USC University of Southern California

EE 105: Introduction to Electrical Engineering

Lecture 2

System design and intro to Arduino

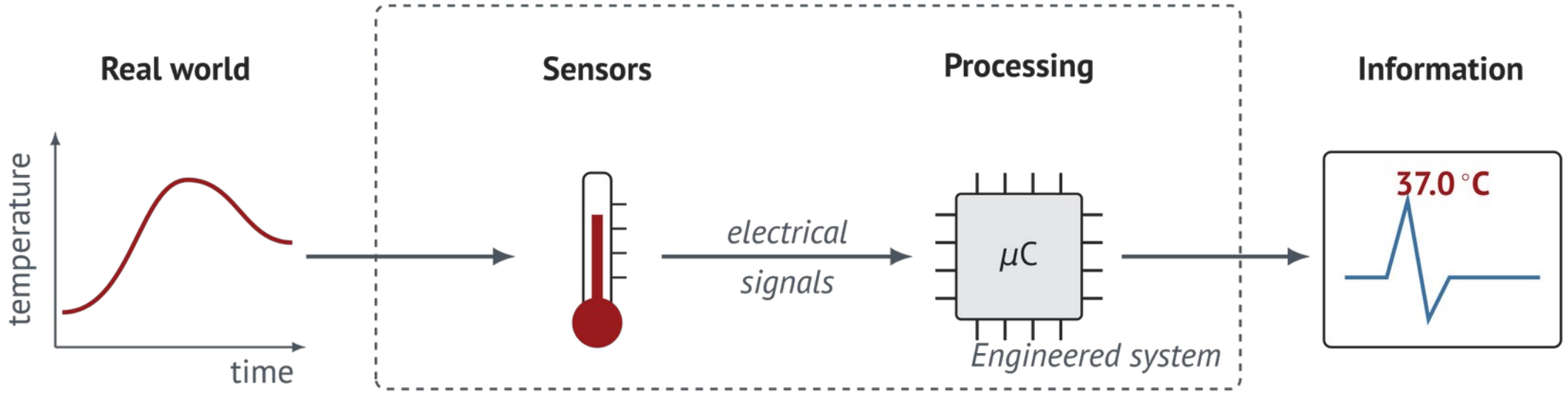
Yasser Khan

Rehan Kapadia

Breaking down engineering systems

USC University of Southern California

A sensor turns a real-world signal into an electrical one; processing turns that into information.



Any signal: temperature, touch, brain signals, video

Temperature sensors, resistive touchscreens, brain electrodes, cameras

EE 105: circuits, devices

Industry: Apple, Intel, Meta, Neuralink

Processing circuits, analog and digital computing

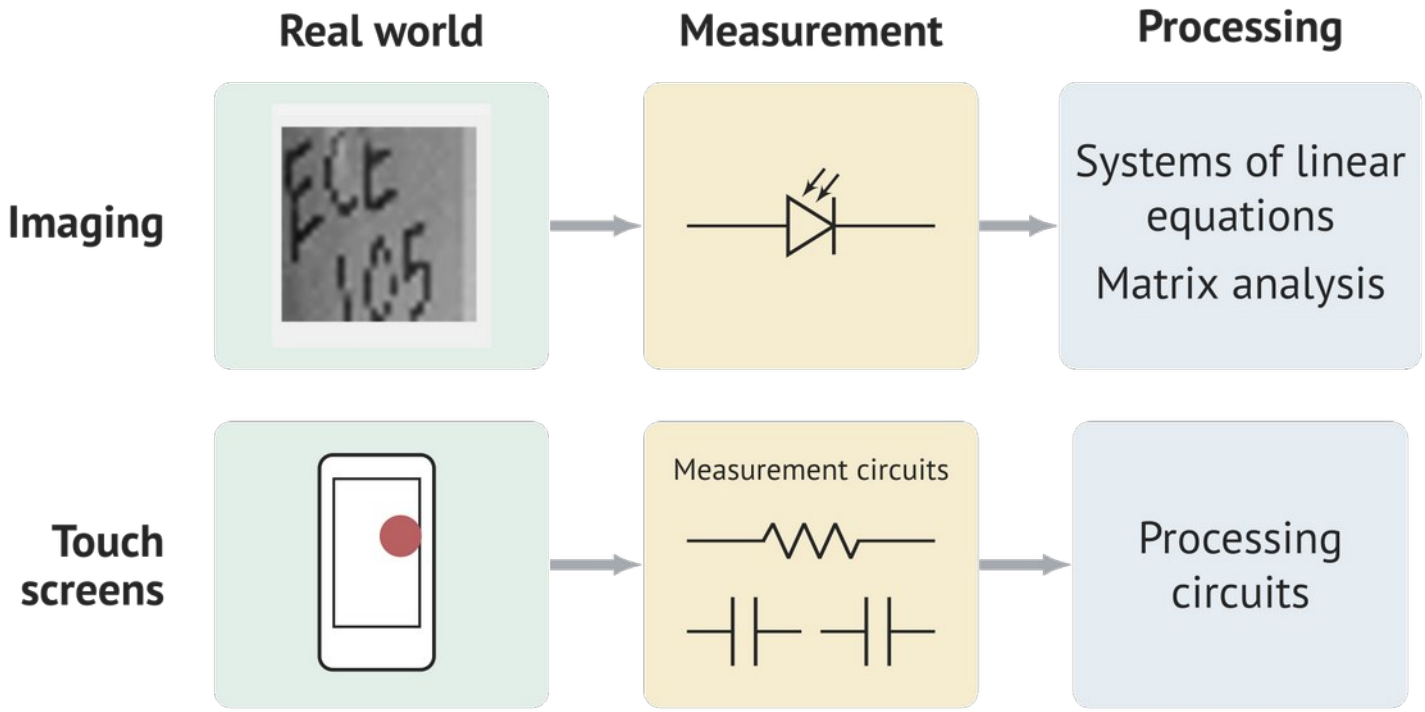
EE 105: biosensors, linear algebra, neural networks, optical comm

Industry: NVIDIA, Raytheon, Qualcomm

A number, a plot or a decision a person can use

Breakdown of hardware and software

In EE 105 the measurement side is hardware you build; processing is hardware plus software.



Measurement: hardware

Our own sensors, connected to an Arduino

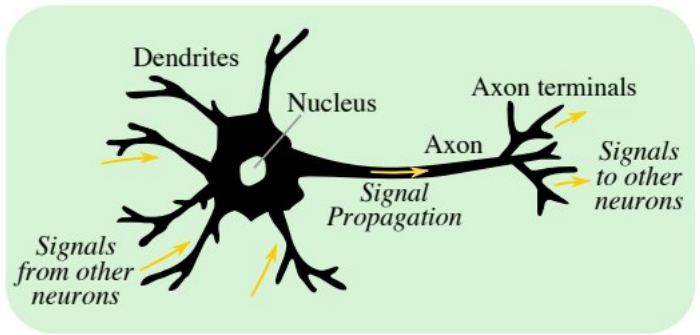
Processing: hardware + software

Code on the Arduino + Python in a Jupyter notebook

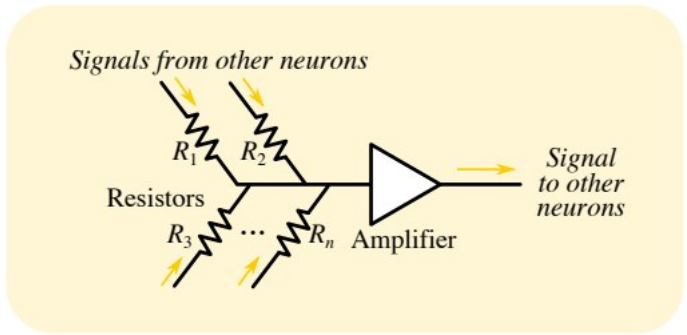
Same chain, different signals: images are processed with linear algebra (Module 4); touch is read with circuits (Module 1).

Equivalence to human body

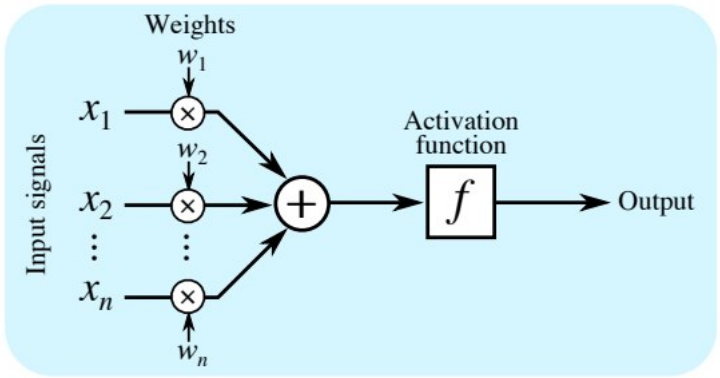
A neuron, its circuit model and an artificial neuron all weight their inputs, add them and fire.



Biological Neuron



Circuit Model

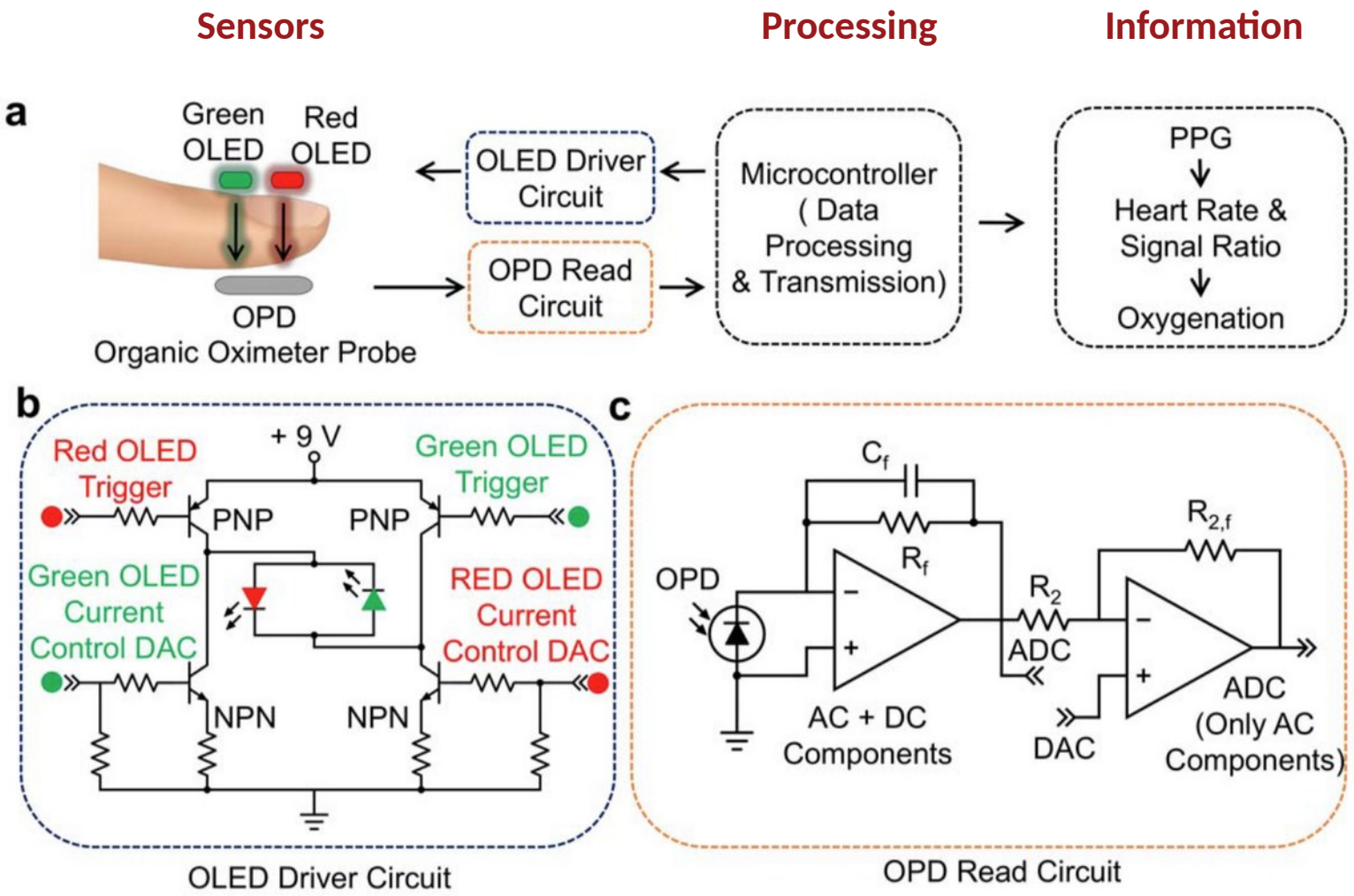


Artificial Neuron Model

- **Biological neuron**: dendrites collect signals, the cell body combines them, the axon sends the output
- **Circuit model**: resistors weight the inputs; an amplifier sums them
- **Artificial neuron**: weighted inputs, a sum and an activation function *f*; the building block of Module 4

Oximeter system breakdown

A pulse oximeter shines light into a finger, measures what comes out, and computes heart rate and oxygen.

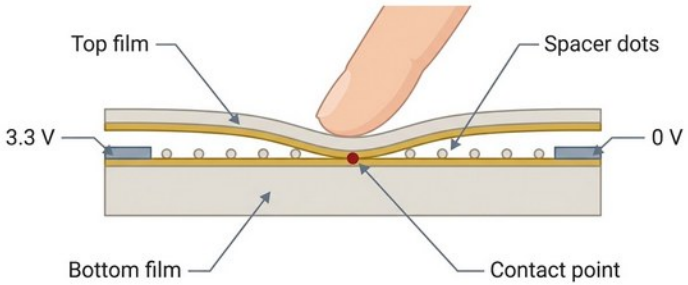


- **Sense**: green and red OLEDs light the finger; an organic photodiode (OPD) measures the light
- **Drive and read**: driver circuits set the OLED currents; the read circuit turns the OPD current into a voltage
- **Process**: a microcontroller digitizes and transmits
- **Information**: the PPG gives heart rate; the red/green signal ratio gives oxygenation

Resistive touchscreen system breakdown

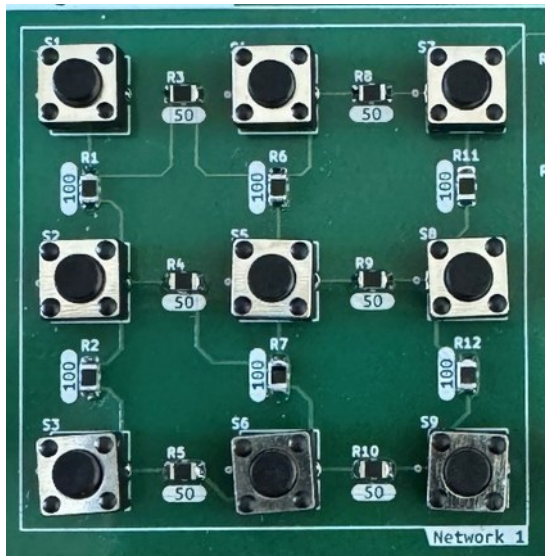
Touch is converted into a voltage, the Arduino reads it, and the output is which button was pressed.

