answer

   Decimal fractions like 0.1 cannot be stored exactly in binary, so tiny rounding errors appear.

8. Hard Write a function tau(r, c) that returns the RC time constant, and give the result for 10 kΩ and 100 µF.

   Show answer

   def tau(r, c): with return r * c; tau(10000, 100e-6) returns 1.0 (seconds).

9. Hard Write a loop that prints the current through a 1 kΩ resistor for voltages 1 to 9 V in steps of 2 V. What are the outputs?

Show answer

for v in range(1, 10, 2): then print(v, v / 1000): 1 V 0.001 A, 3 V 0.003 A, 5 V 0.005 A, 7 V 0.007 A, 9 V 0.009 A.

10. Hard FORTRAN's team spent years making their compiler produce fast code. Why did that matter so much in 1957?

Show answer

Computers were very expensive and slow; engineers would only accept a high-level language if its programs ran nearly as fast as hand-written machine code.

11. Challenge Write a function nearest_e12(r) in words: given any resistance, return the nearest E12 value at or above it. Outline the logic and test it on 250 Ω and 1,600 Ω.

Show answer

Find the decade: divide r by 10 until it is between 1 and 10, counting divisions. Step through [1.0, 1.2, 1.5, 1.8, 2.2, 2.7, 3.3, 3.9, 4.7, 5.6, 6.8, 8.2, 10] and return the first value ≥ the scaled r, times the decade. 250 → 270 Ω; 1,600 → 1,800 Ω.

COMMON MISTAKES

- Forgetting the colon at the end of if, for, while and def lines.
- Mixing tabs and spaces for indentation.
- Forgetting that input() returns text; convert it with float() or int() before doing arithmetic.

> **Make it a game · Python on Paper.** Write a five-line Python program on paper that uses a variable, a for loop and an if. Your parent plays the interpreter and reads it, pointing out indentation errors. Then trace the output line by line. Swap and write a bug for the other to find. The player who finds more bugs wins.

9.4 The Pico and MicroPython

OBJECTIVES

- Tell how MicroPython brought Python to microcontrollers and how the Pico's RP2040 chip was designed.
- Install MicroPython on a Pico, use the REPL, and save and run a main.py program.
- Control outputs with machine.Pin, use time.sleep() and loops, and design LED resistors for 3.3 V.
- Build a Pico blink, a Morse beacon and a traffic signal, and compare MicroPython with Arduino C++.

> **Warm-up.** Compare the Arduino Uno and the Pico side by side. List three differences you can see (size, connectors, pins, chips) and guess two you cannot see.

WATCH

How to Setup a Raspberry Pi Pico and Code with Thonny

Core Electronics · 7:26

https://www.youtube.com/watch?v=_ouzuI_ZPLs

> **WHEN TO WATCH**
> Before the build. Follow along exactly: install MicroPython with the BOOTSEL button, connect Thonny, and blink the onboard LED.

KEY TERMS

MicroPython
A compact version of Python 3 that runs directly on microcontrollers.

REPL
Read–evaluate–print loop: the interactive prompt (»>) where you type a line of Python and the Pico runs it at once.

firmware (UF2)
The MicroPython program itself, copied onto the Pico as a .uf2 file while BOOTSEL is held.

machine.Pin
The MicroPython class that controls a GPIO pin: led = Pin(15, Pin.OUT), then led.value(1) or led.toggle().

main.py

A file saved on the Pico that runs automatically every time it powers up.

CORE IDEAS

The story. For decades microcontrollers were programmed in C or assembly language: fast, but slow to learn and slow to change. In 2013 Damien George, a Cambridge physicist, launched a crowd-funding campaign for MicroPython, a version of Python small enough to run on a microcontroller, together with his pyboard. It worked better than many expected. In January 2021 the Raspberry Pi team released the Pico, built on the RP2040, the first microcontroller they designed themselves, at a price of $4, with MicroPython as one of its two main languages (the other is C/C++). Millions were sold in its first year.

How they figured it out. MicroPython's challenge was size: full Python needs megabytes of memory, while microcontrollers had kilobytes. George rewrote the language's core to be lean, compiled code to a compact form on the chip itself, and kept the interactive prompt, so a beginner can type a line and see a pin change instantly. The RP2040's designers chose two efficient ARM Cortex-M0+ cores, a generous 264 KB of memory, external flash memory (2 MB on the Pico) and clever programmable input/output blocks, and they made the chip impossible to "brick": holding BOOTSEL while plugging in always lets you load new firmware.

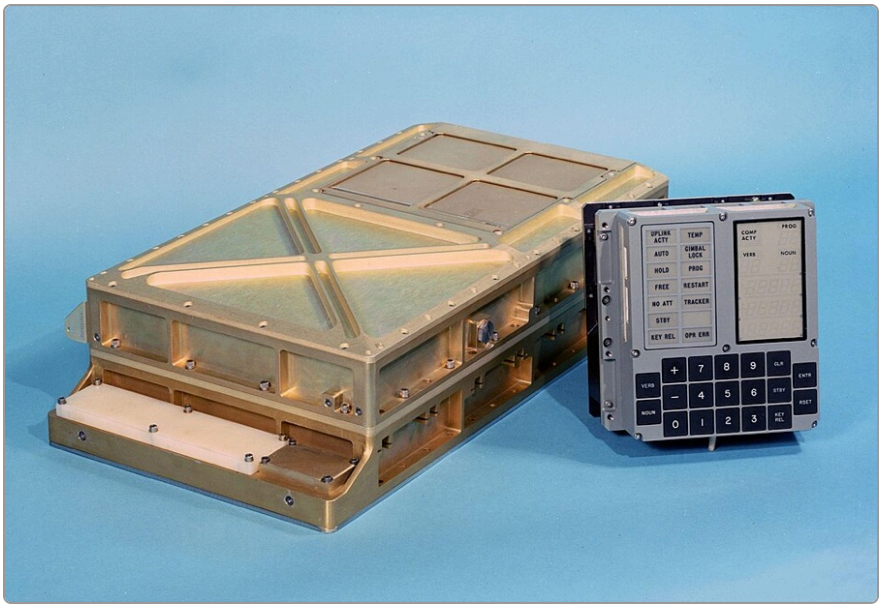
The physics. The Pico's pins work at **3.3 V**, not 5 V. A pin set HIGH is about 3.3 V; inputs must never see more than 3.3 V. An LED resistor for 3.3 V: a red LED at 10 mA needs $R = (3.3 - 2.0)/0.010 = 130\ \Omega$, so use 150 Ω (8.7 mA). Keep pin currents to about 10 mA or less. Blue and white LEDs need about 3 V, leaving only 0.3 V for the resistor, so they are dim and poorly controlled on 3.3 V; drive them through a transistor from VSYS or VBUS (5 V from USB) if they must be bright. The Pico runs at 133 MHz, and MicroPython is slower than C (an interpreter adds work), but still fast enough for most hardware projects.

The engineering. In MicroPython, from machine import Pin and import time load the tools. led = Pin("LED", Pin.OUT) names the onboard LED (on newer firmware this works on both the Pico and Pico W). A loop that runs forever is while True: with the lines inside indented. The same ideas you used on the Arduino (outputs, delays, loops, functions) carry over; only the language changes. Engineers choose

MicroPython when development speed and readability matter most, and C/C++ when speed, timing precision or memory are tight. Saving your program as main.py on the Pico makes it run by itself from a USB power bank, without a computer.

Try it. You will install MicroPython, control the Pico from the REPL, and port your Arduino Morse beacon and traffic signal to Python.

PICTURE STUDY



The Apollo Guidance Computer and DSKY, NASA, 1960s · Photograph · Wikimedia Commons

Image: Wikimedia Commons, public domain

This photograph shows the Apollo Guidance Computer (the flat box) and the display and keyboard through which astronauts talked to it, typing a two-digit "verb" (an action) and a "noun" (what to act on). It was an embedded computer, built into a spacecraft to control one system, as the Pico is built into your projects.

Look closely

- Find the VERB and NOUN keys. Why would short number codes be used instead of words?
- Find the numeric displays. What kinds of numbers would an astronaut need to see?
- Find the warning lights. What would make one light?
- Compare this panel with the Pico's REPL. How are both ways of giving a computer a command?

Talk about it

1. Why is an embedded computer designed for one job easier to make reliable than a general-purpose one?
2. The AGC had about 2 KB of erasable memory; the Pico has 264 KB. What does that difference let you do?

3. What would you want on a “DSKY” for a project of your own?

Safety first. The Pico runs only from a USB data cable to a computer or a USB power bank. Its pins are 3.3 V: never connect 5 V (including the Arduino’s 5 V pin) to a Pico input. Keep each pin’s current below about 10 mA. If you use an optional Raspberry Pi 4 or 5, its power supply plugs into the wall: an adult connects it, and you never open it or touch its plug.

BUILD

First Steps with the Pico: Blink, Morse and a Traffic Signal

You will install MicroPython, control the onboard LED from the REPL, then build external LED circuits and port your Arduino Morse beacon and traffic signal (Lessons 7.1–7.2) to MicroPython, saving the final program as main.py.

You will need

- Raspberry Pi Pico or Pico W, micro-USB data cable, computer with Thonny
- Breadboard, jumpers, red, yellow and green LEDs with 150 Ω resistors
- Optional: a USB power bank to run main.py without the computer

Steps

1. Hold BOOTSEL and plug the Pico into the computer; it appears as a drive called RPI-RP2. In Thonny, choose Tools → Options → Interpreter → MicroPython (Raspberry Pi Pico), and let Thonny install MicroPython (or download the UF2 file from the Raspberry Pi website and copy it onto the drive).
2. In the Shell (REPL), type: from machine import Pin, then led = Pin("LED", Pin.OUT), then led.value(1) and led.value(0). Watch the onboard LED respond to each line.
3. Write a blink program in the editor: from machine import Pin, import time, led = Pin("LED", Pin.OUT), then while True: with two indented lines led.toggle() and time.sleep(0.5). Run it, and stop it with the Stop button.
4. Wire a red LED: GP15 → 150 Ω → LED → GND. Change the program to use Pin(15, Pin.OUT). Measure the pin's high voltage and the LED current with your meter, and compare with Worked Example 1.
5. **Morse.** Define functions def dot(): and def dash(): (each indented: on, sleep 0.2 or 0.6, off, sleep 0.2). In the loop, send SOS as in Lesson 7.1. Compare the length and readability of the Python and C++ versions.
6. **Traffic signal.** Add yellow on GP14 and green on GP13. Write a function def show(r, y, g, seconds): that sets the three LEDs and sleeps. The loop calls it three times for green, yellow and red.

7. Save the traffic program to the Pico as main.py (File → Save as → Raspberry Pi Pico). Unplug the Pico from the computer and plug it into a USB power bank. It should start by itself.
8. **Improve it.** Use a list of states, states = [(0, 0, 1, 5), (0, 1, 0, 2), (1, 0, 0, 5)], and a for loop over it, so that adding a state means adding one line. Comment the program.

Tips

- If Thonny says the device is busy, press Stop, or unplug and replug the Pico.
- Indent the lines inside while True: and inside each def; Thonny helps by indenting automatically.
- Pin numbers in code (GP15) are not the same as the physical pin numbers printed around the board edge; use the GP numbers.

Check your work

☐ I installed MicroPython and controlled the LED from the REPL.

☐ I ported my Morse beacon and traffic signal to MicroPython with functions.

☐ My main.py runs by itself on a power bank.

ENGINEER'S NOTEBOOK

1. The Pico wiring diagram with GP numbers and resistor values.
2. Side-by-side listings of the Morse beacon in Arduino C++ and MicroPython, with notes on the differences.
3. Your measurements of pin voltage and LED current at 3.3 V.

KEY FORMULAS

$$R = \frac{3.3\ \text{V} - V_F}{I}$$

$$T = \frac{1}{133\ \text{MHz}} \approx 7.5\ \text{ns}$$

From history. The RP2040's name encodes its design: RP for Raspberry Pi, 2 for its two processor cores, 0 for the core type (Cortex-M0+), 4 for its memory (about $2^4 \times 16$ KB = 256 KB; it actually has 264 KB) and 0 for no built-in flash. The Pico 2, released in 2024, uses the newer RP2350.

WORKED EXAMPLES

Example 1. Design a resistor for a red LED ($V_F = 2.0$ V) at about 8 mA from a Pico pin. What current flows with a standard 150 Ω resistor?

Show solution

1. $R = (3.3 - 2.0)/0.008 = 163\ \Omega$; nearest standard at or below a safe current: 150 Ω or 180 Ω.
2. With 150 Ω: $I = 1.3/150 = 8.7$ mA, within the 10 mA guideline.

Answer: 150–180 Ω; 8.7 mA with 150 Ω

Example 2. In MicroPython, how long does one pass of this loop take, and how many blinks per minute? while True: then indented led.value(1), time.sleep(0.25), led.value(0), time.sleep(0.75).

Show solution

1. One pass: $0.25 + 0.75 = 1.0$ s.
2. Blinks per minute: 60.

Answer: 1.0 s; 60 per minute

Example 3. An Arduino signal of 5 V is connected straight to a Pico input. Why is that dangerous, and how could you make it safe with two resistors?

Show solution

1. Pico inputs are rated for 3.3 V; 5 V can damage the pin or chip.
2. Use a divider: from the 5 V signal, 10 kΩ to the Pico pin, and 20 kΩ from the pin to ground: $V = 5.0 \times 20/30 = 3.33$ V.
3. (Grounds must be joined.)

Answer: Divide it to about 3.3 V (10 kΩ over 20 kΩ)

PRACTICE

1. Easy What logic voltage does the Pico use?

   Show answer

   3.3 V

2. **Easy** What does holding BOOTSEL while plugging in the Pico do?

   Show answer

   It puts the Pico into a mode where it appears as a USB drive, so you can copy MicroPython (or other) firmware onto it.

3. **Easy** Who created MicroPython, and when was it launched?

   Show answer

   Damien George, 2013.

4. **Medium** Find the resistor for a yellow LED ($V_F = 2.1$ V) at 6 mA from a Pico pin.

   Show answer

   $1.2 / 0.006 = 200\ \Omega$

5. **Medium** Why is a white LED ($V_F = 3.1$ V) a poor choice to drive directly from a 3.3 V pin?

   Show answer

   Only 0.2 V is left for the resistor, so the current depends strongly on small differences in V_F; the LED is dim and inconsistent.

6. **Medium** What is the difference between typing code in the REPL and saving it as main.py?

   Show answer

   The REPL runs each line immediately while connected; main.py is stored on the Pico and runs automatically at every power-up, even without a computer.

7. **Medium** Translate the Arduino line digitalWrite(8, HIGH); into MicroPython.

   Show answer

   With p = Pin(8, Pin.OUT) defined: p.value(1).

8. **Hard** MicroPython runs a simple loop perhaps 50 times slower than compiled C. If the C version toggles a pin in 0.1 µs, about how long does MicroPython take? Is that fast enough to blink an LED? To generate a 1 MHz signal?

   Show answer

   About 5 µs. Plenty for an LED; too slow for 1 MHz by simple toggling (use the hardware PWM or the PIO blocks instead).

9. Hard Your main.py has an error and the Pico now seems to do nothing. How can you recover?

Show answer

Connect Thonny and press Stop (or Ctrl+C) to interrupt the program, then fix or rename main.py; if all else fails, hold BOOTSEL and reinstall the firmware.

10. Hard Compare MicroPython and Arduino C++ for a beginner project and for a high-speed motor controller.

Show answer

Beginner: MicroPython is quicker to write, test and change with the REPL. High-speed control: C/C++ is faster and more precise in timing and uses less memory.

11. Challenge A Pico traffic signal uses three LEDs at 8 mA each, but only one is lit at a time, plus the Pico's 25 mA. On a 2,500 mAh power bank at 85% efficiency (3.7 V cells, 5 V output), estimate how long it runs.

Show answer

Load about 33 mA at 5 V = 0.165 W; usable energy $0.85 \times 2.5 \times 3.7 = 7.9$ Wh; $7.9 / 0.165 = 48$ h.

COMMON MISTAKES

- Using a charge-only USB cable, so the Pico never appears.
- Confusing GP numbers with physical pin numbers.
- Forgetting indentation inside while True:.

> **Make it a game · Pico Setup Order.** Sequence challenge. Write each step of installing MicroPython and running main.py on a scrap, shuffle them, and rebuild the order in thirty seconds. Explain the REPL, UF2 firmware and machine.Pin. Your parent hides one step from the list and you name it. Beat your best time.

9.5 GPIO with Python: Buttons, PWM and the ADC

OBJECTIVES

- Explain general-purpose input/output and the roles of inputs, outputs, pull resistors, PWM and the ADC on the Pico.
- Read buttons with internal pull-ups, use interrupts or polling, and debounce in MicroPython.
- Use the Pico's 16-bit PWM and its ADC, including the internal temperature sensor, with correct conversions.
- Build a Pico control panel: a button-controlled light, a potentiometer dimmer and a temperature display (and optionally the same with gpiozero on a Raspberry Pi).

> **Warm-up.** Look at any control panel: a microwave, a car dashboard, a game controller. List its inputs (buttons, knobs) and outputs (lights, sounds, displays). Which inputs are on/off and which are continuous?

WATCH

Raspberry Pi Pico W LESSON 18: Push Button Control of LEDs in Micropython

Paul McWhorter · 20:02

https://www.youtube.com/watch?v=oztHWvrhKNk

> **WHEN TO WATCH**
> Before the build. Paul McWhorter wires push buttons to a Pico and reads them in MicroPython; follow his wiring and code.

BACKUP VIDEO

How to Use Push Buttons With Raspberry Pi GPIO (with Python gpiozero)

M Heidenreich · 10:17

https://www.youtube.com/watch?v=YICzRCAY73Y

For those with an optional Raspberry Pi: buttons with Python's gpiozero library on the Pi's GPIO header.

