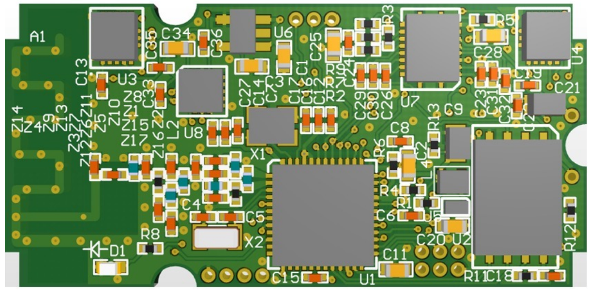
DTU

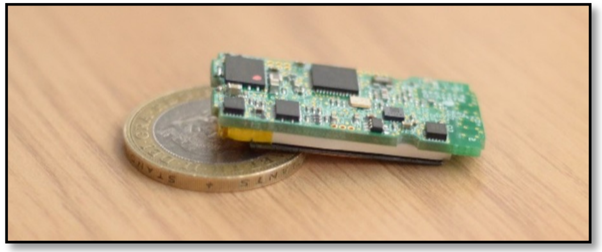
02226 - Networked Embedded Systems

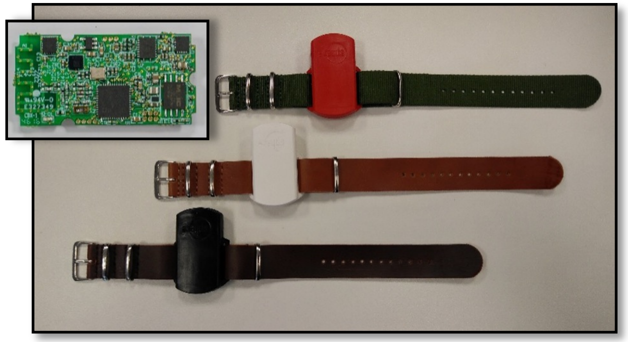
Week 2: Electronics
An Embedded Systems Perspective

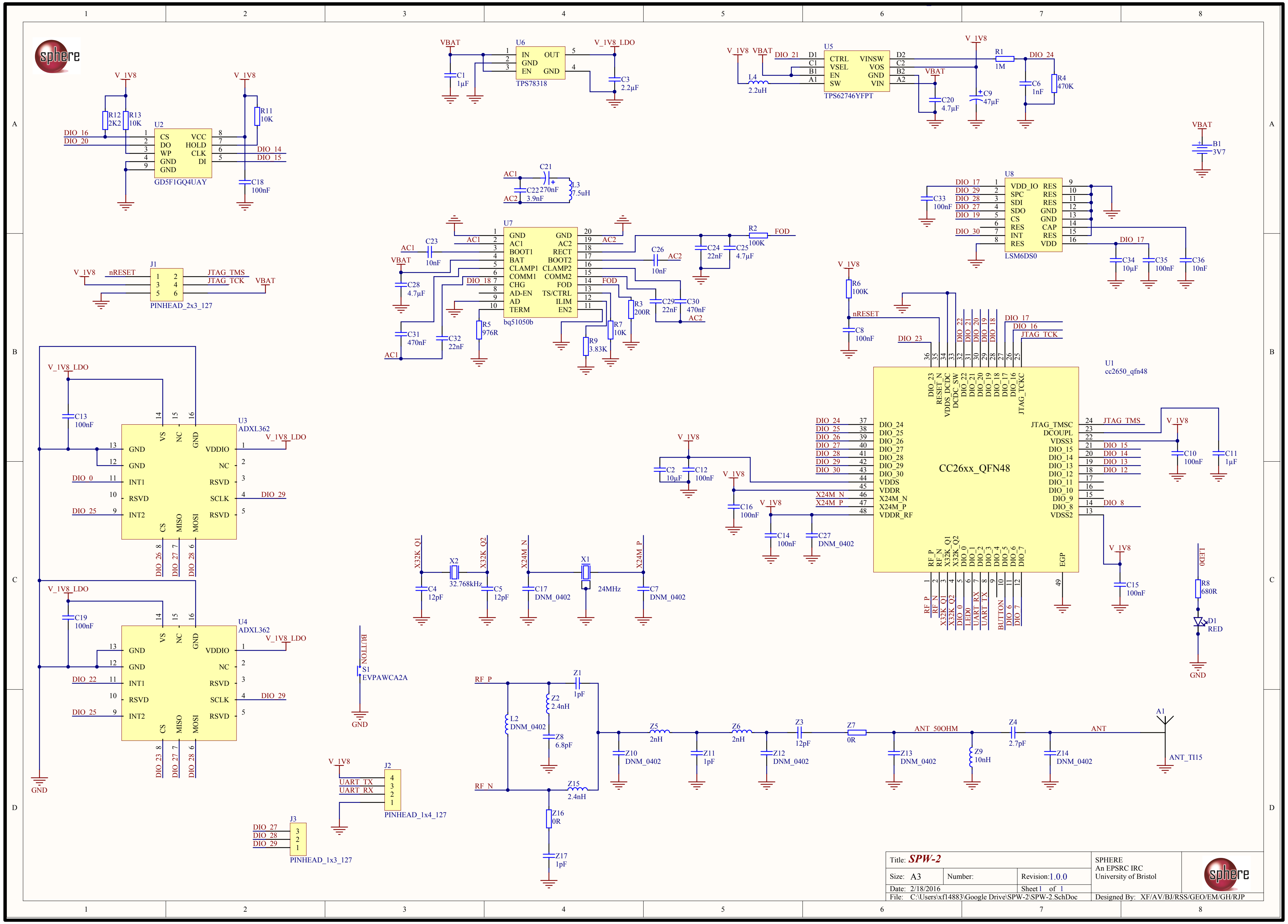
Xenofon (Fontas) Fafoutis
Associate Professor
xefa@dtu.dk
www.compute.dtu.dk/~xefa

A Wearable Embedded System









Schematic (or Circuit Diagram)

- Schematic is a model of an electronic circuit
  - Electronic circuit is electronic components interconnected in a closed loop
- Schematics make our lives easier
  - Abstracts electronic components to basic concepts
  - Easier to read and understand than a circuit

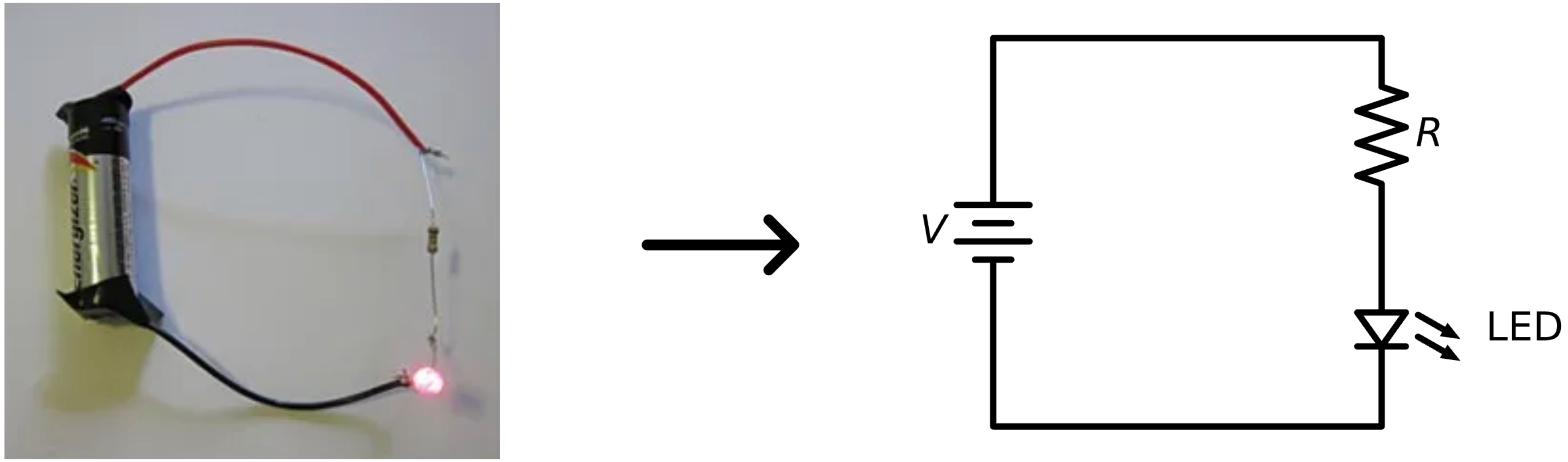
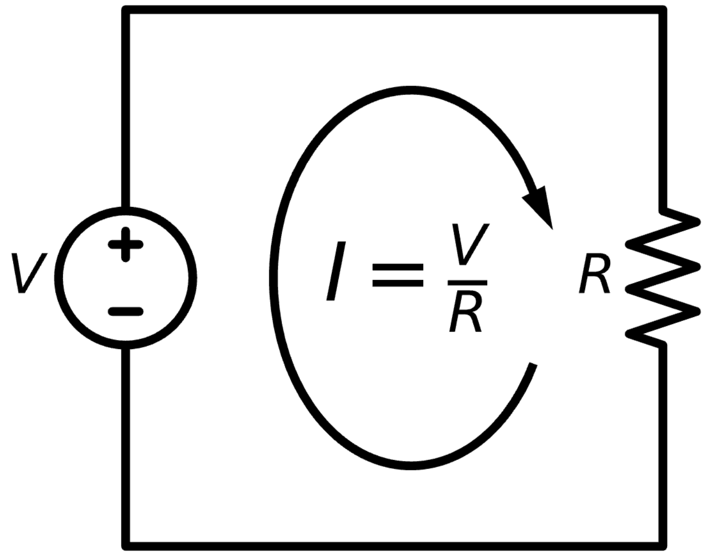


