Electrical Components and Circuits Reference

Jackie Mac Hale

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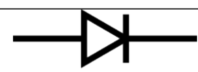
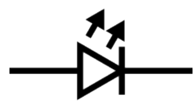
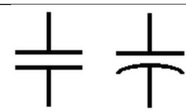
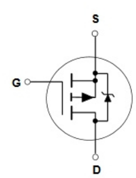
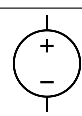
Contents

1 Common Circuit Symbols

Name	Symbol
Ground	
Resistor	
Diode	 
Capacitor	
MOSFET	
Inductor	
Voltage Source	

2 Basic Concepts and Definitions

Physical Quantity	Units	Equations
Time (t)	Second	(SI Unit)
Charge (Q)	Coulomb (C)	(SI Unit)
Current (I)	Ampere (A)	$I = {}^{Q}/_{t}$
Energy (E)	Joule (J)	E $= V \cdot I \cdot t$
Voltage (V)	Volt (V)	V $= {}^{E}/_{Q}$
Power (P)	Watt (W)	P $= {}^{E}/_{t} = V \cdot I$

3 Electricity Basics

Electricity is, as defined by Wikipedia:

> [A] set of physical phenomena associated with the **presence** and **motion** of **electric charge**.

In other words, a flow of **electrical charges**.

3.1 Electric Charge

In short, particles can be positively or negatively charged. **Electric Charge** is a physical property of particles. On an atomic level, charges carried by **electrons** are negative and **protons/nuclei** are positive. Particles with like charges repel each other and particles of opposite charges attract each other.

3.2 Voltage

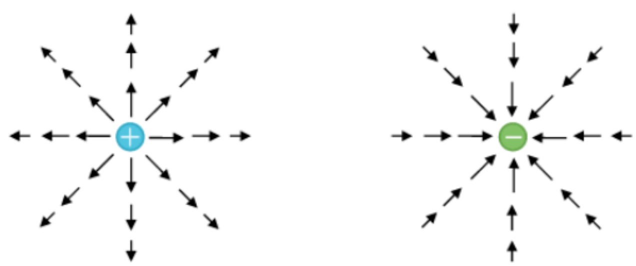


Figure 1: Charged particles create electric fields

Charged particles create electric fields. If a charge is placed in such a field, there exists a potential difference which causes these particles to move.

Voltage is the driving force for electrical applications. It is an **electric field potential difference**. Charged particles naturally move from higher potential to lower potential. The amount of energy required to move from this higher potential to a lower potential is described as electrical potential energy. At any point within an electrical field, the amount of electrical potential energy per unit of charge determines the electric potential, measured in Volts (V). The polarity of voltage does not necessarily matter: charges may flow from 5V to 3.3V and also from -5V to -12V. Charged particles always move if there is a potential difference in place.
We can measure electric potential using the following equation:

Voltage = Electric Potential Energy (in joules)/Charge of Particle (in coulombs)

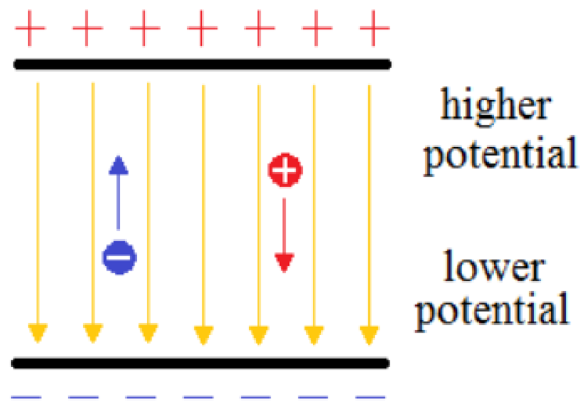


Figure 2: Visual of Electric Potential

3.3 Current

Current is induced when charges flow due to an electric potential.

When a potential difference exists in a circuit, charged particles will flow with a certain speed (called drift speed). The **net flow** of charged particles is called **current(I)**, measured in **Amperes (A)**. By convention, the current direction is **opposite** to the direction of the electron flow. Current is usually induced by voltages, so when there is no voltage, charged particles move randomly so there exists no net flow and thus no current.