Real world



A finger presses the top film onto the bottom film

Sensors



Convert touch to a signal: nine buttons on a resistor grid

Processing



The Arduino reads the voltage

Information



Which button: S1 to S9

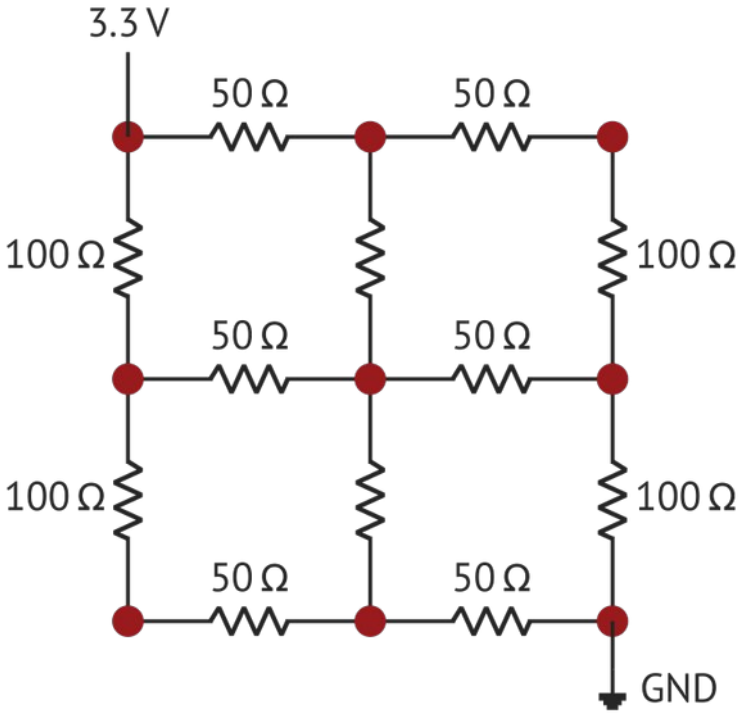
Resistive touchscreen system approach

Build a resistor grid where every button gives its own voltage, then let the Arduino read it.

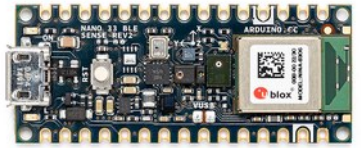
Goal



Build a sensor that can detect touch



Connect to Arduino



Get the location

Each node has its own voltage between 3.3 V and 0 V

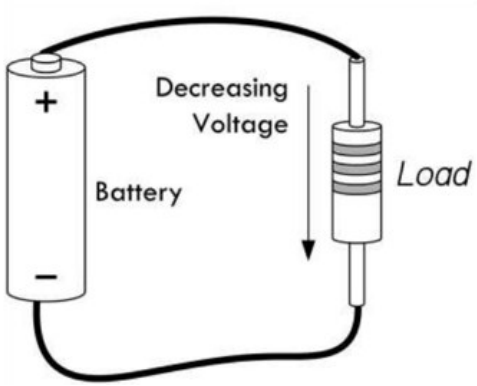
The Arduino measures the voltage and looks up the button

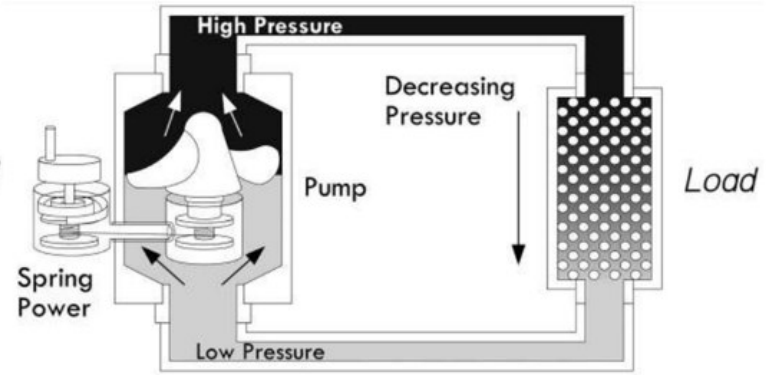
Building blocks: a source (3.3 V), resistors and switches. Next: voltage, current and resistance.

Voltage

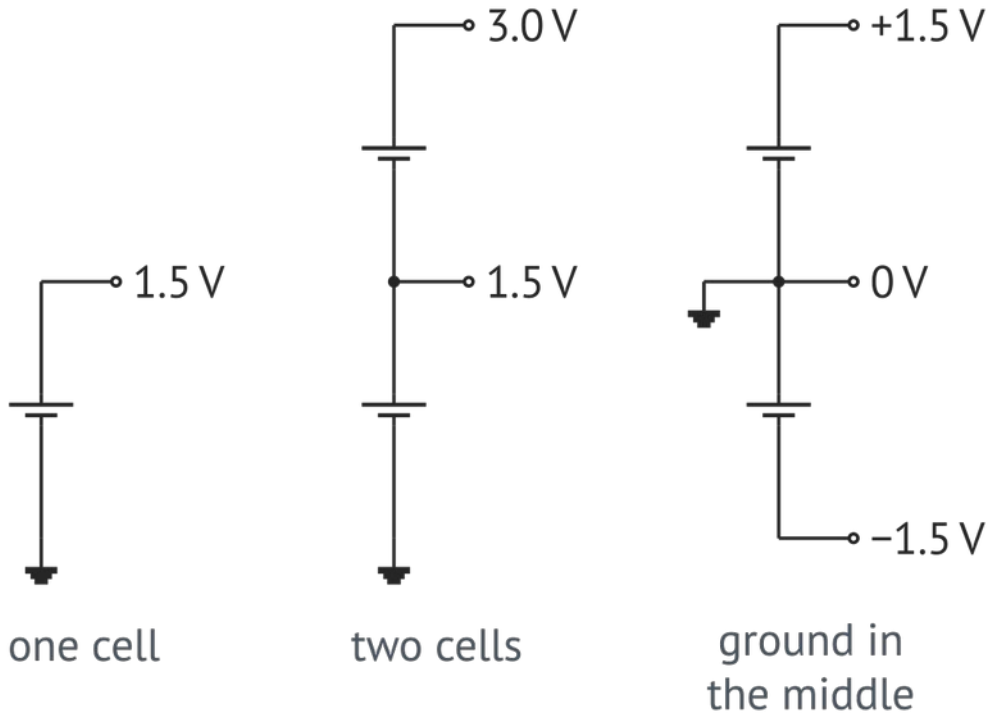
Voltage is the pressure that pushes charges around a loop; it is always measured between two points.

- Voltage is the **pressure** from a source that pushes charges (current) around a closed loop, so they can do work such as lighting a lamp
- Unit: **volt (V)**, after Alessandro Volta (1745-1827), who built the first battery
- Old name: electromotive force (emf)
- A node *at* 1.5 V means 1.5 V above **ground** (0 V)





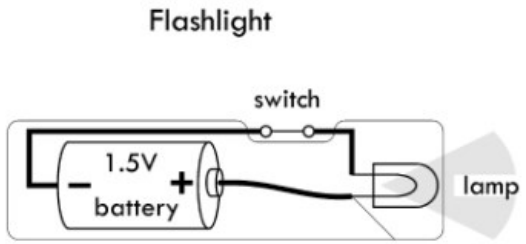
Point voltage is measured from ground

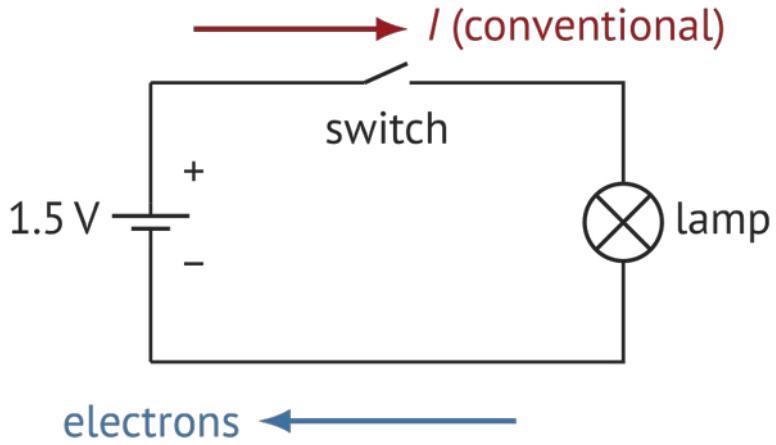


Each cell is 1.5 V. Moving ground changes the labels, not the circuit.

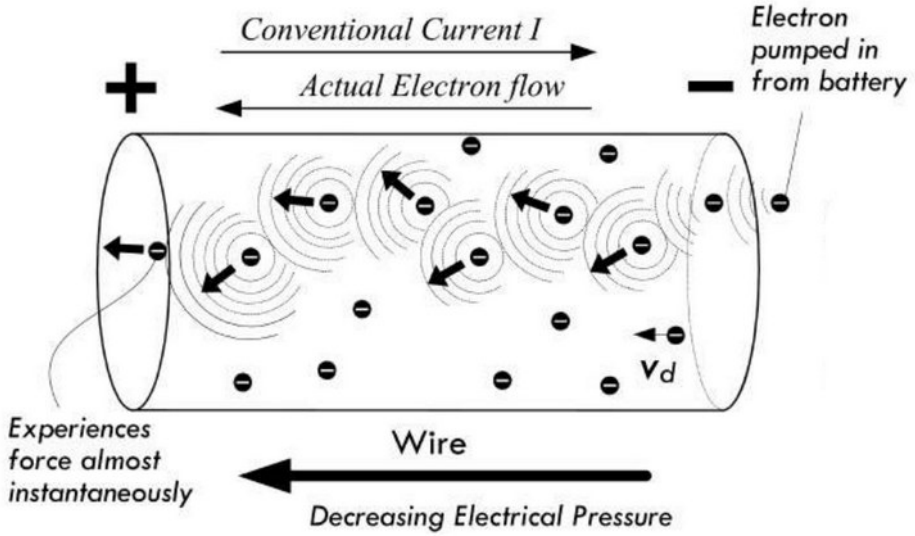
Voltage

In a flashlight the cell pushes current out of its + terminal, through the switch and lamp, and back.





- **Conventional current** I flows out of the + terminal, through the lamp, back to –
- In a metal wire, **electrons** drift the other way
- Every electron feels the push almost at once: the lamp lights immediately

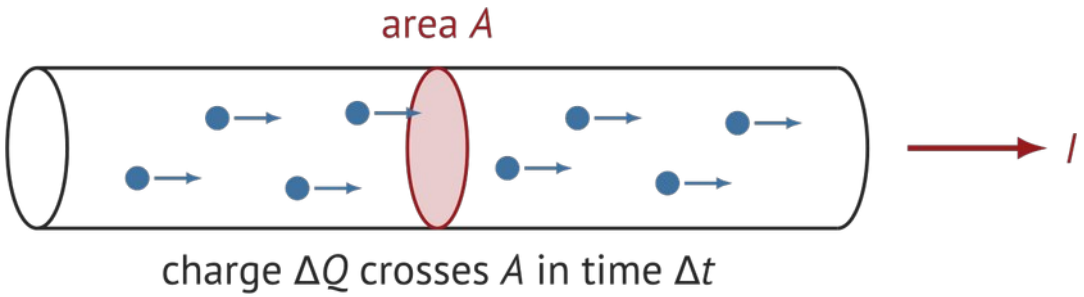


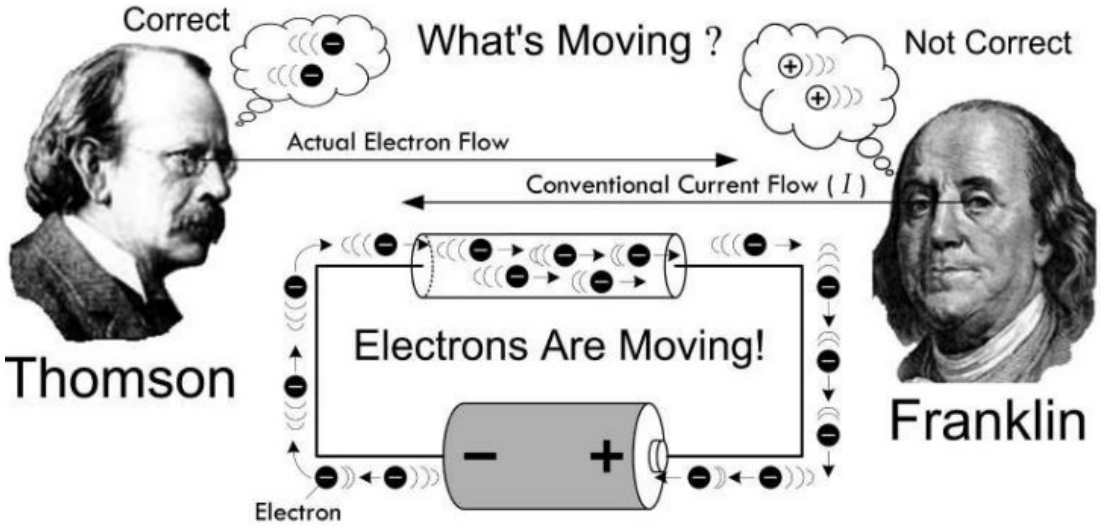
TRY IT Open the switch: what voltage appears across it?

Flow of charge: current

Current is the rate at which charge flows past a point; one ampere is one coulomb per second.

- Current is the **rate** at which charge flows past a point: current = flow
- Unit: **ampere** (A); 1 A = 1 coulomb per second
- 1 coulomb ≈ 6.24×10^{18} electrons
- **Conventional current** (Franklin) flows from + to −; in a wire the moving charges are electrons (Thomson), which drift the other way





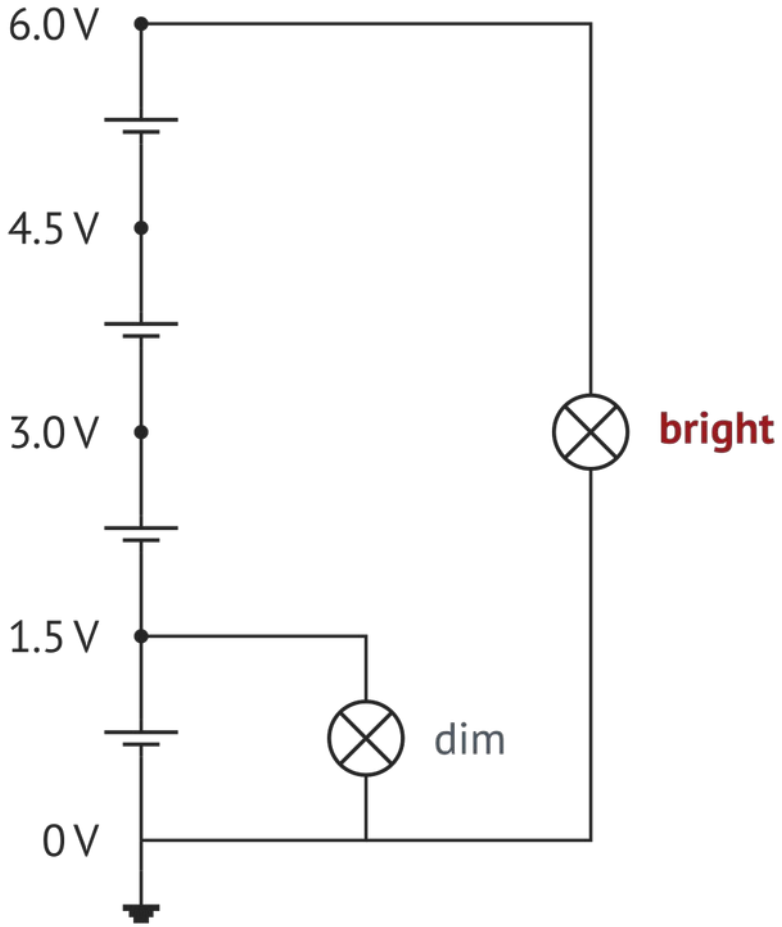
Current

$$I = \frac{\Delta Q}{\Delta t} \qquad 1\ \text{A} = 1\ \frac{\text{C}}{\text{s}}$$

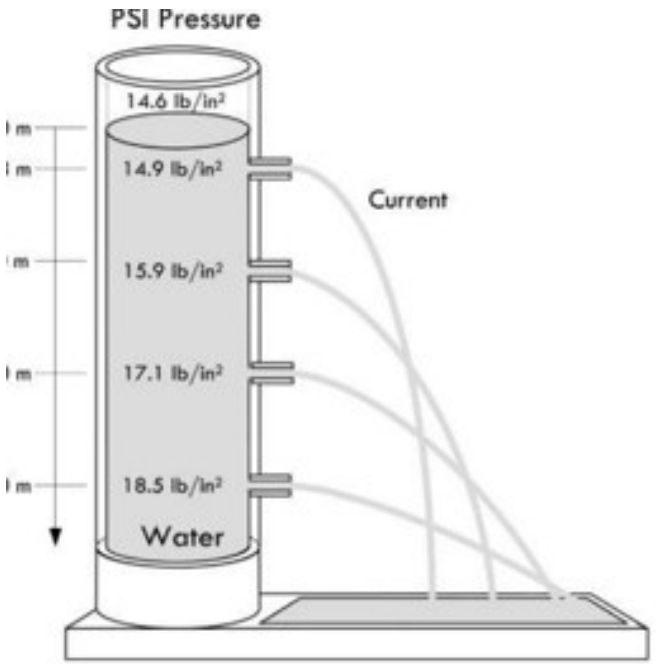
Increasing voltage / increasing water pressure

Stacking cells is like stacking pumps: four 1.5 V cells give 6 V and the lamp glows brighter.