Image source: https://www.sciencebuddies.org/science-fair-projects/project-ideas/Elec_p077/electricity-electronics/led-dance-glove

Basic Concepts

- **Voltage (V, Volts):** Electric potential difference between two points
- **Current (I, Amperes):** Flow of electrically charged particles
- **Resistance (R, Ohm):** A measure of opposition to the flow of electric current
- **Ohm's Law (I=V/R):** The current through two points is directly proportional to the voltage across those points



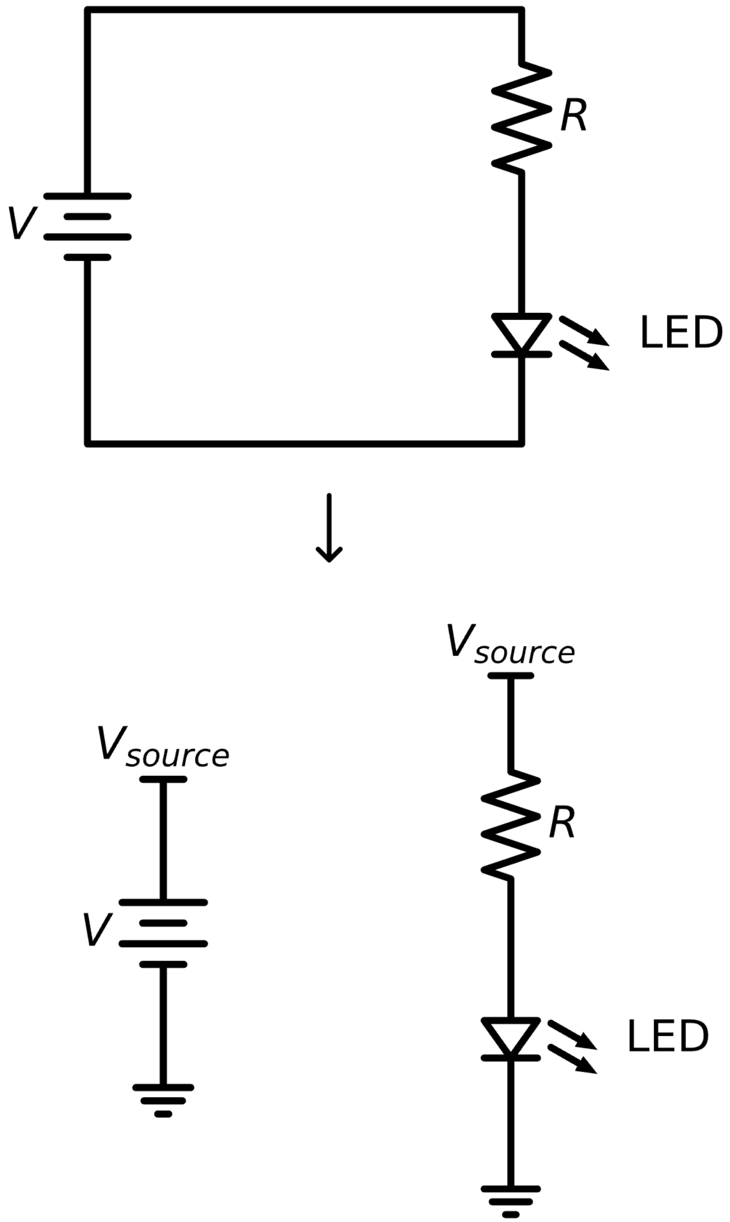
Electric Power Source

- **Direct current (DC)** is one-directional flow of electric charge (e.g. a battery)
- **Alternating current (AC)** is an electric current which periodically reverses direction (e.g. mains)
- **A rectifier** is an electrical device that converts AC to DC
- **Embedded Systems** typically require DC power sources

Image source: Wikipedia

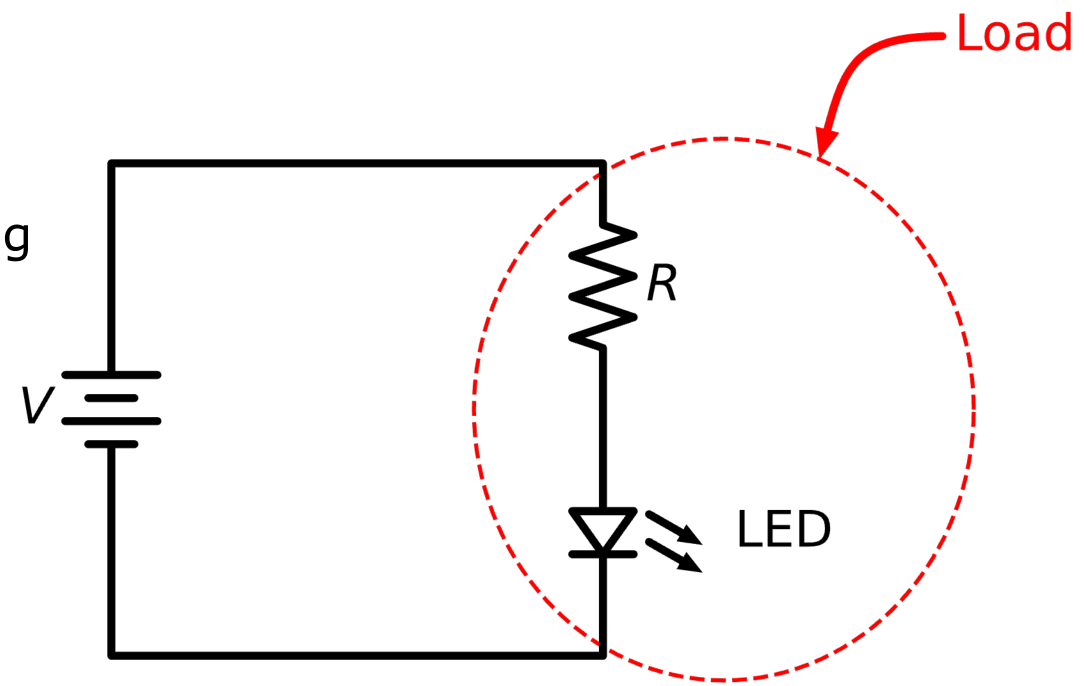
Voltage Sources

- DC sources can be **batteries** (or the mains via rectification)
- Voltage is the potential difference between two points
  - Yet, it is often convenient to measure the voltage from a common reference point, the ground
- **The ground** is a common reference point, sometimes physically connected to the earth
- As circuits grow in size and complexity, we use **labels** to represent the supply voltage and the ground
  - A label implies that all points with the same label are connected to each other



Electric Load (Power Consumers)

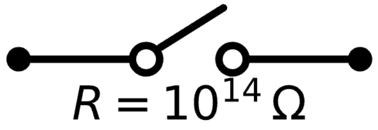
- **Electric Load** is the components or part of the circuit that consume electrical energy, converting it to light, kinetic energy, or heat
- **Electric Power (P, Watt):** Rate of electric transfer (consumption)
- **P = V I**
- The **Energy (E, Joule)** consumed is proportional to the time (t) of operation
- **E = P t = V I t**



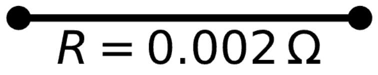
Everything has resistance

- Resistance is opposition to current flow
  - Fixed resistance R from 0 Ohm to hundreds GOhms

- Insulators are assumed to have infinite resistance
  - In reality, an insulator like air has very high resistance

