Crystal Clear Electronics

The development of the Crystal Clear Electronics curriculum was supported by the European Commission in the framework of the Erasmus + programme in connection with the "Developing an innovative electronics curriculum for school education" project under "2018-1-HU01-KA201-047718" project number.

The project was implemented by an international partnership of the following 5 institutions:

- Xtalin Engineering Ltd. – Budapest
- ELTE Bolyai János Practice Primary and Secondary Grammar School – Szombathely
- Bolyai Farkas High School – Târgu Mureș
- Selye János High School – Komárno
- Pro Ratio Foundation working in cooperation with Madách Imre High School – Šamorín

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06 - Linear Power Supplies and Diodes

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Power Supply for Devices

For the operation of our electronic devices, they need energy. The supply of the energy can happen several different ways: for example, the mobile phone works with battery, connecting it to a computer, it can be charged via USB or through a network adapter, moreover energy can be delivered to the device by the help of the car's cigarette lighter or solar panel.

The mobile phone can operate from several different sources, even though, they differ to a large extent. For example, the computer connects 5 V DC to its USB port, while there is 230 V AC in the wall outlet. The cigarette lighter of the car works with 12 V DC. It's also visible that we have to use different chargers for every source, because your phone isn't designed to be directly able to handle so many inputs. Instead of that, manufacturers give out the required data for the phone, based on these data, designers of chargers can make the right converters for them.

These chargers can be called as power supplies too, these convert the energy from the source, as it is acceptable for the phone.

Definition of Power Supply

The power supply (in short supply) is a device, which shapes the energy of the electrical network, for the connected device. So, power supplies make it possible, that our devices can be operated from several different sources.

For each device, you must select the appropriate power supply according to its internal design. For this, we have to know the power supply's properties as well, not just the properties of the device.

The power supply has an input, which receives the energy, and an output which transmits the energy to the connected device.

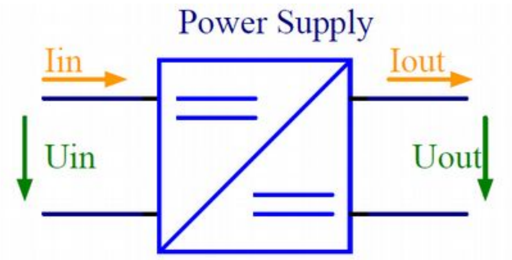

Figure 1 - Power supply

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Properties of Power Supplies

The main properties of the power supply are the parameters of its output and input, as well as the efficiency.

Output of Power Supplies

Most power supplies produce specified value of voltage, but there are power supplies, which voltage level can be set to different levels. Besides this, most power supplies can control their output voltage. This means that, because of the controlling, its output voltage level will be constant, no matter how the current changes on its output.

Take the car's cigarette lighter as an example, which produces 5 V out of 12 V voltage. The voltage level stays at 5 V, even if our phone is not connected to it (in this case, there is no current consumption, i.e. the output current of the power supply is $I_{out} = 0\ [\mathrm{A}]$), and the voltage level of the output is also 5 V, if we just charge our phone (which consumes $I_{out} = 1\ [\mathrm{A}]$ current as an example).

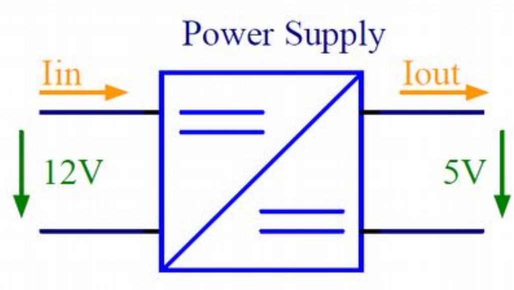

Figure 2 - Operation of power supply

Let's compare the controlling of the power supply and the operation of a simple resistive divider!

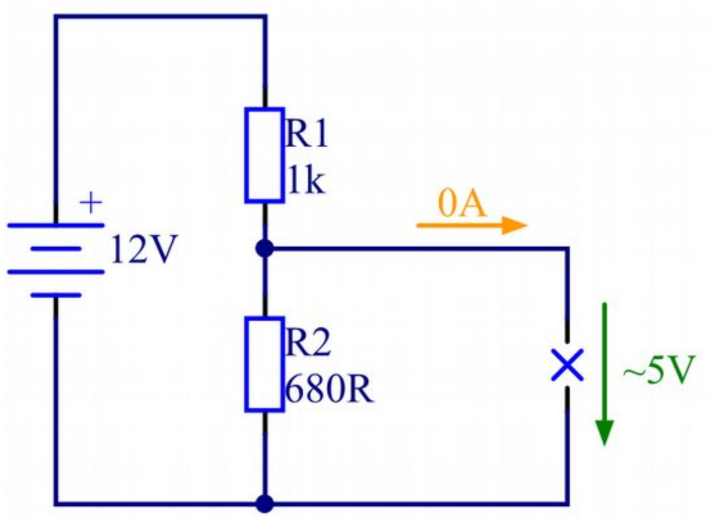

Figure 3 - Resistive divider

Connect a 1 kΩ and a 680 Ω resistor in series on a breadboard, then connect the 12 V power supply's plug to the board as well. Connect the plug's positive output to the 1 kΩ resistor's free lead, and connect the plug's negative point to the free lead of the 680 Ω resistor.

