Hardware Engineering and PCB Design

Session 1

Hardware Team Training

Aquaphoton Academy - 2024

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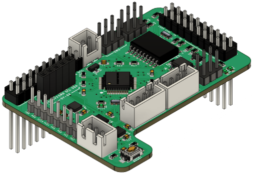
What is a PCB and why we use it?

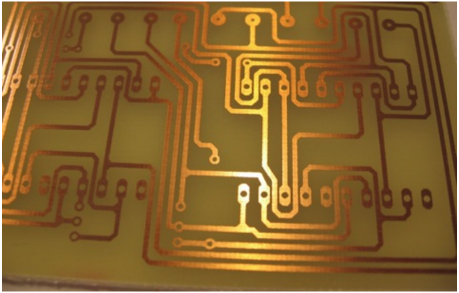
PCB is short for Printed Circuit Board. In simple terms, it's a piece of plastic (substrate) sandwiched between two or more copper layers with holes (or pads) in them. These copper layers are drawn in a way to act as wires (traces) connecting between different components, mounted on the PCB.



Back in the day, people connected their circuits using wires. This was a mess as it resulted in very complex and overlapping connections, difficulty in troubleshooting problems and the inability to design more complex circuits.

Circuit connections using wires

PCBs allowed us to use thin copper layers and traces in place of wires, so that the whole construction is planar, not taking much space and easier to create more complex circuits and troubleshoot them.

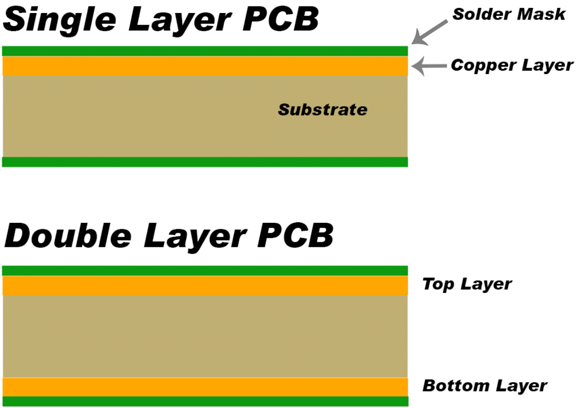


Types of PCBs

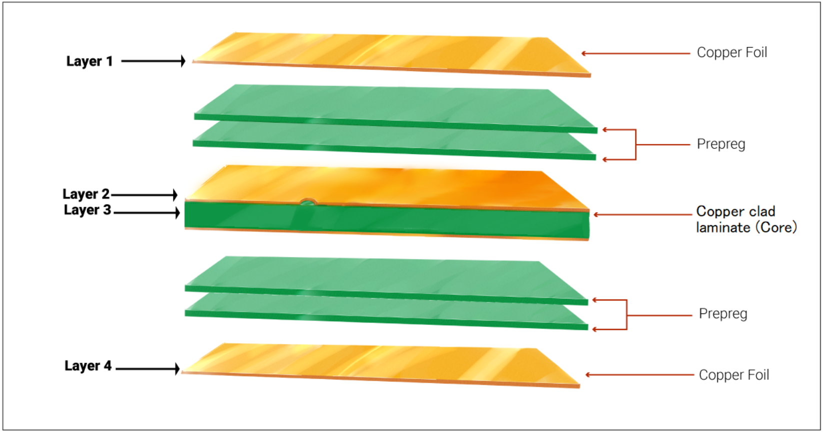
There are several types of PCBs when classifying them according to copper layers.

1. Single Layer PCBs
   - Have a single layer of copper on top of a dielectric (non-conductive) material.
2. Double Layer PCBs
   - Have 2 layers of copper on the top and bottom, and the dielectric material is sandwiched between them.
3. Multilayer PCBs
   - Have top and bottom copper layers, with more layers between them (in even numbers) separated by several dielectric layers.

Single and double layer PCBs



Multilayer (4-layer) PCB



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Types of components

There are two types of components when classifying them according to their "mount" type. The mount type defines how the component is mounted (placed) on the PCB.