3.4 Resistance

Resistance is a measure of the **difficulty for current to pass** through a component, it is measured in Ohms (Ω). The resistance of a component can be calculated by dividing the potential difference (V) across the component by the amount of current (I) passing through it.

Voltage, Resistance, and Current are related through the following equation:

$$\text{Voltage} = \text{Current (I)} \times \text{Resistance (R)}$$

$$V = IR$$

This equation is known as **Ohm's Law**.

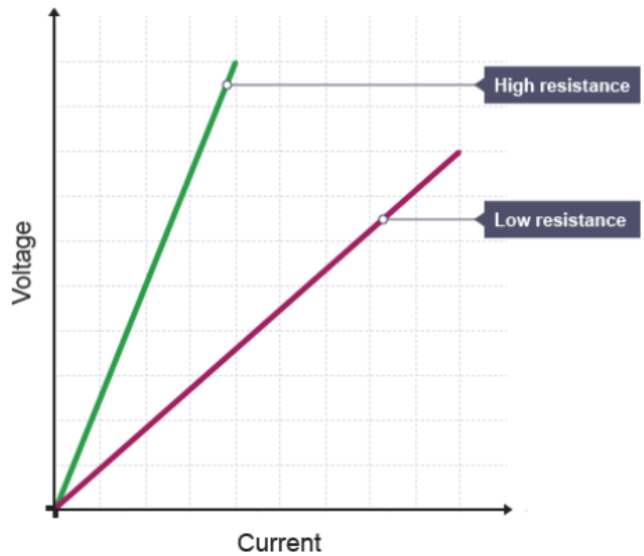


Figure 3: A Voltage vs Current plot. The slope represents resistance.

4 Electrical Components

4.1 Resistor

Resistors are used to reduce current and/or drop voltage.

A **resistor** is a two-terminal **passive** (requires no external energy to operate) component that **resists current flow** between the two terminals. Resistors are used to reduce current flow, adjust signal levels, divide voltage, etc.

Resistors are made of a ceramic material that dissipates electric potential energy by converting it to heat. The voltage drop (reduction in potential energy) across a resistor is calculated by Ohm's Law, $V = IR$.

It is worth noting that in schematics and most analysis, we consider "ideal" wires with no resistance. In real life, all electrical connections have some degree of resistance, as well as capacitance and inductance. Appropriately sized wires should have R, C, and L values small enough to be ignored.

4.2 Capacitor

A **capacitor** is a **passive** two-terminal component that **stores energy in an electric field**. Capacitors are made up of parallel conductive plates, separated by a dielectric material. As current flows into the capacitor, electrons accumulate on the plates, generating an electric field from one to the other. This results in electric potential energy storage. The larger the capacitance (which is noted as C), the more energy a capacitor can store and the longer it takes to

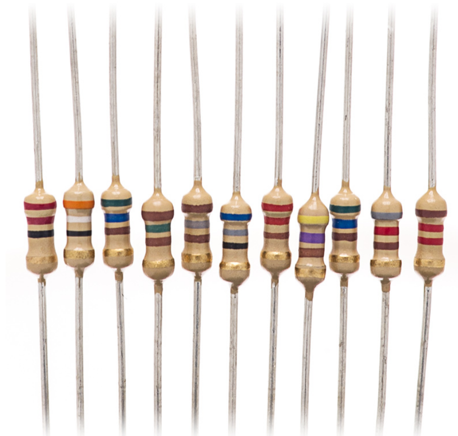


Figure 4: Through-hole resistors come with different resistance values identified by the colored bands

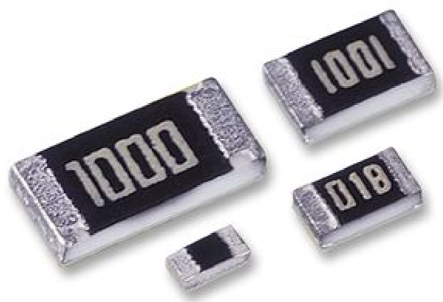


Figure 5: Surface mount resistors are normally used when designing PCBs

charge and discharge.