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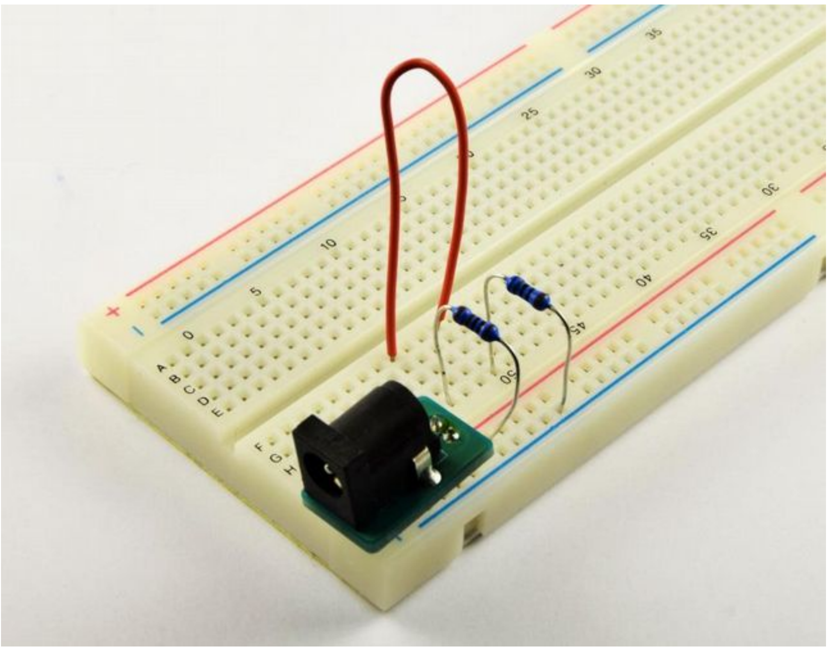

Figure 4 - Resistive divider implemented on Breadboard

Resistance values

Why are we working with such strange value resistance? In practice, we need several different resistance value resistors. The manufacturers of the resistors wouldn't be able to produce infinite different components, like this, most of the time, they make values, with which most of the needed values can be easily produced. The values we get like this way, is called resistance line and it is marked with a letter "E", and also a number is included, as an example, such line is the E12. The number marks, how many values are between 1 and 10, in case of E12, this means there are 12 values, which are the following: 1.0, 1.2, 1.5, 1.8, 2.2, 2.7, 3.3, 3.9, 4.7, 5.6, 6.8, 8.2. We use these values to produce the resistance values, for example the resistance 330 Ω and 680 Ω are produced like this (but the same way 3.3 kΩ and 6.8 kΩ values also).

Resistor colour code

How can we recognize the resistors, if there is no label on them? For this purpose, there are different coloured lines on them, which we call colour codes. There are several pages on the internet, which can help us decoding the values of the components.

The colourful lines on the 680 Ω resistor have to be in the following order: blue, grey, black, black and brown. The blue means the 6, grey means the 8, black means the 0. Out of the first three, the three-digit number is produced, in this case 680. The fourth number means the appropriate power of the 10, the previous number has to be multiplied by this. So, the 680 is multiplied by 10^0, like this we get 680. The final, brown colored line shows that, our resistor has an accuracy of 1%. You can read about what this means later in this section.

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Measure the voltage on the output of the resistive divider, i.e. between the two legs of the 680 Ω resistor! Don't forget those things that you learned in the previous chapter about measuring voltage!

If we worked well, we would measure about 4.86 V. Measure the current as well, that flows through the resistors! This has to be 7.14 mA.

Based on the Ohm's law, we can calculate, that

$$I = \frac{U_{in}}{R_1 + R_2} = \frac{12\ [\mathrm{V}]}{1000\ [\Omega] +\ 680\ [\Omega]} = 7.14\ [\mathrm{mA}]$$

current will flow through the resistors, therefore on the lower resistor

$$U_{out} = I \bullet R_2 = 7.14\ [\mathrm{mA}] \bullet 680\ [\Omega] = 4.86\ [\mathrm{V}]$$

voltage will appear.

Create exactly 5V

Why can't we set the output to exactly 5 V? If we used 952 Ω resistor instead of 1 kΩ, then

$$I = \frac{U_{\mathrm{in}}}{R_1 + R_2} = \frac{12\ [\mathrm{V}]}{952\ [\Omega] +\ 680\ [\Omega]} = 7.35\ [\mathrm{mA}]$$

current would flow, with this

$$U_{\mathrm{out}} = I \cdot R_2 = 7.35\ [\mathrm{mA}] \bullet 680[\Omega] = 5.00\ [\mathrm{V}]$$

The 952 Ω resistor is not available in stores, however we can create it out of multiple components: 820 Ω + 120 Ω + 12 Ω = 952 Ω.

Observe during the measurement, that we didn't measure exactly 4.86 V. This could happen, because the values of the resistors are not accurate, and the multimeter has also some measurement error.