KEY TERMS

GPIO

General-purpose input/output: pins that software can set as inputs or outputs.

interrupt (IRQ)

A signal that makes the processor stop what it is doing and run a short handler function at once, such as when a button is pressed.

read_u16()

Reads a Pico ADC channel as 0–65535 (its 12-bit readings are scaled up to 16 bits); $V = N \times 3.3/65535$.

Pin.PULL_UP

Turns on an internal resistor from a Pico input to 3.3 V, so a button to ground reads 0 when pressed and 1 when released.

duty_u16()

Sets a Pico PWM duty cycle from 0 to 65535 (16 bits): 32768 is 50%.

CORE IDEAS

The story. At NASA's Mission Control in Houston, during the Gemini flights of 1965 and later Apollo, flight controllers such as Gene Kranz sat at consoles covered with buttons, switches, lights and screens. Each console was a human interface to computers and spacecraft systems: inputs that the controllers pressed or turned, and outputs that told them what was happening, often in seconds that mattered. The same pattern is in every embedded system: read inputs, decide, set outputs. Your Pico's general-purpose pins are a tiny console of its own: each can be set by software to be an input or an output, digital or analog.

How they figured it out. Early computers had special-purpose input and output channels for each device. Microcontroller designers realized that making pins general-purpose, configurable by software, would let one cheap chip serve thousands of different products. The RP2040 goes further: each pin can be connected to one of several internal blocks (digital I/O, PWM, ADC, serial buses), and its programmable I/O (PIO) blocks can be programmed to create new interfaces. Engineers also learned to use **interrupts**: rather than checking a button thousands of times a second, the chip can be told to run a function the instant the pin changes.

The physics and the code. A button input: button = Pin(14, Pin.IN, Pin.PULL_UP), with the button from GP14 to GND; button.value() is 0 when pressed. A PWM output: pwm = PWM(Pin(15)), pwm.freq(1000), pwm.duty_u16(16384) for 25% duty, giving an average of $0.25 \times 3.3 = 0.83$ V. The ADC: pot = ADC(26) reads GP26; pot.read_u16() returns 0–65535, so 32768 means $32768 \times 3.3/65535 = 1.65$ V. The RP2040 has a temperature sensor inside the chip on ADC channel 4; its datasheet gives $T = 27 - (V - 0.706)/0.001721$ in °C. A reading of 14,000 gives $V = 0.705$ V and $T \approx 27.6\ ^\circ\text{C}$ (the chip runs a little warmer than the room).

The engineering. Good GPIO design follows the same rules as on the Arduino, at 3.3 V: resistors for LEDs, pull-ups for buttons, dividers for higher voltages, transistors for loads, debouncing in code (ignore changes for about 20–50 ms), and time.ticks_ms() instead of long sleeps so the program stays responsive. Interrupt handlers should be short: set a flag, and let the main loop do the work. On a full Raspberry Pi, the gpiozero library makes the same jobs very readable: led = LED(17), button = Button(2), button.when_pressed = led.on.

Try it. You will build a small control panel on the Pico: a button that toggles a light, a knob that dims it, and a readout of the chip's own temperature.

PICTURE STUDY



Gene Kranz at the Flight Director's Console, NASA, August 21, 1965 · Photograph · NASA

Image: Wikimedia Commons, public domain

Gene Kranz, a flight director during the Gemini and Apollo programs, sits at his console in Mission Control in Houston during Gemini 5. Every switch is an input and every light an output, like the GPIO pins of your Pico on a grand scale.

Look closely

- Find the push buttons and switches. How are they labeled and grouped?
- Find the indicator lights and screens. What kinds of information do they show?
- Look at how the console is laid out around the person. Why does placement matter?
- Find anything a controller could use to talk to others.

Talk about it

1. Which of these inputs are on/off (digital) and which might be continuous (analog)?
2. How would a designer make sure the most important warning is never missed?
3. How would you design a three-button "console" for your Pico project?

Safety first. The Pico runs only from a USB data cable to a computer or a USB power bank. Its pins are 3.3 V: never connect 5 V (including the Arduino's 5 V pin) to a Pico input. Keep each pin's current below about 10 mA. If you use an optional Raspberry Pi 4 or 5, its power supply plugs into the wall: an adult connects it, and you never open it or touch its plug. If you use an optional Raspberry Pi 4 or 5, its GPIO pins are 3.3 V as well, and its pins can be damaged by 5 V or by shorts; wire with the power off and check before switching on.

BUILD

A Pico Control Panel

You will build a small control panel on the Pico: a button that toggles an LED (with debouncing), a potentiometer that dims it with PWM, and a readout of the chip's internal temperature, and you will log the temperature for a few minutes.

You will need

- Raspberry Pi Pico, micro-USB data cable, computer with Thonny
- A push button, a red LED with 150 Ω, a 10 kΩ potentiometer, breadboard, jumpers
- Optional: the LCD from Lesson 8.4 is 5 V and needs care with the Pico; instead print to the Thonny Shell. Optional: a Raspberry Pi 4 or 5 with gpiozero.

Steps

1. Wire: button from GP14 to GND; LED from GP15 through 150 Ω to GND; potentiometer ends to 3V3 (OUT) and GND, wiper to GP26 (ADC0). Never connect the pot to VBUS or VSYS (5 V).
2. Imports: from machine import Pin, PWM, ADC and import time. Set up button = Pin(14, Pin.IN, Pin.PULL_UP), pwm = PWM(Pin(15)), pwm.freq(1000), pot = ADC(26) and sensor = ADC(4).
3. Test the button: in a loop, print button.value() every 0.1 s and press it. Confirm 1 when released and 0 when pressed.
4. Toggle with debounce: keep on = False, last_state = 1 and last_time = time.ticks_ms(). In the loop, read the button; if it reads 0 and last_state was 1 and time.ticks_diff(time.ticks_ms(), last_time) > 50, flip on and record the time. Save the reading in last_state.
5. Dimmer: if on is True, pwm.duty_u16(pot.read_u16()); otherwise pwm.duty_u16(0). Turn the knob and watch the LED. Measure the pin's average voltage at three knob positions and compare with $D \times 3.3$.
6. Temperature: every 2 seconds (using time.ticks_ms(), not sleep), read sensor.read_u16(), convert to volts and then to °C with the datasheet formula, and print it with the time, as CSV.

7. Log the temperature for five minutes while the Pico runs, then copy the output into a spreadsheet and graph it. Warm the chip gently with a fingertip for a minute and watch the graph respond.
8. **Improve it.** Replace the polling of the button with an interrupt: button.irq(trigger=Pin.IRQ_FALLING, handler=pressed), where def pressed(pin): only sets a flag that the main loop checks. If you have a Raspberry Pi, build the same button-and-LED panel with gpiozero and compare the code.

Tips

- read_u16() and duty_u16() use the same 0–65535 scale, so you can pass one into the other directly.
- The internal sensor reads the chip's temperature, often several degrees above the room; compare it with your TMP36 from Lesson 8.1 if you like (on a divider, since the TMP36 also works at 3.3 V).
- Keep interrupt handlers to one or two lines.

Check your work

☐ My button toggles the LED reliably with no double toggles.

☐ The potentiometer dims the LED with PWM, and my measured average voltages match

$D \times 3.3$.

☐ I logged and graphed the chip temperature with time stamps.

ENGINEER'S NOTEBOOK

1. The wiring diagram with GP numbers.
2. Your commented program.
3. A table of knob positions, duty values and measured voltages.
4. The temperature graph and a sentence explaining why the chip reads warmer than the room.

KEY FORMULAS

$V = N \times \dfrac{3.3}{65535}$ (read_u16)

$D = \dfrac{\text{duty\_u16}}{65535}$

$T = 27 - \dfrac{V - 0.706}{0.001721}$ (RP2040 sensor, °C)

From history. Kranz, who led the Mission Control team that brought the crew of Apollo 13 home safely in 1970 after an oxygen tank failed, described the flight controllers' creed in a few words: tough and competent. Their consoles, procedures and training were designed so that people and machines worked together under pressure.

WORKED EXAMPLES

Example 1. pot.read_u16() returns 20,000. What is the voltage? What duty_u16 value would give an LED the same fraction of full brightness?

Show solution

1. $V = 20{,}000 \times 3.3/65535 = 1.01$ V.
2. Fraction: $20{,}000/65535 = 0.305$; use duty_u16(20000) (the scales match, so you can pass the reading straight through).

Answer: 1.01 V; duty_u16(20000)

Example 2. The internal temperature sensor reads 13,500. Find the voltage and the chip temperature.

Show solution

1. $V = 13{,}500 \times 3.3/65535 = 0.680$ V.
2. $T = 27 - (0.680 - 0.706)/0.001721 = 27 + 15.1 = 42.1$ °C.
3. That is warmer than a room; the sensor measures the chip, which heats as it works (and readings vary by a few degrees between chips).

Answer: 0.680 V; about 42 °C

Example 3. A button is read every 1 ms, and it bounces for 8 ms. Describe a debounce in code using time.ticks_ms() and say how quickly the program can respond to genuine presses.

Show solution

1. When the reading changes, record the time with last = time.ticks_ms().
2. Accept the new state only when time.ticks_diff(time.ticks_ms(), last) exceeds 30 ms with no further change.
3. Genuine presses register about 30 ms after they settle, and up to about 30 presses per second are possible: faster than anyone can press.

Answer: Accept changes stable for about 30 ms

PRACTICE

1. Easy With Pin.PULL_UP and the button to ground, what does button.value() return when the button is pressed?

   Show answer

   0

2. Easy What duty cycle is duty_u16(49152)?

   Show answer

   75%

3. Easy What does GPIO stand for?

   Show answer

   General-purpose input/output.

4. Medium read_u16() returns 49,151. What is the voltage?

   Show answer

   2.47 V

5. Medium Why should an interrupt handler be short?

   Show answer

   While it runs, the main program and other interrupts wait; long handlers can miss events or delay timing. Set a flag and let the main loop do the work.

6. Medium Find the average voltage at a PWM duty of 25% on a 3.3 V pin.

Show answer

0.83 V

7. Medium Translate to gpiozero (on a Raspberry Pi): turn on an LED on GPIO 17 whenever a button on GPIO 2 is pressed, and off when released.

Show answer

led = LED(17), button = Button(2), button.when_pressed = led.on, button.when_released = led.off.

8. Hard The internal sensor reads 0.720 V. Find the chip temperature.

Show answer

$27 - (0.014)/0.001721 = 18.9\ ^\circ\mathrm{C}$

9. Hard The Pico's ADC is 12-bit. What is its true resolution at 3.3 V, and why does read_u16() still return values up to 65,535?

Show answer

$3.3/4096 = 0.81$ mV; the 12-bit result is scaled to 16 bits so that code is the same across boards with different ADCs.

10. Hard A Mission Control console had hundreds of switches and lights. Why would engineers use standard, labeled panels and strict procedures for using them?

Show answer

So controllers could find and read each one quickly and without error under pressure; standard layouts and procedures reduce mistakes when seconds matter.

11. Challenge Write (in words) a Pico program where one button cycles an RGB LED through red, green, blue and off, and a potentiometer sets the brightness of whichever color is on, with debouncing.

Show answer

Keep a variable mode 0–3. In the loop: read the button; if it changes to pressed and has been stable 30 ms, add 1 to mode (wrap at 4). Read the pot with read_u16() and set the PWM duty of the active color to that value and the others to 0 (all 0 in mode 3). Use time.ticks_ms() for timing.

COMMON MISTAKES

- Connecting the potentiometer to 5 V instead of 3.3 V, which can damage the ADC pin.
- Using time.sleep() for long waits, so button presses are missed.
- Doing too much work inside an interrupt handler.

> **Make it a game · Pull-Up Teach-Back.** Teach-back. In ninety seconds, explain to your parent how a Pico reads a button with an internal pull-up, when to use polling versus an interrupt, and why you debounce. Your parent slips in one false fact. Catch it. Then name what duty_u16() and read_u16() each do. Score a point per right idea.

> **Scripture.** “The thoughts of the diligent tend only to plenteousness; but of every one that is hasty only to want.” (Proverbs 21:5, KJV)
>
> A debounced button and a carefully planned panel come from diligence, not haste. Careful thought before wiring saves hours of trouble after.

UNIT 9

Raspberry Pi and Python

In this unit you will meet the Raspberry Pi family and the Python language. You will hear how a worry about students in Cambridge became tens of millions of low-cost computers; learn the Linux command line that grew from Unix at Bell Labs; write Python programs that calculate the electronics you have learned all year; and then program the Raspberry Pi Pico microcontroller in MicroPython, controlling LEDs, buttons, PWM and its analog-to-digital converter.

Everything you learned on the Arduino carries over: inputs and outputs, pull-ups and debouncing, PWM and analog readings, timing without blind delays. What changes is the language and the voltage: the Pico works at 3.3 V, and you must protect it from 5 V signals. A Raspberry Pi 4 or 5 is optional; every lesson can be done with your computer and a Pico.

PREREQUISITES

- Units 6–8: binary, logic, Arduino programming, sensors and PWM
- A computer on which you may install Thonny; a Raspberry Pi Pico (about $4–6) with headers and a micro-USB data cable
- Optional: a Raspberry Pi 4 or 5 set up by an adult

MASTERY CHECKLIST

- ☐ I can explain the Raspberry Pi story and the difference between a single-board computer and a microcontroller.
- ☐ I can navigate and organize files from the command line, read permissions, and follow the command-line safety rules.
- ☐ I can write Python with variables, lists, if, loops and functions, and test my code against hand calculations.
- ☐ I can install MicroPython on a Pico, use the REPL and main.py, and design for 3.3 V logic.
- ☐ I can read buttons with pull-ups and debouncing, use PWM and the ADC on the Pico, and log data with time stamps.

OPTIONAL KITS FOR THIS UNIT

- **Raspberry Pi Pico and Pico W**: Required for Units 9–10 (the Pico costs about $4; the Pico W, with Wi-Fi, a little more and is recommended for Lesson 10.3). Buy one with pre-soldered headers, or solder them yourself following Lesson 5.2.
- **Raspberry Pi 4 or 5**: Optional. A full Linux computer for Lessons 9.1–9.2 and the gpiozero extension in 9.5; needs its own power supply (connected by an adult), a microSD card, screen, keyboard and mouse.
- **Thonny (free Python editor)**: A free, beginner-friendly Python editor for Windows, macOS and Linux that also programs the Pico in MicroPython.
- **MicroPython**: The free MicroPython firmware and documentation, including the RP2040 quick reference used in Lessons 9.4–9.5.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

9.1	**The Raspberry Pi Story: Eben Upton and Cambridge**	3 sessions of 50 minutes
9.2	**Linux and the Command Line**	3 sessions of 50 minutes
9.3	**Python Basics**	3 sessions of 50 minutes
9.4	**The Pico and MicroPython**	3 sessions of 50 minutes
9.5	**GPIO with Python: Buttons, PWM and the ADC**	3 sessions of 50 minutes

Unit 9 test

Time: 50 minutes. A scientific calculator is allowed. Write code neatly with correct indentation; small syntax slips lose little credit if the logic is right. Show calculations with units. The test is worth 100 points.

1. **6 pts** **Lesson 9.1**

   Explain why Eben Upton and his colleagues built the Raspberry Pi and how they made it so cheap.

2. **6 pts** **Lesson 9.1**

   Give two differences between a Raspberry Pi 5 and a Pico, and one job for each.

3. **6 pts** **Lesson 9.1**

   A Pico draws 25 mA at 5 V. How long would a 5,000 mAh, 3.7 V power bank (85% efficient) run it?

4. **6 pts** **Lesson 9.2**

   You are in /home/pi/electronics/unit9. Where are you after cd ../data? What does pwd print?

5. **6 pts** **Lesson 9.2**

   Write rwxr--r-- in octal and binary. Who can do what?

6. **6 pts** **Lesson 9.2**

   State three command-line safety rules.

7. **8 pts** **Lesson 9.3**

   What does this print? r = [100, 220, 470], total = 0, for x in r: with indented total = total + x, then print(total, len(r), total / len(r)).

8. **8 pts** **Lesson 9.3**

   Write a Python function divider(vin, r1, r2) that returns the voltage-divider output, and the result of divider(9.0, 10000, 4700).

9. **6 pts** **Lesson 9.3**

   Give 19 // 4, 19 % 4, 19 / 4 and 3 ** 4.

10. **8 pts** **Lesson 9.4**

    Design a resistor for a green LED ($V_F = 2.2$ V) at 6 mA from a Pico pin. Why must a 5 V Arduino output not connect directly to a Pico input, and how would you fix it?

11. **6 pts** **Lesson 9.4**

    What is the difference between the REPL and main.py? How do you recover a Pico whose main.py misbehaves?

12. **8 pts** **Lesson 9.5**

    pot.read_u16() returns 39,321. Find the voltage and the PWM duty cycle if this value is passed to duty_u16(). What average voltage does the PWM pin give?

13. **6 pts** **Lesson 9.5**

    The RP2040 sensor reads 0.690 V. Find the chip temperature.

14. **6 pts** **Lesson 9.5**

    Explain how to debounce a button in MicroPython with time.ticks_ms().

15. **8 pts** **Lesson 9.2**

    Essay (one paragraph). Unix was designed in 1969 around small tools that each do one job and can be combined; Linux was built from 1991 by giving its code away openly. Explain how these two ideas help engineers build large, reliable systems, using an example from your own work this year.