There are primarily two kinds of capacitors: ceramic and electrolytic. In our scope of application, we need to know that electrolytic capacitors easily obtain high capacitance values with low cost and electrolytic ones are usually much larger compared to ceramics, so most capacitors on Printed Circuit Boards (PCBs) are ceramic. Electrolytic capacitors have polarity, so when inserting them into circuits, the positive terminal of the component must be connected to a higher potential than the negative terminal.

Capacitors act as energy sources when discharging, so they're often placed in parallel with voltage sources to maintain voltage levels during sudden load changes to maintain a stable power source. This application is known as "decoupling capacitance."

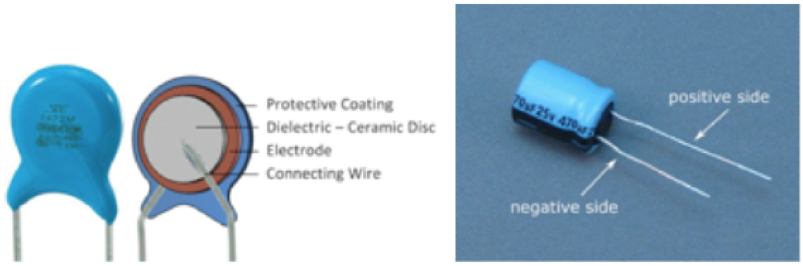


Figure 6: Ceramic (left) and electrolytic capacitor (right).

4.3 Inductor

An **inductor**, is a **passive** two-terminal component that stores energy in a **magnetic field**. The property of inductors is Inductance, noted with L.

Unlike a Capacitor which opposes a change of voltage across their plates, an inductor opposes a change of current flowing through it due to the build up of an opposing magnetic field. In other words, inductors resist or oppose changes of current but allow a constant current. As a result, they can help smooth sudden current spikes in the circuit as it stores current temporarily. They are commonly used in power supplies for this reason.

Many useful electromechanical components (such as relays, motors, and solenoids) contain electromagnetic coils. Therefore they can be modeled as inductors for the purpose of circuit design.

4.4 Diode

In short, a diode allows current flow in one direction.

A **diode** is a two-terminal **passive** component that conducts current primarily in **one direction**. It ideally has zero resistance in one direction and infinite resistance in the other. In order for the diode to start operating in forward-bias mode, there has to be a threshold voltage across the diode (typically 0.7V). After this the diode will conduct electricity freely.

A common diode is the **Light Emitting Diode (LED)** that **emits light** when current passes through it. When designing an LED circuit, one must consider the maximum current the diode can handle and add a resistor if needed, or the LED could burn up from too much current. Below is an example of an LED circuit.

The value of R depends on the voltage applied and the type of LED and can be found from Ohm's Law.

Diodes have many applications for reverse polarity protection (preventing

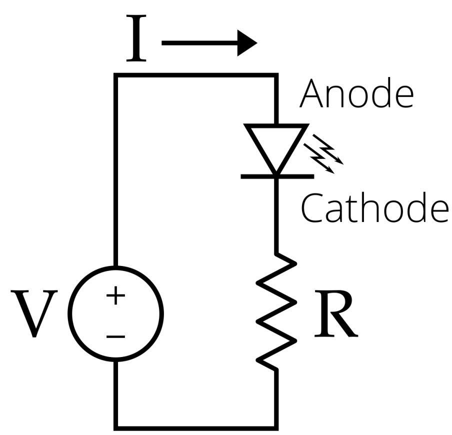


Figure 7: LED Circuit.

current from flowing if the circuit is plugged in backwards) and voltage source protection (preventing current from flowing from one source to another). LEDs are used for indication and signaling of power levels, statuses, or faults.

Most diodes have a maximum **reverse voltage**: the breakdown voltage. Any higher than this voltage, and the diode will break down unless it is a **zener diode**, specifically designed to be reversible.

4.5 Transistor

In short, transistors are **electronic switches**.

There are primarily two types of transistors: Bipolar Junction Transistors (BJTs) and Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs).