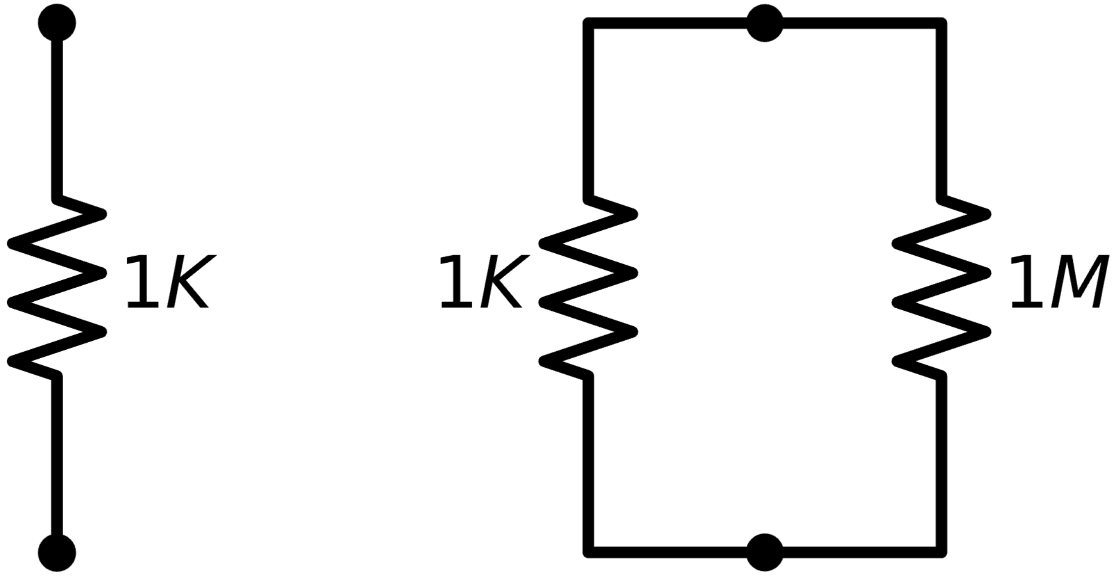


- Conducting wires are assumed to have zero resistance
  - In reality, a conductor like a copper wire has very low resistance



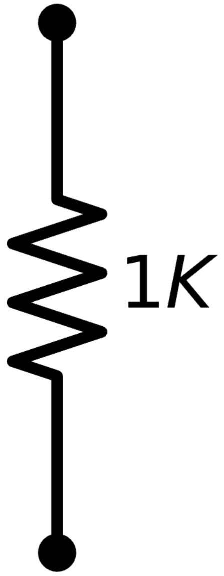
Quiz

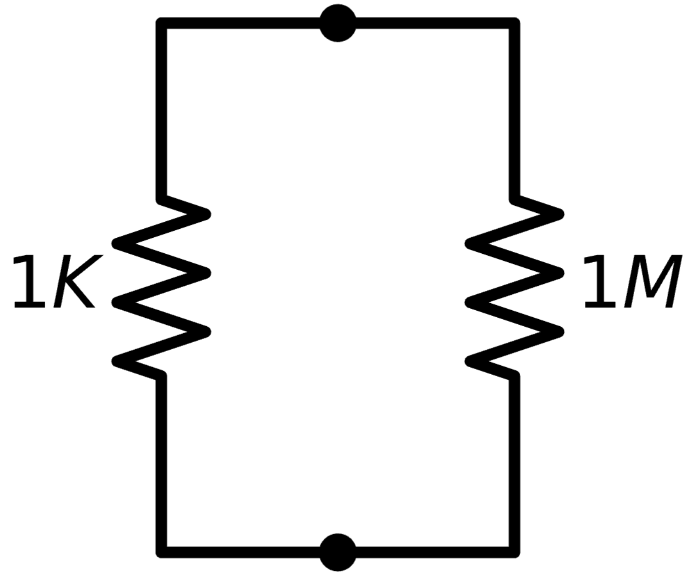
- If we apply the same voltage, which will have higher current?
- How much higher would that current be?
  - 0.1%
  - 1%
  - 10%



“Path of Least Resistance”

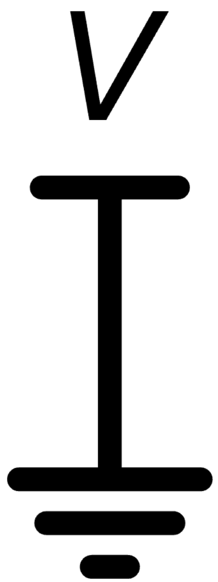
- Let’s say we apply 1 V
- Left
  - $I = V / R = 1 / 1K = 1$ mA
- Right
  - $R = (R_1 \times R_2) / (R_1 + R_2)$
  - $R = 999$
  - $I = V / R = 1 / 999 = 1.001$ mA
- Practically, left and right are equivalent





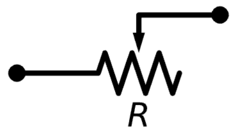
Short Circuit (or short)

- An often unintentional path of “no resistance” from high voltage to ground
- Mathematically, it is an impossibility
  - $I = V/R = V/0 = \infty$
- Practically, any wire or conductive path has some very small resistance
  - Also, if power supply is a battery, batteries have internal resistance
- A short circuit practically leads to very high current, often limited by how much the power supply can provide
  - In high-power electronics this can be dangerous or lethal
  - In low-power electronics in can damage components or chips

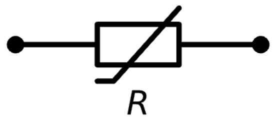


Resistance can be variable

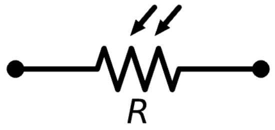
- Potentiometer: Mechanically-controlled resistance



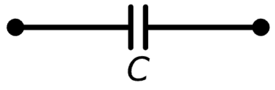
- Thermistor: Temperature-dependent resistance



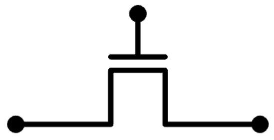
- Photoresistor: Luminosity-dependent resistance



- Capacitor/Inductor: Behave like frequency dependent resistors for AC (we call this reactance)



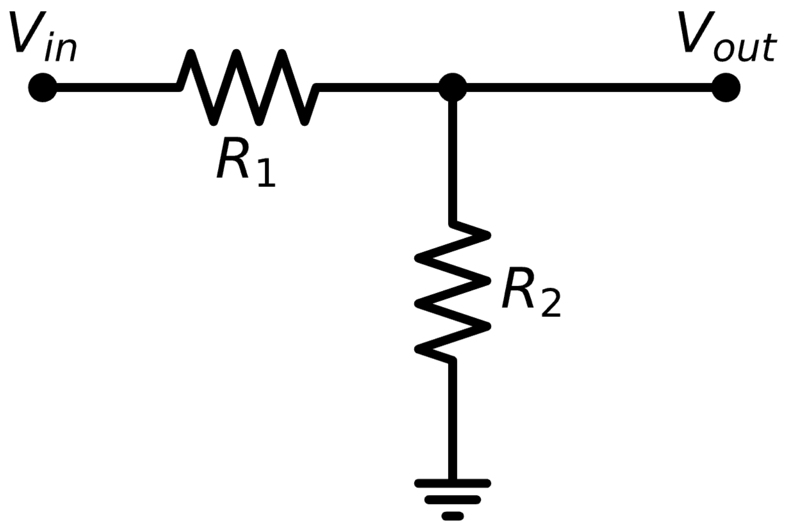
- Transistor: Electrically-controlled resistance



Voltage Divider

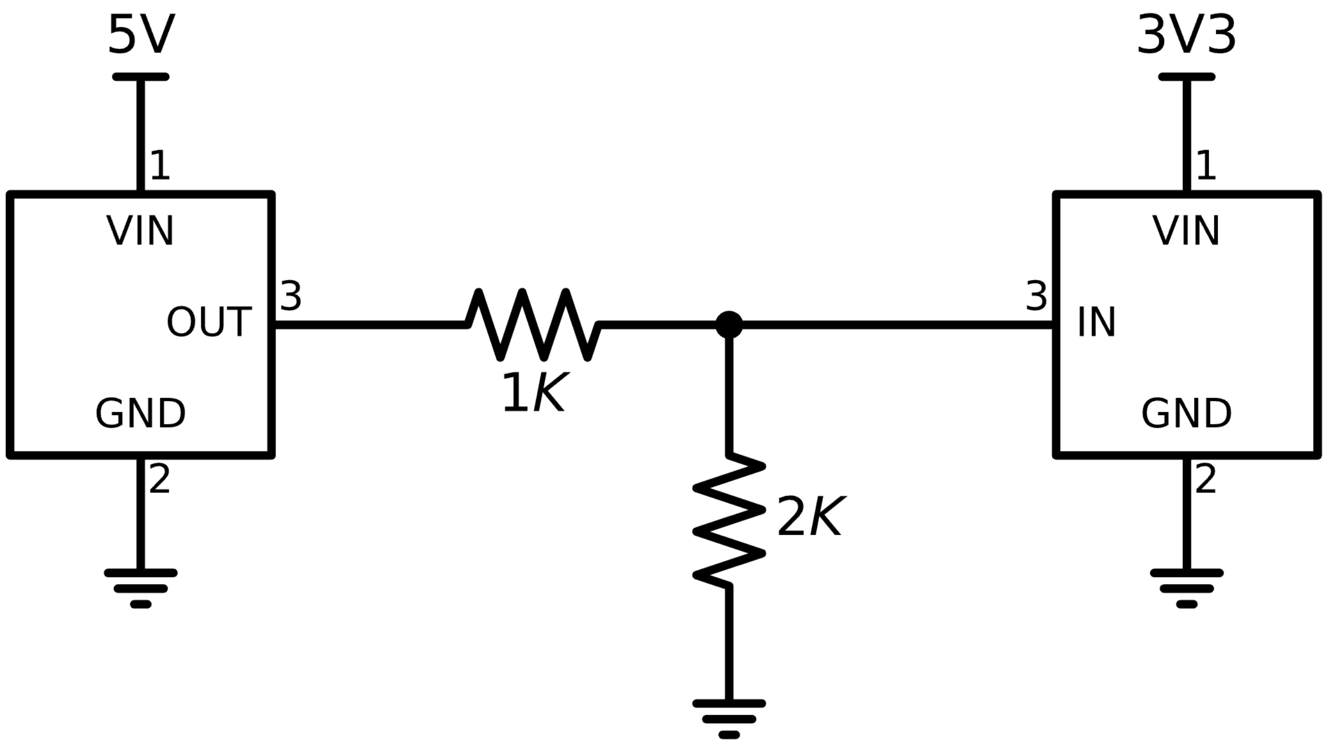
$$V_{out} = V_{in} \frac{R_2}{R_1 + R_2}$$