Accuracy of resistors

In case of most components, the manufacturer gives the nominal values of the parameters (1 kΩ and 680 Ω), and also their accuracy (in this case it's 1%). This means, the value of the 680 Ω resistor can be anything on the scale of 673.2 Ω to 686.8 Ω. This is the result of the technology, used during manufacturing. Of course, we can buy parts with better accuracy too. The resistors, with the accuracy of 5%, 1%, 0.5%, 0.1%, are manufactured together, and the automatic production line sorts out the more precise ones. It follows that, there are much less precise ones, and for that reason they are more expensive.

If we measure a value of about 7.15 V, then we missed something at the wiring! If it happened so, examine the circuit! This type of error can happen in real life too, which can make a sensitive circuit to fail. Different solutions exist to avoid situations like these, you can read about these below.

Now, that the resistive divider with about 5 V, is ready, let's try to use it too! How do we make sure that our power supply works without measuring anything? For example, we connect a device to its output

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which lights up only if there is voltage on it. Such device can be a bulb too, however considering its size, using an LED is more practical. Now let's look at the LED as a lamp, which lights up only if there is voltage on it. For safer operation of the LED, we need to connect a resistor series with the LED. Connect a red LED and a serial 330 Ω resistor to the output of the resistive divider.

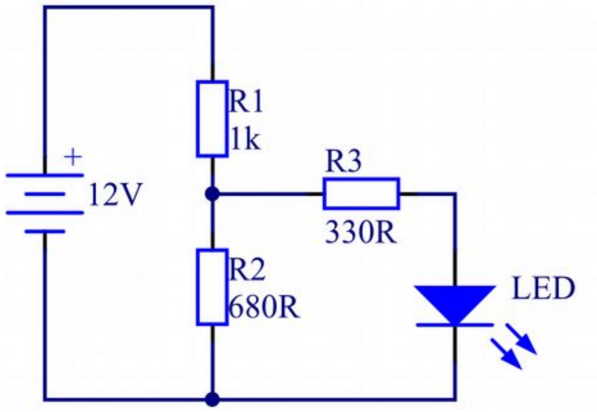

Figure 5 - Resistive divider, with an LED on its output

The LED on the output, will light up, but not with full brightness. Let's measure again the voltage on the output of the power supply! We can measure a value of about 3.3 V, instead of the original 4.86 V. As we load the resistors, the voltage of the output decreased. So, the resistive divider is not able to control its output.

Inside the power supplies, resistive dividers are not used for the conversion. For this purpose, the values of the resistors inside, had to be changed continuously, depending on the load.

Input of Power Supplies

Another important property of the power supply is the characteristics of its input. Power supplies can usually operate on a wide scale of input voltage.

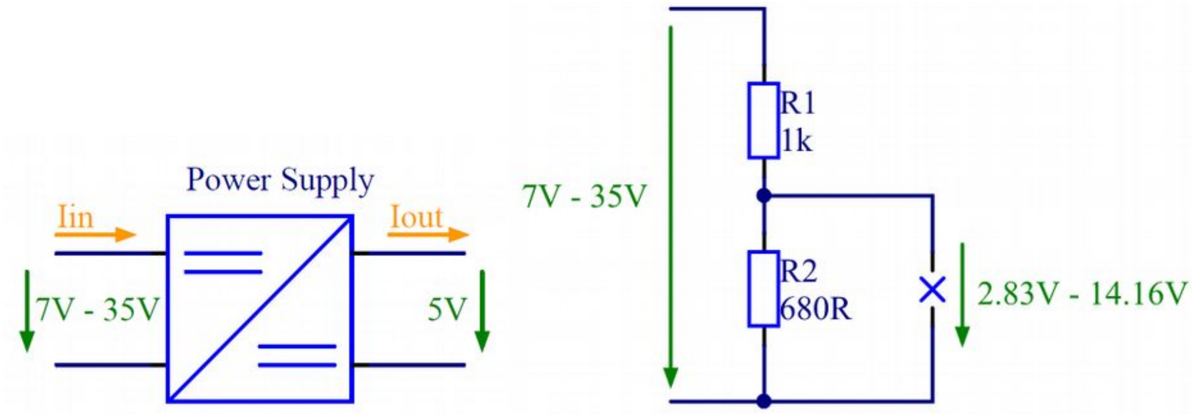

Figure 6 - Controlled power supply and the resistive divider with different voltages

Let's compare this feature with the resistive divider's characteristic, used in the last example. For a 7 V input, 2.83 V appear on its output, connecting 35 V to its input will result an output voltage of 14.16 V. The first one is not enough to light up the LED, however the second one may ruin it.

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Efficiency of Power Supplies

The efficiency of the power supply is also important. It shows, how effectively the power supply can produce the output voltage from the input voltage. This efficiency is defined as the ratio of the output and the input power. Efficiency of a good power supply is approximately 100%, i.e. the output power is almost the same as the input power.