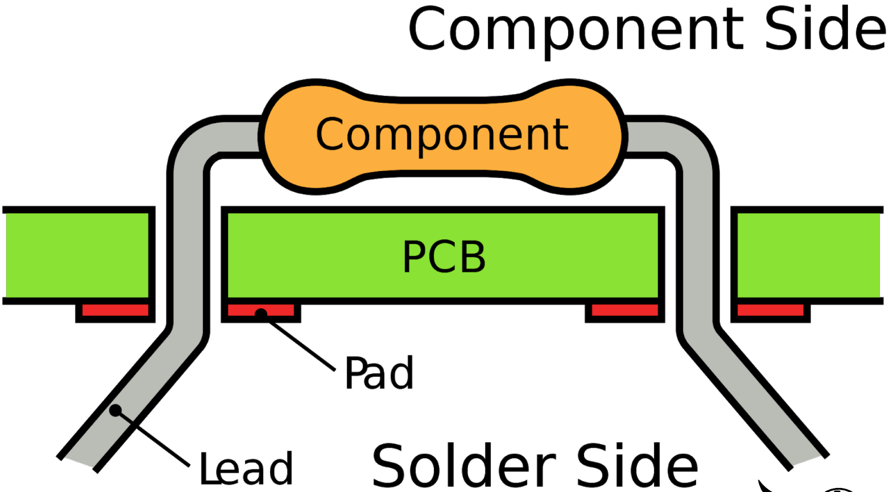
Types of components

- Through-hole (THT) components
  - Through hole components are what came first when PCBs were made.
  - They're called "through-hole" because each component has one or more long leads that go "through" the PCB, then get soldered on the other side.
  - They are easier to hand assemble. However, they have a few disadvantages:
    - They are more difficult to be assembled by machines, which makes their assembly more expensive in mass production.
    - They take up more space in the PCB due to their relatively large sizes and the fact that they are mounted on one side and soldered on the other.

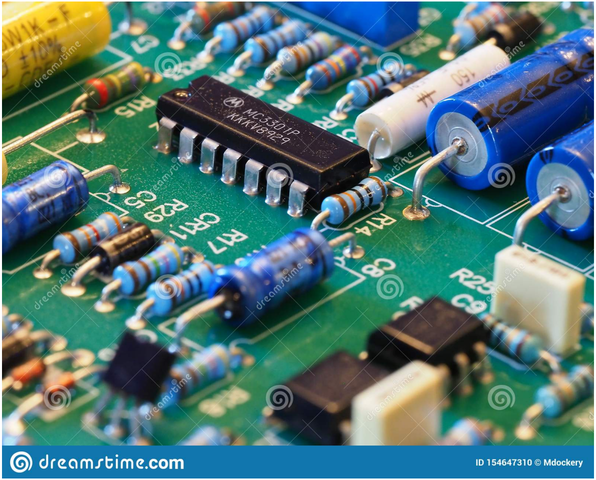
Types of components

- Surface mount (SMD) components
  - They are the more-modern component type which came after THT.
  - As their name implies, they are mounted on the surface of the PCB, meaning they don't have long leads like through hole components.
  - They are harder to hand-assemble. However, they're easier to be assembled by machines which makes them the best choice for mass production.
  - They take up much less space due to their inherently small sizes and the fact that they only take space in the layer they're placed in.
  - Nowadays, SMD components are usually less expensive than their THT counterparts.

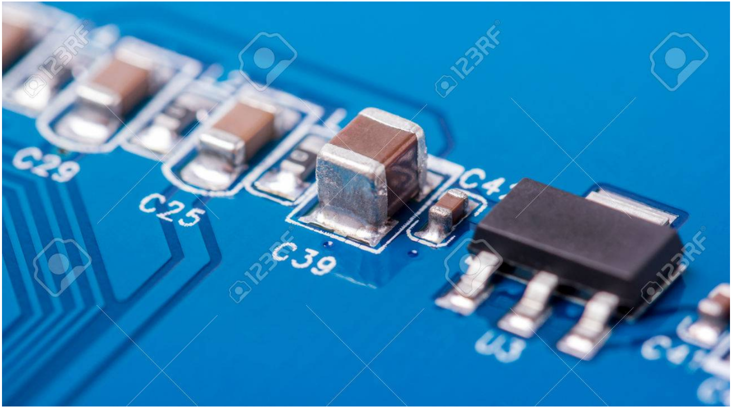
Through-Hole components



Through-Hole components



Surface Mount components



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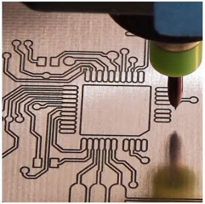
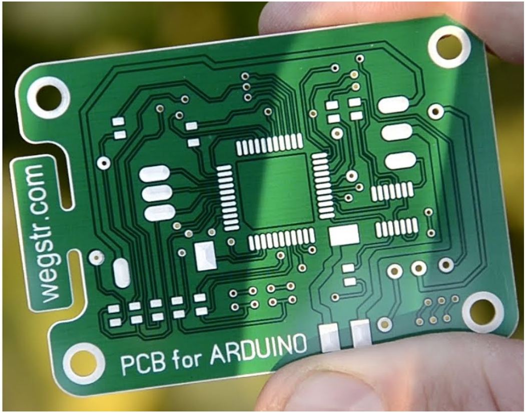
The 3 main layers (layer types)