- **Signal Attenuator:** The output voltage is a fraction of the input voltage
- If R1 is much smaller than R2, most of the input signal goes through (small attenuation)
- If R1 is much larger than R2, most of the input signal does not go through (large attenuation)



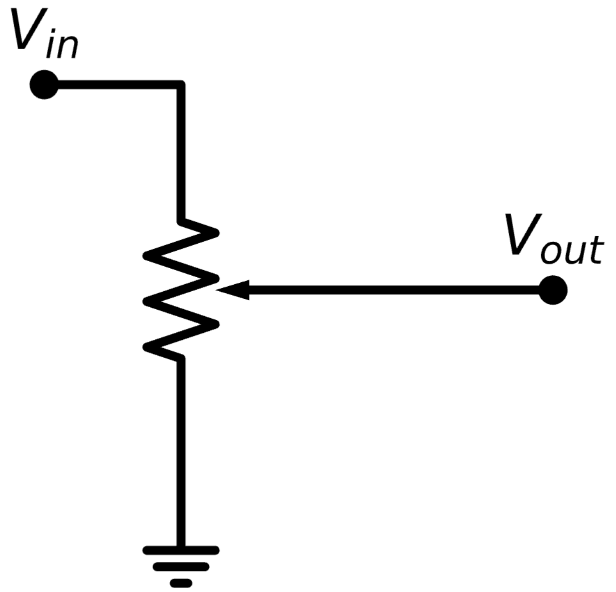
Level Shifter

- Interface the output of a device that encodes ‘1’ as 5V to a device that expects input at maximum 3.3V without damaging the latter



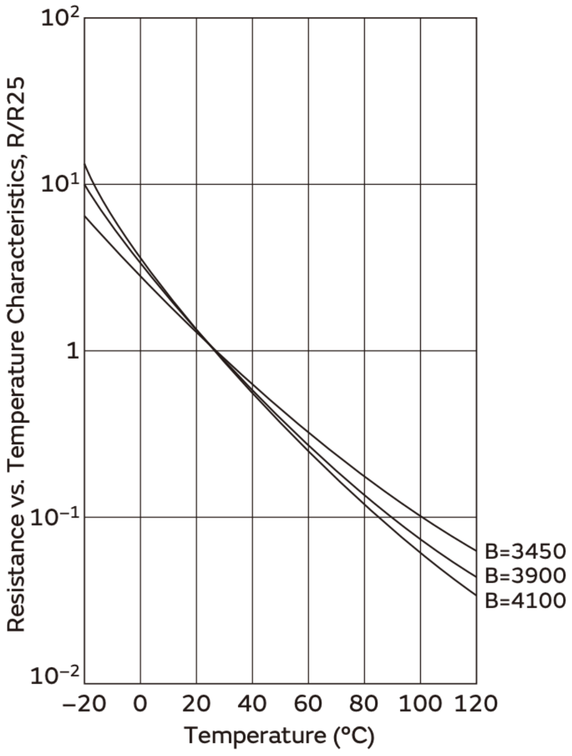
Volume Control

- Mechanically-controlled signal attenuation
- A potentiometer has two terminals at the two ends of a resistor and one at the wiper arm
- The wiper can be moved, cutting the resistor in two parts with adjustable ratio
- This configuration can also be used to for user input
  - An Analog-to-Digital Converter (ADC) measures the output voltage and maps them to a set of numbers



Temperature Sensor

- The embedded systems can measure voltage not resistance
- A thermistor's resistance (R2) depends on the temperature (T)
- The output voltage depends on the ratio of the two resistors
- Therefore, the output voltage depends on the temperature



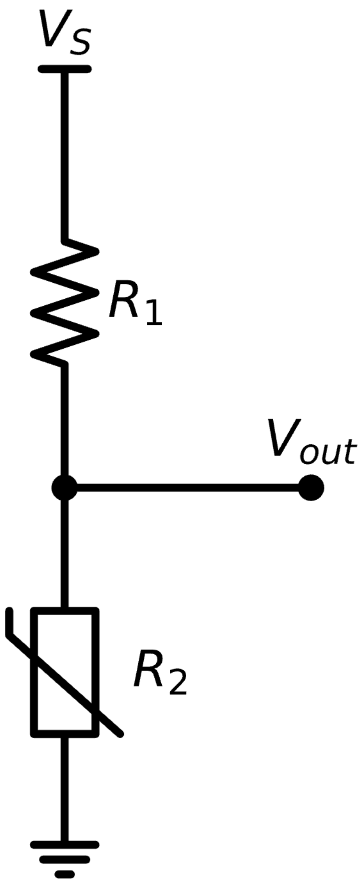
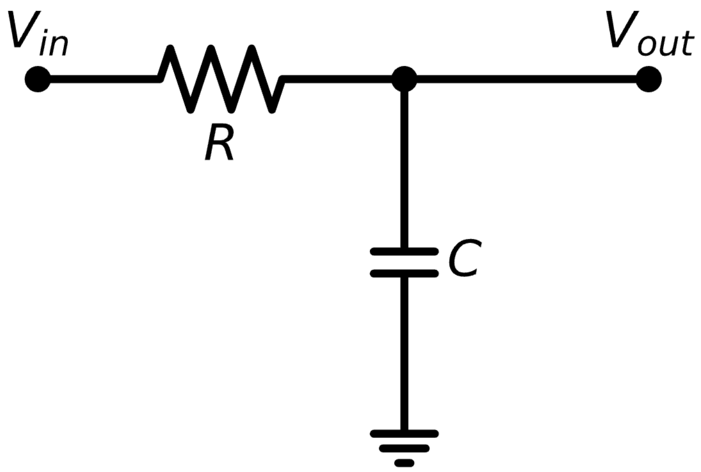