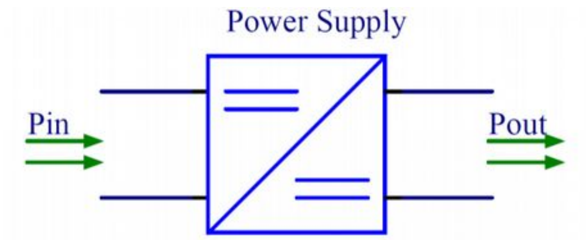

Figure 7 - Efficiency of power supply

In case of a device, which is battery powered, the efficiency is particularly important. Let's compare, how long a device can operate from a battery, using two different efficiency power supplies.

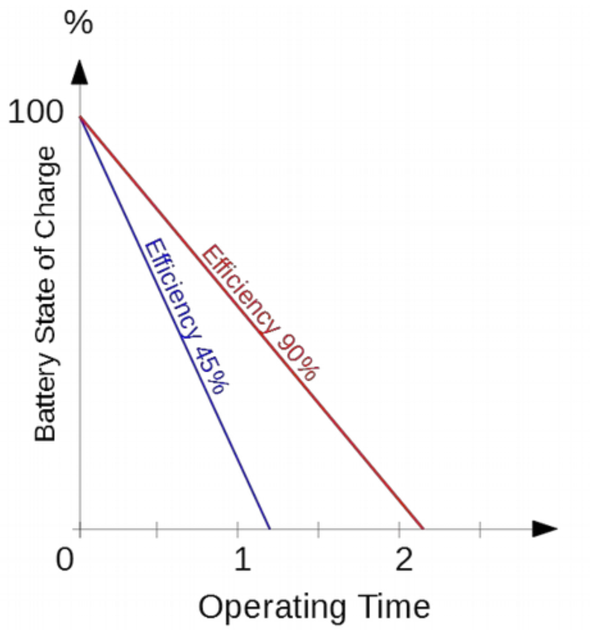

Figure 8 - Battery (12 V @ 1 Ah = 12 Wh), Power Supply 90% | 45%, Consumer (5 V @ 1 A = 5 W)

For example, if we would like to charge our phone with 1 A of current and 5 V of voltage, then it will mean 5 W of power consumption. A charger with 90% of efficiency needs

$$P_{in} = \frac{P_{out}}{\text{efficiency}} = \frac{5\ [\text{W}]}{90\%} \approx 5.56\ [\text{W}]$$

while a charger with 50% of efficiency needs

$$P_{in} = \frac{P_{out}}{\text{efficiency}} = \frac{5\ [\text{W}]}{50\%} = 10\ [\text{W}]$$

of power consumption.

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If we operate the chargers from a 12 V, 12 Wh battery, then the first power supply will able to operate for $\frac{12\ [\mathrm{Wh}]}{5.56\ [\mathrm{W}]} \approx 2.16$ hours. In contrast, the other will able to operate for only $\frac{12\ [\mathrm{Wh}]}{10\ [\mathrm{W}]} \approx 1.2$ hours, so in the second case, we can charge our phone less!

The efficiency is important because of other things: the power supply converts its loss mainly to heat, in other words, it dissipates its loss. The power supply with an efficiency of 90%, the remaining 10% of efficiency is converted into heat, while a power supply with an efficiency of 50%, converts half of its power into heat. This means, in case of equal power inputs, the second one will heat up five times more.

Building a Simple Power Supply

We saw in the previous chapter; it isn't easy to build a power supply that meets every requirement. For this reason, Users can choose out of many manufacturers' already built solutions for this purpose.

The easiest way to produce 5 V of voltage, is using a power supply called 7805. This component has been used for a long time in several applications, for example in phone chargers, in players and in simple UPSs as well.

The 7805 is to be considered as a linear operating power supply. This refers to its internal working, how the component produces its output voltage from the input voltage. There are power supplies which operate differently, for example the switching power supplies. Every type of power supply has its pros and cons too. The main advantage of linear power supplies is their simplicity.

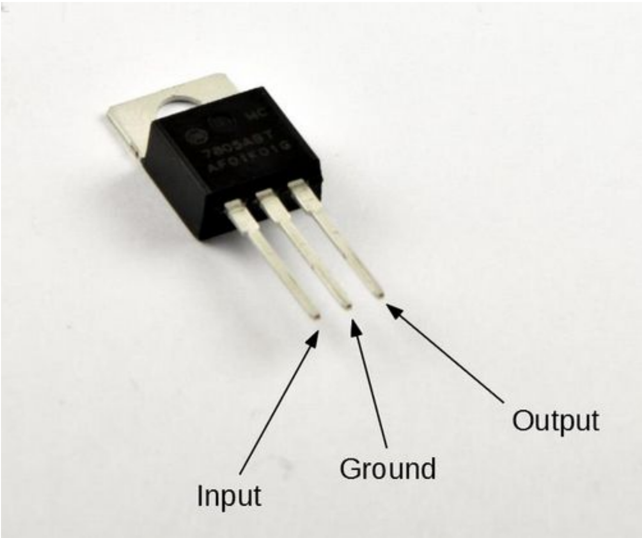

Figure 9 - The 7805 power supply

If we look at the 7805 power supply, then we can see a black „cube", which has three legs. But what is inside the cube? In the previous resistive divider example, we saw, it isn't easy to create a good power supply. We need a bunch of components to create a circuit like this. These components can be created in a tiny little form by the manufacturer, so the whole circuit can fit into a „cube" such small. This is what we call integrated circuit, in short, we call it IC.