Electrical system



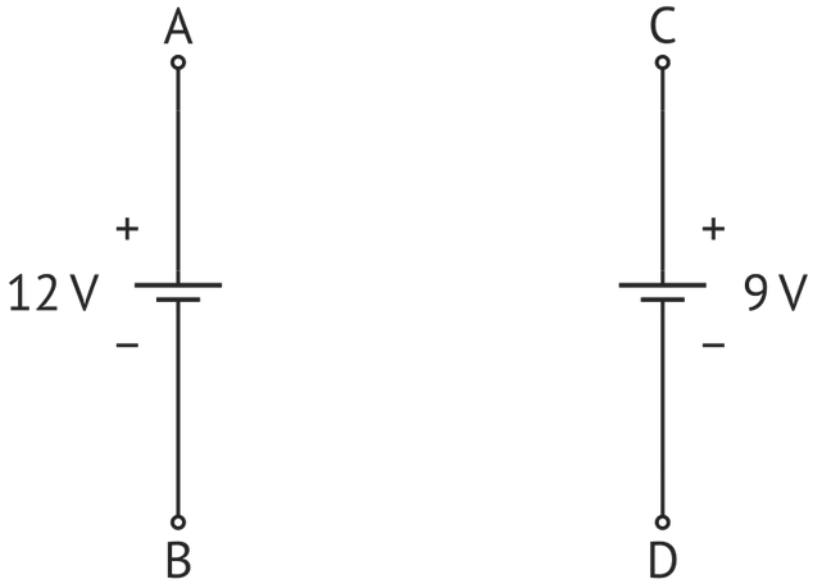
Water system



- Four 1.5 V cells in series: 4 × 1.5 V = **6 V**
- A higher voltage pushes more current through the lamp
- Deeper water is at higher pressure and squirts farther

Voltage difference

A voltage always compares two points: V_{AC} is the voltage at A minus the voltage at C.



PRACTICE

A 12 V battery sits between A (+) and B (−); a 9 V battery between C (+) and D (−). Both − terminals, B and D, are at ground (0 V).

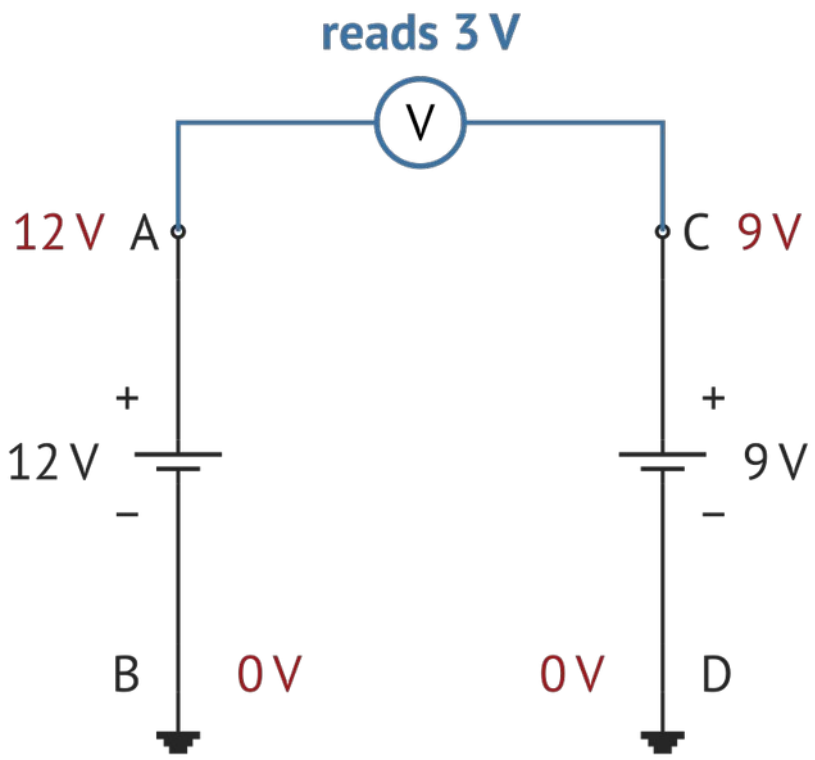
Find V_{AC}, V_{BD}, V_{AD} and V_{BC}.

Notation

$$V_{XY} = V_X - V_Y$$

Voltage difference: solution

Put both − terminals at 0 V; each battery then sets its + terminal, and differences follow.



SOLUTION

1. Ground: $V_B = V_D = 0$ V
2. Each battery sets its + terminal: $V_A = 12$ V, $V_C = 9$ V
3. $V_{AC} = 12 - 9 =$ **3 V**, what the voltmeter reads
4. $V_{BD} = 0 - 0 =$ **0 V**; $V_{AD} = 12 - 0 =$ **12 V**; $V_{BC} = 0 - 9 =$ **−9 V**

A negative voltage is fine: $V_{BC} = -9$ V says B is 9 V **below** C. Without a shared ground the two batteries have no common reference.

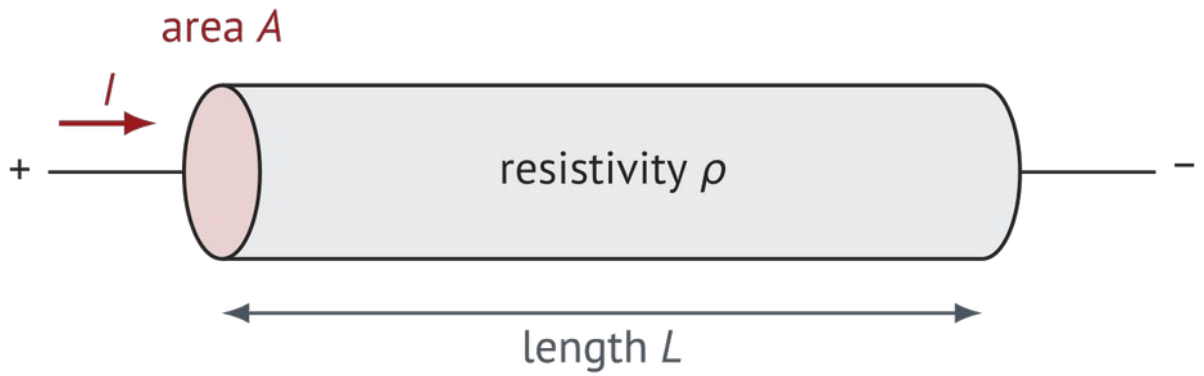
Resistance

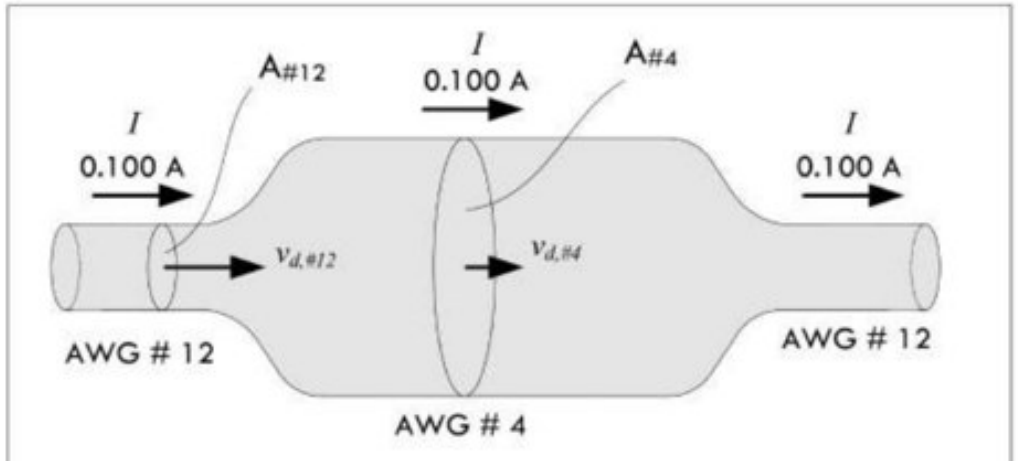
Resistance opposes current; it grows with the length of a conductor and shrinks with its area.

- Resistance is the **opposition** to the flow of current
- It depends on the material (resistivity ρ), the length L, the cross-sectional area A and the temperature
- Longer: more resistance. Thicker: less.

Resistance of a uniform conductor

$$R = \rho \frac{L}{A} \qquad R = \frac{V}{I}$$

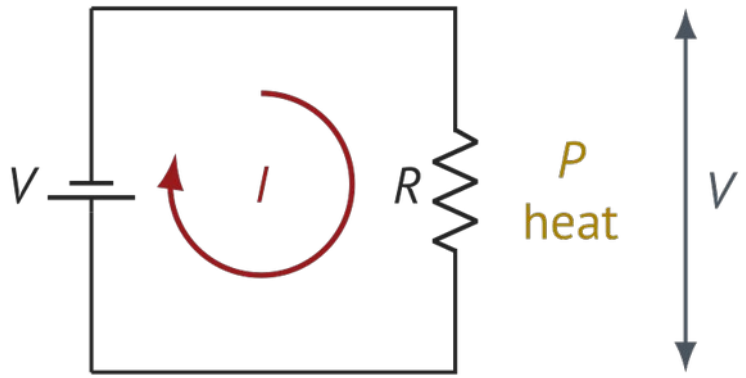




The same 0.100 A flows through thin and thick sections; charges drift more slowly where the wire is wider.

Ohm's law

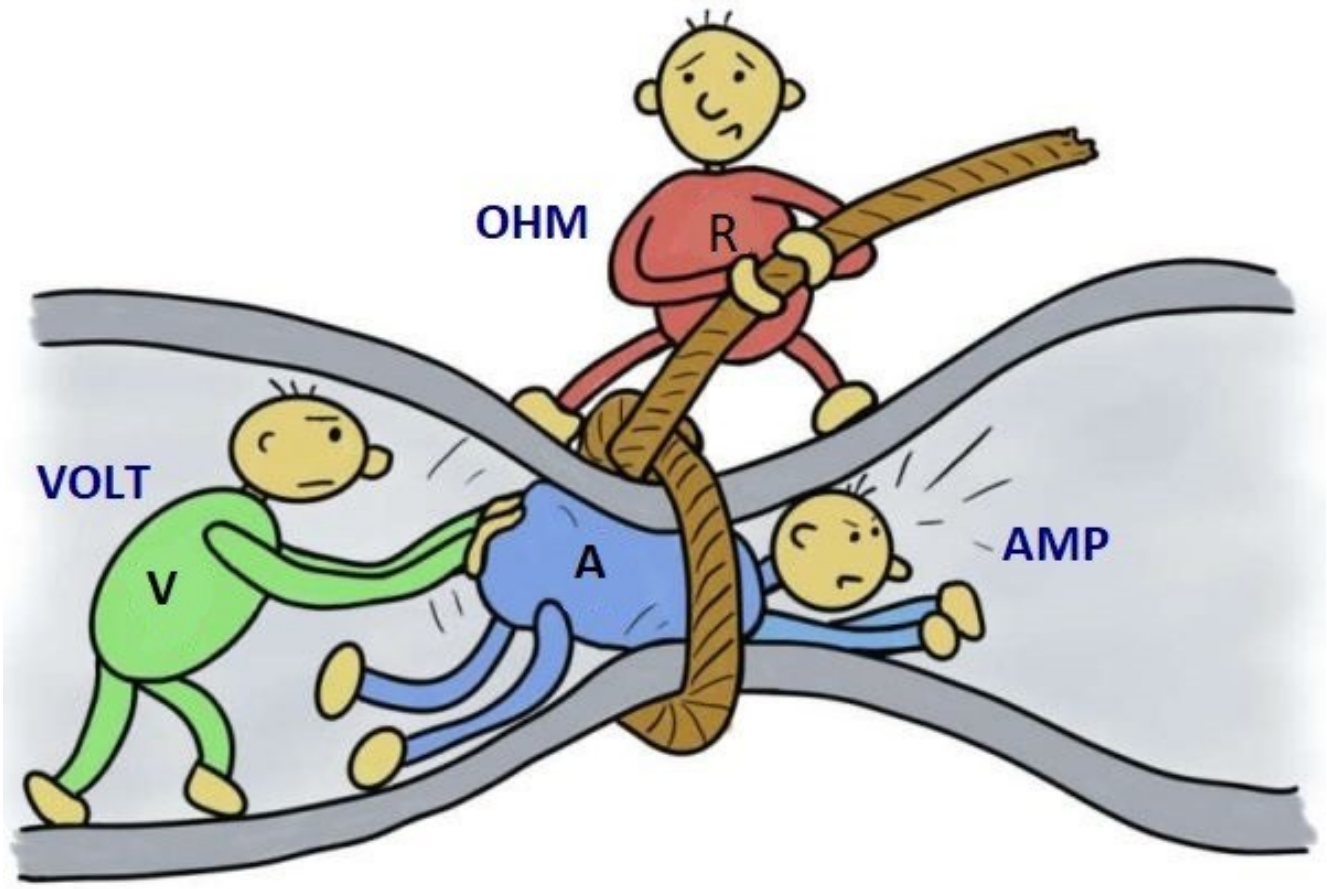
The current through a resistor is proportional to the voltage across it: V = IR.



Ohm's law

$$V = IR$$

- Double V: double I
- The resistor turns energy into heat



Volt pushes, Amp is the flow, Ohm squeezes the pipe.

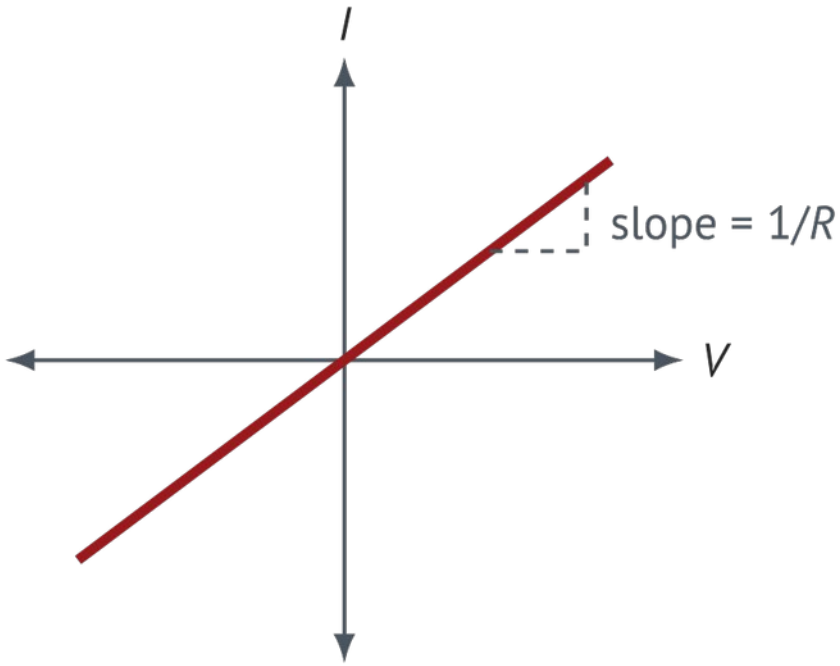
Ohm's law

A resistor's current-voltage graph is a straight line through the origin with slope 1/R.