4.5.1 Bipolar Junction Transistor

BJTs have three terminals, a Base, a Collector, and an Emitter. In a BJT, the current flow into the base determines the amount of current that can flow between the Collector and Emitter. For NPN BJTs, a current flowing into the base allows a larger current to flow between the Collector and Emitter. For PNP BJTs, a current flowing out of the base allows a large current to flow from the Emitter to the Collector.

4.5.2 MOSFET

In contrast to BJTs which operate based on current, MOSFETs operate based on voltage. MOSFETs come in two types: N-type and P-type, which are analogous to NPN and PNP BJTs. MOSFETs have a parameter called threshold voltage (V_{th}).

For an N-Type MOSFET, a large voltage (greater than V_{th}) between the Gate and the Source results in the formation of a low-resistance channel, allowing current to flow from Drain to Source. For a P-Type, a small voltage (less than V_{th}) between the Gate and Source results in current flow from the Source to the Drain.

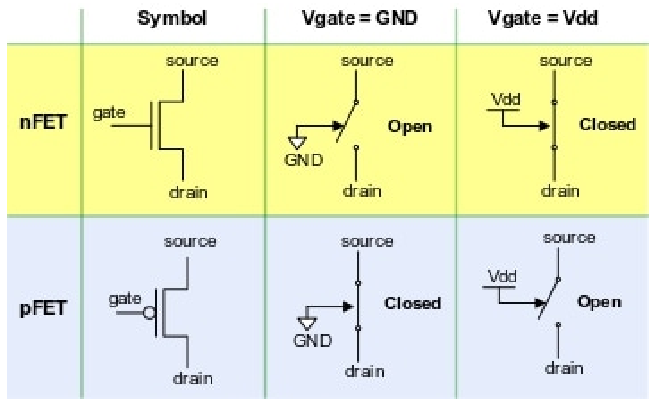


Figure 8: Function of transistors based on gate logic levels

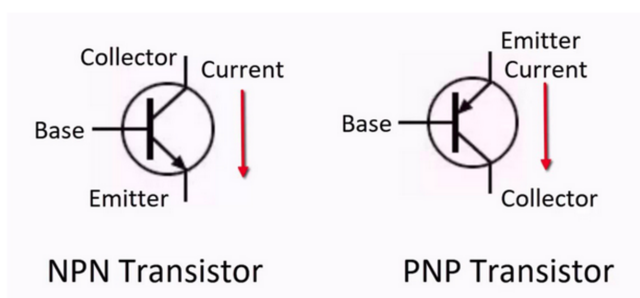


Figure 9: Transistor terminals and direction of current flow

4.6 Fuse

A **fuse** is a component that is designed to fail when there is **too much current** passing through it. When placed in series with your circuit, it is a safety device as it prevents over current.

Blown fuses alert you that there's excessive current, implying either:

1. A component is broken or operating in an unsafe region
2. The circuit must be redesigned taking into account maximum ratings

5 Circuit Analysis

A circuit with components in **series** has all of its components on the same "path" whereas a circuit with its components in **parallel** has all of its components on different "paths."

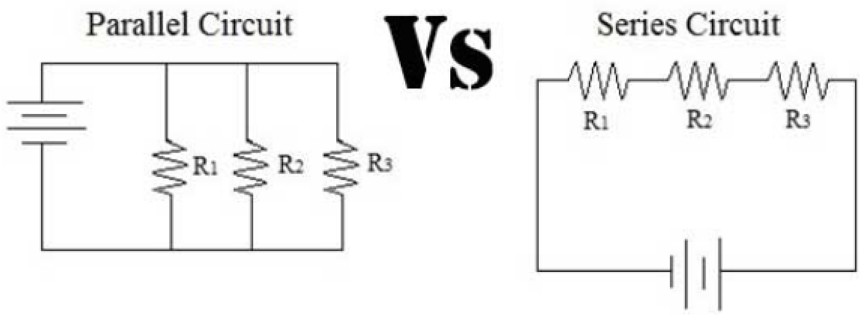


Figure 10: Example of resistors in parallel or series

5.1 Series Circuit Component Formulas

$$
\begin{gathered}
R_{total} = R_1 + R_2 + R_3 + \cdots + R_i \\
\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots + \frac{1}{C_i} \\
C_{total} = \frac{1}{\sum_i {}^{1}/{C_i}} \\
L_{total} = L_1 + L_2 + L_3 + \cdots + L_i
\end{gathered}
$$