Each professionally produced PCB should have 3 main layer types:

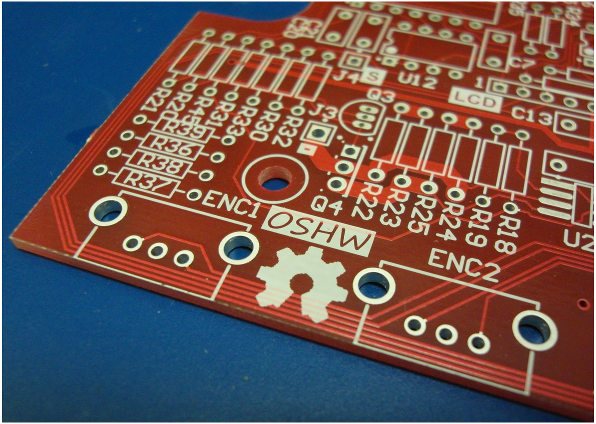
1. Copper Layers
   - Copper layers are the most important layers in a PCB.
   - They contain the pads, on which the components are soldered, and the traces which connect them together.
2. Solder mask
   - Solder mask is a varnish-like layer of polymer, which is placed on top of the copper to protect it from oxidation.
   - Its most famous color is green, but it can come in many colors.
3. Silkscreen
   - The silkscreen is a layer of ink placed on both sides of the PCB to identify components, component outlines or even the company logo.

PCB before and after solder mask





Silkscreen



R36
R38
R37
ENC1
OSHW
J3
J4
U12
Q3
LCD
C13
C7
Q4
R22
R23
R25
R24
R19
R18
ENC2

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Passive components and schematic symbols

The three main passive components used in any circuit are **Resistors**, **Capacitors** and **Inductors**.
Each one of them (or any other component) have a unique symbol in schematic which indicates it.

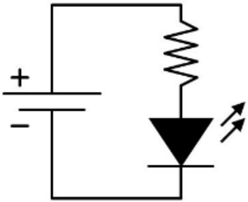
Resistor

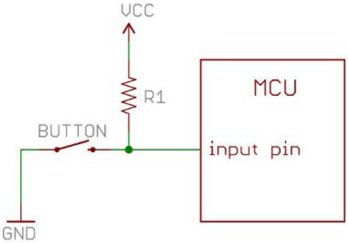
Inductor

Capacitor

Applications on resistors

1. Current limiting
2. Voltage divider
3. Pullup/Pulldown





Applications on capacitors

Due to their tendancy to resist sudden changes in voltage, capacitors can be used for **filtering** ripple voltages in say, a power supply or a rectifier, or as **decoupling** capacitors.
Decoupling capacitors are the ones often placed near the power pins of ICs to **decouple** them from the rest of the circuit by providing a stable DC voltage to the IC.

Applications on inductors

Just like capacitors resist sudden changes in voltage, inductors resist sudden changes in **current**, that's why they're essential in switched-mode power supplies (like smartphone chargers) to provide a smooth current waveform to the device.
There also exists a special type of inductor called **ferrite bead** which is used to suppress high frequency noise in electronic circuits.

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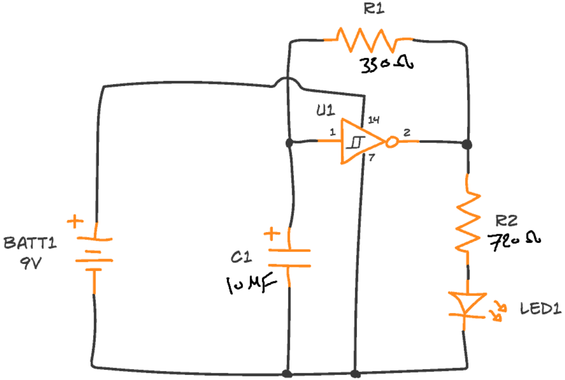
What is a schematic?

A schematic is a type of engineering drawing which represents a circuit using easy to draw symbols instead of realistic shape of the components. A schematic consists of 4 main elements. Seeing the following example of a schematic, can you spot what the 4 elements are?

Schematic example



Schematic main parts

From the previous schematic, we can see that any schematic consists of 4 main parts:

1. Components (symbols)
2. Nets (connecting components with each other)
3. Values
4. Reference designators ex. C1, R2...etc

What is a reference designator?