Image source: NTC Thermistors Datasheet by Murata

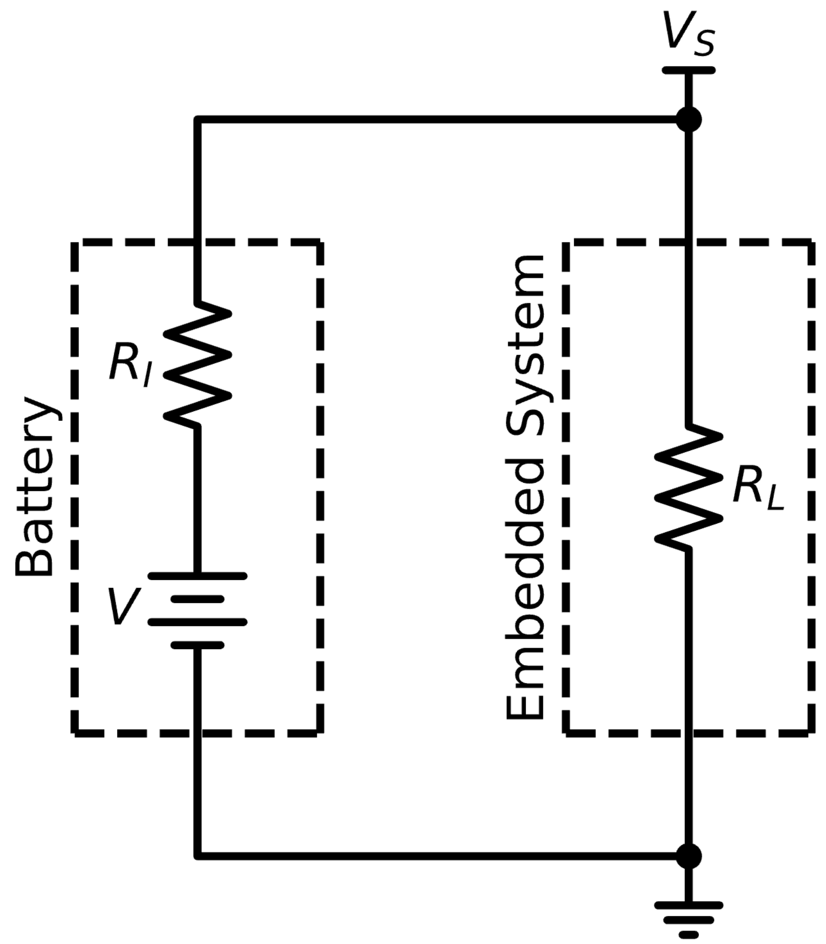
Capacitors

- Capacitors can store and provide electrical energy
  - They behave like tiny "power supplies"
- Capacitors do not let DC current to go through
- Capacitors let AC current go through
- They behave like frequency-dependent "resistors"
  - High frequencies will see low "resistance"
  - Low frequencies will see high "resistance"
- RC Low-Pass Filter
  - High frequencies are attenuated a lot
  - Low frequencies are attenuated a bit



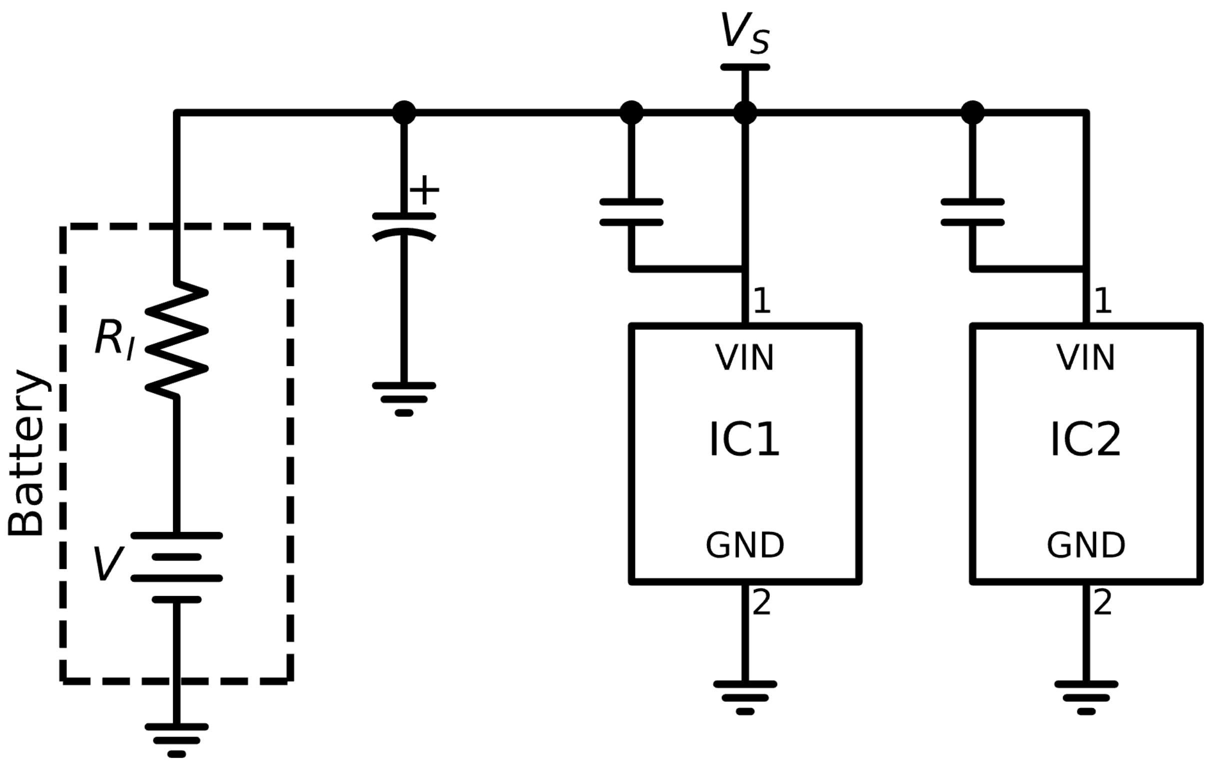
Batteries are imperfect power sources

- Batteries have internal resistance (R_I)
  - It increases as they're used
- The internal resistance creates a voltage drop proportional to the current that the system draws
- The supply voltage (V_S) will be less than the battery voltage (V)
- As the system goes through various states of operation it may need high current for a short period of time
  - Low current -> small voltage drop (no problem)
  - High current -> large voltage drop (dangerous)
- Large voltage drops can get the supply voltage below the minimum operating voltage of the embedded system!



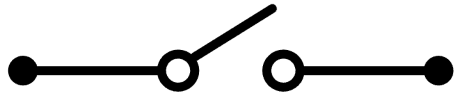
Decoupling Capacitors

- Capacitors in parallel and physically very close to various components and integrated circuits
- Act as local power supply or local energy reservoir
- The filter out high-frequency noise in power supply signals
- Can support the battery in moments that require high peaks of current for a short time
- They oppose changes to supply voltage
  - If voltage goes up, they absorb excess energy
  - If voltage drops, they provide power to the IC

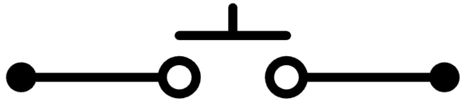


Switches and Buttons

- Mechanically open/close the circuit
- Switch: holds open/closed state

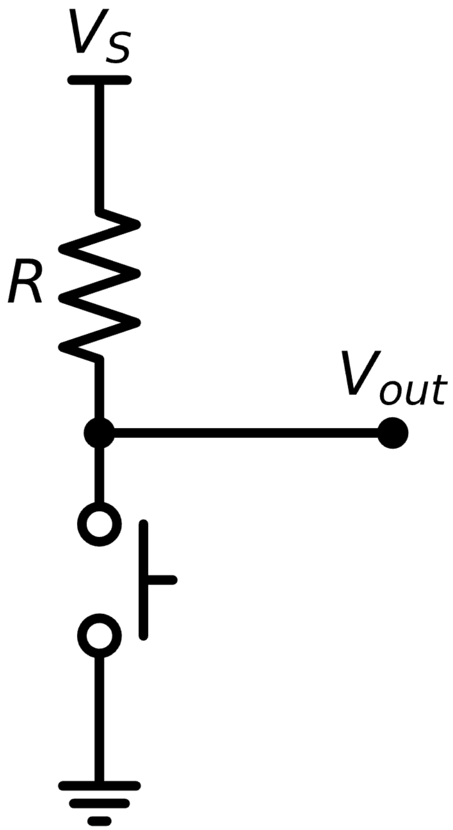


- Button: closed when pressed, open when released



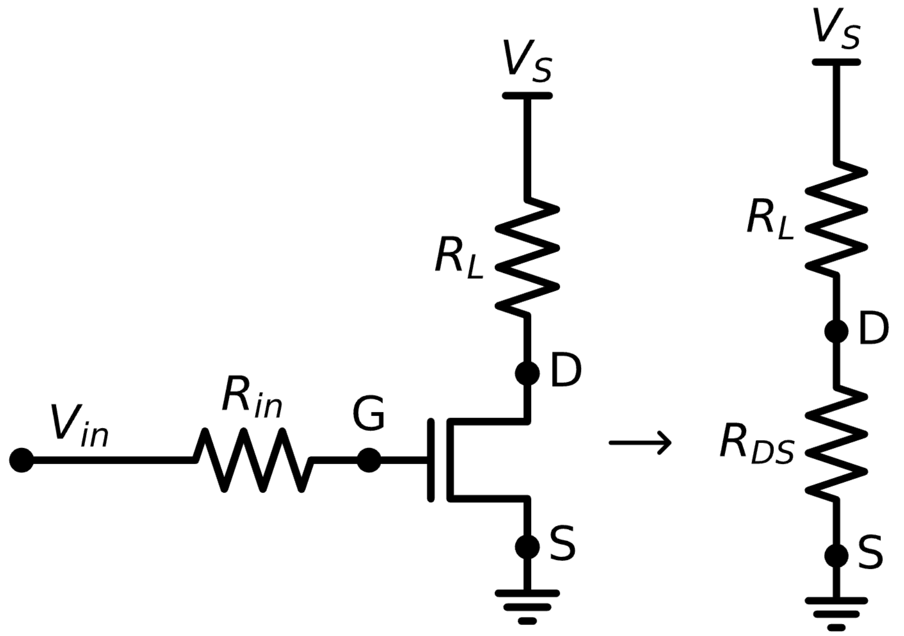
Detecting when a button is pushed

- Embedded Systems can measure voltage
  - We need to convert the push of the button in a change in voltage
- When button is not pushed, the circuit is open, as there is no path to the ground
  - Open circuit -> no current through R -> no voltage drop
  - Therefore, the output voltage is equal to V_S
- When button is pushed, the circuit is closed, as there is a path to the ground
  - Closed circuit -> current goes through R -> output (V_{out}) directly connected to ground
  - Therefore, the output voltage is equal to 0