Let's build a power supply, using the 7805 component! On the breadboard try to implement it as the previously built resistive divider remain untouched for later use.

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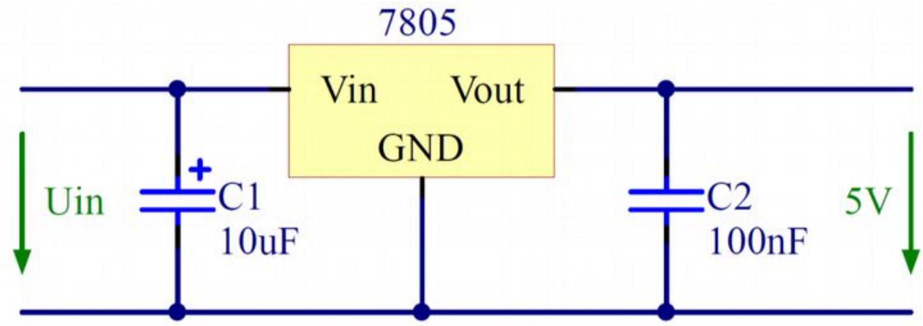

Figure 10 - Wiring of 7805 power supply

We can see in the wiring diagram that besides the 7805 component, we only need 2 capacitors. Without these capacitors, a feedback may start to appear on the output, the voltage level become noisy (uneven) and the power supply may become unfunctional.

Capacitors

How do you use capacitors? The 10 µF capacitor, marked with *C1* in the wiring diagram, is an electrolyte capacitor. It is small, usually it is a blue or black coloured cylinder, with two outputs underneath.

Figure 11 - 10 µF capacitor

On the cylinder, we can find the capacity of the capacitor, as well as the maximum voltage, it tolerates. On these capacitors, the negative terminal is always marked. Be careful with this, because a component like this, is polarity sensitive. It means the following, if we connect it contrary, it may fail (typically it „pops", the top of the cylinder opens with a big explosion).

The other one, the 100 nF capacitor, is a flat, round component with two outputs.

Figure 12 - 100nF capacitor

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This is a ceramic capacitor, which is not polarity sensitive. This means the following, it can be connected to the circuit in any ways, the capacitor won't fail because of that. The value of the capacity is not on the component; however, number code is used to mark them, in this case, it means the code „104”. Similarly, to the resistors' colour code, the value, consists of the first two digits, has to be multiplied by the third number's power of ten ($10 \bullet 10^4 = 100\ 000$). This gives the capacity value of the capacitor in pF (100 000 pF = 100 nF).