Symbol



I-V relationship



Voltage across it

$$V = IR$$

Current through it

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

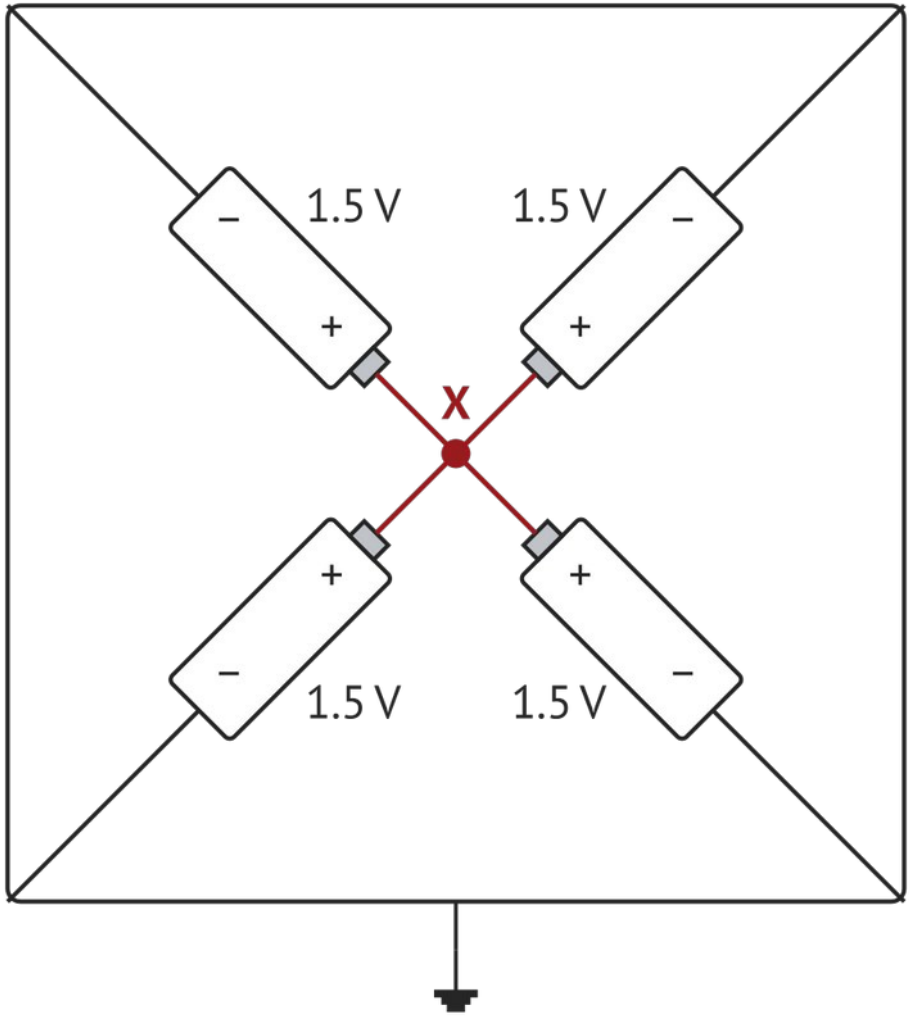
Resistance

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

Steeper line, smaller R. Elements that follow a straight line are *ohmic*; diodes and LEDs are not.

Test problems

Four 1.5 V cells point their + terminals at node X; the outer wire is ground.



PRACTICE

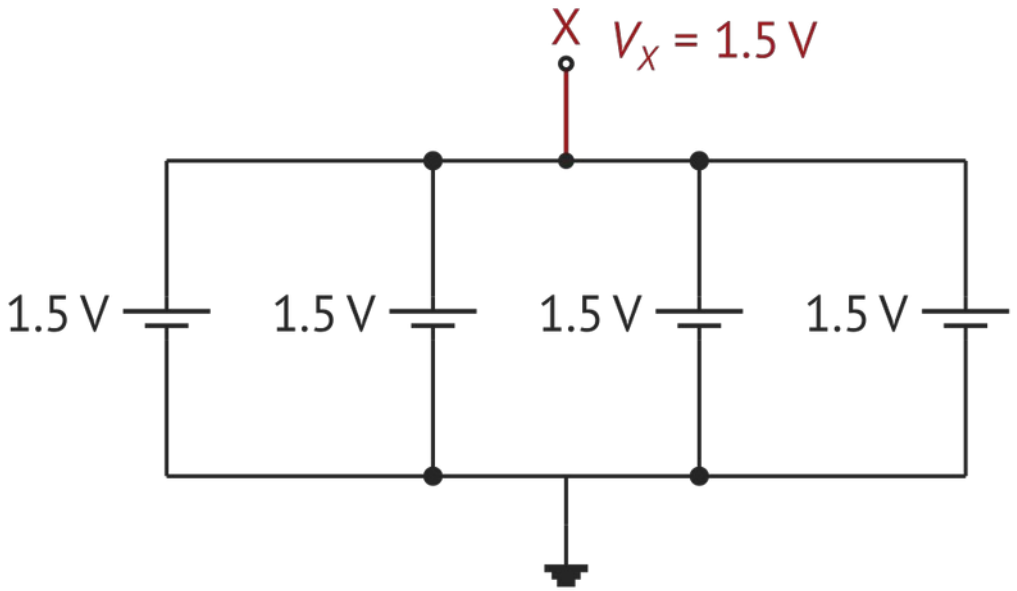
Four 1.5 V cells are wired as shown. The + nub of each cell touches node X; each − end touches the outer wire, which is grounded.

What is the voltage at X?

Hint: count the nodes. How many different wires do the cells connect to?

Test problems: solution

All four cells join the same two nodes, so they are in parallel and X sits at 1.5 V.



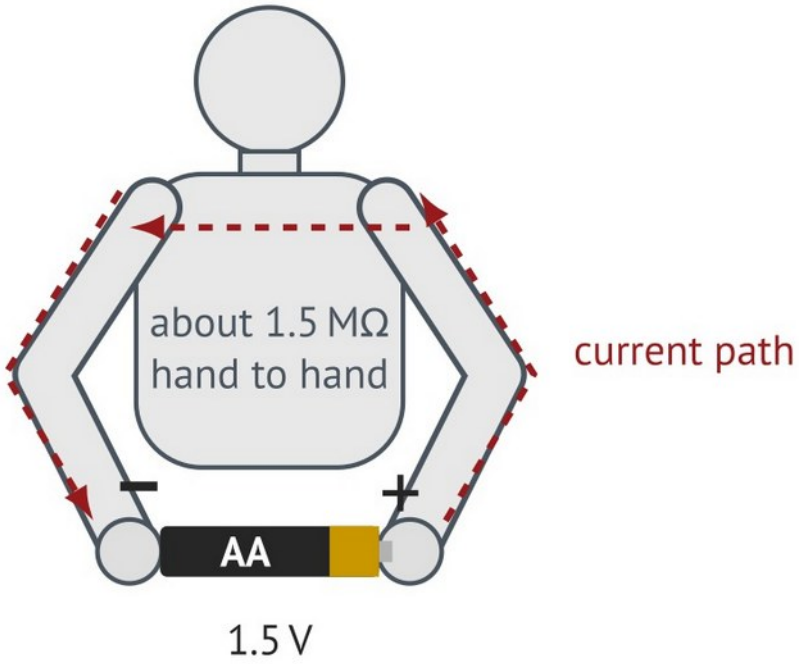
SOLUTION

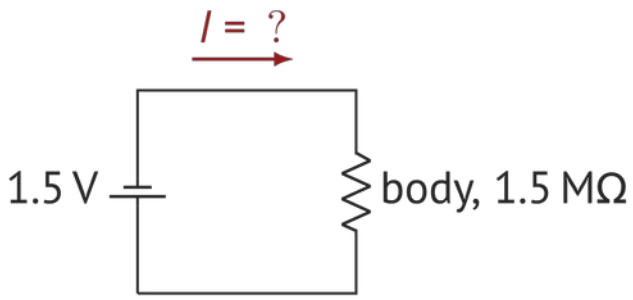
1. Every + terminal touches X; every − terminal touches the ground wire
2. So the circuit has two nodes, and all four cells join them: the cells are **in parallel**
3. Each cell holds its + end 1.5 V above its − end: V_X = **1.5 V**

Parallel cells give one cell's voltage and share the current; cells in **series** add their voltages.

Test problems

Hold a 1.5 V cell between your hands: your body closes the circuit.





PRACTICE

You hold the two ends of a 1.5 V AA cell, one end in each hand. Your body's resistance from hand to hand is about 1.5 MΩ.

What current flows through you?

Ohm's law

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

Test problems: solution

I = V/R = 1.5 V / 1.5 MΩ = 1 µA: write the prefix as a power of ten before you divide.

SOLUTION

1. Ohm's law: I = V / R
2. Write the prefix as a power of ten: 1.5 MΩ = 1.5 × 10^6 Ω
3. I = 1.5 V / (1.5 × 10^6 Ω) = 1 × 10^{-6} A = **1 µA**

Answer

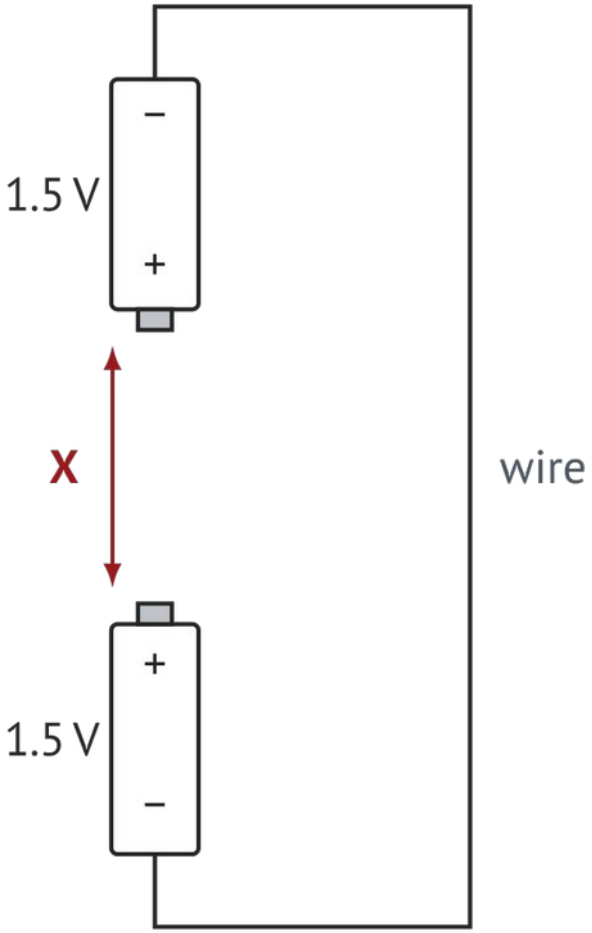
$$I = \frac{1.5\ \text{V}}{1.5 \times 10^6\ \Omega} = 10^{-6}\ \text{A} = 1\ \mu\text{A}$$

Prefix	Symbol	Factor	Example
kilo	k	10^3	1 kΩ = 1000 Ω
mega	M	10^6	1 MΩ = 10^6 Ω
giga	G	10^9	1 GΩ = 10^9 Ω
milli	m	10^{-3}	1 mA = 10^{-3} A
micro	µ	10^{-6}	1 µA = 10^{-6} A
nano	n	10^{-9}	1 nA = 10^{-9} A

Large prefixes for resistance, small ones for current.

Test problems

Two 1.5 V cells face + to +, with a small gap at X; a wire joins their − ends.



PRACTICE

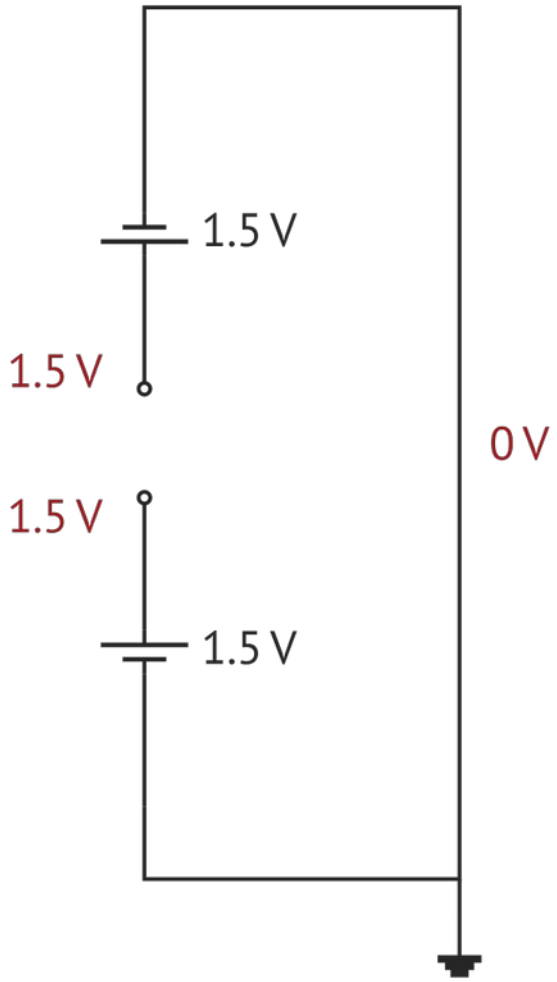
Two 1.5 V cells point their + ends at each other with a small gap at X. A wire joins their − ends; call that wire 0 V.

1. **What is the voltage of each + terminal?**
2. **What is the voltage across the gap at X?**

Hint: start at the wire (0 V) and walk through each cell from − to +.

Test problems: solution

Both + terminals sit at 1.5 V, so the gap sees 0 V: the cells oppose each other.



SOLUTION

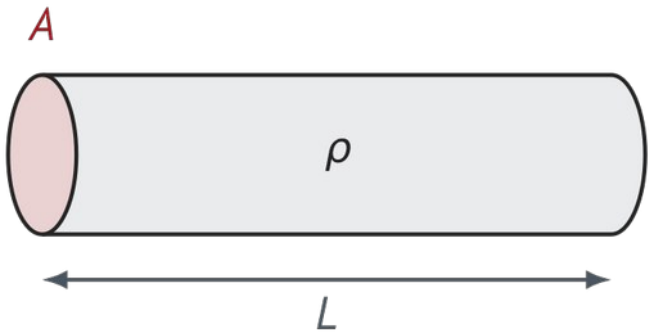
1. From the wire (0 V), each cell lifts its + end by 1.5 V: both + terminals are at **1.5 V**
2. Gap at X: 1.5 − 1.5 = **0 V**
3. Join the + ends and no current flows: around the loop +1.5 − 1.5 = 0. The cells are in parallel

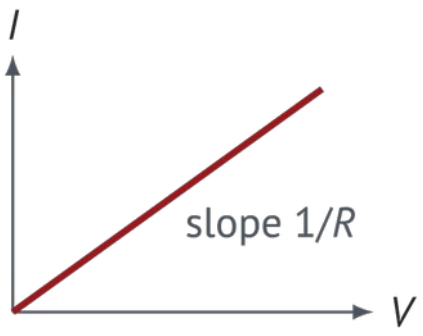
TRY IT Flip the lower cell. What does the gap see now?

Resistor and LED

A resistor's I-V curve is a straight line; an LED passes almost no current until it turns on.