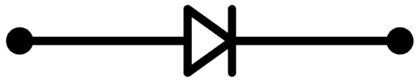
Transistor (MOSFET) as a Switch

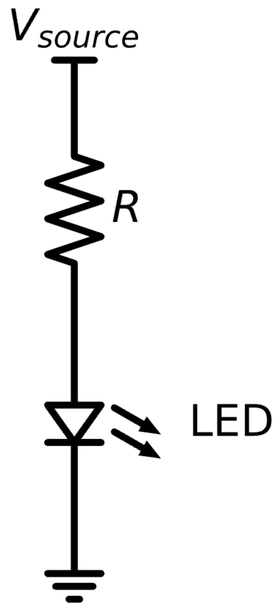
- Controlling a switch with an electric signal
- MOSFETs are like electrically controlled resistors
- The resistance between two terminals depends on the voltage at the third terminal
- V_{in} = V_S -> R_{DS} very very small -> switch closed -> current flows through R_L -> load gets power
- V_{in} = 0 -> R_{DS} very very big -> switch open -> no current flows through R_L -> load gets no power



Diodes and LEDs

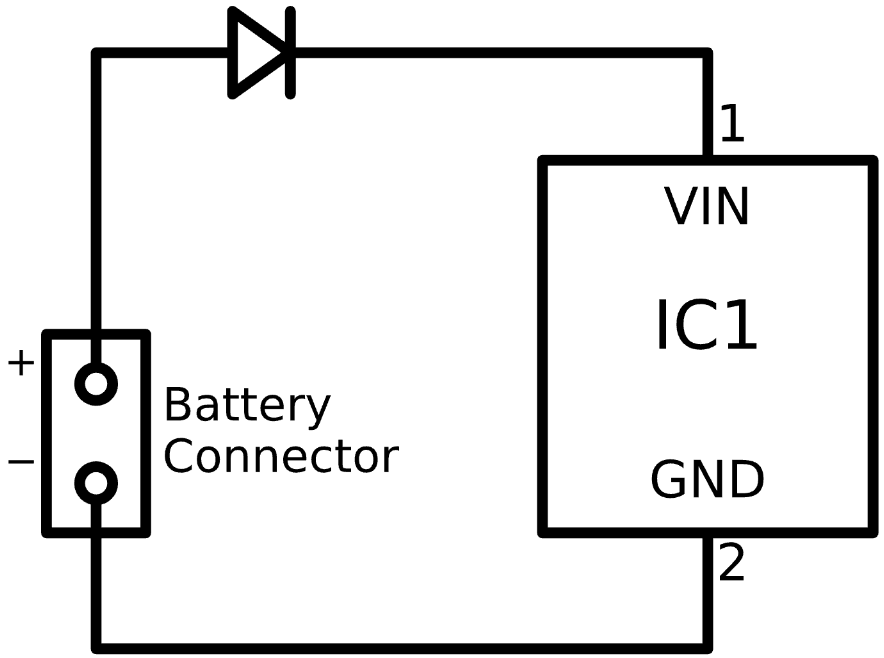
- One-way conductor
- Ideally zero resistance in one direction, infinite resistance in the other direction
- When current goes through there is a voltage drop and consumes power
- LEDs are diodes that emit light
- A series resistor (R) is needed to limit the current that goes through the LED to avoid damage





Reverse Voltage Protection

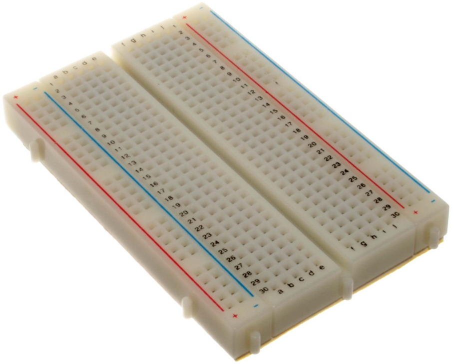
- Diode protects the circuit from reverse voltage
- When battery is connected correctly, current flows as expected and the system is powered properly
- If the battery is connected reversely, the diode will block current flowing in the wrong direction, protecting the system from damage



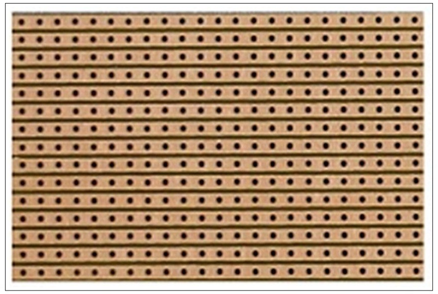
PCB Prototyping

- Before designing a PCB it is often a good idea to prototype the circuit or some parts of it
- Breakout boards allow easy access to the pins of small components

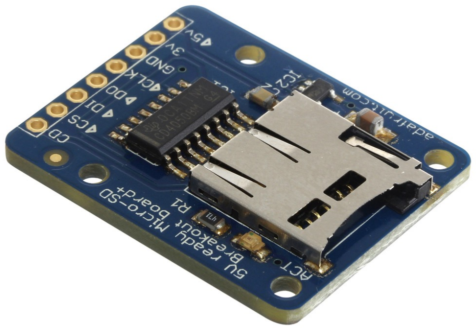
Breadboard



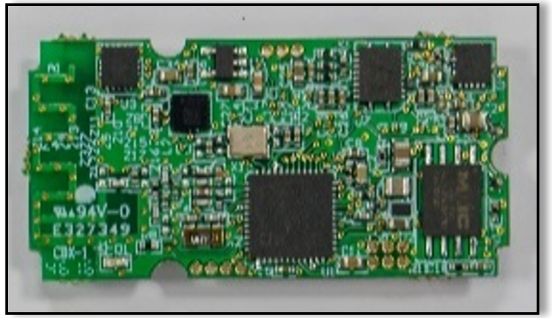
Veroboard



Breakout board

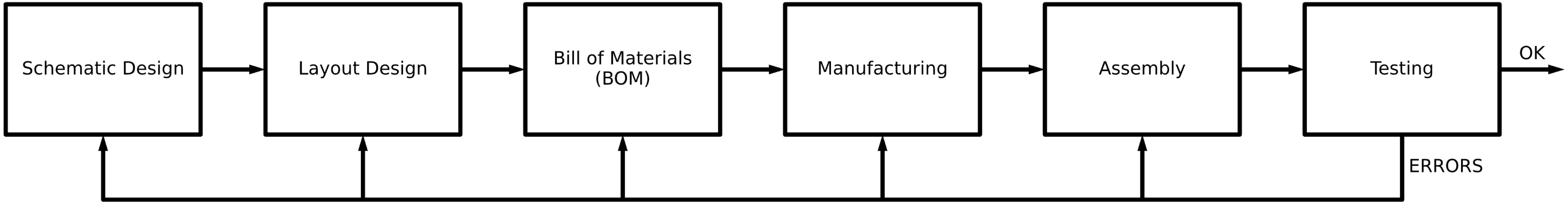


PCB Design



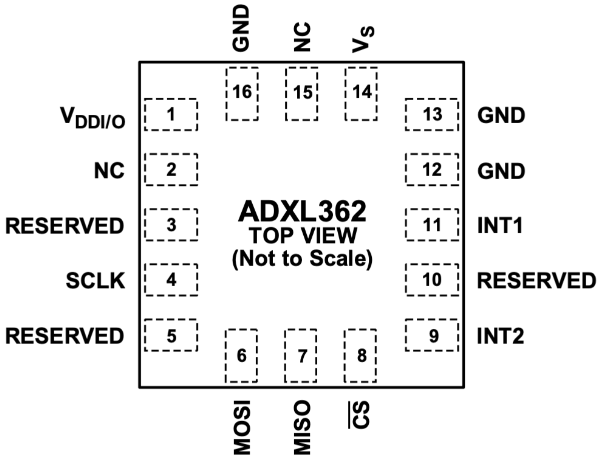
- Printed Circuit Board (PCB)
  - Copper tracks printed on a substrate
  - Exposed copper pads to mount components

- Designed through specialised software, named **Electronic Design Automation (EDA)**
  - Or Electronic Computer-Aided Design (ECAD)