ANSWER KEY

1. Cambridge applicants had little hands-on programming experience compared with earlier students raised on cheap home computers; they aimed for a computer a child could own and break. They used a mass-produced, inexpensive processor from set-top boxes and phones, free Linux and free software.
2. Pi 5: runs an operating system, much more memory and speed, networking and video (job: web server or camera). Pico: no operating system, runs one program instantly, very low power and cost, 3.3 V GPIO (job: sensor or motor control).
3. Power 0.125 W; energy $0.85 \times 18.5 = 15.7$ Wh; about 126 h
4. In /home/pi/electronics/data; pwd prints that path.
5. 744; 111 100 100. Owner: read, write, execute; group and others: read only.
6. Never run a command you do not understand (especially from the internet); check pwd before deleting; rm has no recycle bin, so name single files; use sudo only with a parent for a known task; work in your own project folder.
7. 790 3 263.3333333333333
8. def divider(vin, r1, r2): with indented return vin * r2 / (r1 + r2); result about 2.878 (V).
9. 4, 3, 4.75, 81
10. $1.1/0.006 = 183\ \Omega \rightarrow 180\ \Omega$ (6.1 mA). Pico inputs are rated for 3.3 V; 5 V can damage them. Use a divider (10 kΩ over 20 kΩ gives 3.33 V) with grounds joined, or a level shifter.
11. REPL runs lines interactively while connected; main.py runs automatically at power-up. Stop it from Thonny (Ctrl+C) and fix or rename main.py, or hold BOOTSEL and reinstall firmware.
12. 1.98 V; 60%; about 1.98 V
13. $27 - (0.690 - 0.706)/0.001721 = 27 + 9.3 = 36.3\ ^\circ\mathrm{C}$
14. When the reading changes, record the time; accept the new state only if it stays the same for about 20–50 ms (compare ticks_diff of now and the recorded time); ignore changes during that window.
15. A strong answer: small, single-purpose tools (or functions) are easy to understand, test and reuse; combining them builds complex behavior; openly published code with review catches errors and lets many contribute; examples:

your Python calculator's small tested functions, reusable dot()/dash() functions, publishing schematics for others to check.

PORTFOLIO PIECE: A STAND-ALONE PICO INSTRUMENT

Build a Pico project that runs by itself from a USB power bank (saved as main.py), with at least one button, one analog input and one PWM output, using debounced input and ticks_ms() timing. Examples: a night light with a brightness knob and an on/off button; a temperature-warning lamp that brightens as the chip or a sensor warms; a reaction game ported from Lesson 7.3; a metronome with a tempo knob and an LED and piezo beat. Submit the wiring diagram with GP numbers and resistor values, commented MicroPython code, a short Python program on your computer that analyzes a log from the device, and a demo.

LOOK FOR	WHAT IT MEANS
Hardware at 3.3 V	Correct resistors and pull-ups, no 5 V on any input, neat wiring diagram with GP numbers.
MicroPython code	Readable, commented, with functions; debounced input; ticks_ms() timing; runs as main.py.
Data and analysis	A time-stamped log from the device analyzed with a Python program on the computer, with a graph.
Demo	Runs from a power bank without a computer and does what the requirements say.

UNIT 10

Communication and Capstone

In this final unit your devices learn to talk: to each other over serial, I²C and SPI buses, through the air by infrared and radio, and over Wi-Fi on your home network, with the internet-safety rules every engineer must follow. You will hear the stories behind each: Baudot's five-key telegraph, Marconi's letter S across the Atlantic, Tesla's unfinished tower and the engineers who made Wi-Fi.

Then you will put the whole year together in a capstone: a device of your own design for a real person, planned with requirements, a budget and a schedule as carefully as the Apollo software team planned for the Moon, built in stages, tested against every requirement, validated with its user, and presented in a design review, as Hewlett and Packard tested every instrument that left their garage.

PREREQUISITES

- Units 7–9: Arduino and Pico programming, sensors, actuators, displays and data logging
- A Raspberry Pi Pico (a Pico W for Lesson 10.3) and the Arduino starter kit
- A parent's permission and help for any Wi-Fi connection

MASTERY CHECKLIST

- ☐ I can compare UART, I²C and SPI, calculate transfer times, and connect 5 V and 3.3 V boards safely.
- ☐ I can use $c = e^{x}$ explain modulation, and build an infrared remote-controlled device.
- ☐ I can explain how a device joins a home network and serve a local web page, following the internet-safety rules.
- ☐ I can write testable requirements, a decision matrix, a BOM with contingency, a schedule and a test plan.
- ☐ I can build in stages, verify and validate a design, analyze test data, and present it honestly.

OPTIONAL KITS FOR THIS UNIT

- **Raspberry Pi Pico W**: The Wi-Fi version of the Pico, used in Lesson 10.3 and for capstones that need a local web page. Without one, Lesson 10.3 can be done over the USB serial link.
- **ELEGOO Uno starter kits**: Many include an IR receiver and remote (Lesson 10.2) and I²C devices such as a real-time clock or an LCD backpack (Lesson 10.1).
- **KiCad (free software)**: For capstone builders who want to draw a professional schematic or design a printed circuit board for their device.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

10.1	**Serial, I²C and SPI: How Chips Talk**	3 sessions of 50 minutes
10.2	**Radio from Marconi to Bluetooth**	3 sessions of 50 minutes
10.3	**Wi-Fi Devices and Internet Safety**	3 sessions of 50 minutes
10.4	**Capstone Design: Requirements, Budget and Schedule**	3 sessions of 50 minutes
10.5	**Build, Test and Present**	3 sessions of 50 minutes

Unit 10 test

Time: 50 minutes. A scientific calculator is allowed. Show formulas, substitutions with units and answers with units; write clear sentences for explanations. The test is worth 100 points.

1. **6 pts** **Lesson 10.1**
   How long does a 120-byte message take over a UART at 9600 baud? At 115,200 baud?

2. **6 pts** **Lesson 10.1**
   Compare UART, I²C and SPI in wires, clock and how a device is chosen.

3. **6 pts** **Lesson 10.1**

   Design a divider so a 5 V output can drive a 3.3 V input, and check the voltage.

4. **8 pts** **Lesson 10.2**

   Find the wavelength of a 915 MHz radio and a quarter-wave antenna for it. How long does a radio signal take to travel 4,800 km?

5. **6 pts** **Lesson 10.2**

   Explain why an IR remote uses a 38 kHz carrier and how the receiver uses it.

6. **6 pts** **Lesson 10.2**

   What did Marconi achieve on December 12, 1901, and what changed for ships after 1912?

7. **8 pts** **Lesson 10.3**

   Compare the time to try every 10-character lowercase password and every 14-character password from 62 symbols, at 10^{10} guesses per second.

8. **8 pts** **Lesson 10.3**

   State five internet-safety rules for a connected hobby device.

9. **6 pts** **Lesson 10.3**

   How long does a 6.0 MB file take at 15 Mbit/s? How much data does a sensor sending 250 bytes every 30 s use in a day?

10. **8 pts** **Lesson 10.4**

    Design D scores function 4, cost 2, ease 5 and design E scores function 3, cost 5, ease 3, with weights 0.5, 0.2, 0.3. Which wins? A BOM of $36 with 15% contingency gives what budget?

11. **6 pts** **Lesson 10.4**

    Rewrite these as testable requirements: “The night light should not be too bright” and “The battery should last a long time.”

12. **6 pts** **Lesson 10.4**

    Explain the Apollo 11 1202 alarm and the engineering lesson it teaches.

13. **8 pts** **Lesson 10.5**

Twelve timing trials of an alert (required within 3.0 s): 2.1, 2.4, 1.9, 3.2, 2.2, 2.0, 2.5, 2.3, 2.6, 2.1, 2.2, 2.4 s. Find the mean and pass rate, and say what to do.

14. **8 pts** **Lesson 10.5**

Essay (one paragraph). Using the stories of the Hewlett-Packard garage and Apollo, explain why honest testing and clear presentation are part of an engineer’s responsibility, and describe how you applied them in your capstone.

15. **4 pts** **Lesson 10.2**

Find the frequency of 850 nm infrared light.

ANSWER KEY

1. $120/960 = 0.125$ s; $120/11{,}520 = 10.4$ ms
2. UART: TX, RX, ground; no shared clock (agreed baud); point to point. I^2C: SDA and SCL with pull-ups; shared clock; 7-bit addresses on a shared bus. SPI: SCK, MOSI, MISO plus a chip-select per device; shared clock; device chosen by its select line.
3. For example 10 kΩ from the 5 V output to the input and 20 kΩ to ground: $5 \times 20/30 = 3.33$ V (with grounds joined).
4. $\lambda = 0.328$ m; quarter wave 8.2 cm; $t = 16$ ms
5. Switching the infrared LED at 38 kHz makes its light distinguishable from steady sunlight and lamps; the receiver module responds only to light flickering at 38 kHz and outputs the bursts as a digital code.
6. He received the letter S sent by radio across the Atlantic from Poldhu to Newfoundland. After the *Titanic*, ships were required to keep a radio watch day and night, so distress calls would always be heard.
7. $26^{10} = 1.41 \times 10^{14}$: 1.4×10^4 s ≈ 3.9 h. $62^{14} = 1.24 \times 10^{25}$: 1.24×10^{15} s $\approx 3.9 \times 10^7$ years.
8. Any five: parent permission and parent enters the password; keep passwords out of shared code (secrets file); change default passwords; keep the device on the home network, no port forwarding; no recording of audio, video or personal data; keep firmware updated; do not join networks that are not yours.
9. 3.2 s; $2880 \times 250 = 720{,}000$ bytes (720 KB)
10. D: $2.0 + 0.4 + 1.5 = 3.9$; E: $1.5 + 1.0 + 0.9 = 3.4$; D wins. Budget $41.40.
11. For example: “The light’s brightness can be set from off to no more than about 20 lux at 1 m,” and “The device runs at least 14 days on 4 AA cells.”
12. The overloaded computer shed low-priority tasks and restarted the essential ones, as designed; controllers trained by simulations knew it was safe and continued. Lesson: define priorities in requirements, protect the must-haves, and test failure cases in advance.
13. Sum 27.9, mean 2.33 s; 11 of 12 pass (91.7%). Find the cause of the 3.2 s case, fix it and retest.
14. A strong answer: HP tested every instrument and improved designs from feedback; Apollo tested failure cases and taught controllers what alarms meant; people rely on engineers’ claims, so results must be measured and reported

truthfully, including failures; presentation lets users and reviewers understand and trust the work; examples from the student's test report, validation and design review.

15. $3.0 \times 10^{8} / 850 \times 10^{-9} = 3.5 \times 10^{14}$ Hz

PORTFOLIO PIECE: THE CAPSTONE DESIGN FILE

Assemble the complete record of your capstone: the approved proposal (need, requirements, constraints, options, decision matrix, block diagram, BOM with contingency, schedule, test plan), the final schematic and wiring diagram, the commented code, photographs of the finished device, the build and debugging logs, the test report with measured results, the validation notes and improvement, the presentation slides or poster, the questions asked in the design review with your answers, and a one-page reflection on the whole year.

LOOK FOR	WHAT IT MEANS
Design process	Testable requirements, a reasoned choice among options, and a realistic budget and schedule with contingency.
Working device	Meets its must-have requirements, follows every safety rule, and is built neatly with clear, commented code.
Testing	Every requirement tested with measured results, failures fixed and retested, validated with the real user.
Presentation	Clear explanation, live demo, honest data including failures, and thoughtful answers to questions.
Reflection	Honest account of planned against actual cost and time, lessons learned, and next steps.

UNIT 10 · COMMUNICATION AND CAPSTONE · LESSON 10.1 OF 50 · 3 SESSIONS OF 50 MINUTES

10.1 Serial, I²C and SPI: How Chips Talk

OBJECTIVES

- Trace serial communication from Baudot's telegraph code to the UART, and explain bits, frames and baud rate.
- Compare UART, I²C and SPI: wires, clocks, addressing, speed and typical uses.
- Calculate transfer times and data rates, and level-shift a 5 V signal for a 3.3 V device.
- Make an Arduino and a Pico exchange messages over a UART, and scan an I²C bus.

> **Warm-up.** Send a friend a four-letter word using only flashes of a flashlight, one letter at a time, without agreeing on anything first. What went wrong? Now agree on a code, a starting signal and a speed, and try again. Write down what you had to agree on.

WATCH

Serial Communications Explained: UART, I2C, and SPI

Electronoobs · 11:58

https://www.youtube.com/watch?v=IyGwvGzrqp8

> **WHEN TO WATCH**
> After the story. Watch the three protocols one at a time and pause after each to fill in a row of your comparison table: wires, clock, speed, how devices are chosen.

BACKUP VIDEO

Understanding I2C

Rohde & Schwarz · 10:57

https://www.youtube.com/watch?v=CAvawEcxoPU

A deeper, clear explanation of I²C from Rohde & Schwarz, with real oscilloscope traces; watch before the I²C step.

KEY TERMS

serial communication

Sending data one bit at a time over a single wire (or pair), as opposed to parallel, which sends several bits at once on several wires.

UART

Universal asynchronous receiver-transmitter: two wires (TX and RX) and ground, no shared clock; both sides agree on the baud rate. Each byte is framed by a start bit and a stop bit.

baud rate

Symbols per second; for a UART, bits per second, such as 9600 or 115200. Named after Émile Baudot.

I²C

Inter-Integrated Circuit: two shared wires, SDA (data) and SCL (clock), with pull-up resistors. Each device has a 7-bit address, so many devices share the same two wires.

SPI

Serial Peripheral Interface: a clock (SCK), data out (MOSI or COPI), data in (MISO or CIPO) and one chip-select line per device. Fast and simple, but needs more wires.

CORE IDEAS

The story. In 1874 the French telegraph engineer Émile Baudot patented a printing telegraph that sent every letter as a pattern of five on-or-off pulses, all of equal length. Operators pressed five keys like a chord, and a machine at the far end printed the letter. Baudot's five-unit code was the ancestor of the codes used by teleprinters for a century and of ASCII, and his name lives on in the unit of signaling speed, the **baud**. In 1982 the Dutch company Philips introduced I²C, a two-wire bus to let the chips inside a television talk to each other; in the mid-1980s Motorola introduced SPI. Today every phone, car and microcontroller is full of chips talking by UART, I²C and SPI.

How they figured it out. To send bits one at a time, both ends must agree on when each bit begins. Baudot's machines used synchronized rotating distributors. A UART solves it without a clock wire: the line rests HIGH; a **start bit** (LOW) says "a byte is coming," and the receiver, knowing the baud rate, samples each following bit in the

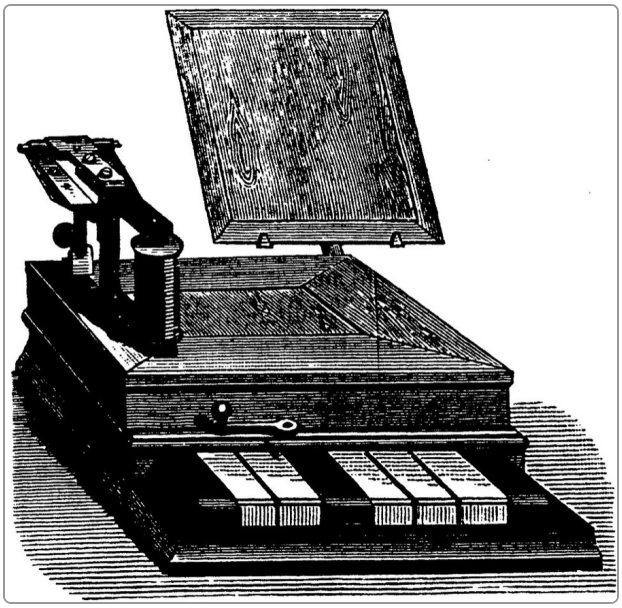
middle of its time slot, then expects a **stop bit** (HIGH). I²C and SPI share a clock wire instead, so the speed can vary. I²C adds addresses so many chips can share two wires, at the cost of speed; SPI gives each chip its own select wire and runs much faster.

The physics. At 9600 baud each bit lasts $1/9600 = 104\ \mu$s; one byte with its start and stop bits is 10 bits, so 960 bytes per second, and "Hello" plus a newline (6 bytes) takes 6.25 ms. At 115,200 baud it is 11,520 bytes per second. I²C's standard mode is 100 kHz (fast mode 400 kHz); each byte takes 9 clock pulses (8 bits and an acknowledge), about 11,000 bytes per second at 100 kHz. Its wires are open-drain: devices only pull them LOW, and pull-up resistors (often 4.7 kΩ) pull them HIGH. SPI at 4 MHz moves 500,000 bytes per second. Voltage levels must match: a 5 V Arduino output into a 3.3 V Pico input needs a divider (for example 10 kΩ over 20 kΩ), or a level-shifter chip.

The engineering. Engineers pick a bus for the job: UART for a link between two devices or to a computer (the Arduino's USB connection is a UART inside); I²C for many slow sensors, displays and clocks on two wires; SPI for fast devices such as SD cards, displays and memory chips. They read datasheets for each device's address, speed and voltage, keep wires short, add pull-ups on I²C, join grounds, and use checks such as a known start byte or a checksum so that a corrupted message is detected rather than believed.

Try it. You will connect your Arduino and Pico so they can talk, then use the Pico to find every device on an I²C bus.

PICTURE STUDY



Baudot's Five-Key Keyboard, Unknown engraver, 1884 · Engraving · Wikimedia Commons

Image: Wikimedia Commons, public domain

Baudot's operators sent each letter by pressing a chord on these five keys: each key an on-or-off pulse, five pulses a letter. It was a serial code of fixed-length characters, like the bytes your boards send today.

Look closely

- Count the keys. How many different letters or symbols can five on-or-off keys make?
- Look for how the keys connect to the line. Did the code go out all at once or one pulse after another?
- Look at the shape and spacing of the keys. How would an operator use both hands?