A reference designator is usually made up of one or two letters followed by a number, it indicates with type of component is it and it's place in the schematic/PCB There are more benefits to having properly managed reference designators on your PCB, but that will be left for you to figure out. When in doubt about which designator is the correct one for your component, you can always refer to the IEEE/ANSI 315-1975 standard.

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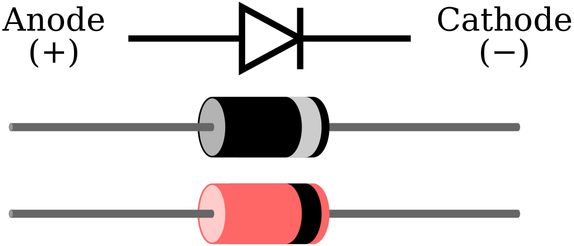
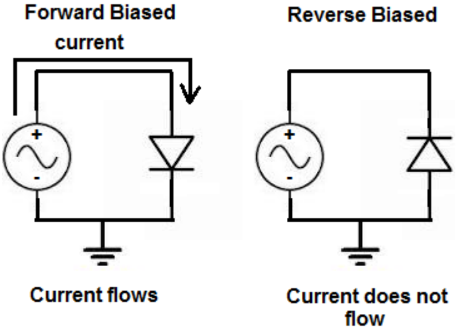
What is a diode?

A diode is a special component which lets current flow only in one direction, but not the other. Much like a fluid check valve.



Diode modes

When the *anode* of the diode is connected to the positive terminal of the DC source, and the *cathode* to the negative terminal, the diode is said to be **forward biased**, meaning it permits the flow of current. If however the terminals are swapped, the diode is said to be **reverse biased**, which is does not permit the flow of current.



Application 1: LEDs

A very famous and important application of diodes, which I'm sure you're all familiar with, are LEDs. **LED** stands for **L**ight **E**mitting **D**iode, It's a special type of diode which emits light when it is forward biased.

Now that we have an idea what a diode is, and are familiar with an application on it. Let's get back to the diode characteristics to be able to figure out more applications and their trade-offs.
In the next slide, we'll be discussing important parameters we should be looking for when choosing a diode. And what better place to look at component characteristics than it's own **datasheet**!
A **datasheet** is a document made by the manufacturer of the component, which specifies all of it's parameters, performance characteristics and even mechanical properties. We'll be looking into the datasheet of a jellybean[1] diode, which is the 1N4007.

[1] A jellybean-part is a term often used by electronics engineers, to describe a component which is popular and can be easily replaced by a similar one, often from different manufacturers.

The 1N4007 datasheet: The main page

When looking at the first page of most datasheets, you'll be greeted with a small summary which describes the main features/characteristics of this component.

The 1N4007 datasheet: The main page

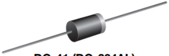
1N4001, 1N4002, 1N4003, 1N4004, 1N4005, 1N4006, 1N4007

VISHAY.

www.vishay.com

Vishay General Semiconductor

General Purpose Plastic Rectifier



DO-41 (DO-204AL)

FEATURES

- Low forward voltage drop
- Low leakage current
- High forward surge capability
- Solder dip 275 °C max. 10 s, per JESD 22-B106
- Material categorization: for definitions of compliance please see www.vishay.com/doc?99912

Pb

e3

RoHS COMPLIANT

PRIMARY CHARACTERISTICS	
$I_{F(AV)}$	1.0 A
V_{RRM}	50 V, 100 V, 200 V, 400 V, 600 V, 800 V, 1000 V
I_{FSM} (8.3 ms sine-wave)	30 A
I_{FSM} (square wave t_p = 1 ms)	45 A
V_F	1.1 V
I_R	5.0 μA
T_J max.	150 °C
Package	DO-41 (DO-204AL)
Circuit configuration	Single

TYPICAL APPLICATIONS

For use in general purpose rectification of power supplies, inverters, converters, and freewheeling diodes application.