PCB Design: Schematic

- The first step is the identification of key components and power source
  - Ensure compatibility, identify voltage level(s), etc
  - Keep it simple
- Often we don’t have to select the values of passive components (resistors, capacitors, etc)
  - Components provide reference circuits (e.g. the decoupling capacitor should be 100nF)
  - There are lots of “open hardware” circuits that can be used as reference
- For each component, we need to make a schematic model based on the datasheet (matching pin numbers to functionality)



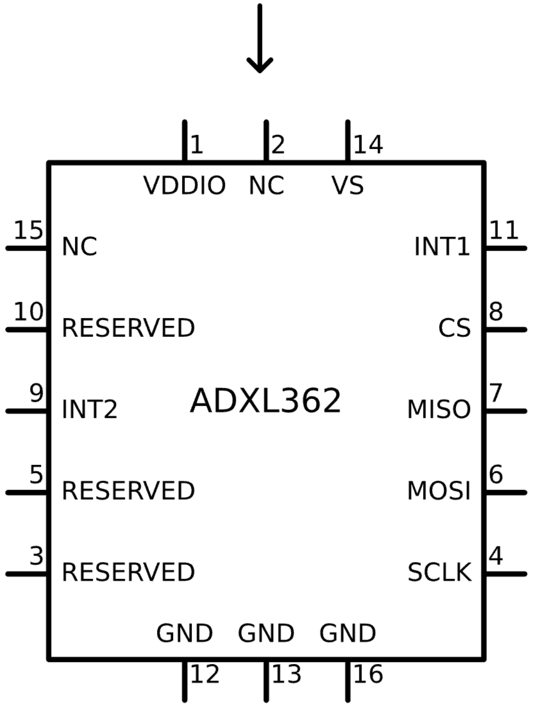
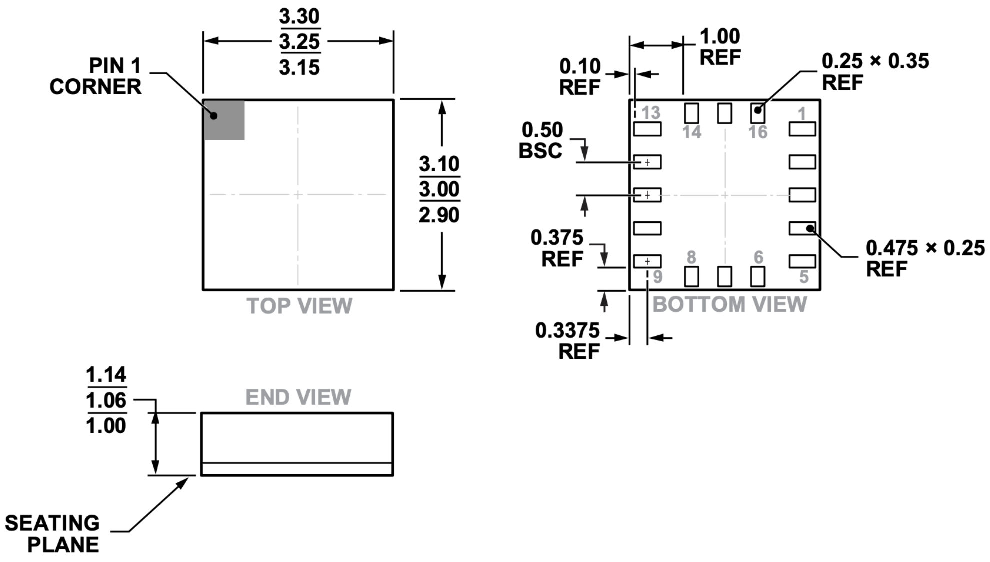


Image source: ADXL362 Datasheet by Analog Devices

PCB Design: Component Layout

- For each component, we need to create a footprint with exact dimensions, following the datasheet
- Attention: the bottom view is the mirror image of the top view
- Passive components come in standard sizes
- Imperial sizes (inches) and metric sizes (mm) are both used



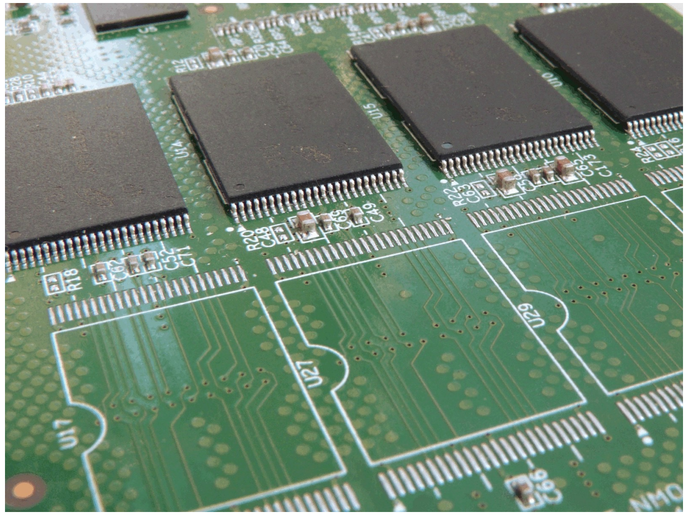
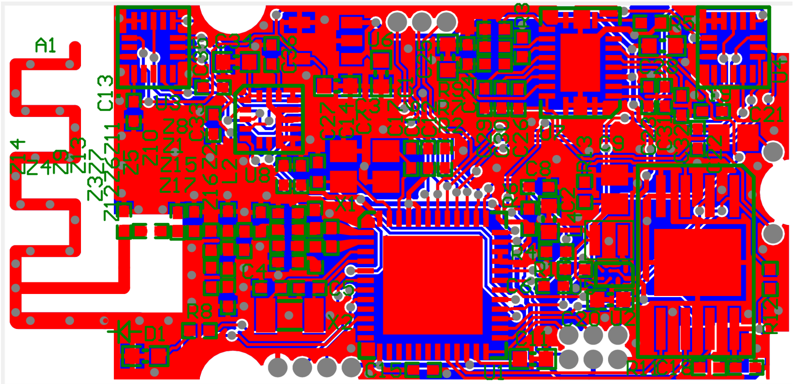
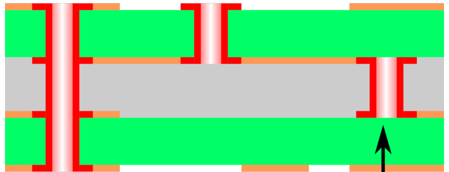


Image source: ADXL362 Datasheet by Analog Devices (top), Wikipedia (bottom)

PCB Design: Board Layout



- Place components on a board and connect them (routing)
- PCBs have 2 or more copper layers
  - Components can be placed at top and bottom layers
  - Internal layers have copper tracks for wiring



- Vias
  - Layers are connected vertically with vias
    1. Through hole via (top to bottom)
    2. Blind via (top/bottom to internal)
    3. Buried via (internal to internal)
- Ground Plane/Layer: Large copper areas connected to ground
  - Reduces noise and electromagnetic interference
  - Heat dissipation

Image source: Wikipedia

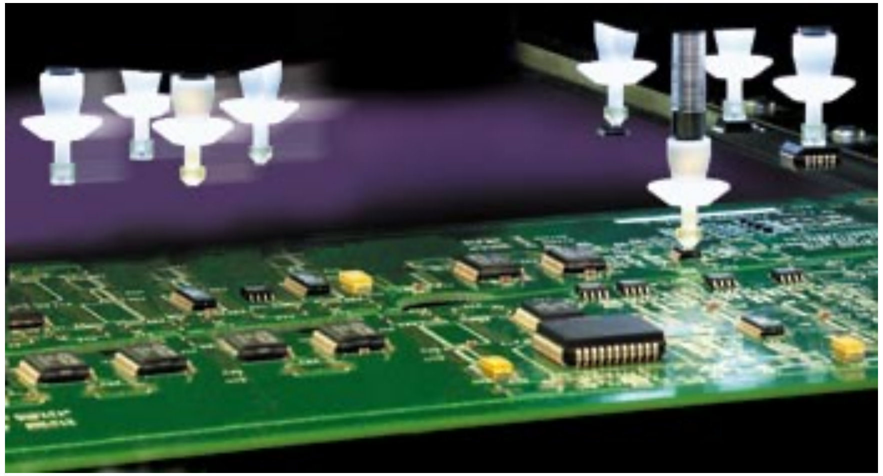
PCB Design: Bill of Materials (BOM)

- A shopping list of components (typically a spreadsheet)
  - Specifies manufacturer, supplier, price, etc