Talk about it

1. Five units give $2^5 = 32$ patterns. How could Baudot send both letters and numbers with only 32?
2. How is a UART's byte like a Baudot character, and how is it different?
3. Why do both ends of any serial link need to agree on the speed?

> **Safety first.** Boards run only from USB cables or USB power banks; never wall power. The Arduino is 5 V and the Pico 3.3 V: join their grounds, and never connect a 5 V output straight to a Pico input (use a divider). Unplug both boards before rewiring.

BUILD

Two Boards Talking

You will connect the Arduino and the Pico with a UART link (with a level divider), send messages both ways, measure the timing, and scan an I^2C bus for devices.

You will need

- Arduino Uno and Raspberry Pi Pico, each with its USB cable (two USB ports or a power bank for one)
- Resistors 10 kΩ and 20 kΩ (or 10 kΩ + 10 kΩ + 10 kΩ), jumpers, breadboard, an LED with resistor on each board
- Any I^2C device you have (an I^2C LCD backpack, a real-time clock, an accelerometer); optional

Steps

1. Wire the link: Arduino pin 11 (its software-serial TX) → 10 kΩ → Pico GP1 (UART0 RX), with 20 kΩ from GP1 to GND. Pico GP0 (UART0 TX) → Arduino pin 10 (software-serial RX). Join an Arduino GND to a Pico GND.
2. Arduino sketch: #include <SoftwareSerial.h>, SoftwareSerial link(10, 11);. In setup(): Serial.begin(9600); link.begin(9600);. In loop(): if link.available(), read a character with char c = link.read(); and echo it with Serial.write(c);; also every 2 s send link.println("Hello Pico");.
3. Pico program: from machine import UART, Pin, import time, uart = UART(0, baudrate=9600, tx=Pin(0), rx=Pin(1)). In while True:, uart.write("Hello Arduino\\n"), then if uart.any(), print(uart.read()), then time.sleep(2).
4. Run both, with the Arduino's Serial Monitor and Thonny's Shell open. Confirm messages arrive in both directions.
5. Measure: before and after sending a 40-character message, record time.ticks_us() on the Pico. Compare with Worked Example 1.
6. Make one board control the other: when the Pico receives "ON" it lights its LED; when it receives "OFF" it turns it off. Add a button on the Arduino that sends "ON" and "OFF" alternately.

7. **I²C scan.** If you have an I²C device, connect it to the Pico (3.3 V, GND, SDA to GP4, SCL to GP5; most modules have pull-ups). Run from machine import I2C, Pin, i2c = I2C(0, sda=Pin(4), scl=Pin(5)), print([hex(a) for a in i2c.scan()]). Compare the address with the datasheet.
8. **Improve it.** Add the corruption check of practice problem 11. Then deliberately change one board's baud rate to 4800 and record what happens.

Tips

- TX goes to RX and RX to TX: each board's transmitter talks to the other's receiver.
- Many I²C modules are labeled for 5 V; check that they work at 3.3 V before connecting them to the Pico.
- If messages are garbled, check the baud rates and the shared ground first.

Check your work

- ☐ My boards exchanged messages both ways over a UART with a level divider.
- ☐ I measured transfer time and compared it with the baud-rate calculation.
- ☐ I can compare UART, I²C and SPI and choose one for a job.

ENGINEER'S NOTEBOOK

1. The wiring diagram of the link, with the divider and the shared ground.
2. A comparison table: UART, I²C and SPI (wires, clock, addressing, typical speed, uses).
3. A timing diagram of the byte "A" (ASCII 65 = 01000001) as sent by a UART, with start and stop bits (UARTs send the least significant bit first).

KEY FORMULAS

$$t_{\text{bit}} = \frac{1}{\text{baud}}$$

$$\text{bytes/s (UART)} = \frac{\text{baud}}{10}$$

$$\text{bytes/s (I}^2\text{C)} \approx \frac{f_{\text{SCL}}}{9}$$

$$\text{bytes/s (SPI)} = \frac{f_{\text{SCK}}}{8}$$

From history. Baudot's code was developed further by Donald Murray around 1901 and became the International Telegraph Alphabet No. 2, used by teleprinters for most of the twentieth century. ASCII, standardized in 1963, used seven bits, and its first 128 characters are still the start of the Unicode text on every web page.

WORKED EXAMPLES

Example 1. How long does a 40-character message take over a UART at 9600 baud and at 115,200 baud?

Show solution

1. At 9600 baud: 960 bytes/s, so $40/960 = 0.0417$ s $= 41.7$ ms.
2. At 115,200 baud: 11,520 bytes/s, so $40/11{,}520 = 3.5$ ms.

Answer: 41.7 ms; 3.5 ms

Example 2. A sensor on an I²C bus at 100 kHz sends 6 bytes of data per reading, plus 3 bytes of address and command. How many readings per second could the bus carry at most?

Show solution

1. Each reading: 9 bytes × 9 clocks = 81 clocks.
2. Readings per second: $100{,}000/81 \approx 1230$.

Answer: About 1,200 readings per second

Example 3. The Arduino's TX pin (5 V) must drive the Pico's RX pin (3.3 V maximum). Design a divider, and check the current it draws.

Show solution

1. Use 10 kΩ from Arduino TX to the Pico RX pin, and 20 kΩ from the Pico RX pin to ground: $V = 5.0 \times 20/30 = 3.33$ V.
2. Current when TX is HIGH: $5.0/30$ kΩ $= 0.17$ mA, harmless.
3. The Pico's 3.3 V TX into the Arduino's RX usually reads as HIGH (the ATmega needs at least about 3.0 V), so that direction needs no divider.

Answer: 10 kΩ over 20 kΩ gives 3.33 V; 0.17 mA

PRACTICE

1. **Easy** How many bits does a UART send for one byte with one start and one stop bit?

   Show answer

   10

2. **Easy** Which bus uses two shared wires and device addresses?

   Show answer

   I^2C

3. **Easy** What is the baud named after?

   Show answer

   Émile Baudot, the French telegraph engineer.

4. **Medium** How long is one bit at 115,200 baud?

   Show answer

   8.7 µs

5. **Medium** A 7-bit I^2C address allows how many addresses? Why are fewer than that actually usable?

   Show answer

   128; some addresses are reserved for special purposes (16 in the standard), leaving 112.

6. **Medium** Why does I^2C need pull-up resistors?

   Show answer

   Its lines are open-drain: devices can only pull them LOW, so resistors are needed to pull them HIGH when no device is pulling down.

7. **Medium** What happens if two UART devices use different baud rates?

   Show answer

   The receiver samples bits at the wrong times and reads garbage characters.

8. Hard An SD card is written over SPI at 8 MHz. How long does 1 MB take, ignoring overhead?

Show answer

1,000,000 bytes at 1,000,000 bytes/s: about 1.0 s

9. Hard Explain why a UART can work without a clock wire, and what limits how long a message it can send at once.

Show answer

The start bit marks the beginning of each byte and both sides know the baud rate, so the receiver times each bit; small differences between the two clocks add up over a byte, so the start bit resynchronizes every byte (clock error must be under a few percent).

10. Hard You wire an I^2C display and the scan finds nothing. List four things to check.

Show answer

Grounds joined; SDA and SCL not swapped and on the right pins; pull-ups present; the display powered at the right voltage; the address expected; loose jumpers.

11. Challenge Design a simple message format so the Pico can send a temperature to the Arduino and the Arduino can tell if a message is corrupted. Give an example message.

Show answer

For example: a start character, the value, a comma, a checksum (the sum of the value's digit characters modulo 256, or simply the value repeated), and a newline: "T24.8,24.8\n". The Arduino accepts it only if it starts with T and the two copies match.

COMMON MISTAKES

- Connecting TX to TX and RX to RX.
- Forgetting the shared ground.
- Feeding 5 V into a 3.3 V input.

Make it a game · Who Talks How?. Compare cards: UART, I^2C, SPI. Your parent calls a feature, such as two wires with addresses or four wires and fast, and you name the protocol in five seconds. Then explain baud rate and a frame. Tell Baudot's telegraph story in thirty seconds. Ten right answers in a row beats the record.

10.2 Radio from Marconi to Bluetooth

OBJECTIVES

- Tell the story of radio from Hertz's waves and Marconi's transatlantic signal to Bluetooth.
- Use $c = f\lambda$ for radio and infrared, and explain carriers and modulation (AM, FM and on-off keying).
- Explain how an infrared remote sends codes on a 38 kHz carrier and how a receiver module decodes them.
- Build an infrared remote-controlled device and measure its range and angle.

> **Warm-up.** Point a TV remote at your phone's camera (front cameras often work best) and press a button. What do you see on the screen that you cannot see with your eyes? Write a guess about why.

WATCH

How Radio Works: Part 1

Cambridge Museum of Technology · 9:14

https://www.youtube.com/watch?v=nR8ghFj0MWw

> **WHEN TO WATCH**
> After the story. Watch how a signal is put onto a carrier wave (modulation); pause at the AM and FM diagrams and sketch them.

BACKUP VIDEO

Control your LEDs with your TV remote?! || Arduino IR Tutorial

GreatScott! · 7:30

https://www.youtube.com/watch?v=ftdJ0R_5NZk

GreatScott! looks at real infrared remote signals on an oscilloscope and decodes them with an Arduino; watch before the build.

KEY TERMS

electromagnetic wave

A wave of electric and magnetic fields that travels at the speed of light, $c = 3.0 \times 10^8$ m/s: radio, infrared, light and more.

carrier

A steady wave of fixed frequency that is changed (modulated) to carry information.

modulation

Changing a carrier to carry a signal: amplitude (AM), frequency (FM), or switching it on and off (on-off keying).

infrared remote

A remote control that sends codes as bursts of invisible infrared light, switched on and off at about 38 kHz.

Bluetooth

A short-range radio standard at 2.4 GHz for linking devices such as earphones, keyboards and phones, developed at Ericsson in the 1990s.

CORE IDEAS

The story. In 1887 Heinrich Hertz, in Karlsruhe, made sparks jump in one circuit and saw tiny sparks appear in a separate loop of wire across the room: he had made and detected the electromagnetic waves that James Clerk Maxwell had predicted. Hertz thought they had no practical use. A young Italian, Guglielmo Marconi, disagreed. Experimenting at his family's estate near Bologna from 1894, he made his waves carry Morse code farther and farther, moved to England, and on December 12, 1901, at Signal Hill in Newfoundland, heard the three dots of the letter S sent from Poldhu in Cornwall, across the Atlantic. In 1912 the wireless distress call from the *Titanic* brought the *Carpathia*, which rescued more than 700 people, and laws soon required ships to keep radio watch day and night. Marconi shared the 1909 Nobel Prize in Physics. A devout Catholic, he later built Vatican Radio, opened in 1931.

How they figured it out. Marconi found by trial and measurement that taller antennas and a good ground connection greatly increased range, and that tuned circuits let many stations share the air without interfering. Engineers later learned to carry voice and music by modulating a continuous carrier wave (Fessenden, 1906; Armstrong's FM, 1933), to switch frequencies rapidly to avoid interference, and to

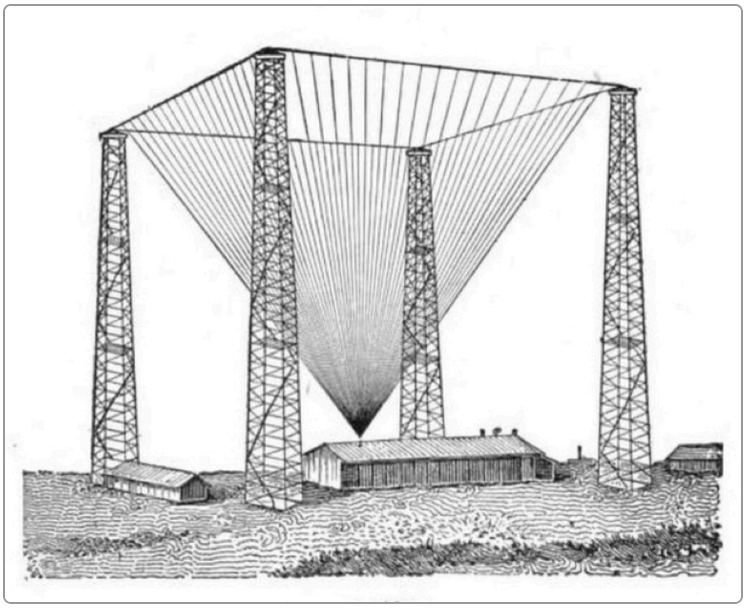
send digital data. In 1994 Jaap Haartsen at Ericsson in Sweden began the design that became Bluetooth, a cheap, low-power short-range radio. It was named after Harald Bluetooth, a tenth-century Danish king who united warring tribes, as the standard was meant to unite devices.

The physics. All electromagnetic waves travel at $c = 3.0 \times 10^8$ m/s, and $c = f\lambda$. An AM station at 1 MHz has a wavelength of 300 m; FM at 100 MHz, 3 m; Bluetooth and Wi-Fi at 2.4 GHz, 12.5 cm. A good antenna is often a quarter-wavelength long, 3.1 cm at 2.4 GHz, which is why phone antennas are small. Infrared remotes use light of about 940 nm wavelength ($f = 3.2 \times 10^{14}$ Hz), invisible to the eye but visible to many cameras. To ignore sunlight and lamps, the remote switches the infrared LED on and off at 38 kHz (period 26.3 µs); the receiver module listens only for light flickering at that rate, and outputs the bursts as a digital signal: on-off keying, like Morse code on a carrier.

The engineering. Engineers choose a wireless link by range, data rate, power, cost and rules. Infrared is cheap and private but needs a line of sight; 433 MHz modules reach far but slowly; Bluetooth suits short links to phones; Wi-Fi carries the most data. All radio transmitters must follow national rules on frequency and power (in the United States, the Federal Communications Commission's rules), which is why engineers use certified modules. Radio also has a duty of care: emergency frequencies must be kept clear, and radio watch at sea still saves lives.

Try it. You will decode a TV-style remote with an infrared receiver and use it to control your own device, then measure its range and beam angle.

PICTURE STUDY



Marconi's Poldhu Wireless Station, Unknown illustrator, about 1901 (published 1915) · Drawing · Wikimedia Commons

Image: Wikimedia Commons, public domain

From this station at Poldhu, on the cliffs of Cornwall, the letter S was sent across the Atlantic on December 12, 1901. Its huge antenna of wires was held up by tall masts.

Look closely

- Count the masts. How tall do they look compared with the buildings?
- Find the wires of the antenna. How are they arranged?
- Why do you think the station was built on a cliff by the sea?
- Look for the buildings where the transmitter was. What would be inside?

Talk about it

1. Using $c = f\lambda$, why did Marconi's low-frequency transmitter need such a large antenna?
2. How is this station like your IR remote, and how is it different?
3. What did Marconi's success change for ships at sea?

> **Safety first.** Boards run only from USB cables or USB power banks; never wall power. The Arduino is 5 V and the Pico 3.3 V: join their grounds, and never connect a 5 V output straight to a Pico input (use a divider). Unplug both boards before rewiring. Do not open TV remotes or appliances; use the remote that comes with your kit or an old remote with its own batteries. Remotes use AA, AAA or coin cells: keep coin cells away from small children.

BUILD

An Infrared Remote-Controlled Device

You will decode the codes of an infrared remote with a receiver module, use them to control LEDs and a servo, and measure how far and at what angle the link works.

You will need

- Arduino Uno (or the Pico) and USB cable, an IR receiver module (such as a VS1838B or a kit IR module) and the kit's small remote, or any spare TV remote
- LEDs with resistors, the micro servo from Lesson 8.2 with its 4-AA supply
- Tape measure, protractor, a phone camera

Steps

1. Look at the remote's LED through your phone camera while pressing buttons. Describe what you see.
2. Wire the IR receiver: its output pin to Arduino pin 2, its power pin to 5V and its ground pin to GND (check your module's pin labels; module pin orders differ).
3. Install the IRremote library (Tools → Manage Libraries → search "IRremote"). Open its ReceiveDemo example (File → Examples → IRremote), upload it, and open the Serial Monitor. Press each remote button and record its code in a table.
4. Write your own sketch using the library's receive functions as in the example: when a code arrives, compare it with your table in a series of if statements; button 1 turns a red LED on, button 2 turns it off, button 3 toggles a green LED.
5. Add the servo (Lesson 8.2): the volume-up and volume-down buttons move it 10° each press, limited to 10–170°.
6. Measure range: walk away along a tape measure, pressing a button, and find the farthest distance at which it works every time (5 tries). Measure the beam angle by standing at a fixed distance and moving sideways.

7. Test what blocks infrared: a sheet of paper, a glass window, your hand, a mirror (bounce the signal off it). Record the results.
8. **Improve it.** Turn it into a useful or fun device: a remote-controlled pointer, a remote-operated toy, or a lamp you can dim from across the room with PWM. Add a small LED that blinks whenever any code is received, so the user knows the signal arrived.

Tips

- Fluorescent lamps and bright sunlight can confuse IR receivers; test indoors away from windows.
- Library versions differ in their function names; follow the examples installed with your version.
- If codes repeat as "FFFFFFFF", that is the remote's "button held" repeat code; handle it separately.

Check your work

- ☐ I decoded at least six remote buttons and controlled LEDs and a servo with them.
- ☐ I measured the link's range and beam angle.
- ☐ I can explain carriers, modulation and

$c =$ for radio and infrared.
$f\lambda$

ENGINEER'S NOTEBOOK

1. The table of buttons and their codes.
2. A sketch of an IR code burst: the 38 kHz carrier inside each pulse, and the pattern of pulses that makes the code.
3. Range and angle measurements, and the results of the blocking tests.
4. A table of wireless technologies with frequency, wavelength, range and typical use.