MECHANICAL DATA

Case: DO-41 (DO-204AL), molded epoxy body
Molding compound meets UL 94 V-0 flammability rating
Base P/N-E3 - RoHS-compliant, commercial grade

Terminals: matte tin plated leads, solderable per J-STD-002 and JESD 22-B102
E3 suffix meets JESD 201 class 1A whisker test

Polarity: color band denotes cathode end

What to look for in a diode's datasheet

The following are perhaps the most important diode parameters we should look for first, for basic applications:

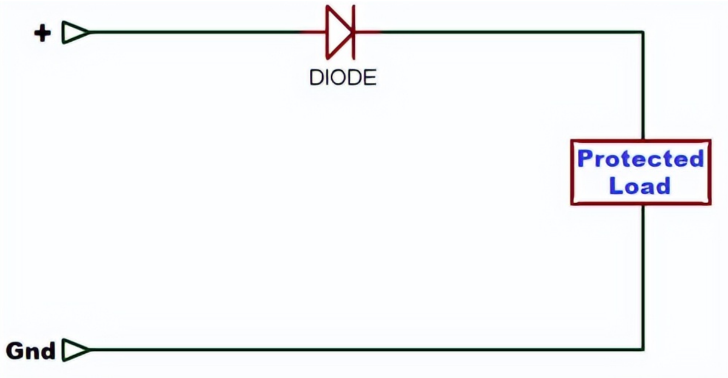
- I_F **(forward current)** is the maximum current a diode can withstand when forward biased.
- V_F **(forward voltage)** is the voltage drop across the diode in forward bias mode.
- V_{RRM} **(maximum repetitive reverse voltage)** is the maximum voltage a diode can withstand in repeated pulses, when reverse biased.

Thankfully, the three parameters were listed in the dataheet's first page.

Application 2: Reverse polarity protection

As we all know, most electronic circuits and ICs do not tolerate reverse polarity (plugging your supply backwards). So if you've ever been unfortunate to do that, you'll find that your component burns, releasing the magic smoke. To solve this issue, we could simply connect a diode in series with our circuit, so that it only permits the flow of current in the correct direction. However, if we connect the supply the wrong way, the diode is reverse biased and no current passes. It's that simple, **right**?

Application 2 Illustration: Reverse polarity protection

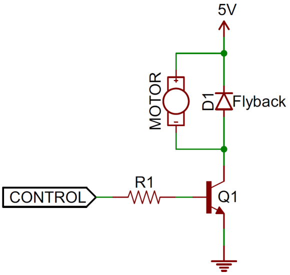


Application 2 Observations: Reverse polarity protection

Now our circuit is protected from reverse polarity. However, there's a little trade-off.
Let's do some calculations:
We know that $P = VI$, which is the power dissipated through the diode.
Assuming that our device draw a current of 1A, and we already know that the forward voltage of the diode is 1.1V, by plugging our numbers in the previous equation we can see that the power dissipated through the diode equates to **1.1 Watts**! This is a huge power loss. That, in addition to other problems like voltage drop on the load, makes the **series diode** method a not-so-good option for reverse polarity protection.

Application 3: Back-EMF protection

As we discussed briefly in the interviews, when an inductive load (like a motor) is suddenly switched off, a huge **back-emf** is generated across its terminals, which might result in the transistor blowing up. That's why we need to place a **flyback diode** in reverse to the supply. This phenomenon is also called **inductive kickback**.



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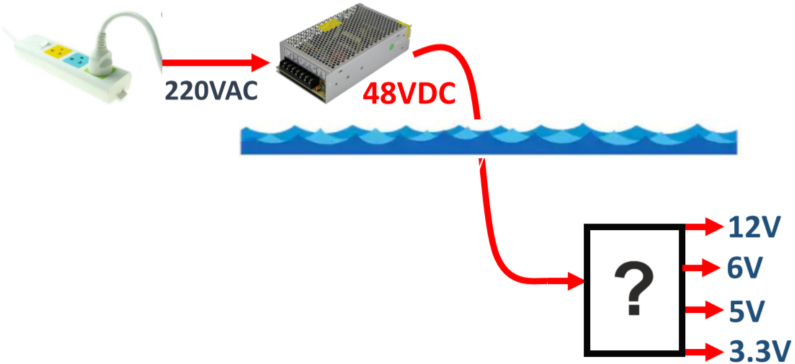
What is voltage regulation?

Voltage regulation is the practice of getting a fixed voltage output from a power source, irrespective of the attached load or its characteristics. So why do we need voltage regulation?
Voltage regulation is necessary as most electronic circuits or ICs work with a specified fixed voltage, like 5V or 3.3V.
So what should we do if our power supply only outputs 48V? That's what we'll figure out next.

Problem illustration



DC step-down methods

DC step-down is the practice of obtaining a smaller voltage, like 5V from a voltage source of higher potential, like 48V.
There are several ways to do that, each with its own advantages and disadvantages, among them are:

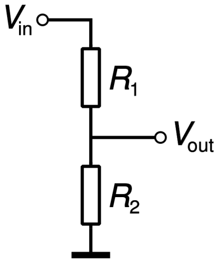
- Voltage (resistor) dividers
- Zener diodes
- Linear voltage regulators
- Switched-mode step-down converters (buck converters)

In the next slides we are going to discuss only some of them.