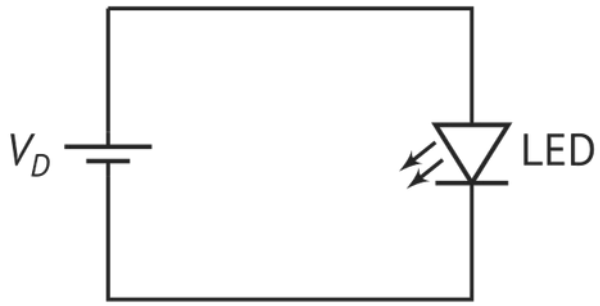
Resistor: R = ρ L / A

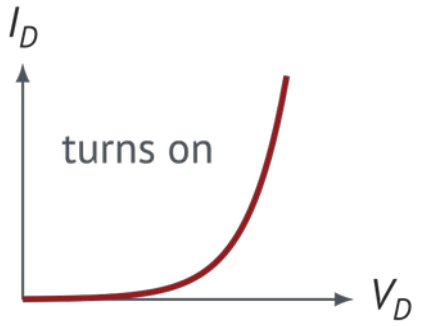




- **Resistor**: I = V / R, a straight line through the origin (ohmic)
- **LED**: almost no current at low voltage, then a steep rise once it turns on
- An LED does not obey Ohm's law; Module 2 explains why

LED: not a straight line

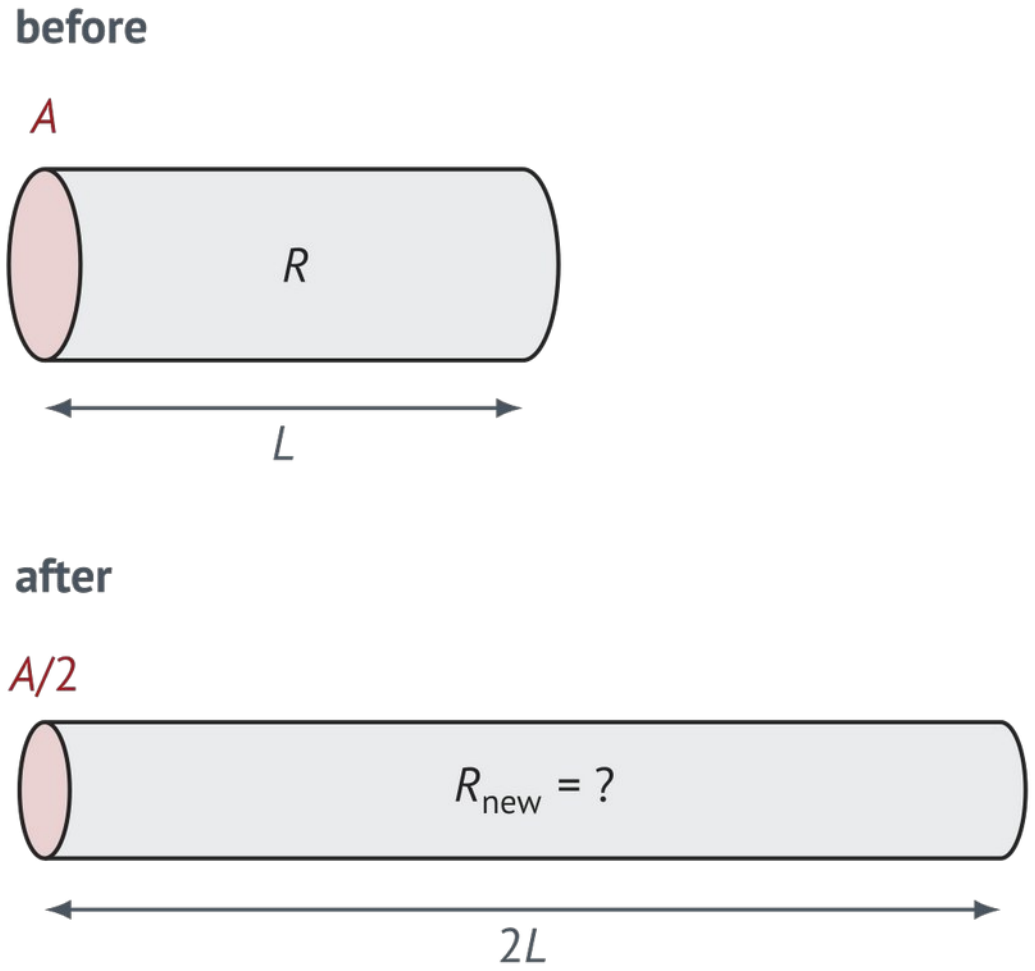




In practice: put a resistor in series with an LED to limit its current.

Test problems

Stretch a conductor to twice its length and half its area: what happens to R?



PRACTICE

A conductor has resistance R. Its length is increased to 2L and its cross-sectional area is decreased to A/2; the material stays the same.

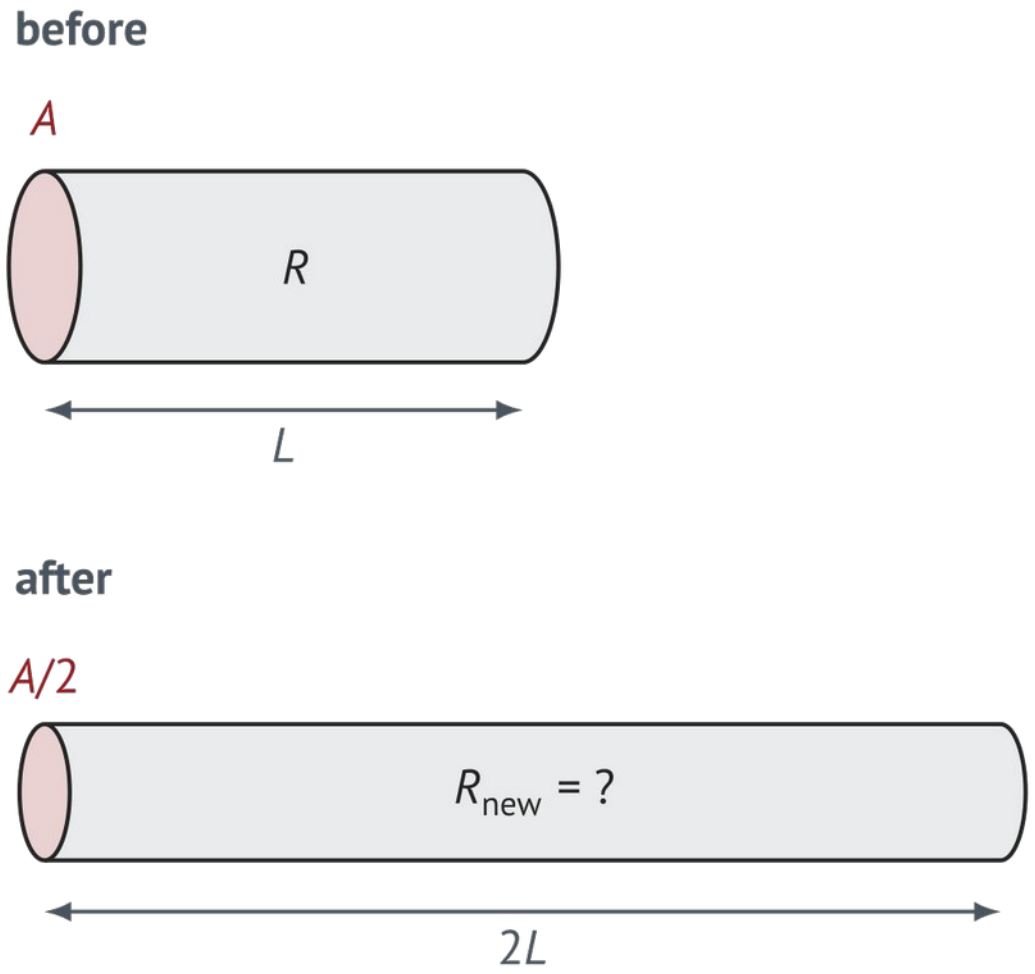
What is the new resistance?

Resistance of a conductor

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

Test problems: solution

Doubling L doubles R, and halving A doubles it again: the new resistance is 4R.



SOLUTION

1. Length doubles: R doubles
2. Area halves: R doubles again
3. $R_{new} = 2 \times 2 \times R =$ **4R** (a 10 Ω wire becomes 40 Ω)

Answer

$$R_{new} = \rho \frac{2L}{A/2} = 4\rho \frac{L}{A} = 4R_{old}$$

Resistors

Four color bands give a resistor's value: two digits, a power-of-ten multiplier and a tolerance.

Resistor color code calculator

Use this calculator to find out the ohm value and tolerance based on resistor color codes.

Number of Bands: 4 Band

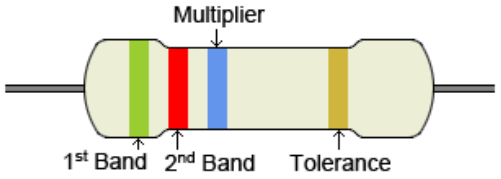
1st Band Color:
black brown red orange yellow
green blue violet grey white

2nd Band Color:
black brown red orange yellow
green blue violet grey white

Multiplier Color:
black brown red orange yellow
green blue violet grey white
gold silver

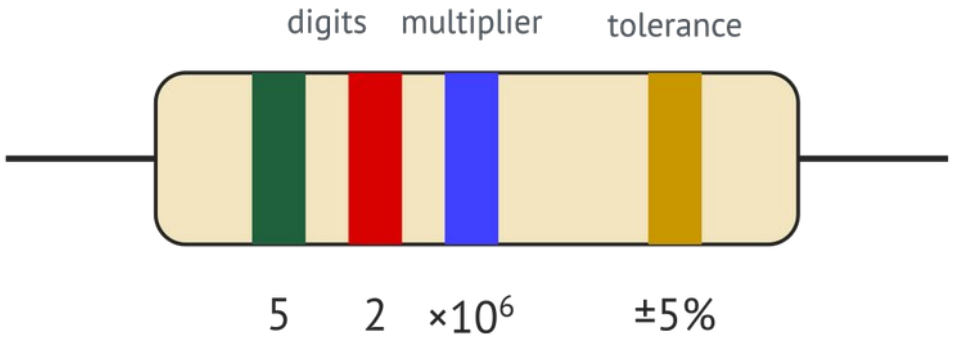
Tolerance Color:
brown red orange yellow green
blue violet grey gold silver

Calculate



Color	1st, 2nd Band Significant Figures	Multiplier	Tolerance
Black	0	× 1	
Brown	1	× 10	±1% (F)
Red	2	× 100	±2% (G)
Orange	3	× 1K	±0.05% (W)
Yellow	4	× 10K	±0.02% (P)
Green	5	× 100K	±0.5% (D)
Blue	6	× 1M	±0.25% (C)
Violet	7	× 10M	±0.1% (B)
Grey	8	× 100M	±0.01% (L)
White	9	× 1G	
Gold		× 0.1	±5% (J)
Silver		× 0.01	±10% (K)

calculator.net/resistor-calculator.html



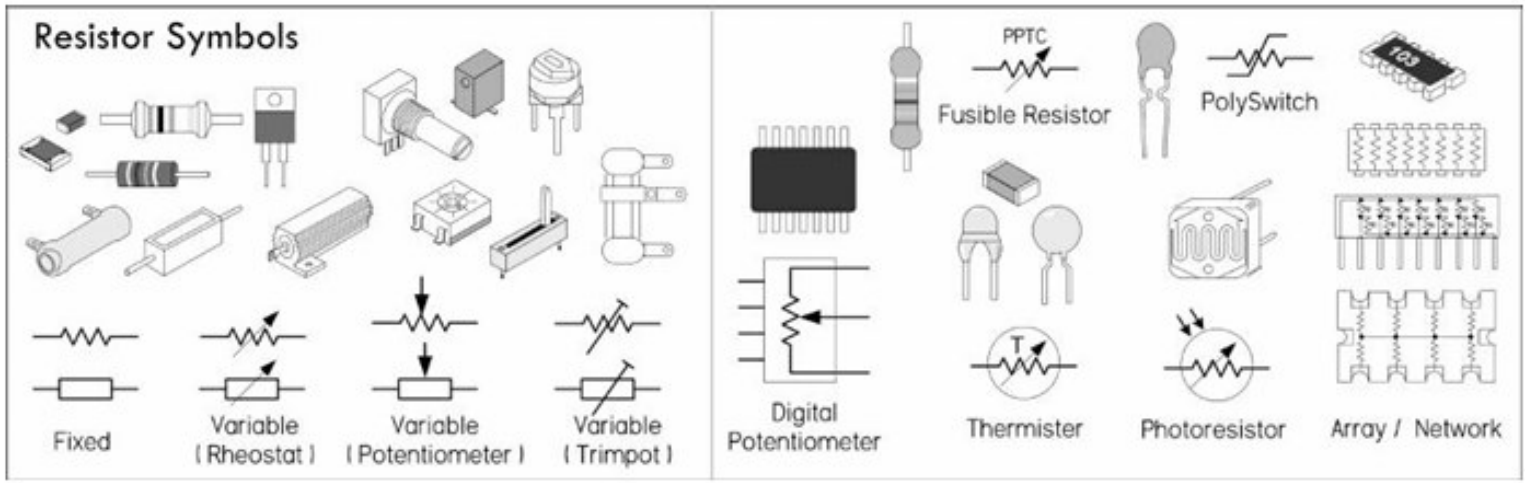
$$R = (10\,d_1 + d_2) \times \text{multiplier}$$

EXAMPLE

1. Green, red, blue, gold: $52 \times 10^6\ \Omega$ = **52 MΩ** ± 5%
2. Brown, black, red, gold: $10 \times 100\ \Omega$ = **1 kΩ** ± 5%

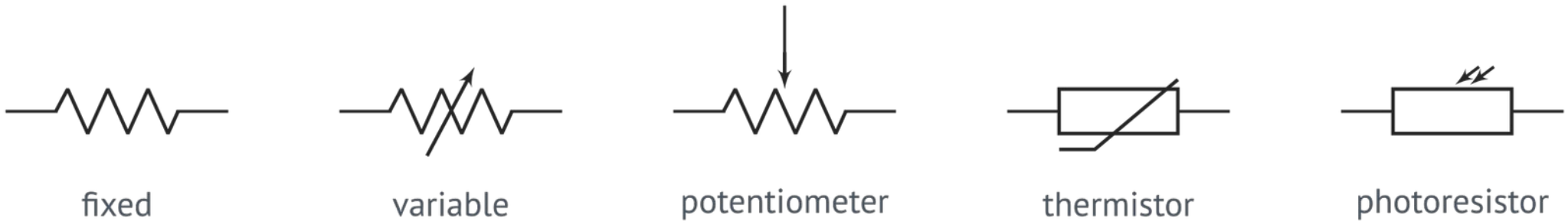
Resistors

Resistors come fixed, variable or sensing; the symbol tells you which.



- **Fixed**: through-hole (color bands) or surface-mount (SMD)
- **Variable**: rheostat, potentiometer, trimpot
- **Sensing**: thermistor (temperature), photoresistor (light)

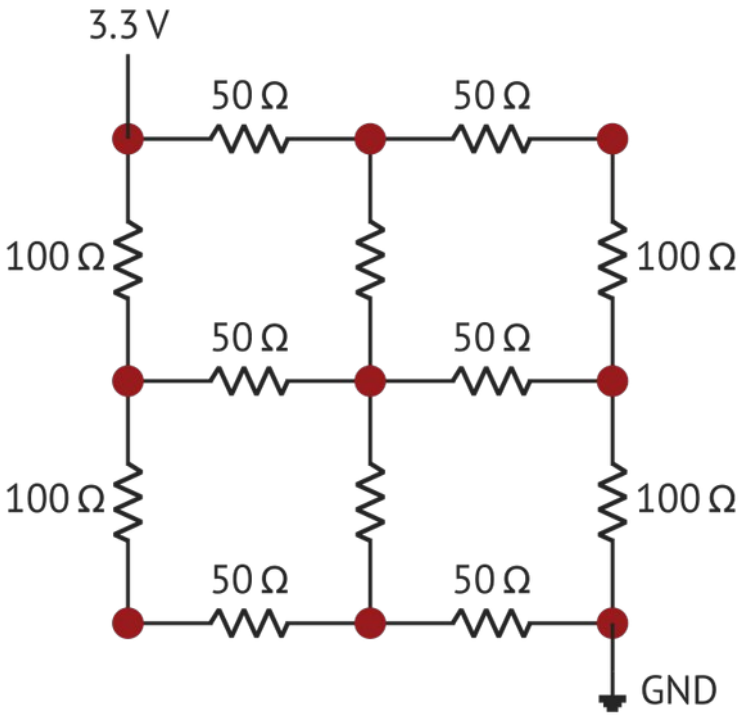
Symbols



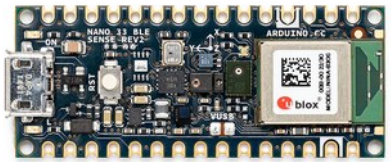
Going back to the touchscreen

We know the circuit; now we have to build it, first on a breadboard and then on a board.