KEY FORMULAS

$$c = f\lambda$$

$$\lambda_{1/4} = \frac{c}{4f}$$

$$T_{\text{carrier}} = \frac{1}{f} = \frac{1}{38\ \text{kHz}} = 26.3\ \mu\text{s}$$

$$t = \frac{d}{c}$$

From history. Before the Atlantic test, Marconi's signals had already crossed the English Channel in 1899. His company trained operators and ran stations on ships and shores worldwide; the operators of the *Titanic*, Jack Phillips and Harold Bride, were Marconi employees.

WORKED EXAMPLES

Example 1. Find the wavelength of (a) an AM station at 1.0 MHz, (b) FM at 100 MHz, (c) Bluetooth at 2.4 GHz, and a quarter-wave antenna for (c).

Show solution

1. (a) $\lambda = 3.0 \times 10^8 / 1.0 \times 10^6 = 300\ \text{m}$.
2. (b) $3.0 \times 10^8 / 10^8 = 3.0\ \text{m}$.
3. (c) $3.0 \times 10^8 / 2.4 \times 10^9 = 0.125\ \text{m} = 12.5\ \text{cm}$; quarter wave $= 3.1\ \text{cm}$.

Answer: 300 m; 3.0 m; 12.5 cm (3.1 cm antenna)

Example 2. Marconi's 1901 signal traveled about 3,500 km from Poldhu to Signal Hill. How long did it take?

Show solution

1. $t = d/c = 3.5 \times 10^6 / 3.0 \times 10^8 = 0.0117\ \text{s} = 11.7\ \text{ms}$.

Answer: About 12 ms

Example 3. An infrared receiver detects a 38 kHz carrier. How many carrier cycles are in a 560 µs burst (a typical code pulse)? What is the frequency of 940 nm infrared light?

Show solution

1. Cycles: $560\ \mu\text{s} / 26.3\ \mu\text{s} = 21$.
2. Light: $f = c/\lambda = 3.0 \times 10^{8} / 940 \times 10^{-9} = 3.2 \times 10^{14}$ Hz.

Answer: About 21 cycles; 3.2×10^{14} Hz

PRACTICE

1. Easy What is the speed of all electromagnetic waves in a vacuum?

   Show answer

   $3.0 \times 10^{8}\ \text{m/s}$

2. Easy When and between which places did Marconi first send a signal across the Atlantic?

   Show answer

   December 12, 1901, from Poldhu, Cornwall, to Signal Hill, Newfoundland.

3. Easy Why does an IR remote switch its LED at 38 kHz instead of just turning it on?

   Show answer

   So the receiver can tell its signal from steady light (sunlight, lamps) by listening only for light flickering at 38 kHz.

4. Medium Find the wavelength of a 433 MHz radio module and of a 5.8 GHz Wi-Fi signal.

   Show answer

   0.69 m; 5.2 cm

5. Medium What is the difference between AM and FM?

   Show answer

   AM changes the carrier’s amplitude with the signal; FM changes its frequency.

6. Medium Why can a phone camera see an IR remote's LED when your eyes cannot?

Show answer

The camera's sensor responds to near-infrared light (about 940 nm), beyond the red end of human vision.

7. Medium How long does a radio signal take to reach a satellite 36,000 km away?

Show answer

0.12 s

8. Hard Give two advantages and two disadvantages of infrared compared with Bluetooth for a remote control.

Show answer

IR: cheap and simple; does not pass through walls (private, no interference between rooms). But it needs line of sight and has short range; Bluetooth works through obstacles and carries more data but is more complex and costly.

9. Hard After the *Titanic*, why did laws require ships' radios to be staffed day and night?

Show answer

A nearby ship's operator had gone off duty and did not hear the distress call; continuous watch ensures that distress calls are always heard.

10. Hard An IR code is 32 bits, each about 1.1 ms (a 0) or 2.25 ms (a 1), plus a 13.5 ms header. If half the bits are 1, how long does one code take?

Show answer

$13.5 + 16(1.125) + 16(2.25) = 13.5 + 18 + 36 = 67.5$ ms

11. Challenge Explain, with $c = f\lambda$, why low-frequency radio (such as AM) needs very tall towers, while phones fit Wi-Fi antennas inside.

Show answer

Efficient antennas are a sizable fraction of a wavelength (often a quarter). At 1 MHz a quarter wave is 75 m; at 2.4 GHz it is 3.1 cm, small enough to fit in a phone.

COMMON MISTAKES

- Wiring the IR receiver's pins in the wrong order; check the module's label or datasheet.
- Confusing the speed of light with the carrier frequency; the 38 kHz is the flicker rate, not the light's frequency.
- Expecting infrared to pass through walls.

Make it a game · Wavelength Duel. Calculation drill. Your parent gives a frequency; you calculate the wavelength using c = fλ in fifteen seconds. Then explain a carrier, AM, FM and on-off keying with hand gestures. Retell Marconi's transatlantic signal in thirty seconds. Eight correct answers in a row sets the record.

Scripture. "There is no speech nor language, where their voice is not heard. Their line is gone out through all the earth, and their words to the end of the world." (Psalm 19:3-4, KJV)

The Psalmist says the heavens speak to every nation. Radio made human words go out "through all the earth" too, but the heavens declared God's glory first.

10.3 Wi-Fi Devices and Internet Safety

OBJECTIVES

- Tell how Wi-Fi came to be, from Tesla's dream of world wireless to the IEEE 802.11 standard.
- Explain IP addresses, the local network and the internet, and how a device can serve a web page.
- Calculate data rates and transfer times, and estimate password strength.
- Build a Pico W sensor that serves a web page on your home network, following internet-safety rules.

> **Warm-up.** List every device in your house that connects to Wi-Fi. Circle the ones that have a camera or microphone. Which would you least want a stranger to control? Keep the list for the safety discussion.

WATCH

How Information Travels Wirelessly

MITK12Videos · 7:55

https://www.youtube.com/watch?v=Ax7dYaRiY6o

> **WHEN TO WATCH**
> Before the physics paragraph. A clear MIT explanation of how information travels on waves; note how a digital signal is encoded.

BACKUP VIDEO

Connecting To The Internet With The Raspberry Pi Pico W (via WiFi)

Core Electronics · 5:53

https://www.youtube.com/watch?v=GiT3MzRzG48

Core Electronics connects a Pico W to Wi-Fi in MicroPython; follow it in the build (with a parent for the network password).

KEY TERMS

Wi-Fi

Wireless local networking under the IEEE 802.11 standards, mostly at 2.4 GHz and 5 GHz (and 6 GHz in newer versions).

router

The device that connects a home network to the internet, gives local devices their addresses and, with its firewall, blocks unrequested traffic from outside.

default password

A password set at the factory and shared by many devices of the same model; it must be changed before a device is used.

IP address

A number that identifies a device on a network, such as 192.168.1.42 on a home network.

HTTP

The protocol by which web browsers request pages and servers send them.

CORE IDEAS

The story. In 1901 Nikola Tesla began building Wardenclyffe Tower on Long Island, a 57-meter tower meant to send messages, pictures and even power wirelessly around the world. His money ran out, and the tower was torn down in 1917. Wireless networks for data came decades later. In 1985 the U.S. Federal Communications Commission opened certain radio bands for unlicensed use; engineers at NCR in the Netherlands, led by Vic Hayes, who chaired the IEEE 802.11 committee, wrote the first wireless networking standard, published in 1997. In Australia, John O'Sullivan and colleagues at the national science agency, CSIRO, patented techniques to overcome the echoes that blur radio signals indoors, ideas they had first explored in radio astronomy. In 1999 the name Wi-Fi was adopted, and wireless networking spread to nearly every home.

How they figured it out. Indoors, a radio signal bounces off walls and furniture and arrives by many paths at slightly different times, smearing fast data together. The solution, used in modern Wi-Fi, is to split the data across many slower sub-carriers

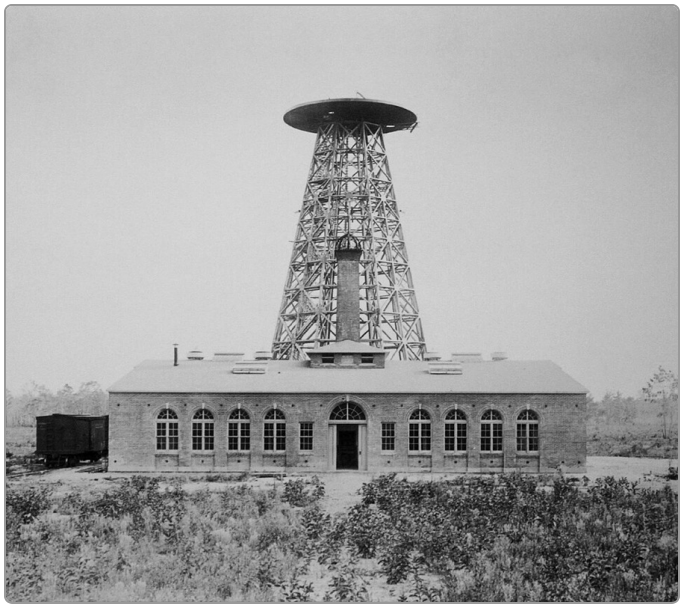
at once (a method called OFDM), so the echoes matter much less, and to check and correct errors. Security came the hard way: early Wi-Fi encryption (WEP, 1997) was broken within a few years and replaced by WPA and WPA2; today WPA3 is standard. Engineers learned that a network is only as safe as its weakest device and its weakest password.

The physics and the numbers. Wi-Fi at 2.4 GHz has a wavelength of 12.5 cm; walls, water (including people) and metal absorb or reflect it, so range indoors is tens of meters. Data rate tells how long a transfer takes: 1 MB (8 million bits) at 10 Mbit/s takes 0.8 s. A sensor sending 100 bytes a minute uses only 144 KB a day. Password strength grows with length: 8 lowercase letters give $26^8 \approx 2.1 \times 10^{11}$ possibilities, which a fast computer guessing 10^9 times a second could try in about 3.5 minutes; 12 characters from letters of both cases and digits give $62^{12} \approx 3.2 \times 10^{21}$, about 100,000 years at the same rate. Length beats cleverness.

Internet safety (the engineering). Connected devices can be misused if they are careless. In 2016 the Mirai malware took over hundreds of thousands of cameras and routers that still had their factory default passwords and used them to flood websites with traffic. The rules for this course: (1) Connect a device to your home network only with a parent's permission, and let the parent enter the network password. (2) Keep passwords and network keys out of any code you share or post; store them in a separate file (such as secrets.py) that stays on the device. (3) Change every default password on any device you set up. (4) Keep your Pico's web page on your home network only; never forward router ports or expose a device to the internet. (5) Never build a device that records or transmits audio, video or other people's personal information. (6) Keep firmware up to date. (7) Be courteous: do not connect to networks that are not yours.

Try it. With a parent, you will connect a Pico W to your home Wi-Fi and have it serve a small web page showing a sensor reading, which you can open from a phone or computer on the same network.

PICTURE STUDY



Tesla's Wardenclyffe Tower, Unknown photographer, about 1902–1904 · Photograph · Wikimedia Commons

Image: Wikimedia Commons, public domain

Nikola Tesla built this tower to send messages and power wirelessly around the world. It was never finished; the dream of world wireless communication came true a century later in a very different form.

Look closely

- Find the dome-shaped framework at the top. What do you think it was meant to be?
- Look at the tower's structure. What material is it, and why might that matter for radio?
- Find the laboratory building. What would have been inside?
- Compare the tower's size with a Wi-Fi router. Why such a difference?

Talk about it

1. What would Tesla think of a Wi-Fi network in an ordinary home?
2. Why do you think his tower failed?
3. What responsibilities come with being able to send information anywhere instantly?

Safety first. Boards run only from USB cables or USB power banks; never wall power. The Arduino is 5 V and the Pico 3.3 V: join their grounds, and never connect a 5 V output straight to a Pico input (use a divider). Unplug both boards before rewiring. Internet-safety rules for this lesson: a parent gives permission and enters the Wi-Fi password; the password lives only in secrets.py on the Pico W and is never shared or posted; the web page stays on your home network (no port forwarding); the device collects no audio, video or personal information.

BUILD

A Pico W Web Thermometer on the Home Network

With a parent, you will connect a Pico W to your home Wi-Fi and serve a small web page that shows the chip's temperature (from Lesson 9.5), refreshing every few seconds, viewable on a phone or computer on the same network. (If you have a plain Pico, do the same with the USB serial link to your computer instead, and display the reading in Thonny.)

You will need

- Raspberry Pi Pico W with MicroPython (the Pico W version of the firmware), USB cable, computer with Thonny
- A parent to enter the Wi-Fi network name and password
- A phone or computer on the same home network; optional LED with 150 Ω on GP15

Steps

1. With a parent, write the safety rules from the core ideas into your notebook and sign them together.
2. On the Pico W, create a file secrets.py containing two lines, SSID = "..." and PASSWORD = "...", with the parent typing the real values. Never copy this file into shared work.
3. In main.py: import network, socket, time, from machine import ADC, import secrets. Connect: wlan = network.WLAN(network.STA_IF), wlan.active(True), wlan.connect(secrets.SSID, secrets.PASSWORD). Wait in a loop until wlan.isconnected() is True (or 10 s pass), then print wlan.ifconfig()[0], the IP address.
4. Make a server: addr = socket.getaddrinfo("0.0.0.0", 80)[0][-1], s = socket.socket(), s.bind(addr), s.listen(1). In a while True: loop, accept a connection with cl, a = s.accept(), read the request with cl.recv(1024), build a short HTML page showing the temperature, send it with cl.send("HTTP/1.0 200 OK\\r\\nContent-type: text/html\\r\\n\\r\\n") followed by the page, and cl.close().

5. Compute the temperature with the Lesson 9.5 formula each time a page is requested. Add a refresh tag so the page reloads every 5 seconds.
6. On a phone or computer on the same network, type http:// followed by the Pico's IP address. Record what you see and how long a page takes to load.
7. Check the safety: confirm that the page cannot be reached from a phone using mobile data (not the home Wi-Fi). Record the result.
8. **Improve it.** Add a link on the page that turns the LED on or off (the request text contains the path, such as "/on" or "/off"), and show the Pico's uptime. Then write a one-paragraph "security review" of your device: what could go wrong, and what protects against it.

Tips

- If the Pico never connects, check that you flashed the Pico W firmware (not the plain Pico firmware) and that your network is 2.4 GHz (the Pico W does not use 5 GHz).
- Keep the page tiny; the Pico W has limited memory.
- Use try: and except: around the network code so one bad request does not crash the program.

Check your work

- ☐ My Pico W serves a page with a live reading on my home network.
- ☐ My Wi-Fi password is stored only in secrets.py and was entered by a parent.
- ☐ I can explain IP addresses, the router's role, and why the device is not reachable from outside.

ENGINEER'S NOTEBOOK

1. The signed internet-safety rules.
2. A network diagram: Pico W, phone, router, internet, with arrows showing which connections are allowed.
3. Your security review paragraph.
4. Password-strength calculations for three example passwords (do not use your real ones).

KEY FORMULAS

$$t = \frac{\text{bits}}{\text{data rate}}$$

$N = (\text{symbols})^{\text{length}}$ (password possibilities)

$$t_{\text{guess}} = \frac{N}{\text{guesses per second}}$$

From history. O’Sullivan and his CSIRO colleagues had studied faint radio signals from space, where the problem of smeared, echoing signals is similar. Their Wi-Fi patents became among the most valuable ever held by a government research agency, an example of pure research turning into practical engineering.

WORKED EXAMPLES

Example 1. How long does it take to send a 3.0 MB photo at 20 Mbit/s? How much data does a sensor sending 100 bytes every minute use in a day?

Show solution

1. Bits: $3.0 \times 10^6 \times 8 = 2.4 \times 10^7$; $t = 2.4 \times 10^7 / 2.0 \times 10^7 = 1.2$ s.
2. Sensor: 1440 minutes $\times\ 100 = 144{,}000$ bytes $= 144$ KB per day.

Answer: 1.2 s; 144 KB per day

Example 2. Compare the time to try every 8-letter lowercase password and every 12-character password of upper- and lower-case letters and digits, at 10^9 guesses per second.

Show solution

1. 8 lowercase: $26^8 = 2.09 \times 10^{11}$; $t = 209$ s ≈ 3.5 min.
2. 12 characters from 62: $62^{12} = 3.23 \times 10^{21}$; $t = 3.23 \times 10^{12}$ s $\approx 1.0 \times 10^5$ years.

Answer: About 3.5 minutes against about 100,000 years

Example 3. A Pico W shows its IP address as 192.168.1.57. Which devices can open its web page, and why can a stranger across town not reach it?

Show solution

1. Any device on the same home network, by typing http://192.168.1.57 into a browser.
2. 192.168.x.x addresses are private; they are not reachable from the internet. The router does not pass unrequested outside traffic to them unless someone deliberately sets up port forwarding, which this course forbids.

Answer: Only devices on the same home network

PRACTICE

1. Easy What standard defines Wi-Fi, and when was its first version published?

   Show answer

   IEEE 802.11, 1997.

2. Easy Why must default passwords be changed?

   Show answer

   Many devices share the same factory password, and attackers know them; a device with a default password can be taken over (as in the 2016 Mirai attacks).

3. Easy Where should a Wi-Fi password be kept in a project?

   Show answer

   In a separate file on the device (such as secrets.py), never in code that is shared or posted, and entered by a parent.

4. Medium How long does a 50 MB file take at 25 Mbit/s?

   Show answer

   16 s

5. Medium How many possibilities does a 6-digit PIN have? How long at 10^9 guesses per second? Why do phones still use them safely?

Show answer

10^6; 1 ms. Phones limit the number of tries and add delays, so fast guessing is impossible.

6. Medium Why does Wi-Fi range drop through walls and people?

Show answer

At 2.4–5 GHz, walls, water (people are mostly water) and metal absorb or reflect the waves.