Voltage divider method

Voltage dividers are perhaps the simplest method to step down voltage. It's simply a couple of resistors connected in series, so voltage is divided among them. The output of the voltage divider is calculated using the following formula:

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



Pros and cons of the voltage divider method

- Simple and cheap.
- Output voltage is not fixed (dependent on the load).
- Output current is limited.
- Power loss as heat $V = \frac{V^2}{R}$

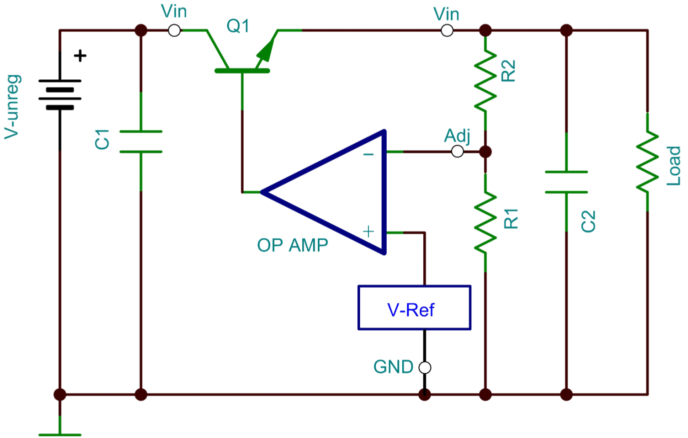
The previous disadvantages make the voltage divider method a bad choice for voltage regulation. However, it could be useful for other applications.

Linear voltage regulators

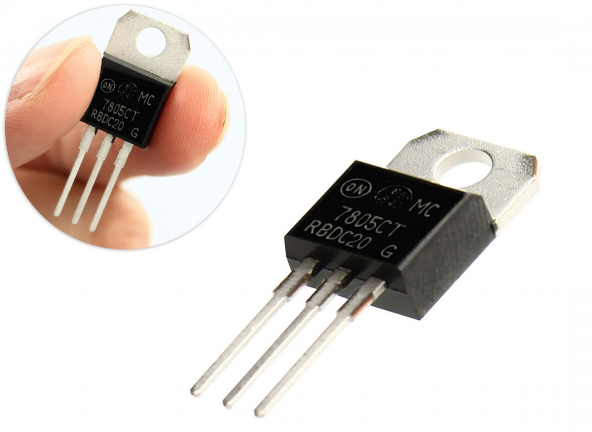
Unlike voltage dividers which use only passive components, a voltage regulator is an integrated circuit (IC) which has what's called a *feedback network* inside it. The feedback network feeds the output voltage back to the IC to monitor it, compare it to a voltage reference[2] and adjust the output voltage accordingly to keep it fixed irrespective of the load.

[2] A voltage reference is an electronic component which outputs a fixed DC voltage irregardless of the external conditions. However, they can't replace voltage regulators

Simplified schematic of linear regulators



7805 regulator in real life



Before discussing the pros and cons of using a linear voltage regulator, first let's dive into the datasheet of one of them. For that, we'll be looking into the datasheet of a jellybean voltage regulator family called *78XX*, where the XX denotes the output voltage.
e.g. 7805

The 78XX regulator datasheet: The main page

When we look at the first page of the 78XX regulator datasheet, we'll be greeted with the main features of this device as usual. In addition to that, we'll see different package options for this IC. A package is how the actual IC looks like in real life. There exist different standard packages for ICs, each with it's own dimensions and shape.

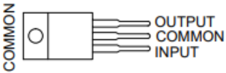
The 78XX regulator datasheet: The main page

µA7800 SERIES
POSITIVE-VOLTAGE REGULATORS

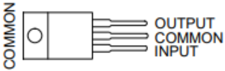
SLVS056J – MAY 1976 – REVISED MAY 2003

- **3-Terminal Regulators**
- **Output Current up to 1.5 A**
- **Internal Thermal-Overload Protection**
- **High Power-Dissipation Capability**
- **Internal Short-Circuit Current Limiting**
- **Output Transistor Safe-Area Compensation**

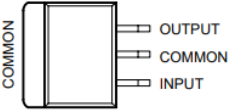
KC (TO-220) PACKAGE
(TOP VIEW)



KCS (TO-220) PACKAGE
(TOP VIEW)



KTE PACKAGE
(TOP VIEW)



Important parameters of a voltage regulator

Going forward, we need to know what to look for in a linear regulator's datasheet. There are a few important parameters we need to look for first before deciding to use any regulator, like we did for the diode. There parameters include:

- Input voltage range.
- Output voltage range.
- Output current.
- Dropout voltage.
- Thermal resistance.