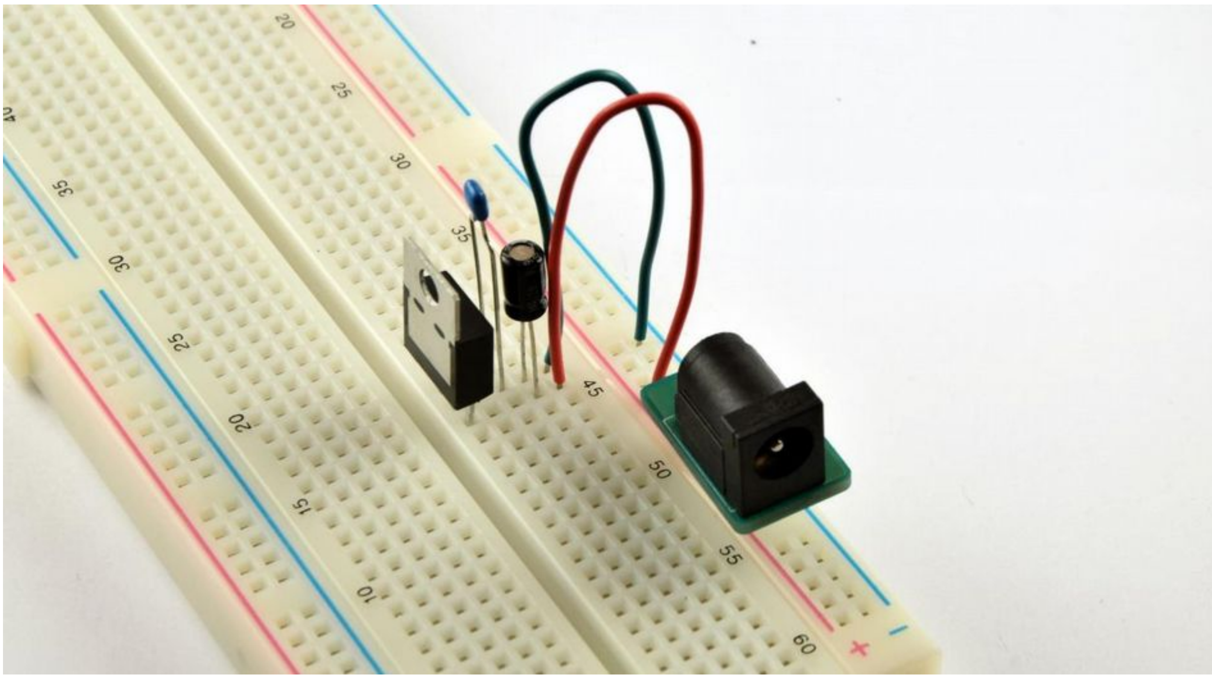

Figure 13 - Wiring of breadboard

Let's connect the 12 V network adapter to the input of our circuit and measure the output voltage! We can measure an output voltage of about 5 V. Important to notice, we don't get exactly 5 V of voltage in this case either. The datasheet of the used component gives precisely how accurately the component can produce its output voltage. In this case, the value can be a value form 4.75 V to 5.25 V.

Output voltage accuracy

How to find out this from the datasheet? For the ON Semiconductor manufacturer's MC7805AB component, the electrical properties (in English „electrical characteristics”) can be found on the 4th page of its datasheet, in a table. The output voltage can be found in the first row of the table and in the column named „Min” (4.8 V) is the smallest value, the nominal value (5.0 V) is in the „Typ” column, in the „Max” column the biggest possible voltage (5.2 V) can be found. (We have to mention that, datasheets can change over time.)

Symbol	Parameter	Conditions	Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C	4.80	5.00	5.20	V
		I_O = 5 mA to 1 A, $P_O \leq$ 15 W, V_I = 7 V to 20 V	4.75	5.00	5.25	

Figure 14 - Output voltage of 7805

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Until this point, the power supply has behaved as the resistive divider in the last section. The first problem appeared when a load was connected to the power supply. Let's connect an LED to the output of the 7805 power supply, through a 330 Ω resistor.

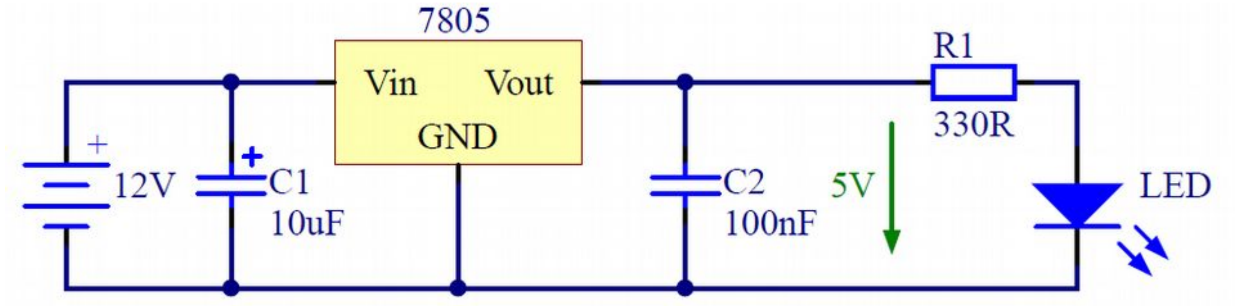

Figure 15 - 7805 power supply with an LED on its output

Compare the brightness of the LEDs, which are connected to the output of the resistive divider and which is connected to the output of the 7805 power supply. In the second case, the LED will light up brighter. If we measure the output voltage of the 7805 power supply, the voltage has to be the same as it was measured, while there wasn't any load. So, the 7805 has an output voltage regulator, which holds the output voltage at the same level, independently of the size of the load. However, this part also has some limitations: the manufacturer set the maximum current level to 1 A. This means, it can produce the given output voltage until the current is not greater than 1 A, for currents bigger than 1 A, the component overheats, and thanks to the internal protections, its output will turn off. Because the LED means about 10 mA of load (measure it!), it can power the LED without problems.

Let's connect further LEDs to the output, to increase the load of the power supply!