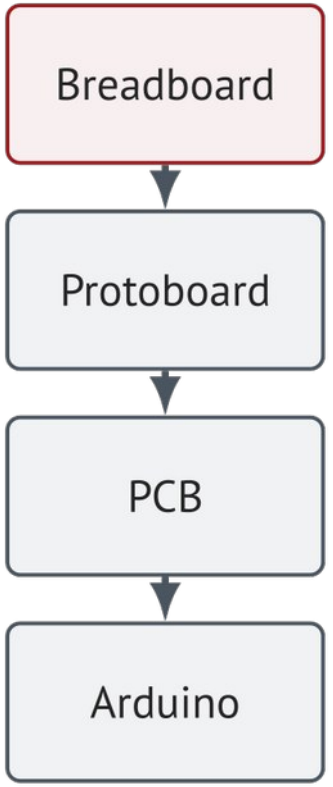
Build a sensor that can detect touch



Connect to Arduino

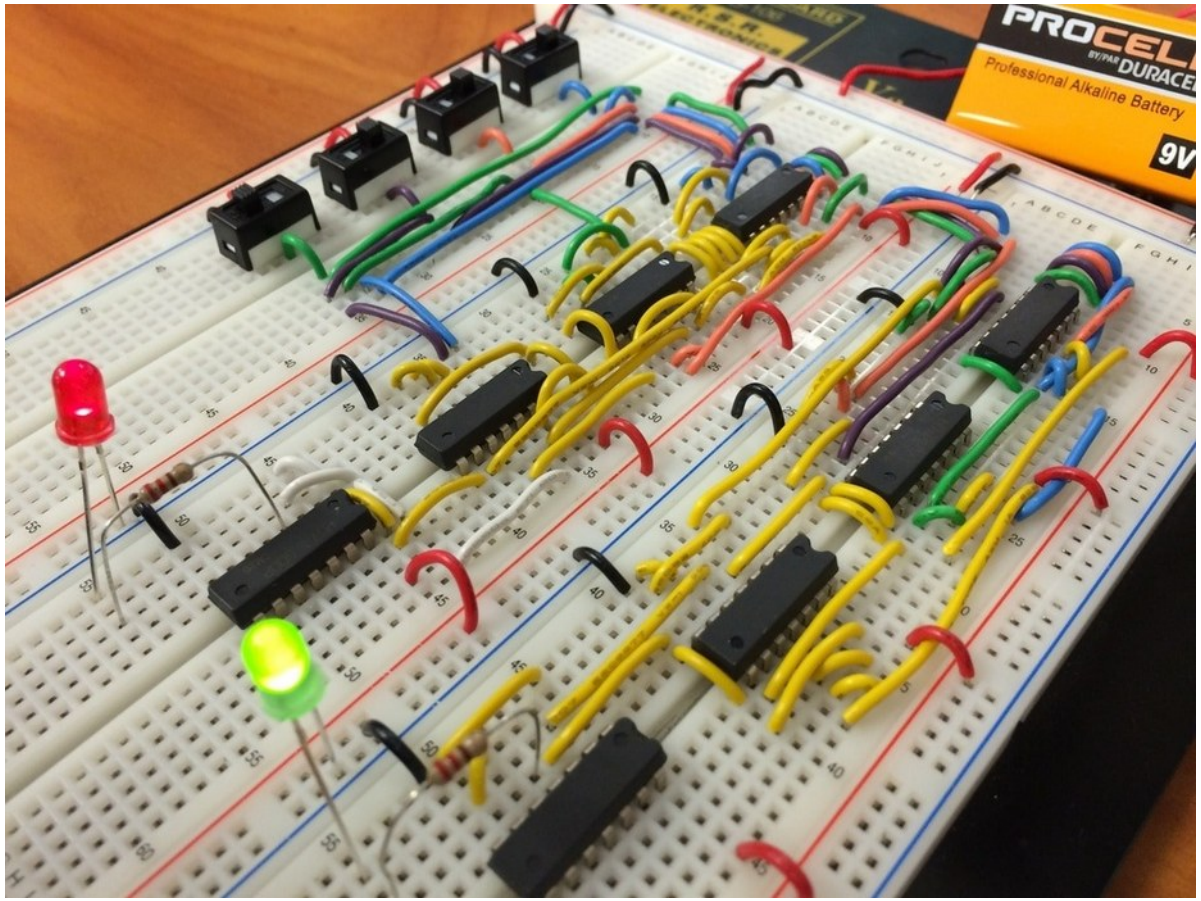


How we build it

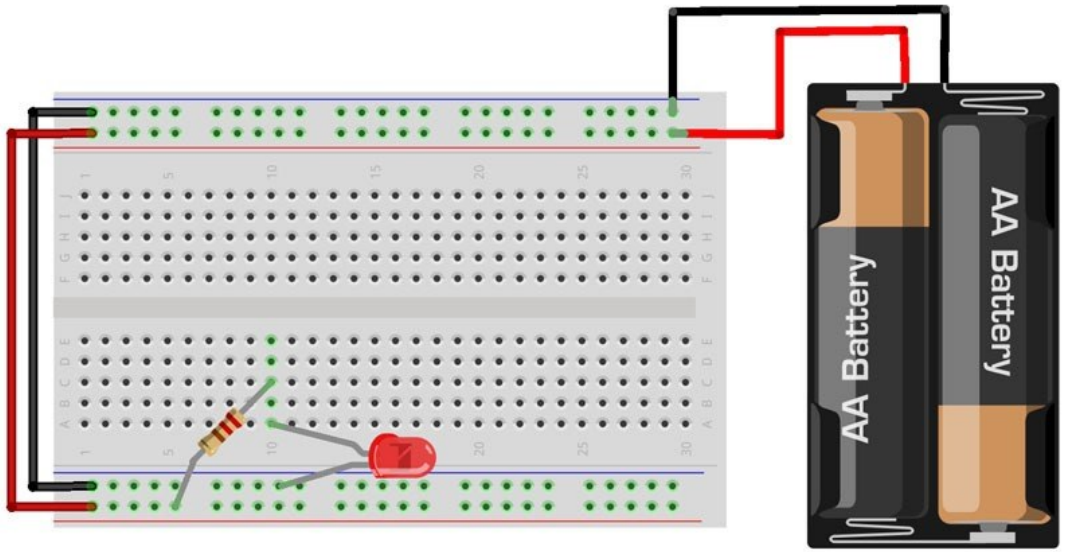


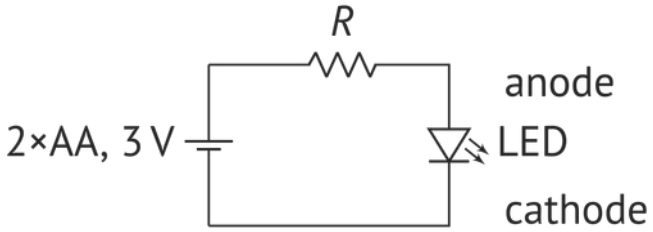
Step 1/a: Breadboarding

A breadboard grips component leads in spring clips, so a prototype circuit can change in seconds.



Components are inserted in the breadboard to test the prototype circuit.

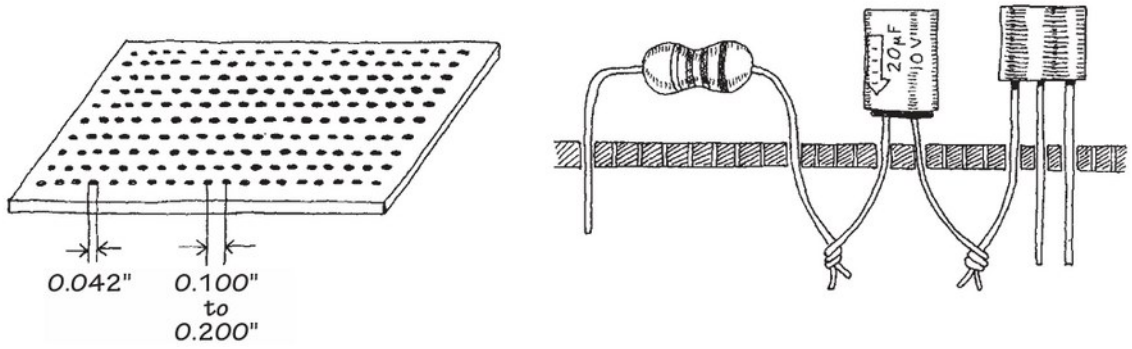




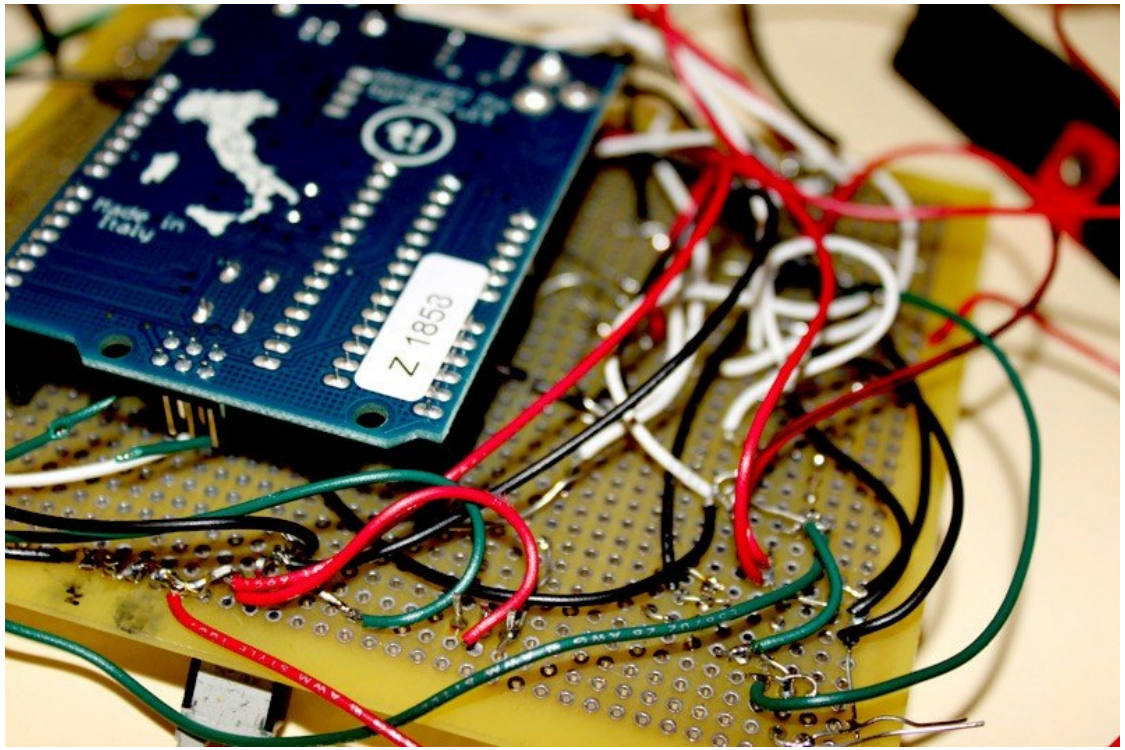
- Rows of holes are connected inside
- Rails carry the supply

Step 1/b: Protoboards

A protoboard is a perforated board with copper-plated holes where parts are soldered and wired.



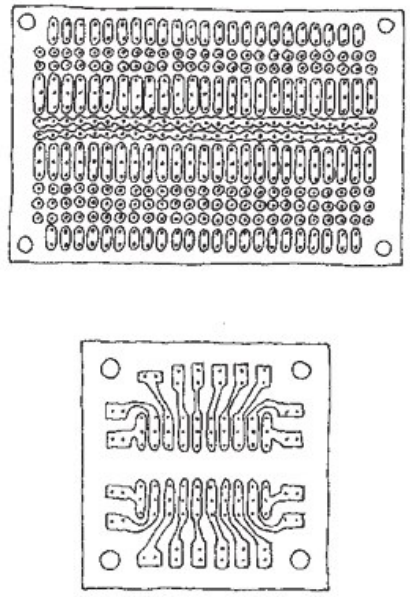
- Copper-plated holes on a **0.1 in** (2.54 mm) grid
- Leads go through the holes and are **soldered** to the pads
- Permanent and sturdier than a breadboard; every connection is still a wire

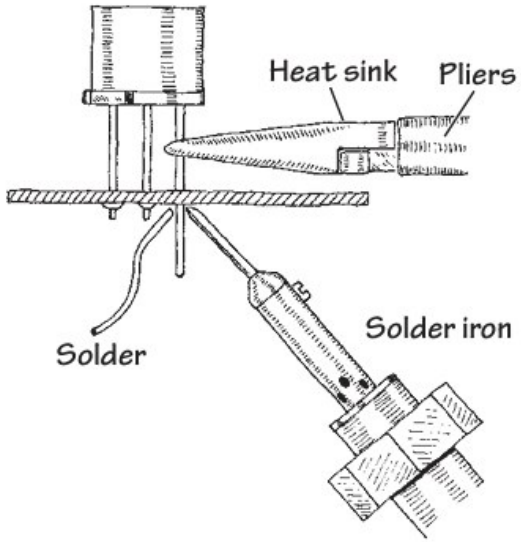


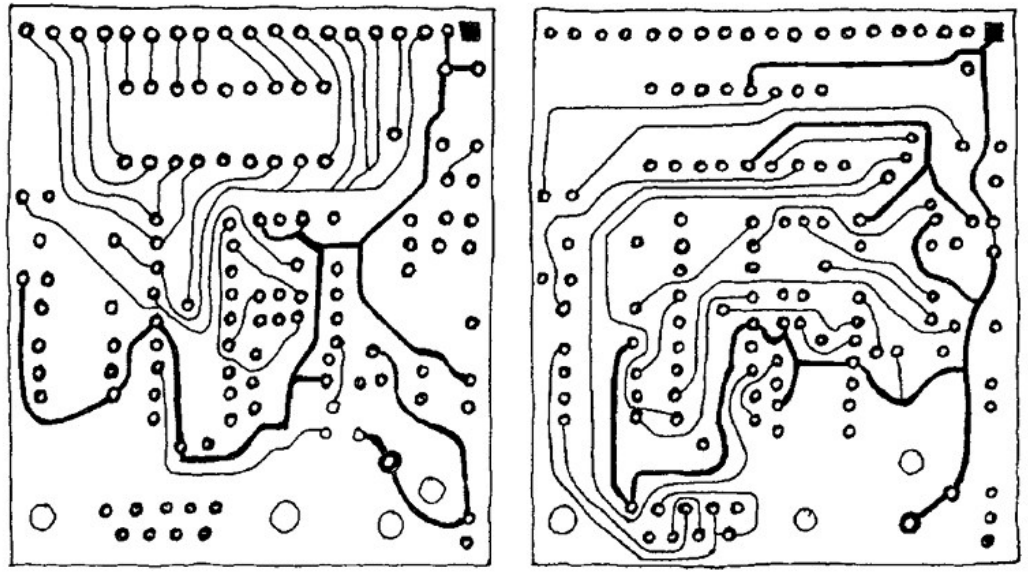
Yasser's first protoboard project (2010)

Protoboard soldering and connection

Solder joins a lead to its pad; copper traces or wires then connect the pads into a circuit.