7. Medium What does a router's firewall do for a home network?

Show answer

It blocks unrequested traffic from the internet from reaching devices inside the home network.

8. Hard Your Pico W project needs to show its readings to a grandparent in another city. Why should you not forward a port on your router, and what is a safer approach?

Show answer

Forwarding exposes your device (and possibly your network) to anyone on the internet, and a hobby device is not hardened against attacks. Safer: email or message a summary, or have the device send data to a trusted, secured service set up with a parent.

9. Hard Explain in two sentences why indoor echoes were a problem for early wireless networks and how splitting data across many sub-carriers helps.

Show answer

Reflected copies of a fast signal arrive at different times and blur successive bits together. Sending many slow streams in parallel makes each bit long compared with the echo delays, so the echoes matter much less.

10. Hard A Pico W draws about 45 mA with Wi-Fi active and 25 mA without. On a 10,000 mAh, 3.7 V bank (85%, 5 V output), how long does each last?

Show answer

With Wi-Fi: 0.225 W, $31.5/0.225 = 140$ h; without: 0.125 W, 252 h.

11. **Challenge** Tesla’s Wardenclyffe failed while 802.11 succeeded. Give two engineering reasons, using what you know of physics and standards.

    Show answer

    Tesla’s plan to send power and signals through the earth and air at a global scale was not supported by physics as he hoped and was enormously costly; Wi-Fi uses short range, low power, efficient digital coding and an open standard that many companies could build to, so devices worked together and costs fell.

COMMON MISTAKES

- Putting the Wi-Fi password in code that is shared or posted.
- Leaving default passwords on routers, cameras or devices.
- Forwarding a router port to make a hobby device reachable from the internet.

> **Make it a game · Network Safety Check.** Quiz-master drill. Your parent lists five habits for a home network, three safe and two risky, such as keeping the default password. You name the risky ones and fix them. Then explain an IP address, a router and HTTP in simple terms. Retell Wi-Fi's history in thirty seconds. Perfect score earns the round.

UNIT 10 · COMMUNICATION AND CAPSTONE · LESSON 10.4 OF 50 · 3 SESSIONS OF 50 MINUTES

10.4 Capstone Design: Requirements, Budget and Schedule

OBJECTIVES

- Tell the story of the Apollo 11 “1202” alarm and what it shows about requirements, testing and priorities.
- Write measurable requirements and constraints for a device, and choose among options with a weighted decision matrix.
- Build a block diagram, a bill of materials with costs and a contingency, and a schedule with milestones.
- Write a complete capstone proposal for an electronic device that serves a real person or need.

> **Warm-up.** Think of a person you know who has a small daily problem a gadget could solve: a grandparent who forgets to water plants, a sibling who loses track of time, a teacher who needs a timer. Write down three such problems and who they belong to.

WATCH

Apollo 11's "1202 Alarm" Explained

The Vintage Space · 6:55

https://www.youtube.com/watch?v=kGD0zEbiDPQ

> **WHEN TO WATCH**
> At the start of the lesson. Watch for what the computer was designed to do when overloaded, and why that design decision mattered.

BACKUP VIDEO

How did the Apollo flight computers get men to the moon and back ?

Curious Droid · 9:05

https://www.youtube.com/watch?v=ULGi3UkgW30

A fuller overview of the Apollo Guidance Computer and its design; optional.

KEY TERMS

requirement

A statement of what a design must do, written so it can be tested: “The alarm sounds within 2 s when the soil reading falls below 30%.”

constraint

A limit the design must respect: budget, size, power source, safety rules, time.

decision matrix

A table that scores each design option against weighted criteria to choose among them fairly.

bill of materials (BOM)

A list of every part with its quantity, value, source and cost.

milestone

A checkpoint in a schedule with a deliverable, such as “breadboard prototype working” by a date.

CORE IDEAS

The story. On July 20, 1969, as the lunar module *Eagle* descended toward the Moon, the Apollo Guidance Computer flashed program alarms, 1202 and then 1201. A radar switch had been left in a position that fed the computer extra work it had not been designed to expect, and it was overloaded. In Mission Control, young engineers Jack Garman and Steve Bales knew from simulations that the alarms meant the computer was shedding low-priority tasks and restarting the important ones, exactly as designed. They called “Go,” and Neil Armstrong and Buzz Aldrin landed. The software team at MIT, led by Margaret Hamilton, had built the computer’s executive so that, under overload, it kept doing what mattered most: guiding the landing.

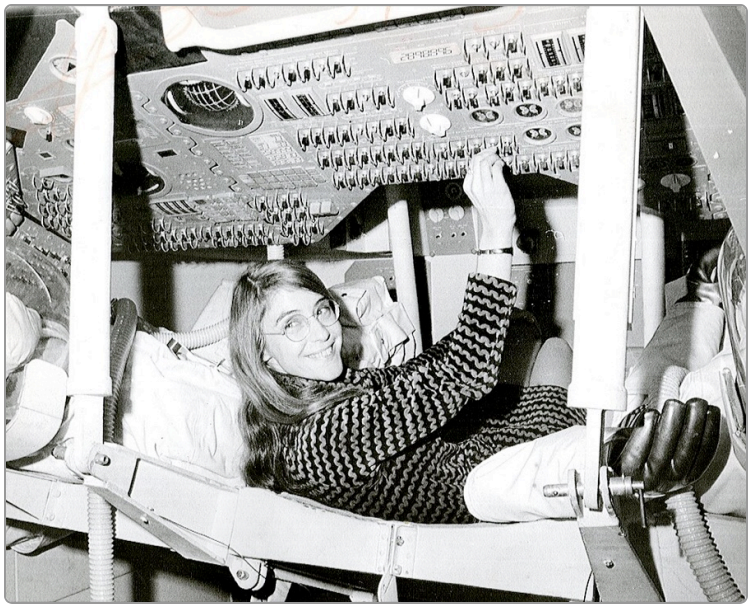
How they figured it out. The AGC’s designers could not test every possible situation in space, so they wrote clear requirements about priorities: if the computer ran short of time, navigation and guidance must never stop. They built and tested restart behavior on the ground, ran thousands of simulated landings with deliberately injected failures, and taught the controllers what each alarm meant. A requirement written down, tested and understood by the whole team turned a frightening moment into a routine decision.

The engineering method. A capstone follows the same path. (1) **Define the need**: who is it for, and what problem does it solve? Talk to that person. (2) **Write requirements** that can be tested, with numbers, and **constraints**: in this course, battery or USB power only, a budget, a size, the parts you can get, safety rules. (3) **Generate options**: at least two different ways to meet the requirements. (4) **Choose** with a weighted decision matrix: weight each criterion (for example function 40%, cost 30%, ease of building 30%), score each option, and multiply and add. (5) **Plan**: a block diagram (sensors → microcontroller → outputs → power), a bill of materials with a contingency of about 15% for surprises, a schedule with milestones, and a test plan with one test for each requirement.

The engineering of priorities. Real projects face trade-offs: a feature that would be nice versus the budget, a faster sensor versus battery life. Engineers rank requirements as must-have, should-have and nice-to-have, and like the AGC, they make sure the must-haves are protected when something goes wrong. Counting the cost before you begin, in money, time and risk, is old wisdom: “For which of you, intending to build a tower, sitteth not down first, and counteth the cost.”

Try it. In this lesson you will write a full proposal for your capstone device, ready to build and test in Lesson 10.5.

PICTURE STUDY



Margaret Hamilton in the Apollo Command Module, NASA, 1960s · Photograph · Wikimedia Commons

Image: Wikimedia Commons, public domain

Margaret Hamilton led the team at the MIT Instrumentation Laboratory that wrote the onboard flight software for Apollo. Here she is in a command-module mock-up, seeing the cockpit from the astronauts' seat: designing for the real user.

Look closely

- Look at the panels above her. How many switches and displays can you count?
- Look at her position. Why would a software engineer want to sit where the astronaut sits?
- Find the hand controller beside the seat. Which inputs would an astronaut use most?

Talk about it

1. Why would a team writing software for a Moon landing need written requirements and careful reviews?
2. Hamilton is credited with using the term "software engineering." Why might calling it engineering matter?
3. What part of your capstone will need the most careful checking?

> **Safety first.** Boards run only from USB cables or USB power banks; never wall power. The Arduino is 5 V and the Pico 3.3 V: join their grounds, and never connect a 5 V output straight to a Pico input (use a divider). Unplug both boards before rewiring. Your capstone must follow every course safety rule: batteries or USB only, no wall power, no lithium cells except sealed commercial power banks, no recording of people, and soldering only with an adult present.

BUILD

The Capstone Proposal

You will write a complete proposal for your capstone: a battery- or USB-powered device, built with the Arduino or the Pico, that meets a real need for a real person. It must use at least two inputs, two outputs and code you write. You will build and test it in Lesson 10.5.

You will need

- Your engineer's notebook and graph paper, or a word processor and spreadsheet
- Your parts kit, to check what you have
- A conversation with the person you are designing for

Steps

1. **Need.** Choose a person and a problem (from the warm-up). Interview them for ten minutes: what is the problem, when does it happen, what would help, what must the device not do? Write a one-paragraph problem statement.
2. **Requirements.** Write 6–10 testable requirements, each with a number where possible, marked must, should or nice-to-have. Write the constraints: power source, budget (for example $30), size, time (sessions available), safety rules.
3. **Options.** Sketch at least two different designs (for example Arduino with an LCD versus Pico W with a web page, or a servo pointer versus an LED bar).
4. **Decide.** Make a weighted decision matrix with at least three criteria and choose a design. Explain the choice in two sentences.
5. **Plan the design.** Draw a block diagram (inputs → microcontroller → outputs, plus power), then a first schematic. Write a power budget and battery-life estimate.
6. **Bill of materials.** List every part with quantity, value, source and cost; add 15% contingency. Mark the parts you already have.
7. **Schedule and tests.** Make a schedule of tasks with sessions and milestones (breadboard prototype, code working, soldered or enclosed version, testing, presentation). Write one test for each requirement, with a pass condition.

8. **Improve it.** Show the proposal to your parent or mentor and to the person you are designing for. Record their questions and suggestions, revise the proposal, and get it approved (signed) before you start building.

Tips

- Choose a project you can finish in about 10–12 sessions; a simple device that works and is well tested beats an ambitious one that does not.
- Reuse your earlier builds: the sensor code of Unit 8, the PWM of Unit 7, the Wi-Fi page of Lesson 10.3.
- Write requirements before you choose parts, not after.

Check your work

- ☐ My proposal has a problem statement, testable requirements, constraints, options, a decision matrix, a block diagram, a schematic, a BOM with contingency, a schedule and a test plan.
- ☐ My design follows every course safety rule.
- ☐ I revised the proposal after feedback and it is approved.

ENGINEER'S NOTEBOOK

1. The interview notes and problem statement.
2. The requirements table and decision matrix.
3. The block diagram, schematic, power budget and BOM.
4. The schedule (a simple bar chart by session) and the test plan.

KEY FORMULAS

$$\text{score} = \sum(\text{weight} \times \text{rating})$$

$$\text{budget} = \text{BOM total} \times (1 + \text{contingency})$$

$$\text{battery life} = \frac{\text{capacity}}{I_{\text{avg}}}$$

From history. Margaret Hamilton received the Presidential Medal of Freedom in 2016 for her work on Apollo software. She often told of her young daughter crashing a simulation by pressing keys at the wrong time, which convinced her to add protections against operator errors: a lesson in designing for the people who will use a system.

WORKED EXAMPLES

Example 1. Two designs for a plant-watering reminder: A (Pico W with soil sensor and web page) and B (Arduino with soil sensor, LED and buzzer). Criteria and weights: function 0.4, cost 0.3, ease of building 0.3. Ratings (1–5): A scores function 5, cost 3, ease 2; B scores function 4, cost 4, ease 4. Which wins?

Show solution

1. A: $0.4(5) + 0.3(3) + 0.3(2) = 2.0 + 0.9 + 0.6 = 3.5$.
2. B: $0.4(4) + 0.3(4) + 0.3(4) = 1.6 + 1.2 + 1.2 = 4.0$.
3. B wins; A's web page is a nice-to-have that costs ease of building.

Answer: B, 4.0 against 3.5

Example 2. A bill of materials: microcontroller $6, sensor $3, servo $4, display $5, enclosure and wire $4, batteries $5. Find the total and the budget with 15% contingency.

Show solution

1. Total: $6 + 3 + 4 + 5 + 4 + 5 = 27$.
2. With contingency: $27 \times 1.15 = 31.05$.

Answer: $27; budget about $31

Example 3. A device must run 7 days on 4 AA cells (2,500 mAh). What is the largest average current allowed? If the microcontroller sleeps at 2 mA and wakes for 1 s every minute at 40 mA, does it meet the requirement?

Show solution

1. Allowed: $2500 \text{ mAh} / 168 \text{ h} = 14.9 \text{ mA}$ average.
2. Actual: $2 \times (59/60) + 40 \times (1/60) = 1.97 + 0.67 = 2.6 \text{ mA}$.
3. Yes, with a large margin: about 40 days ideally.

Answer: 14.9 mA allowed; about 2.6 mA used: meets it

PRACTICE

1. Easy Rewrite “the alarm should be loud” as a testable requirement.

Show answer

For example: “The alarm produces at least 70 dB at 1 m,” or “The alarm can be heard from the next room with the door closed.”

2. Easy What is the difference between a requirement and a constraint?

Show answer

A requirement is what the design must do; a constraint is a limit it must respect (cost, power, size, time, rules).

3. Easy What did the 1202 alarm on Apollo 11 mean?

Show answer

The computer was overloaded and was shedding lower-priority tasks and restarting the important ones, as designed.

4. Medium Score a third design C (function 3, cost 5, ease 5) with the weights of Worked Example 1. Does it beat B?

Show answer

$1.2 + 1.5 + 1.5 = 4.2$: yes, narrowly; check whether its lower function still meets the must-have requirements.

5. Medium A BOM totals $42. What is the budget with 15% contingency?

Show answer

$48.30

6. Medium Why do engineers add a contingency to a budget and a schedule?

Show answer

Something always goes wrong: a part breaks, a price changes, a bug takes longer; contingency keeps the project on track when it does.

7. Medium Give one must-have, one should-have and one nice-to-have requirement for a bedside reading light.

Show answer

For example: must, gives enough light to read at 40 cm; should, dims smoothly with a knob; nice, turns off automatically after 30 minutes.

8. Hard Your schedule has five tasks of 2, 3, 2, 4 and 1 sessions, in order. Add 20% contingency. If you have 14 sessions, is there time?

Show answer

$12 \times 1.2 = 14.4$ sessions: just over 14; trim a nice-to-have or start one task in parallel.

9. Hard Explain how the AGC's handling of overload is like ranking must-have and nice-to-have requirements.

Show answer

The designers decided in advance which tasks must never stop (guidance) and which could be dropped (lower-priority displays and tasks); under stress, the design protected the must-haves, as a good project plan protects its must-have requirements.

10. Hard A device draws 30 mA continuously. How long will 4 AA cells (2,500 mAh) last? What duty cycle of a 30 mA active state (with 1 mA otherwise) would make it last 30 days?

Show answer

83 h (3.5 days). 30 days = 720 h needs ≤ 3.47 mA average: $1 + 29D \leq 3.47$, so $D \leq 8.5\%$.

11. Challenge Write a test for each of three requirements of a plant-watering reminder: it detects dry soil, it alerts within 2 s, and it lasts 7 days on batteries. Say what you would measure and what counts as a pass.

Show answer

Dry soil: compare readings in wet, damp and dry soil with a manual check; pass if it alerts only for dry. Alert time: time from moving the sensor into dry soil to the alert, 10 trials; pass if all under 2 s. Battery: measure average current over an hour and compute life, then run a 7-day test; pass if still working.

COMMON MISTAKES

- Writing requirements that cannot be tested ("easy to use," "looks nice") without saying how they will be judged.
- Choosing parts before writing requirements.
- Planning with no contingency in time or money.

Make it a game · Requirements Review. Your parent proposes a device in one sentence. You write three measurable requirements and a constraint, then score three options on a weighted decision matrix. Your parent challenges any vague requirement. Then retell the Apollo 11 1202 alarm and what it teaches about priorities. Most defensible matrix wins.

Scripture. “For which of you, intending to build a tower, sitteth not down first, and counteth the cost, whether he have sufficient to finish it?” (Luke 14:28, KJV)

Our Lord used an engineer’s planning as a picture of counting the cost of discipleship. A proposal with a budget, a schedule and a test plan is the engineer’s way of sitting down first.

10.5 Build, Test and Present

OBJECTIVES

- Tell how Hewlett and Packard built, tested and sold their first product from a garage, and what it teaches about finishing well.
- Build a capstone device in stages, test it against every requirement, and record the results honestly.
- Analyze test data (pass rates, means, battery life) and decide what to fix.
- Present the design to an audience with a demo, data and an honest account of what did and did not work.

> **Warm-up.** Think of the best explanation or demo you have ever seen: a teacher, a museum guide, a video. What made it clear? List three things the presenter did well.

WATCH

HP Origins - Hewlett Packard Documentary

EEVblog2 · 26:06

https://www.youtube.com/watch?v=Iqv6DhtLay4

> **WHEN TO WATCH**
> At the start of the lesson. Watch the first ten minutes, on the garage, the audio oscillator and its first customers; the rest of the company's history is optional.

KEY TERMS

prototype

An early working version of a design, built to test ideas before the final version.

verification

Testing that the device meets each written requirement.

validation

Checking with the real user that the device actually solves their problem.

test report

A record of each test: what was done, the measured result, pass or fail, and what was changed.

design review

A meeting in which the designer presents a design and others question it, to find problems early.