	A	B	C	D	E	F	G
1	**SPW-2 (BOM v1.0)**						
2							
3	Designator	Description	Comment	Manufacturer 1	Manufacturer Part Number 1	Supplier 1	Supplier Part Number 1
4							
5	SPW-2 PCB v1.0						
6	B1	LIPO261534	DNM				
7	C1	Capacitor, X5R, ±10%	1µF	TDK Corporation	C1608X7R1C105M080AC	Digi-Key	445-5131-1-ND
8	C2	Capacitor, X5R, ±10%	10µF	Murata Electronics North America	GRM188R60J106ME47D	Digi-Key	490-3896-1-ND
9	C3	Capacitor, X5R, ±10%	2.2µF	Taiyo Yuden	JMK107BJ225KA-T	Digi-Key	587-1254-1-ND
10	C4	Capacitor, NP0, ±2%	12pF	Murata Electronics	GRM1555C1H120JA01D	Mouser	81-GRM1555C1H120JA1D
11	C5	Capacitor, NP0, ±2%	12pF	Murata Electronics	GRM1555C1H120JA01D	Mouser	81-GRM1555C1H120JA1D
12	C6	Capacitor, X7R, ±10%	1nF	AVX	04025C102KAT2A	Mouser	581-04025C102K
13	C7		DNM_0402				
14	C8	Capacitor, X7R, ±10%	100nF	Murata Electronics North America	GRM155R70J104KA01D	Digi-Key	490-6319-1-ND
15	C9	Capacitor, X5R, ±20%	47µF	Samsung Electro-Mechanics America, Inc.	CL21A476MQCLRNC	Digi-Key	1276-2420-1-ND
16	C10	Capacitor, X7R, ±10%	100nF	Murata Electronics North America	GRM155R70J104KA01D	Digi-Key	490-6319-1-ND
17	C11	Capacitor, X5R, ±10%	1µF	TDK Corporation	C1608X7R1C105M080AC	Digi-Key	445-5131-1-ND
18	C12	Capacitor, X7R, ±10%	100nF	Murata Electronics North America	GRM155R70J104KA01D	Digi-Key	490-6319-1-ND
19	C13	Capacitor, X7R, ±10%	100nF	Murata Electronics North America	GRM155R70J104KA01D	Digi-Key	490-6319-1-ND
20	C14	Capacitor, X7R, ±10%	100nF	Murata Electronics North America	GRM155R70J104KA01D	Digi-Key	490-6319-1-ND
21	C15	Capacitor, X7R, ±10%	100nF	Murata Electronics North America	GRM155R70J104KA01D	Digi-Key	490-6319-1-ND
22	C16	Capacitor, X7R, ±10%	100nF	Murata Electronics North America	GRM155R70J104KA01D	Digi-Key	490-6319-1-ND
23	C17		DNM_0402				
24	C18	Capacitor, X7R, ±10%	100nF	Murata Electronics North America	GRM155R70J104KA01D	Digi-Key	490-6319-1-ND
25	C19	Capacitor, X7R, ±10%	100nF	Murata Electronics North America	GRM155R70J104KA01D	Digi-Key	490-6319-1-ND
26	C20	Capacitor, X5R, ±10%	4.7µF	Kemet	C0603C475K9PACTU	Digi-Key	399-3482-1-ND
27	C21	Capacitor, X5R, ±20%	270nF	Vishay / Vitramon	VJ0805Y274MXXTW1BC	Mouser	77-VJ0805Y274MXXTBC
28	C22	Capacitor, X7R, ±10%	3.9nF	Murata Electronics	GRM155R71H392KA01J	Mouser	81-GRM155R71H392KA1J
29	C23	Capacitor, X7R, ±10%	10nF	Kemet	C0402C103K5RACTU	Mouser	80-C0402C103K5R

PCB Design: Manufacturing and Assembly

- Manufacturing
  - Create the PCB itself
- Assembly
  - Place and solder the components on it
- These stages require machinery and often need to be outsourced to **PCB Fabrication Manufacturers** (fab)
- Cost increases with precision requirements
  - The smaller the costlier



A pick-and-place machine

Image source: Wikipedia

PCB Design: Testing

- PCBs like software may have bugs
  - Hardware revisions may be required

- PCB Fabrication Manufacturers would typically test their products
  - Errors can also be in the design stages

- Types of testing include:
  - Functional testing
  - Performance testing (power measurement)
  - Signal quality testing
  - Mechanical testing
  - Thermal testing
  - Specification verification
  - Safety certification

Electronic Testing Instruments: Multimeter

- Multimeter (Digital Multimeter, DMM)
  - Voltmeter (measures voltage, DC and/or AC)
  - Ammeter (measures current, DC and/or AC)
  - Ohmmeter (measures resistance, beeps when resistance is very low)
  - Other

- Operates at specific ranges

- Ideal for measuring constant values

Image source: Wikipedia

Electronic Testing Instruments: DC Power Supply

- Provides DC electric power
- Output voltage is typically configurable
  - At a specified resolution
- Often come with multiple individually configurable outputs
- Output current can be limited to avoid accidental damage
- Operates at specific ranges

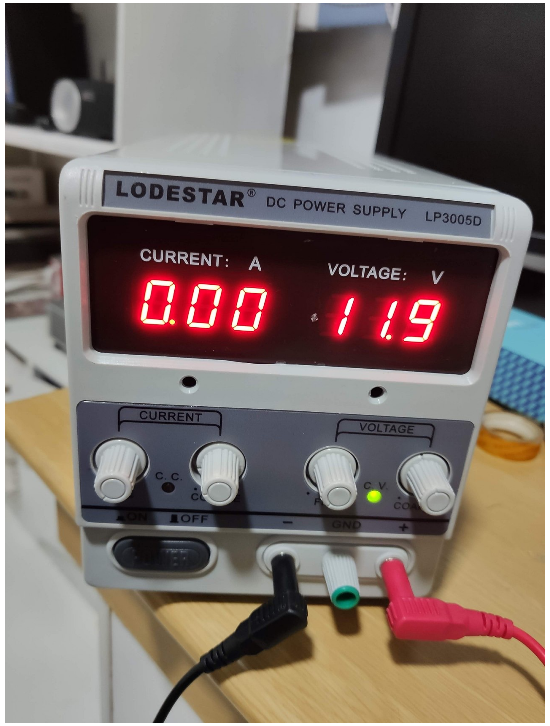


Image source: Wikipedia

Electronic Testing Instruments: Oscilloscope

- Measures and displays voltage signals over time
- Typically multiple voltage signals can be measured and displayed in parallel
- Possible to set triggers for the measurements
- Possible to calculate statistics (min, max), frequency, time duration
- Possible to extract data in a file

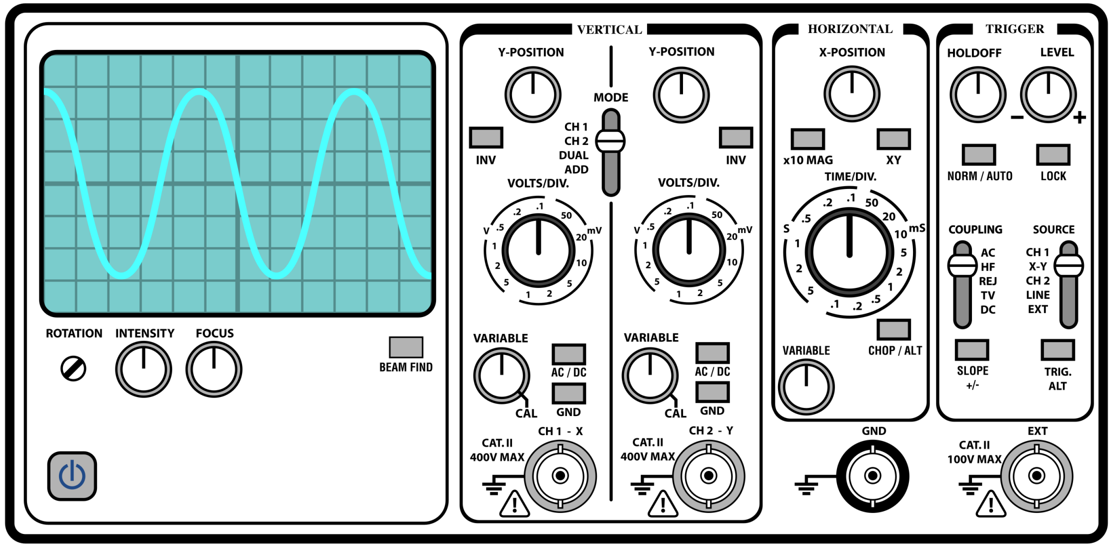


Image source: Wikipedia

Electronic Testing Instruments

- Logic Analyser
  - Captures and displays multiple digital voltage signals
- Spectrum Analyser
  - Measures magnitude of input signal over a frequency range (spectrum)
- Signal/Function Generator
  - Generates signals, such as sine waves, square waves, etc
- Source Measurement Unit (SMU)
  - Supplies power and measure its voltage and current at the same time

Image source: Wikipedia