Input voltage and output current

Both input voltage range and output current can be found in the *recommended operating conditions* table in the datasheet. The input voltage range is the range we need to keep in order for the regulator to maintain regulation. While the output current is the maximum current we can draw from this regulator.

			MIN	MAX	UNIT
V_I	Input voltage	µA7805C	7	25	V
		µA7808C	10.5	25	
		µA7810C	12.5	28	
		µA7812C	14.5	30	
		µA7815C	17.5	30	
		µA7824C	27	38	
I_O	Output current			1.5	A

Output voltage and dropout voltage

Both the output voltage range and dropout voltage can be found in the *electrical characteristics* table in the datasheet, among other parameters. **Output voltage range** is necessary for us to make sure that this regulator complies with the operating conditions of the circuit that we need to power, while **dropout voltage** is the minimum differential voltage required between the input and the output $(V_{in} - V_{out})$ in order for the regulator to maintain regulation.

Electrical characteristics

PARAMETER	TEST CONDITIONS	T_J†	µA7805C MIN	µA7805C TYP	µA7805C MAX	UNIT
Output voltage	I_O = 5 mA to 1 A, V_I = 7 V to 20 V, $P_D \leq$ 15 W	25°C	4.8	5	5.2	V
		0°C to 125°C	4.75		5.25	
Input voltage regulation	V_I = 7 V to 25 V	25°C		3	100	mV
	V_I = 8 V to 12 V			1	50	
Ripple rejection	V_I = 8 V to 18 V, f = 120 Hz	0°C to 125°C	62	78		dB
Output voltage regulation	I_O = 5 mA to 1.5 A	25°C		15	100	mV
	I_O = 250 mA to 750 mA			5	50	
Output resistance	f = 1 kHz	0°C to 125°C		0.017		Ω
Temperature coefficient of output voltage	I_O = 5 mA	0°C to 125°C		–1.1		mV/°C
Output noise voltage	f = 10 Hz to 100 kHz	25°C		40		µV
Dropout voltage	I_O = 1 A	25°C		2		V

Thermal characteristics

Next, we need to look into *thermal characteristics* of the regulator, which include the **thermal resistance** we said we needed to know and the **operating temperature** of the IC. Thermal resistance is a measure of how hot our regulator will get with each watt of power dissipated through it.

Symbol	Parameter		Value	Unit
V_I	Input Voltage	V_O = 5 V to 18 V	35	V
		V_O = 24 V	40	
$R_{\theta JC}$	Thermal Resistance, Junction-Case (TO-220)		5	°C/W
$R_{\theta JA}$	Thermal Resistance, Junction-Air (TO-220)		65	°C/W
T_{OPR}	Operating Temperature Range	LM78xx	-40 to +125	°C
		LM78xxA	0 to +125	
T_{STG}	Storage Temperature Range		- 65 to +150	°C

Temperature calculations

To calculate the temperature of our regulator we need to use the following formula:

$$T = T_a + (R_{\theta JA} * P)$$

Where T_a is the ambient temperature, $R_{\theta JA}$ is the junction-to-air thermal resistance (from the datasheet), and P is the power dissipated through the regulator.

Temperature calculation

Assuming the following operating conditions:

- Input voltage = 20V.
- Output voltage = 5V.
- Output current = 1A.
- Ambient temperature = $25^{\circ}C$

And we already know from the datasheet that $R_{\theta JA} = 60\ ^{\circ}C/W$.
By calculating the voltage drop $(V_{in} - V_{out}) = 15$V.
Power dissipated $= VI = 15 * 1 = 15$W.
We can now calculate the temperature using the previous equation $(T = T_a + (R_{\theta JA} * P))$, $25 + 60 * 15 = 925^{\circ}C$!

Temperature problem

$925^{\circ}C$ is definitely enough to burn our IC having an operating temperature of $125^{\circ}C$!
So how de we solve this?
Above the $R_{\theta JA}$ we used, we'll find another parameter $R_{\theta JC}$ called junction to case thermal resistance. By redoing our calculations with this new number $25 + 5 * 15 = 100^{\circ}C$, so our problem is solved!
But what is *junction to case thermal resistance*?
It is the thermal resistance if we're going to attach a heatsink to our IC!

Heatsinks

A heatsink is a type of heat exchanger made up of metal (usually Aluminum or Copper) which transfers the heat from your IC to a fluid medium, like air. The heatsink is designed to allow a larger surface area for heat dissipation. a special type of paste called *thermal paste* is also attached between the heatsink and the IC, to maximize thermal efficiency.