CORE IDEAS

The story. In 1939 two young Stanford engineering graduates, Bill Hewlett and David Packard, set up a workshop in a one-car garage behind a rented house at 367 Addison Avenue in Palo Alto, California, with about $538 of capital. Their first product was the Model 200A audio oscillator, a precise, stable signal generator based on a circuit Hewlett had designed in graduate school. Hewlett's clever trick was to use a small incandescent lamp in the feedback loop: as the output grew, the lamp's filament heated and its resistance rose, automatically holding the amplitude steady. The instrument was simpler and much cheaper than its competitors. One of their first customers was Walt Disney Studios, which bought eight oscillators (the Model 200B) to test the sound systems for the film *Fantasia*. The garage is now a California Historical Landmark, often called the birthplace of Silicon Valley.

How they figured it out. Hewlett and Packard tested every instrument before it left the garage, and they used customers' feedback to improve each model. Packard later wrote that they tried to make a real contribution with every product, and to treat customers, employees and competitors honestly. Their method is the one you have practiced all year: build a prototype, measure it against what it should do, find the weak points, improve, and do not ship it until it works.

The engineering of testing. Build in stages and test as you go: power first, then each input, each output, then the code that joins them. For each requirement, run the test you wrote in Lesson 10.4, several times, and record the measured values, not just "it worked." Calculate what the data say: a pass rate (9 of 10 trials = 90%), a mean and range, a measured average current and the battery life it implies. A requirement that fails is not a disaster; it is information. Fix the cause, retest, and record both results. Then validate: give the device to the person it is for and watch them use it without your help.

Presenting the design. Engineers must explain their work so others can trust it, use it and build on it. A good presentation (about 8–10 minutes) has: the need and who it is for; the requirements; the design (block diagram and schematic, briefly); a live

demo; the test results, including what failed and what you changed; the cost and the schedule as planned and as actually happened; and what you would do next. Speak to the audience, not the screen; show data in tables and graphs; be honest about limits. Then answer questions: a design review is a gift, because every question finds something to improve.

Today and beyond. *Fabricando fit faber*: by making, one becomes a maker. You began the year measuring a coin pile; you end it with a device of your own design that senses, decides and acts, built safely, tested honestly and explained clearly. That is what engineers do, in a garage or at NASA.

PICTURE STUDY



Workers outside Edison's Menlo Park Laboratory, Unknown photographer, about 1880 · Photograph · Wikimedia Commons

Image: Wikimedia Commons, public domain

Long before the Hewlett-Packard garage, Thomas Edison's laboratory at Menlo Park was an "invention factory" where a team built, tested and showed new devices, among them the electric lighting system of Lesson 2.1. Edison invited the public to see his lights in operation at Menlo Park at the end of 1879: showing your work in public is part of engineering.

Look closely

- Count the people. What does that tell you about how inventions were made here?
- Look at the building. What would a laboratory of 1880 need: light, space, power?
- Look at the clothing. Who might be machinists, who scientists, who assistants?

Talk about it

1. Why would a team need to show an invention to the public and to investors?
2. How is this laboratory like the HP garage, and how is it different?
3. What makes a demo convincing and honest?

Safety first. Boards run only from USB cables or USB power banks; never wall power. The Arduino is 5 V and the Pico 3.3 V: join their grounds, and never connect a 5 V output straight to a Pico input (use a divider). Unplug both boards before rewiring. Every capstone build follows the full course safety rules: batteries or USB only, soldering only with an adult present, no lithium cells except sealed commercial power banks, flyback diodes on motors and relays, and guards on any moving parts.

BUILD

Build, Test and Present the Capstone

You will build your approved capstone in stages, test it against every requirement, validate it with its user, and present it in a design review to your family or friends.

You will need

- The parts in your approved bill of materials
- Multimeter, stopwatch, notebook, a way to show slides or posters (optional)
- An audience of at least three people, including the person you designed for

Steps

1. **Stage 1: power and the brain.** Build the power section and microcontroller; check voltages and current with nothing else connected. Record the readings.
2. **Stage 2: one function at a time.** Add each input and output with a small test program (reusing your earlier lessons' code), and check it before going on. Keep a debugging log.
3. **Stage 3: the whole program.** Combine the functions in your final program, commented, using millis() or ticks_ms() timing. Save versions as you go.
4. **Stage 4: the finished device.** Move it to perfboard or an enclosure if planned, with strain relief, labels and a power switch. Re-run the stage 1 checks.
5. **Verification.** Run every test from your test plan, with at least the number of trials you planned. Record measured values in a test report, calculate pass rates, means and battery life, and fix and retest anything that fails.
6. **Validation.** Give the device to its user with only a one-page user guide. Watch silently, then ask what was confusing and what they would change. Record it and make at least one improvement.
7. **Prepare the presentation.** Make 6–10 slides or a poster: need, requirements, design, demo plan, test results (table and graph), cost and schedule actual

against planned, lessons learned, next steps. Practice it aloud twice and time it.

8. **Present and review.** Give the presentation (8–10 minutes) with a live demo, then take questions for 5 minutes. Record every question and your answer. Finish your design file and write a one-page reflection on the year: what you built, what you learned and what you would build next.

Tips

- Bring the device fully charged or with fresh batteries, and have a backup video of it working in case of a failure during the demo.
- Show real numbers. “It lasts 16 days (calculated from a measured 6.5 mA)” is more convincing than “the battery lasts a long time.”
- If something fails during the demo, stay calm, say what you think happened, and explain how you would find out. That is engineering too.

Check your work

- ☐ My device was built in stages and passes its must-have requirements, with a test report of measured results.
- ☐ I validated it with its user and made at least one improvement from their feedback.
- ☐ I presented the design with a demo, data, honest limits and answers to questions.

ENGINEER’S NOTEBOOK

1. The stage-by-stage build log with measurements and the debugging log.
2. The test report: each requirement, test, measured results, pass/fail, fixes.
3. Validation notes and the improvement made.
4. Your presentation outline, the questions you were asked, and your reflection on the year.

KEY FORMULAS

$$\text{pass rate} = \frac{\text{passes}}{\text{trials}} \times 100\%$$

$$\bar{x} = \frac{\sum x_i}{n}$$

$$t_{\text{battery}} = \frac{\text{capacity}}{I_{\text{avg}}}$$

From history. Hewlett and Packard decided who would have his name first by flipping a coin. Their company grew to make calculators, computers and printers, but the founders always pointed back to the habits of the garage: build carefully, test honestly, listen to customers, and treat people fairly.

WORKED EXAMPLES

Example 1. A capstone's alert must sound within 2.0 s. Ten trials give 1.2, 1.4, 1.1, 1.6, 2.3, 1.3, 1.2, 1.5, 1.4, 1.2 s. Find the mean, the pass rate, and what you should do.

Show solution

1. Mean: $(1.2 + 1.4 + 1.1 + 1.6 + 2.3 + 1.3 + 1.2 + 1.5 + 1.4 + 1.2)/10 = 14.2/10 = 1.42$ s.
2. Passes: 9 of 10 (the 2.3 s trial failed): 90%.
3. Investigate the failure (perhaps a long delay in the loop or a slow sensor reading), fix it, and retest; the requirement says "within 2.0 s," not "on average."

Answer: Mean 1.42 s; 90% pass; find and fix the slow case

Example 2. You measure your device's current over one minute: 3 mA for 55 s and 45 mA for 5 s. It runs on 4 AA cells (2,500 mAh). Predict the battery life and compare with a 7-day requirement.

Show solution

1. Average: $(3 \times 55 + 45 \times 5)/60 = (165 + 225)/60 = 6.5$ mA.
2. Life: $2500/6.5 = 385$ h $= 16$ days.
3. Passes the 7-day requirement with more than double margin (ideal; real batteries deliver somewhat less).

Answer: About 16 days: passes

Example 3. Your budget was $31 and your schedule 12 sessions. You spent $34 and 15 sessions. Find the percent overrun of each, and state one honest lesson for your presentation.

Show solution

1. Cost overrun: $(34 - 31)/31 = 9.7\%$.
2. Schedule overrun: $(15 - 12)/12 = 25\%$.
3. A lesson might be: the enclosure took three extra sessions; next time, plan the enclosure in the design stage.

Answer: 9.7% over budget, 25% over schedule

PRACTICE

1. Easy What was Hewlett-Packard's first product, and who was an early customer?

   Show answer

   The Model 200A audio oscillator; Walt Disney Studios, which bought eight (Model 200B) for *Fantasia*.

2. Easy What is the difference between verification and validation?

   Show answer

   Verification checks the device meets its written requirements; validation checks with the real user that it solves their problem.

3. Easy A test passes 17 of 20 trials. What is the pass rate?

   Show answer

   85%

4. Medium Why should a test report record measured values rather than just "passed"?

   Show answer

   Measured values show how close to the limit each result was, reveal trends, allow others to check the work, and help find causes of failures.

5. Medium How did the lamp in Hewlett's oscillator keep the output steady?

Show answer

As the output grew, the lamp's filament heated and its resistance rose, reducing the feedback gain; this automatic negative feedback held the amplitude constant.

6. Medium Name five parts of a good capstone presentation.

Show answer

Any five: the need and user; requirements; design (block diagram, schematic); live demo; test results including failures and fixes; cost and schedule actual against planned; what you would do next; answering questions.

7. Medium Your device draws 5 mA for 50 s and 60 mA for 10 s of every minute. Find the average current and life on 2,500 mAh.

Show answer

$(250 + 600)/60 = 14.2$ mA; 176 h (7.3 days)

8. Hard In your presentation, a classmate asks a question that reveals a flaw you had not noticed. What should you do, and why is it good?

Show answer

Thank them, admit it honestly, note it, and explain how you would test and fix it; finding flaws before the device is used is exactly what design reviews are for.

9. Hard Your user validation shows that your grandparent cannot read the LCD without glasses, although every written requirement passed. What does this teach?

Show answer

Requirements can miss real needs; validation with the actual user is essential. Add a requirement (larger display, or a light or sound instead) and redesign.

10. Hard A Fantasia sound system was tested with eight oscillators. Why would a film studio need precise, stable test signals?

Show answer

To measure and adjust the response of amplifiers and speakers at each frequency, so the sound in theaters was faithful; that needs signals of known, steady frequency and amplitude.

11. Challenge Ten devices are built. Each passes its tests with probability 0.95, independently. What is the chance all ten pass? What does that mean for a product made in thousands?

Show answer

$0.95^{10} = 0.60$. In large numbers, many units would fail; manufacturers need higher per-unit reliability, testing of every unit, and designs with margin.

COMMON MISTAKES

- Building everything at once and then trying to debug it all together.
- Reporting only successes and hiding failures.
- Skipping validation with the real user.

> **Make it a game · Honest Test Report.** Report drill. Pick any device in the house and test it against three requirements you write, recording pass or fail honestly. Your parent plays review board and asks one hard question per result. Distinguish verification from validation. Then retell the Hewlett and Packard garage story in thirty seconds. No fudged numbers earns the point.

UNIT 10

Communication and Capstone

In this final unit your devices learn to talk: to each other over serial, I²C and SPI buses, through the air by infrared and radio, and over Wi-Fi on your home network, with the internet-safety rules every engineer must follow. You will hear the stories behind each: Baudot's five-key telegraph, Marconi's letter S across the Atlantic, Tesla's unfinished tower and the engineers who made Wi-Fi.

Then you will put the whole year together in a capstone: a device of your own design for a real person, planned with requirements, a budget and a schedule as carefully as the Apollo software team planned for the Moon, built in stages, tested against every requirement, validated with its user, and presented in a design review, as Hewlett and Packard tested every instrument that left their garage.

PREREQUISITES

- Units 7–9: Arduino and Pico programming, sensors, actuators, displays and data logging
- A Raspberry Pi Pico (a Pico W for Lesson 10.3) and the Arduino starter kit
- A parent's permission and help for any Wi-Fi connection

MASTERY CHECKLIST

- ☐ I can compare UART, I²C and SPI, calculate transfer times, and connect 5 V and 3.3 V boards safely.
- ☐ I can use $c = e^{x}$ explain modulation, and build an infrared remote-controlled device.
- ☐ I can explain how a device joins a home network and serve a local web page, following the internet-safety rules.
- ☐ I can write testable requirements, a decision matrix, a BOM with contingency, a schedule and a test plan.
- ☐ I can build in stages, verify and validate a design, analyze test data, and present it honestly.

OPTIONAL KITS FOR THIS UNIT

- **Raspberry Pi Pico W**: The Wi-Fi version of the Pico, used in Lesson 10.3 and for capstones that need a local web page. Without one, Lesson 10.3 can be done over the USB serial link.
- **ELEGOO Uno starter kits**: Many include an IR receiver and remote (Lesson 10.2) and I²C devices such as a real-time clock or an LCD backpack (Lesson 10.1).
- **KiCad (free software)**: For capstone builders who want to draw a professional schematic or design a printed circuit board for their device.

Not required. Every project in this unit can be built with household materials. School Launch has no ties to these companies.

LESSONS IN THIS UNIT

10.1	**Serial, I²C and SPI: How Chips Talk**	3 sessions of 50 minutes
10.2	**Radio from Marconi to Bluetooth**	3 sessions of 50 minutes
10.3	**Wi-Fi Devices and Internet Safety**	3 sessions of 50 minutes
10.4	**Capstone Design: Requirements, Budget and Schedule**	3 sessions of 50 minutes
10.5	**Build, Test and Present**	3 sessions of 50 minutes

Unit 10 test

Time: 50 minutes. A scientific calculator is allowed. Show formulas, substitutions with units and answers with units; write clear sentences for explanations. The test is worth 100 points.

1. **6 pts** **Lesson 10.1**
   How long does a 120-byte message take over a UART at 9600 baud? At 115,200 baud?

2. **6 pts** **Lesson 10.1**
   Compare UART, I²C and SPI in wires, clock and how a device is chosen.

3. **6 pts** **Lesson 10.1**

   Design a divider so a 5 V output can drive a 3.3 V input, and check the voltage.

4. **8 pts** **Lesson 10.2**

   Find the wavelength of a 915 MHz radio and a quarter-wave antenna for it. How long does a radio signal take to travel 4,800 km?

5. **6 pts** **Lesson 10.2**

   Explain why an IR remote uses a 38 kHz carrier and how the receiver uses it.

6. **6 pts** **Lesson 10.2**

   What did Marconi achieve on December 12, 1901, and what changed for ships after 1912?

7. **8 pts** **Lesson 10.3**

   Compare the time to try every 10-character lowercase password and every 14-character password from 62 symbols, at 10^{10} guesses per second.

8. **8 pts** **Lesson 10.3**

   State five internet-safety rules for a connected hobby device.

9. **6 pts** **Lesson 10.3**

   How long does a 6.0 MB file take at 15 Mbit/s? How much data does a sensor sending 250 bytes every 30 s use in a day?

10. **8 pts** **Lesson 10.4**

    Design D scores function 4, cost 2, ease 5 and design E scores function 3, cost 5, ease 3, with weights 0.5, 0.2, 0.3. Which wins? A BOM of $36 with 15% contingency gives what budget?

11. **6 pts** **Lesson 10.4**

    Rewrite these as testable requirements: “The night light should not be too bright” and “The battery should last a long time.”

12. **6 pts** **Lesson 10.4**

    Explain the Apollo 11 1202 alarm and the engineering lesson it teaches.

13. **8 pts** **Lesson 10.5**

Twelve timing trials of an alert (required within 3.0 s): 2.1, 2.4, 1.9, 3.2, 2.2, 2.0, 2.5, 2.3, 2.6, 2.1, 2.2, 2.4 s. Find the mean and pass rate, and say what to do.

14. **8 pts** **Lesson 10.5**

Essay (one paragraph). Using the stories of the Hewlett-Packard garage and Apollo, explain why honest testing and clear presentation are part of an engineer’s responsibility, and describe how you applied them in your capstone.

15. **4 pts** **Lesson 10.2**

Find the frequency of 850 nm infrared light.

ANSWER KEY

1. $120/960 = 0.125$ s; $120/11{,}520 = 10.4$ ms
2. UART: TX, RX, ground; no shared clock (agreed baud); point to point. I^2C: SDA and SCL with pull-ups; shared clock; 7-bit addresses on a shared bus. SPI: SCK, MOSI, MISO plus a chip-select per device; shared clock; device chosen by its select line.
3. For example 10 kΩ from the 5 V output to the input and 20 kΩ to ground: $5 \times 20/30 = 3.33$ V (with grounds joined).
4. $\lambda = 0.328$ m; quarter wave 8.2 cm; $t = 16$ ms
5. Switching the infrared LED at 38 kHz makes its light distinguishable from steady sunlight and lamps; the receiver module responds only to light flickering at 38 kHz and outputs the bursts as a digital code.
6. He received the letter S sent by radio across the Atlantic from Poldhu to Newfoundland. After the *Titanic*, ships were required to keep a radio watch day and night, so distress calls would always be heard.
7. $26^{10} = 1.41 \times 10^{14}$: 1.4×10^4 s ≈ 3.9 h. $62^{14} = 1.24 \times 10^{25}$: 1.24×10^{15} s $\approx 3.9 \times 10^7$ years.
8. Any five: parent permission and parent enters the password; keep passwords out of shared code (secrets file); change default passwords; keep the device on the home network, no port forwarding; no recording of audio, video or personal data; keep firmware updated; do not join networks that are not yours.
9. 3.2 s; $2880 \times 250 = 720{,}000$ bytes (720 KB)
10. D: $2.0 + 0.4 + 1.5 = 3.9$; E: $1.5 + 1.0 + 0.9 = 3.4$; D wins. Budget $41.40.
11. For example: “The light’s brightness can be set from off to no more than about 20 lux at 1 m,” and “The device runs at least 14 days on 4 AA cells.”
12. The overloaded computer shed low-priority tasks and restarted the essential ones, as designed; controllers trained by simulations knew it was safe and continued. Lesson: define priorities in requirements, protect the must-haves, and test failure cases in advance.
13. Sum 27.9, mean 2.33 s; 11 of 12 pass (91.7%). Find the cause of the 3.2 s case, fix it and retest.
14. A strong answer: HP tested every instrument and improved designs from feedback; Apollo tested failure cases and taught controllers what alarms meant; people rely on engineers’ claims, so results must be measured and reported

truthfully, including failures; presentation lets users and reviewers understand and trust the work; examples from the student's test report, validation and design review.