5.2 Parallel Circuit Component Formulas

$$
\begin{gathered}
\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_i} \\
R_{total} = \frac{1}{\sum_i {}^{1}/{R_i}} \\
C_{total} = C_1 + C_2 + C_3 + \cdots + C_i \\
\frac{1}{L_{total}} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \cdots + \frac{1}{L_i} \\
L_{total} = \frac{1}{\sum_i {}^{1}/{L_i}}
\end{gathered}
$$

5.3 Further Reading

Capacitors - learn.sparkfun.com
Characteristics of the Ideal Silicon Diode - Technical Articles

6 Circuit Basics

6.1 Kirchoff's Laws

Kirchhoff's Current Law is that the sum of current flowing into a node (or a junction) must be equal to the sum of current flowing out of it. Kirchhoff's Voltage Law is that the algebraic sum of the voltage (potential) differences in any closed circuit must equal zero.

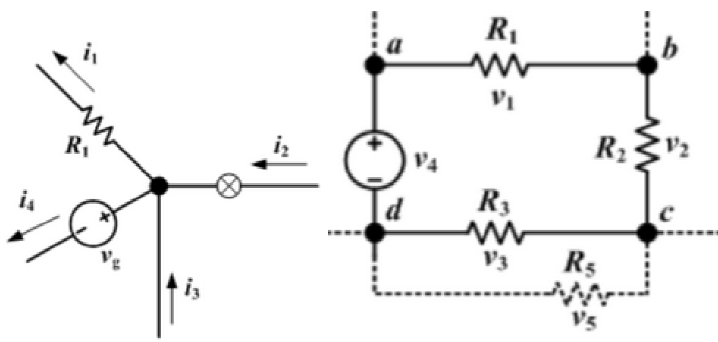


Figure 11: Kirchoff's junction and loop laws

As defined by Kirchhoff's law, in the left diagram $i_2 + i_3 = i_1 + i_4$; in the right figure, $v_1 + v_2 + v_3 + v_4 = 0$

6.2 Breadboard

In short, a **breadboard** is a device allowing you to **prototype** circuits.

It offers the ability to let you connect circuits by directly plugging them into it, saving you the effort of making a PCB.

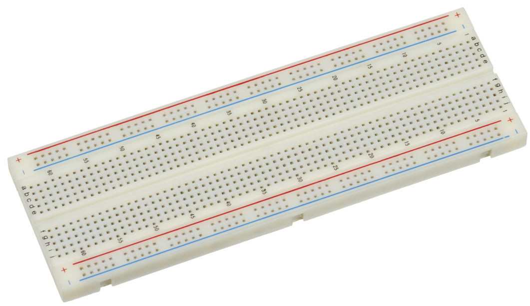


Figure 12: A Breadboard

7 Common Circuit Designs

7.1 Voltage Divider

The goal of a voltage divider is to reduce the voltage in your circuit. The input voltage is distributed among the two resistors shown below, with the output voltage emerging from the connection between the resistors and the second resistor being connected to ground.

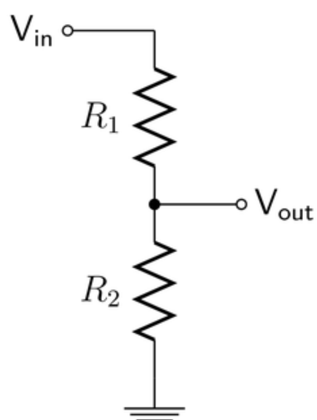


Figure 13: A voltage divider circuit.

To calculate the output voltage of the circuit, the following formula can be used.

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

7.2 High/Low Side Switch

One use of a transistor is to allow a low voltage signal to control power flow in another circuit. Low and High Side switches are two designs used to switch a load on and off, based on the voltage of the transistor's gate. These circuit designs are shown in Figure 14.