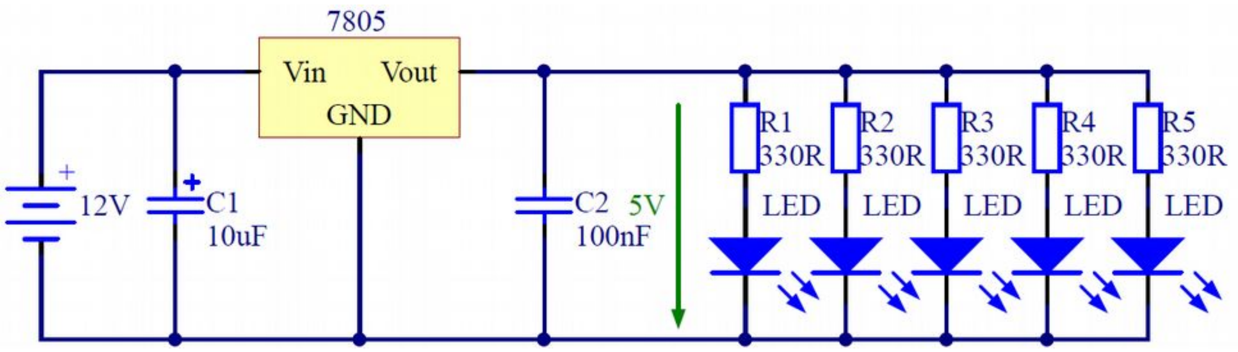

Figure 16 - 7805 power supply with five LEDs on its output

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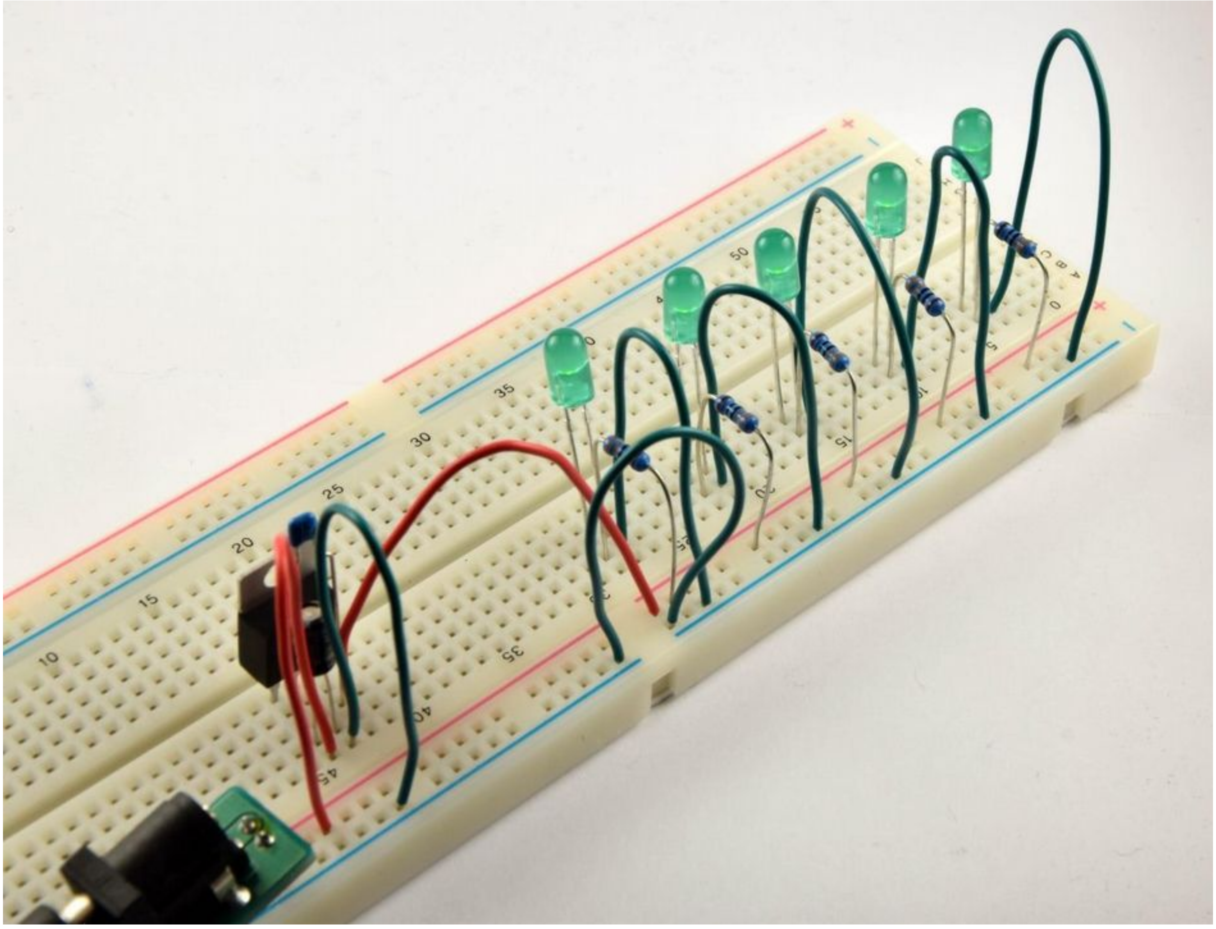

Figure 17 - 5 LED connected to the output, on breadboard

In the case of 5 LEDs, every LED will light up with the same brightness, and also the voltage of the output won't change considerably by that much (measure it!), however the load of the output is 50 mA (measure the full current of the output!).

After extended time of operation, we can notice, that our 7805 component is heating up. This originates from the operation, and during use, you have to be careful with this. If we don't take care of proper cooling for our components, in the case of enduring high load, most components may fail. Fortunately, the used 7805 linear power supply has overtemperature protection, i.e. it will automatically turn off, if it overheats.

There is also a given limit for the input voltage of the 7805 device, by the manufacturer: it can receive voltage between 7 V and 35 V. As the linear power supply works, it can operate appropriately only, if the input voltage level is bigger than the output voltage level (you can read more about this in a later chapter). If the input voltage is lower than that certain minimum level, it won't be able to produce the required voltage level on its output. If the input voltage is bigger than its upper limit, the device can fail. In this case, the device can be short circuited, then the input voltage can appear on the output, which can cause further malfunctions and be dangerous too.