15. $3.0 \times 10^{8} / 850 \times 10^{-9} = 3.5 \times 10^{14}$ Hz

PORTFOLIO PIECE: THE CAPSTONE DESIGN FILE

Assemble the complete record of your capstone: the approved proposal (need, requirements, constraints, options, decision matrix, block diagram, BOM with contingency, schedule, test plan), the final schematic and wiring diagram, the commented code, photographs of the finished device, the build and debugging logs, the test report with measured results, the validation notes and improvement, the presentation slides or poster, the questions asked in the design review with your answers, and a one-page reflection on the whole year.

LOOK FOR	WHAT IT MEANS
Design process	Testable requirements, a reasoned choice among options, and a realistic budget and schedule with contingency.
Working device	Meets its must-have requirements, follows every safety rule, and is built neatly with clear, commented code.
Testing	Every requirement tested with measured results, failures fixed and retested, validated with the real user.
Presentation	Clear explanation, live demo, honest data including failures, and thoughtful answers to questions.
Reflection	Honest account of planned against actual cost and time, lessons learned, and next steps.

COURSE EXAM

Midterm Exam

Covers Units 1–5. Time: 100 minutes.

You have 100 minutes. A scientific calculator is allowed. Show the formula, the substitution with units and the answer with its unit for every calculation; correct setup earns partial credit even if the arithmetic slips. Write complete sentences for explanations and the essay. The exam has 24 problems worth a total of 100 points.

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1. **4 pts** **Lesson 1.1**

   A current of 0.40 A flows for 3.0 minutes. How much charge passes, and how many electrons is that?

2. **4 pts** **Lesson 1.2**

   A 9.0 V battery is rated 550 mAh. How much energy does it store, in Wh and J?

3. **4 pts** **Lesson 1.3**

   Find the current through 3.3 kΩ on 6.0 V, and the resistance of 15 m of copper wire with a cross-section of $0.75\ \text{mm}^2$ ($\rho = 1.68 \times 10^{-8}\ \Omega \cdot \text{m}$).

4. **4 pts** **Lesson 1.4**

   A 68 Ω resistor is across 5.0 V. Find its power and choose a suitable power rating with a 2× margin.

5. **4 pts** **Lesson 1.5**

   Two 2.2 MΩ resistors in series are across 10.0 V. A 10 MΩ meter reads the bottom one. What does it read, and why is it not 5.00 V?

6. **4 pts** **Lesson 2.1**

   A 1.0 kΩ resistor is in series with a parallel pair of 2.2 kΩ and 3.3 kΩ, across 9.0 V. Find the total current and the current in each of the pair.

7. **4 pts** **Lesson 2.2**

   A 12 V source feeds node A through 1.0 kΩ; a 6.0 V source feeds node A through 1.0 kΩ; 2.0 kΩ connects A to ground. Find V_A and all three currents.

8. **4 pts** **Lesson 2.3**

   A 6.8 kΩ / 4.7 kΩ divider (4.7 kΩ to ground) is on 12 V. Find the output unloaded and with a 10 kΩ load.

9. **4 pts** **Lesson 2.5**

   A 6.0 V series string of 2 kΩ, 1 kΩ and 3 kΩ should read 2, 1 and 3 V. You read 0, 6.0 and 0 V. What is the fault?

10. **4 pts** **Lesson 3.1**

    Read blue-gray-red-gold and brown-green-yellow-silver, with tolerances.

11. **4 pts** **Lesson 3.2**

    A 220 µF capacitor charges through 47 kΩ from 5.0 V. Find τ and the voltage after 20 s.

12. **4 pts** **Lesson 3.3**

    A 50 mH coil carrying 0.20 A is switched off in 10 µs. Estimate the voltage spike, and name the part that prevents it.

13. **4 pts** **Lesson 3.5**

    Design a resistor for a blue LED ($V_F = 3.2$ V) at 12 mA from 9.0 V. Give the standard value, the actual current and the resistor power.

14. **4 pts** **Lesson 3.4**

    A silicon diode and 1.5 kΩ are in series on 9.0 V, diode forward. Find the current. What changes if the diode is reversed?

15. **4 pts** **Lesson 4.2**

    An Arduino pin must switch a 200 mA load with an NPN transistor of minimum β = 80, with 5× overdrive. Find the base current and base resistor. Is it safe for the pin?

16. **4 pts** **Lesson 4.3**

    A common-emitter stage on 9.0 V has $R_1 = 22$ kΩ, $R_2 = 4.7$ kΩ, $R_E = 1.0$ kΩ, $R_C = 3.3$ kΩ. Find V_B, I_C, V_C and the approximate gain in dB.

17. **4 pts** **Lesson 4.4**

Compare the heat in a MOSFET ($R_{DS(on)} = 0.035\ \Omega$) and a BJT ($V_{CE(sat)} = 0.30$ V) each switching 4.0 A.

18. **4 pts** **Lesson 4.5**

The Intel 4004 (1971) had about 2,300 transistors. Predict the count in 1991 with Moore's law (doubling every 2 years), and name the two inventors of the integrated circuit.

19. **4 pts** **Lesson 5.3**

A 555 astable has $R_1 = 4.7$ kΩ, $R_2 = 22$ kΩ, $C = 4.7\ \mu$F. Find the frequency and duty cycle.

20. **4 pts** **Lesson 5.4**

A 7805 supplies 5.0 V at 150 mA from a 9.0 V battery. Find the regulator heat and efficiency, and the battery current a 90% switching regulator would draw instead.

21. **4 pts** **Lesson 5.2**

State three soldering safety rules and three lithium-battery safety rules.

22. **4 pts** **Lesson 5.5**

Describe the staged test of a newly soldered board before and during its first power-up.

23. **4 pts** **Lesson 3.2**

A delay must turn off an LED when a capacitor discharging from 5.0 V through R falls to 2.0 V after 6.0 s. With 220 µF, find R.

24. **8 pts** **Lesson 2.2**

Essay. Choose one of these stories: Edison's parallel lamps, Kirchhoff's laws, Joseph Henry's relay, or the transistor at Bell Labs. Explain the problem the engineers faced, how they solved it, the physics behind the solution, and what it teaches an engineer today.

ANSWER KEY

1. $Q = It = 0.40 \times 180 = 72$ C; $n = 72 / 1.602 \times 10^{-19} = 4.5 \times 10^{20}$
2. $0.55 \times 9.0 = 4.95$ Wh; $\times 3600 = 17{,}800$ J
3. 1.82 mA; $R = (1.68 \times 10^{-8})(15)/(0.75 \times 10^{-6}) = 0.34\ \Omega$
4. $P = 25/68 = 0.37$ W; at least 0.74 W, so a 1 W resistor.
5. $2.2 \parallel 10 = 1.80$ MΩ; $V = 10 \times 1.80/4.00 = 4.50$ V. The meter's resistance in parallel loads the divider.
6. Pair $= 1.32$ kΩ; total 2.32 kΩ; $I = 3.88$ mA; pair voltage 5.12 V; 2.33 mA and 1.55 mA
7. $(12 - V) + (6 - V) = V/2$ (mA, kΩ) $\rightarrow V_A = 7.2$ V; 4.8 mA from the 12 V source; 1.2 mA flows back into the 6 V source; 3.6 mA to ground.
8. 4.90 V; loaded bottom $= 3.20$ kΩ, output 3.84 V
9. The 1 kΩ resistor (or its connection) is open: no current flows, so the whole supply appears across the break.
10. 6.8 kΩ ±5%; 150 kΩ ±10%
11. $\tau = 10.3$ s; $V = 5.0(1 - e^{-1.93}) = 4.28$ V
12. $V = 0.050 \times 0.20 / 10^{-5} = 1000$ V; a flyback diode across the coil.
13. 483 Ω → 510 Ω; 11.4 mA; 0.066 W
14. $(9.0 - 0.7)/1500 = 5.5$ mA; reversed, almost no current, and the full 9.0 V is across the diode.
15. $I_B = 5 \times 0.2/80 = 12.5$ mA; $R_B = 4.3/0.0125 = 344\ \Omega \rightarrow 330\ \Omega$ (13 mA), under the 20 mA guideline.
16. $V_B = 1.58$ V; $I_C \approx 0.88$ mA; $V_C = 6.1$ V; $A_v \approx -3.3$, about 10.4 dB
17. MOSFET 0.56 W; BJT 1.2 W
18. $2300 \times 2^{10} \approx 2.4$ million; Jack Kilby and Robert Noyce.
19. $f = 1.44/(48{,}700 \times 4.7 \times 10^{-6}) = 6.3$ Hz; duty $26.7/48.7 = 55\%$
20. 0.60 W; 56%; $0.75/0.90 = 0.83$ W, about 93 mA
21. Soldering, any three: adult present; safety glasses; iron always in its stand; fan and ventilation; never solder powered circuits; hold parts with clips; wash hands. Lithium, any three: never cut, puncture, crush or short; never charge damaged or swollen cells; never charge unattended; use proper charger; stop using hot or swelling cells; recycle properly; coin cells away from children.

22. Inspect every joint and part orientation; with chip out, measure + to ground for shorts; insert the chip correctly; first power through the meter on mA and compare with the power budget; then connect directly.
23. $\tau = 6.0/\ln 2.5 = 6.55$ s; $R = 6.55/220 \times 10^{-6} = 29.8$ kΩ (use 30 kΩ)
24. A strong answer names the real people and dates, describes the problem precisely (for example, Edison's need for independent lamps without huge currents), the method (high-resistance filaments tested by trial and calculation), the physics (parallel currents add; $P = VI$; Ohm's law), and a lesson (physics sets requirements; careful testing; honesty about results).

COURSE EXAM

Final Exam

Covers Units 1–10. Time: 120 minutes.

You have 2 hours. A scientific calculator is allowed. Show the formula, the substitution with units and the answer with its unit for every calculation; correct setup earns partial credit. Write code neatly; small syntax slips lose little credit if the logic is right. Write complete sentences for explanations and the essay. The exam has 30 problems worth a total of 100 points.

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1. **3 pts** **Lesson 1.3**

   Find the current through 4.7 kΩ on 12 V.

2. **3 pts** **Lesson 1.4**

   A 330 Ω resistor is across 12 V. Find its power and choose a rating.

3. **3 pts** **Lesson 1.2**

   Four 2,000 mAh AA cells in series: voltage, capacity and energy?

4. **3 pts** **Lesson 2.1**

   Three 1.5 kΩ resistors in parallel across 6.0 V: equivalent resistance and total current?

5. **3 pts** **Lesson 2.2**

   A 9.0 V battery drives three resistors in series with drops of 2.7 V and 4.1 V across two of them. Find the third drop and name the law.

6. **3 pts** **Lesson 2.3**

   Design a divider from 5.0 V to about 3.3 V with a 1.8 kΩ top resistor; choose a standard bottom resistor and give the output.

7. **4 pts** **Lesson 3.2**

   A 10 µF capacitor charges through 100 kΩ. Find τ and the time to reach 90% of the supply.

8. **3 pts** **Lesson 3.5**

   Choose a resistor for a red LED ($V_F = 2.0$ V) at about 8 mA from a 3.3 V Pico pin; give the actual current.

9. **3 pts** **Lesson 3.4**

   A bridge rectifier protects a device drawing 200 mA. What voltage and power does it lose?

10. **4 pts** **Lesson 4.2**

    Design an NPN base resistor so a 3.3 V Pico pin can switch 120 mA (β ≥ 100, 5× overdrive). Is the pin current acceptable?

11. **3 pts** **Lesson 4.4**

    Why is a logic-level MOSFET better than a standard MOSFET for a 3.3 V or 5 V microcontroller, and what three parts go with it in a motor driver?

12. **4 pts** **Lesson 5.3**

    Design a 555 astable at about 2 Hz with $C = 10\ \mu\text{F}$ and $R_1 = 1.0\ \text{k}\Omega$. Find R_2 and the frequency with the nearest standard value.

13. **3 pts** **Lesson 5.4**

    A 20,000 mAh, 3.7 V power bank at 85% efficiency runs a 0.50 W project. How long?

14. **3 pts** **Lesson 6.1**

    Simplify $A\overline{B} + AB + \overline{A}\,\overline{B}$.

15. **4 pts** **Lesson 6.2**

    Convert 2026 to hexadecimal and 0xFF to decimal, and write −20 in 8-bit two's complement.

16. **3 pts** **Lesson 6.3**

    Write the truth table of a three-input majority gate and its simplest Boolean expression.

17. **3 pts** **Lesson 6.4**

    How many toggle stages divide a 32,768 Hz crystal to 1 Hz? Why?

18. **3 pts** **Lesson 7.2**

    How long does this take and how many flashes? for (int i = 0; i < 12; i++) { digitalWrite(7, HIGH); delay(150); digitalWrite(7, LOW); delay(350); }

19. **3 pts** **Lesson 7.3**

Why does a reaction-time game use millis() rather than delay() for its random wait?

20. **3 pts** **Lesson 7.4**

analogRead() returns 717 on a 5 V Uno. Find the voltage and the resolution.

21. **3 pts** **Lesson 7.5**

analogWrite(9, 204): duty cycle and average voltage?

22. **3 pts** **Lesson 8.1**

An ultrasonic echo lasts 2,915 µs at 20 °C. How far is the object?

23. **3 pts** **Lesson 8.2**

A 2.2 kg·cm servo lifts 80 g at 12 cm. Find the torque needed and the safety factor.

24. **3 pts** **Lesson 8.3**

An L293D drops 1.8 V from a 6.0 V supply at 0.35 A. Find the motor voltage, motor power and driver loss.

25. **3 pts** **Lesson 8.5**

A sensor cooling toward an 18 °C room reads 30 °C at $t = 0$ and 22 °C at $t = 150$ s. Find τ.

26. **3 pts** **Lesson 9.3**

What does this Python print? v = [1.5, 3.0, 4.5], print(sum(v) / len(v), v[-1] * 2, 17 // 3)

27. **3 pts** **Lesson 9.5**

A Pico read_u16() returns 26,214. Find the voltage, and the PWM duty if it is passed to duty_u16().

28. **3 pts** **Lesson 10.1**

How long does a 64-byte message take over a UART at 19,200 baud?

29. **4 pts** **Lesson 10.3**

Find the wavelength of 2.4 GHz Wi-Fi, and state three internet-safety rules for a connected hobby device.

30. **8 pts** **Lesson 10.5**

Essay. This course began with Volta's pile and ended with your capstone. Choose three lessons, from three different units, and explain how each one's story, physics and engineering prepared you for your capstone. Include one example of a failure you met and how honest testing helped you fix it.

ANSWER KEY

1. 2.55 mA
2. 0.44 W; use a 1 W resistor.
3. 6.0 V; 2,000 mAh; 12 Wh
4. 500 Ω; 12 mA
5. 2.2 V; Kirchhoff's voltage law
6. Ideal $R_2 = 3.49$ kΩ; 3.3 kΩ gives 3.24 V (or 3.6 kΩ gives 3.33 V).
7. $\tau = 1.0$ s; $t = \tau \ln 10 = 2.3$ s
8. 162 Ω → 180 Ω; 7.2 mA
9. About 1.4 V; 0.28 W
10. $I_B = 6.0$ mA; $R_B = 2.6/0.006 = 433\ \Omega \rightarrow 430\ \Omega$ (6.0 mA), within the Pico's ~10 mA guideline.
11. Its $R_{DS(on)}$ is specified at logic gate voltages, so it turns fully on and stays cool. Gate resistor, gate pull-down, flyback diode.
12. $R_1 + 2R_2 = 72$ kΩ; $R_2 = 35.5$ kΩ; with 33 kΩ, $f = 1.44/(67{,}000 \times 10^{-5}) = 2.15$ Hz
13. 74 Wh; 62.9 Wh usable; about 126 h
14. $A(\overline{B} + B) + \overline{A}\,\overline{B} = A + \overline{A}\,\overline{B} = A + \overline{B}$
15. 0x7EA; 255; 20 = 00010100 → 11101011 + 1 = 11101100
16. 1 for 011, 101, 110, 111; 0 otherwise; $Y = AB + BC + AC$
17. 15, because $2^{15} = 32{,}768$ and each stage halves the frequency.
18. 12 flashes; 6.0 s
19. delay() stops the program, so an early press would not be seen; checking millis() repeatedly lets it wait and watch the button at once.
20. 3.50 V; about 4.9 mV
21. 80%; 4.0 V
22. $0.0343 \times 2915/2 = 50.0$ cm
23. 0.96 kg·cm; 2.3
24. 4.2 V; 1.47 W; 0.63 W
25. Difference falls from 12 to 4: $\tau = 150/\ln 3 = 137$ s
26. 3.0 9.0 5
27. 1.32 V; 40%

28. 1,920 bytes/s; 33 ms
29. 12.5 cm. Any three: parent permission and parent enters the password; passwords only in a secrets file, never shared; change default passwords; local network only, no port forwarding; no audio, video or personal data; keep firmware updated.
30. A strong answer names three lessons accurately (for example Ohm's law and power, the transistor switch, debouncing and millis()), connects each to a specific capstone design decision with correct physics, and describes a real failure, the measurements that diagnosed it, the fix and the retest, reflecting on honesty in measurement and service to the user.