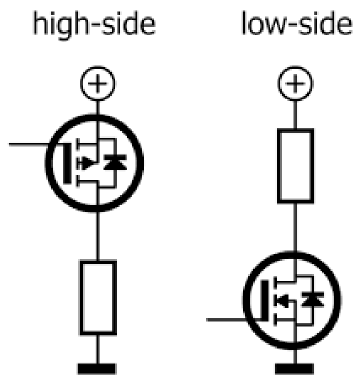


Figure 14: A high-side switch, using a PFET, and a low-side switch, using an NFET

In a Low-side switch, an N-type transistor is wired in series **after** the load. Sending a High signal ($V > V_{th}$) allows current to flow through the transistor and powers the load.

The opposite works for the high-side switch, which uses a P-type transistor wired **before** the load. Sending a Low signal ($V < V_{dd} - V_{th}$) allows current to flow.

Low-side switches are more common (and often preferred) since the input voltage range must only swing between 0 and V_{th}. For a High-side switch, the voltage must swing between V_{dd} and $V_{dd} - V_{th}$. If V_{dd} is large (e.g. 24V), a small signal (e.g. 0-3.3V) would not be able to switch a high-side circuit. Additionally, N-type MOSFETs are easier to manufacture, so these circuits are lower cost.

7.3 Pull Up/Pull Down Resistor

In a digital logic circuit, there must only be a Low state (GND or 0) or a High state (Vcc or 1) and a Pull-Up and Pull-Down resistor ensures this.

In figure 15 for a Pull-Up Resistor, we see a +5V source, resistor, ground, switch, and an input to a microcontroller. When the switch is opened, the 5V source provides an input current to the microcontroller which is a logic of 1. When the switch is closed, the resistor causes a small amount of current to flow to ground thus making the microcontroller input a logic of 0.

A similar process applies to a Pull-Down Resistor as well. When the switch is closed in this circuit, the input of the microcontroller with get 5V or a logic

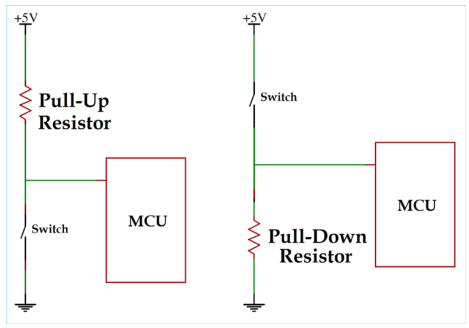


Figure 15: Pull up and pull down resistors on a Microcontroller's input pins

of 1. When it is open, it receives a logic 0.

Note, if we didn't have the resistor in these circuits, the 5V source would be directly connected to ground without any resistance and this will end up shorting the circuit which we never want to do.

8 Decoupling/Bypass Capacitor

In short, a decoupling capacitor's job is to suppress high-frequency noise in power supply signals.

Many electronics use decoupling capacitors to make sure the chip is not subjected to any big dips or spikes in voltage. Decoupling capacitors are used between the power source and ground as shown in the figure below. It is quite common to use more than one capacitor to bypass the power supply.

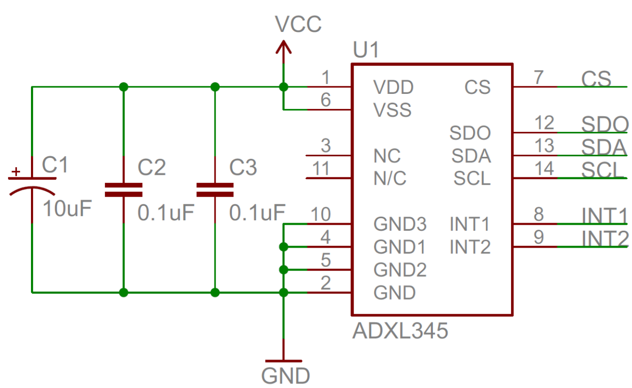


Figure 16: Decouling Capacitors used for an IC. Source: Sparkfun.com