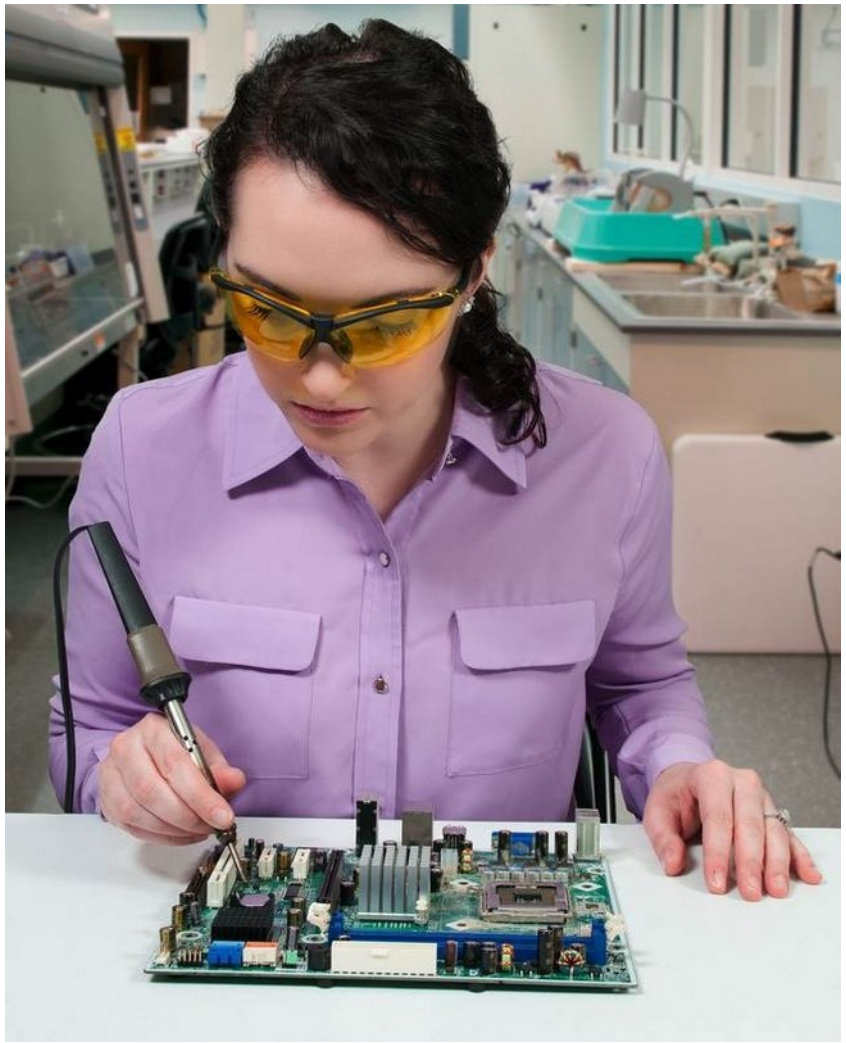


1. Heat the pad and the lead together
2. Feed solder into the joint, not onto the iron
3. Remove the solder, then the iron
4. Pliers on the lead act as a heat sink

What is happening here?

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Look at the hand, the iron and the face: what is right and what is wrong?



TRY IT

- Where are her fingers on the iron?
- What protects her eyes?
- What is missing for a solder joint?

The tip of a soldering iron is about 300 to 400 °C: hold only the insulated grip.

Correct way to hold soldering iron

Hold the iron like a pen, on the insulated grip, well back from the hot tip.

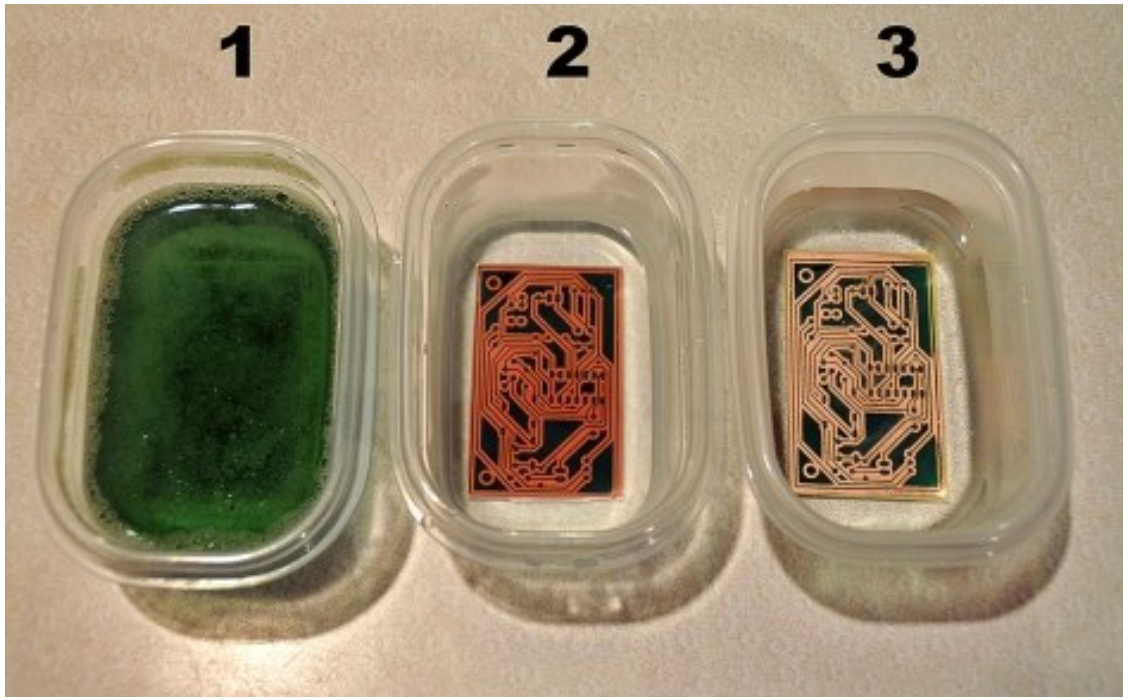


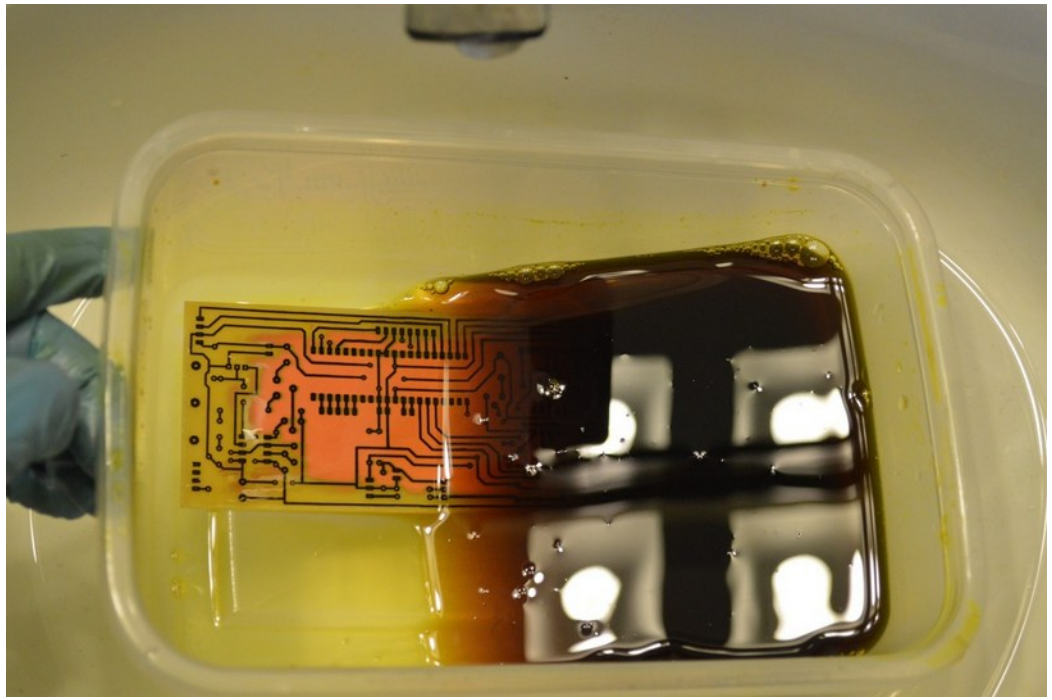
- Hold it **like a pen**, on the insulated grip
- Rest your wrist on the bench
- Return the iron to its stand between joints
- Wear **safety glasses**

Very old way of making printed circuit boards

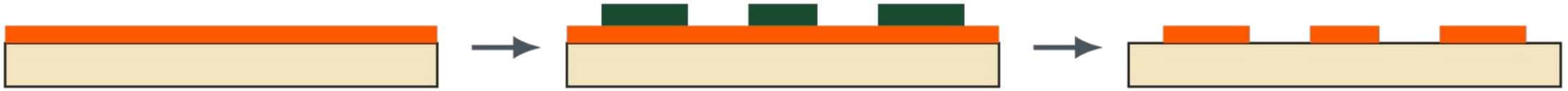
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Protect the trace pattern on copper-clad board, then etch the exposed copper away.





Ferric chloride etching of copper boards



1. copper-clad board

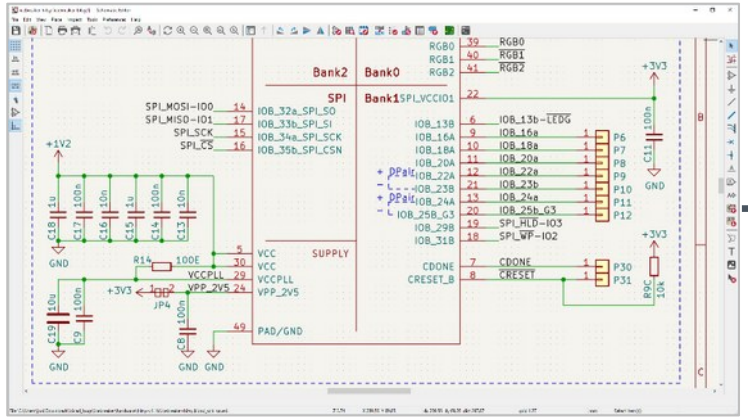
2. mask the traces

3. etch the rest away

Use of PCB design tools such as Eagle / KiCad

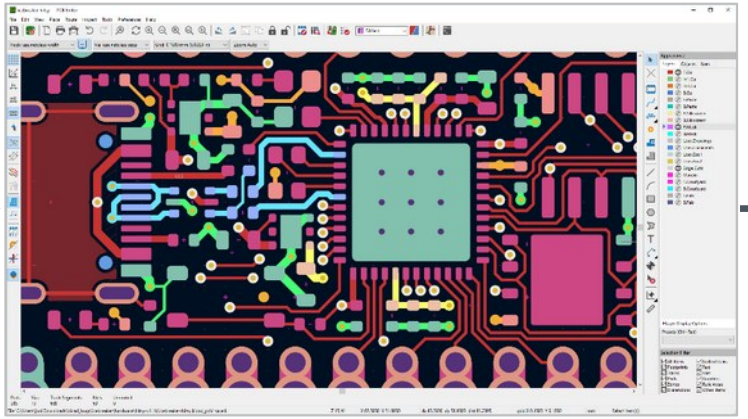
Draw the schematic, lay out the board, then send the files to a fabricator.

1. Schematic design



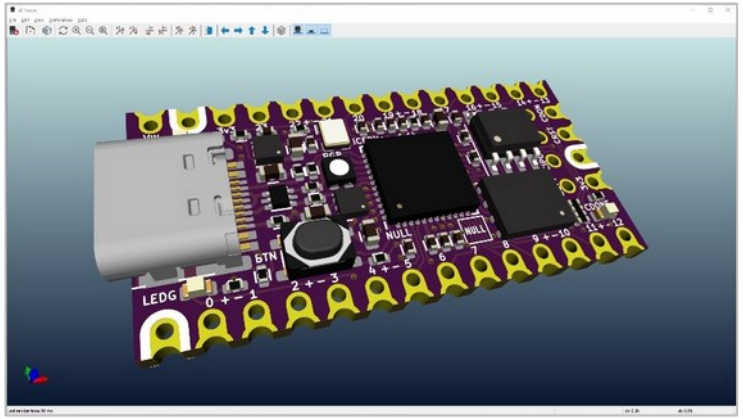
Components and wires as symbols

2. Board layout



Place parts and route copper traces

3. Fabrication



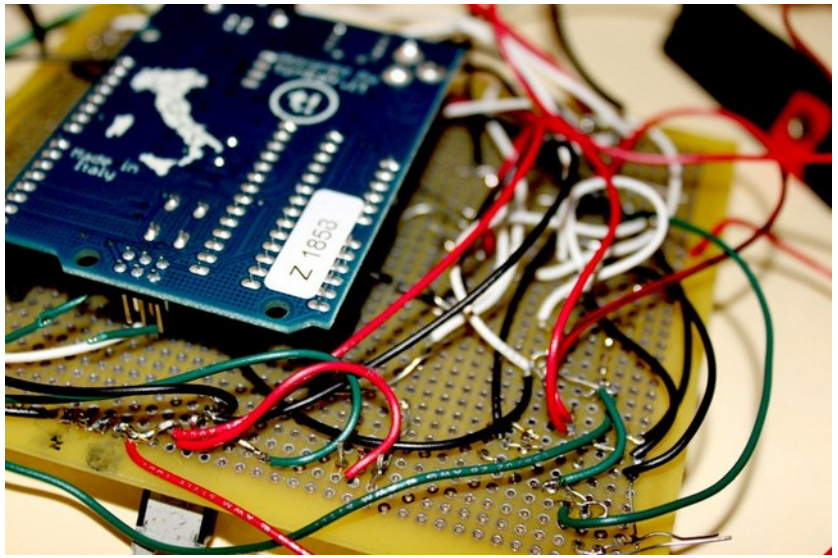
Check the 3D view, send the files to a fabricator

The EE 105 demo board went through exactly these steps.

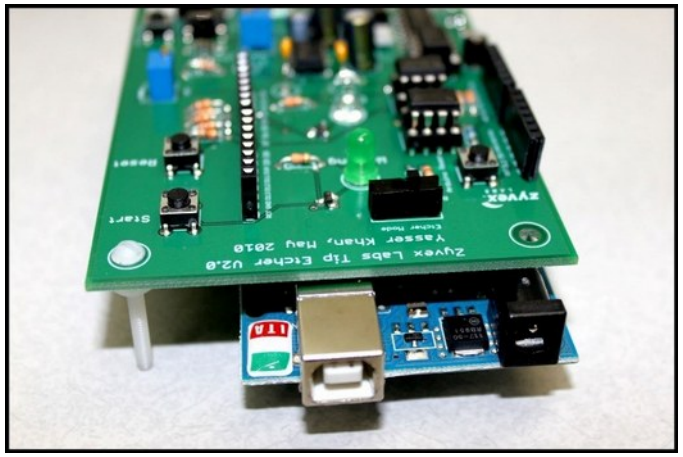
Yasser's first electronics project (2010)

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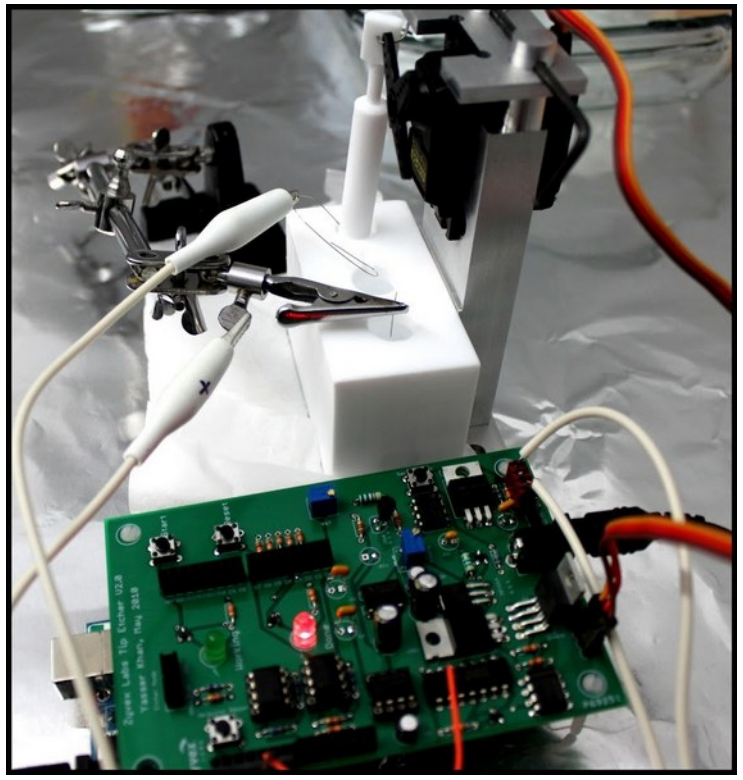
The same circuit before and after learning PCB design.