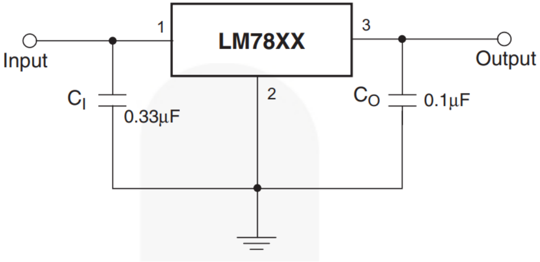
Pros and cons of linear regulators

After our little adventure with the datasheet and parameters of the 78XX linear voltage regulators, we can come to a conclusion about the advantages and disadvantages of using one in our projects.

- Cheap and simple to use.
- Provides clean output with small ripples.
- Can't handle high currents.
- Power loss is proportional to the voltage drop across it, making it inefficient unless you'll only draw a few milliamps of current.

Using linear regulators

Using linear regulators in our circuit is pretty straight forward. Even better, by referring to the product's datasheet, you can often find what's called a *reference schematic* which is a schematic that's already tried and tested so you can use it directly.



Brief summary on buck converters

The buck converter is the more efficient brother of the linear voltage regulator. They work with a different principal, we're not going to discuss them in details as this is outside the scope of this session. A few things to know about buck converters are:

- They are more efficient.
- Can handle higher currents.
- More complex to implement and need external components.
- More expensive.
- Have higher output ripple than linear regulators.

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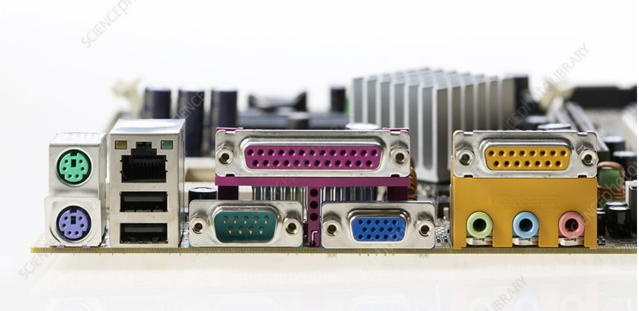
What are connectors?

Connectors are components that allow us to connect external things to our PCB, of vice versa.

e.g. the charging connector on our phone



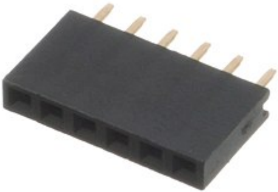
Famous connectors: The terminal block

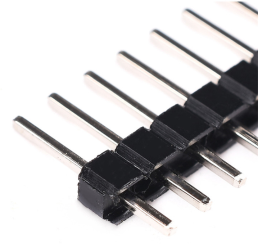
One of the most famous connectors in electronics is the terminal block. It comes in many shapes, sizes and number of terminals and is used to connect wires to our PCB.

First the wires are inserted into their openings, then they're fixed in place by tightening the screws of the connector.

Famous connectors: The pin headers

Pin headers are those black connectors you see on an Arduino board. They exist in both male, female, straight and bent variants and even more. They're usually used for signals or low power as they cannot handle high currents.





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What are design rules?

Design rules are certain rules that we need to follow in order for our PCB to be **manufacturable**.
Design rules are often obtained from the PCB manufacturing company we're going to use, and they include, but are not limited to, the following:

- Minimum trace width.
- Minimum clearance (trace-trace, trace-pad, pad-pad).
- Minimum drill/hole size.
- Minimum annular ring

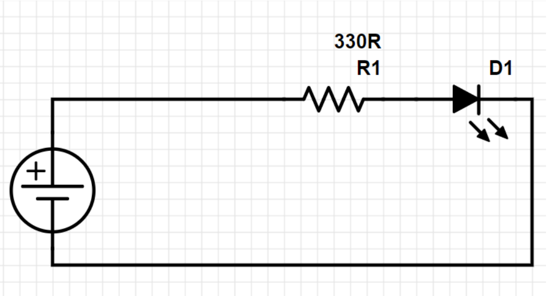
PCB design steps

In order to design and manufacture PCBs professionally, there are some steps that we need to follow:

1. Component selection.
2. Component creation (in design software).
3. Schematic design.
4. **Layout** component placement.
5. **Layout** routing.
6. **Layout** Silkscreen improvement
7. Generating output files.
8. Manufacturing.
9. Assembly.
10. Testing and troubleshooting.

Our first PCB project

To get started with PCB design, we'll be implementing the following circuit in Altium Designer.



It's your turn now!