Before learning PCB design



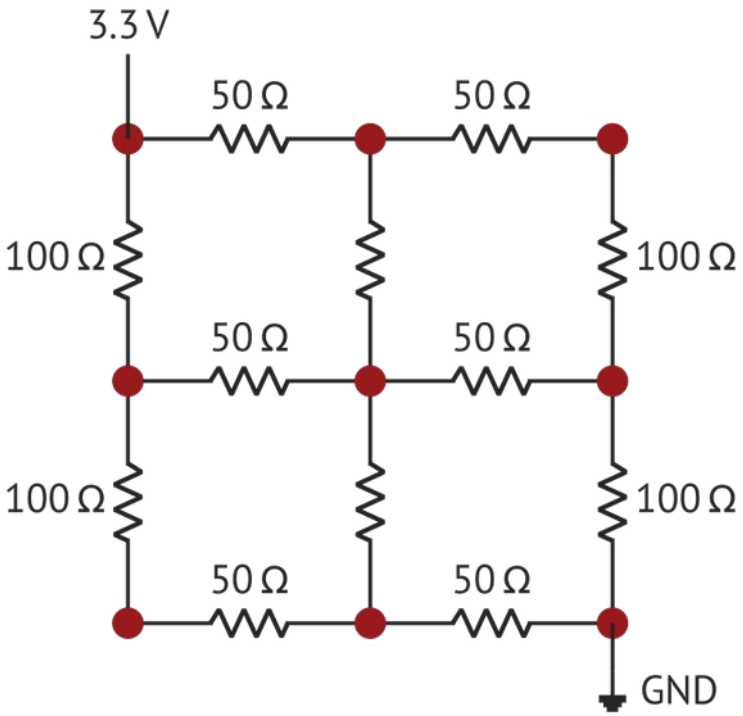
After learning PCB design



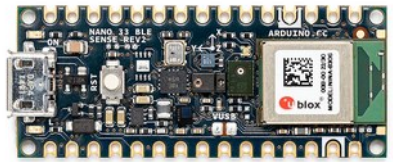
What's remaining now?

The sensor can be built; what remains is connecting it to the Arduino for processing.

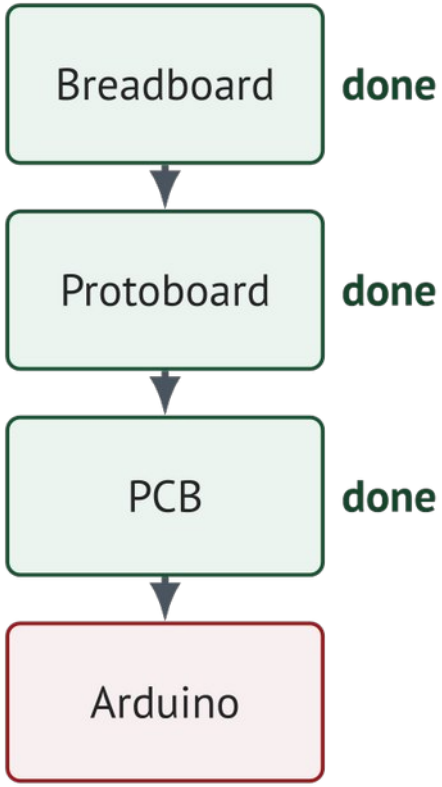
Build a sensor that can detect touch



Connect to Arduino

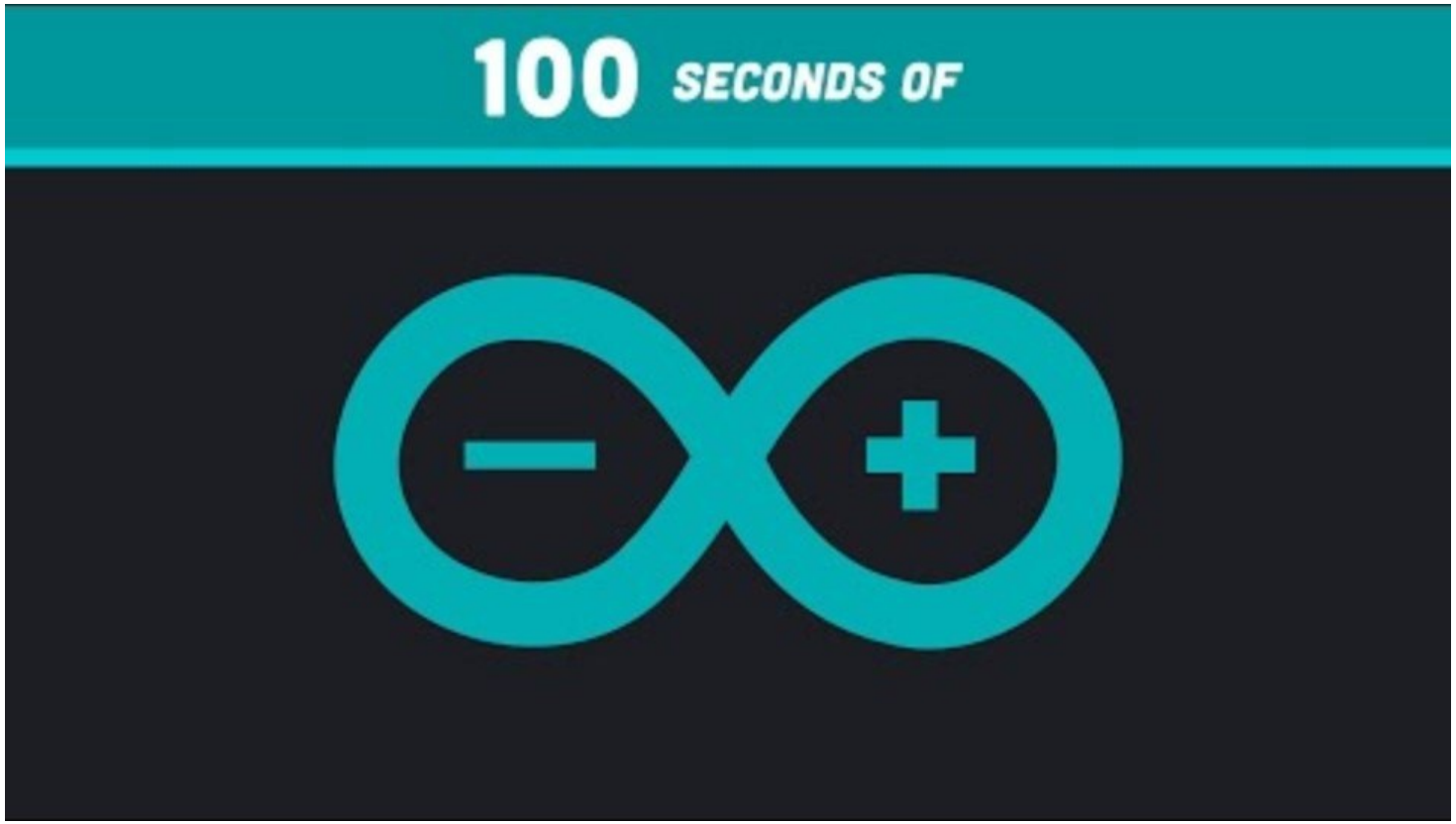


Where we are



Arduino

Arduino is a family of open-source microcontroller boards with a simple programming environment.



- A **microcontroller**: processor, memory and inputs/outputs on one chip
- Open-source boards and a free IDE
- Libraries for almost every sensor
- A gentle entry into **embedded systems**

Video: youtube.com/watch?v=1ENiVwk8idM

Arduino Nano 33 BLE

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The Nano 33 BLE is faster than the classic Uno and has Bluetooth, but its pins run at 3.3 V.

	Arduino Uno	Nano 33 BLE
Processor	ATmega328P, 8-bit	nRF52840, 32-bit Cortex-M4F
Clock speed	16 MHz	64 MHz
Flash / SRAM	32 KB / 2 KB	1 MB / 256 KB
EEPROM	1 KB	none
Operating voltage	5 V	**3.3 V**
Current per I/O pin	20 mA	15 mA
Digital I/O pins	14	14
PWM pins	6	all digital pins
Analog inputs	6	8
Analog output	PWM only	PWM only (no DAC)
Wireless	none	Bluetooth 5
Built-in sensors	none	IMU (LSM9DS1)



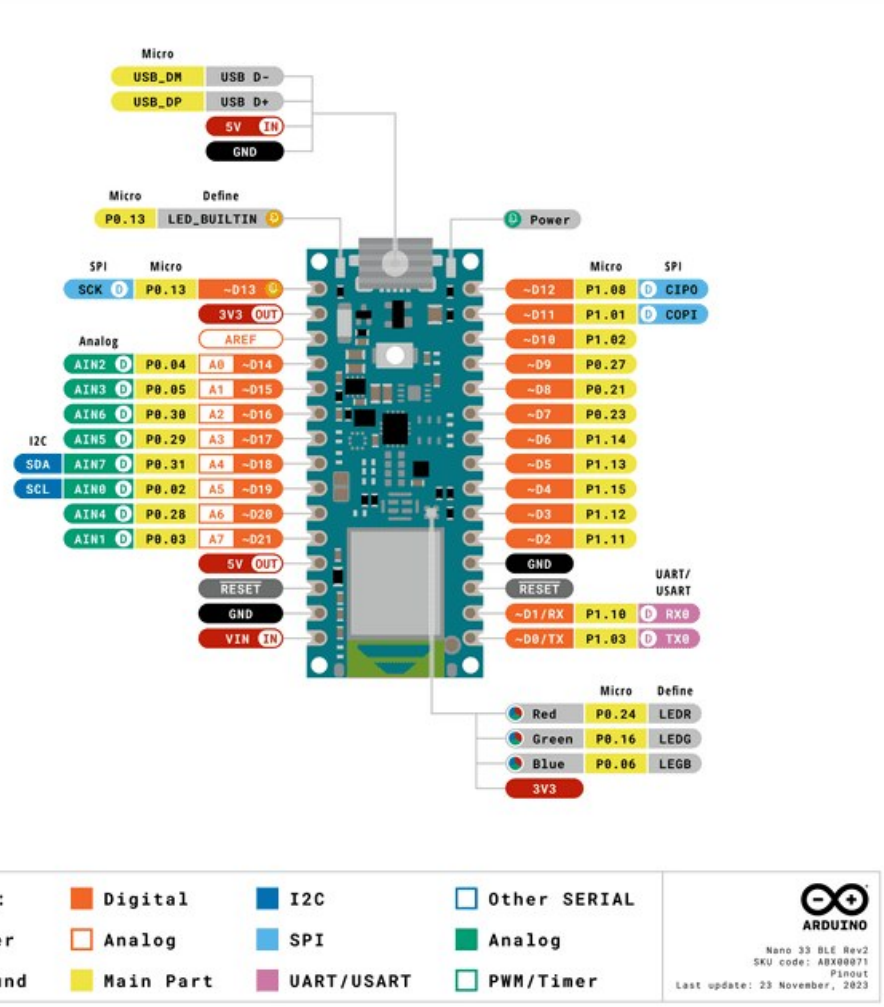
Arduino Uno

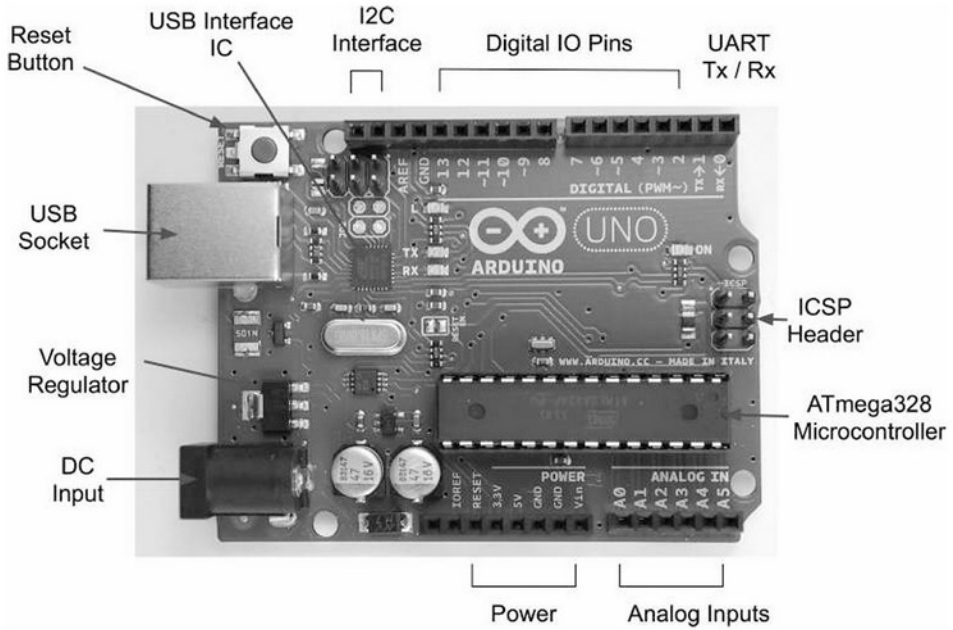


Arduino Nano 33 BLE

Arduino pinout

Every pin has a job: digital, analog, power, or a communication bus.





The same pin groups on the Arduino Uno

- Nano: **D2-D13** digital (all PWM), **A0-A7** analog, **3.3 V, 5 V, VIN, GND**
- **A4, A5** double as I2C (SDA, SCL); the LED is on **pin 13**

Running examples on Arduino

Two demos: blink the on-board LED, then stream sensor data wirelessly to a web app.

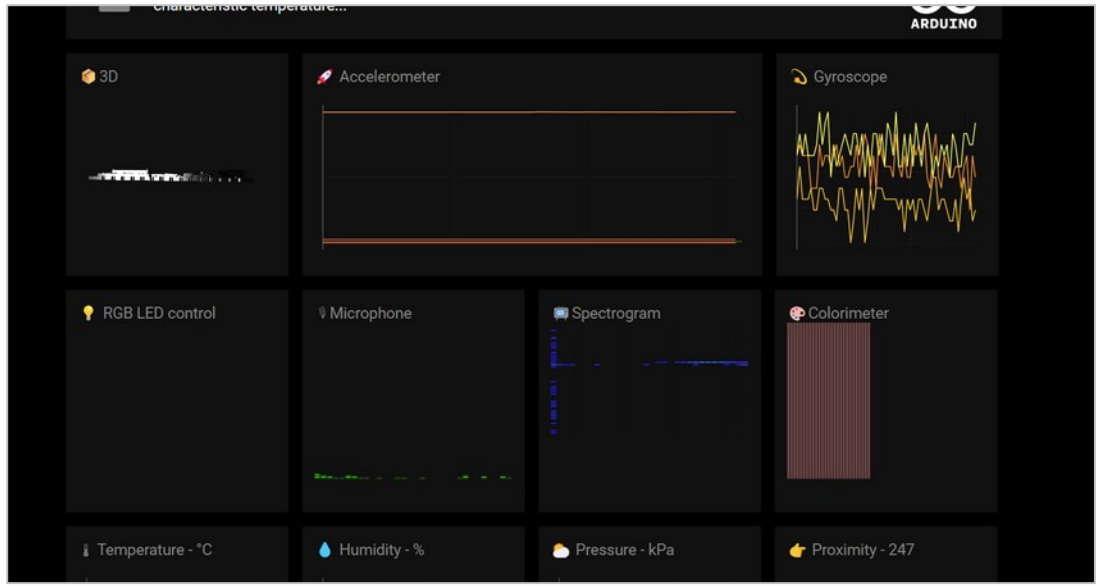
DEMO 1 **Blink the LED**

```
void setup() {
  pinMode(LED_BUILTIN, OUTPUT);     // pin 13
}

void loop() {
  digitalWrite(LED_BUILTIN, HIGH);  // LED on
  delay(1000);                      // wait 1 s
  digitalWrite(LED_BUILTIN, LOW);   // LED off
  delay(1000);
}
```

In Lab 0.1, step B1 (a %%arduino blink cell) uploads it

DEMO 2 **Wireless data to a web app**



arduino.github.io/ArduinoAI/BLESense-test-dashboard

Step by step: the lab kit setup, Blink, printing and plotting, and the on-board sensors are in the Lab 0.1 slides.