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Input voltage range

Where can we find the operating voltage of the power supply, in the datasheet? The maximum ratings can be found on the 1st page of the datasheet of the On Semiconductor MC7805AB component, in this table, you find the maximum input voltage. This maximum value for the 5 V power supply, is 35 V.

Symbol	Parameter		Value	Unit
V_I	Input Voltage	V_O = 5 V to 18 V	35	V
		V_O = 24 V	40	

Figure 18 - Maximum allowed input voltage of 7805

Reading the value of the minimum voltage is easy, we need to know how the linear power supply operates (you can read more about this in a later chapter). To calculate this value, you have to find the voltage in the line of „Dropout voltage" from the table of electrical characteristics, which table is on the 4th page, in this case, this value is 2 V. You have to add this number to the output voltage, which is 5 V. Like this, we have the minimal voltage, which is 7 V.

Symbol	Parameter	Conditions		Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C		4.80	5.00	5.20	V
		I_O = 5 mA to 1 A, $P_O \leq$ 15 W, V_I = 7 V to 20 V		4.75	5.00	5.25	
Regline	Line Regulation(2)	T_J = +25°C	V_I = 7 V to 25 V		4.0	100.0	mV
			V_I = 8 V to 12 V		1.6	50.0	
Regload	Load Regulation(2)	T_J = +25°C	I_O = 5 mA to 1.5 A		9.0	100.0	mV
			I_O = 250 mA to 750 mA		4.0	50.0	
I_Q	Quiescent Current	T_J = +25°C			5	8	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1 A			0.03	0.50	mA
		V_I = 7 V to 25 V			0.30	1.30	
$\Delta V_O/\Delta T$	Output Voltage Drift(3)	I_O = 5 mA			-0.8		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C			42		µV
RR	Ripple Rejection(3)	f = 120 Hz, V_I = 8 V to 18 V		62	73		dB
V_{DROP}	Dropout Voltage	T_J = +25°C, I_O = 1 A			2		V
R_O	Output Resistance(3)	f = 1 kHz			15		mΩ
I_{SC}	Short-Circuit Current	T_J = +25°C, V_I = 35 V			230		mA
I_{PK}	Peak Current(3)	T_J = +25°C			2.2		A

Figure 19 - 7805 Dropout voltage

It is also important, the input of the 7805 has to be powered with appropriate polarity. If we connected the network adapter to component the other way around, then the 7805 would fail.

PROTECTION OF POWER SUPPLIES

We saw it in the previous part, that our power supply can fail in two different ways: if we connect the plug the other way around to the input, or if we connect too high voltage to it. Let's build protection into the circuit to eliminate these weaknesses!

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Polarity Protection of Power Supplies

Let's discuss the polarity protection at first. With this, it's avoidable that an inversely connected plug makes our circuit to fail. For this purpose, we need a component, which allows our circuit to operate in one direction only.

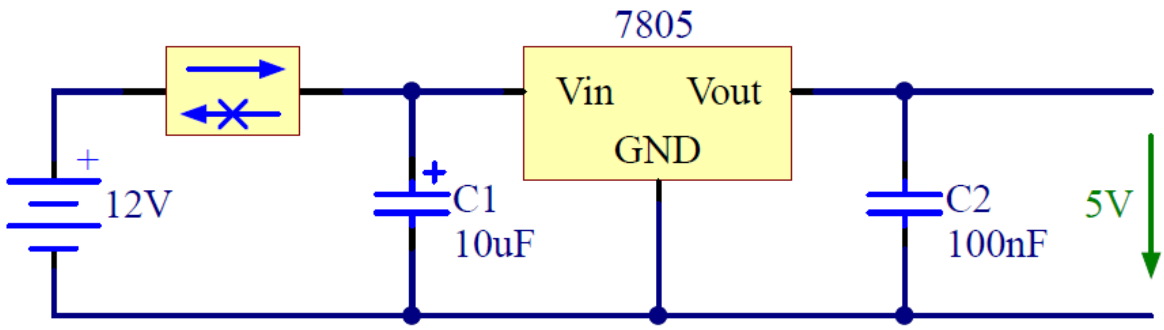

Figure 20 - Power supply with polarity protection

For a problem like this, a perfect solution is one of the simplest semiconductor components, the diode. For the time being, it is enough to look at it, that allows the current to flow in one direction only. The diode has two terminals: the anode and the cathode. The current is able to flow only from the anode to the cathode.

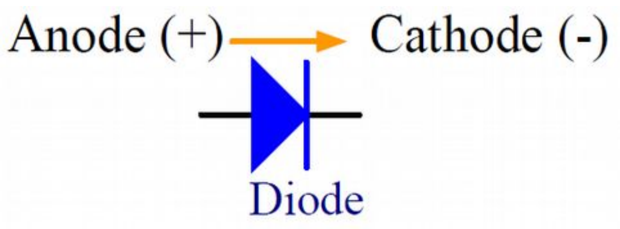

Figure 21 - Symbol of diode

With the help of a diode, we can protect our power supply against reverse polarity wiring. Connecting the diode between the positive output of the source and the input of the 7805 component, it allows through only positive direction current, which can happen only if the connected voltage is positive.

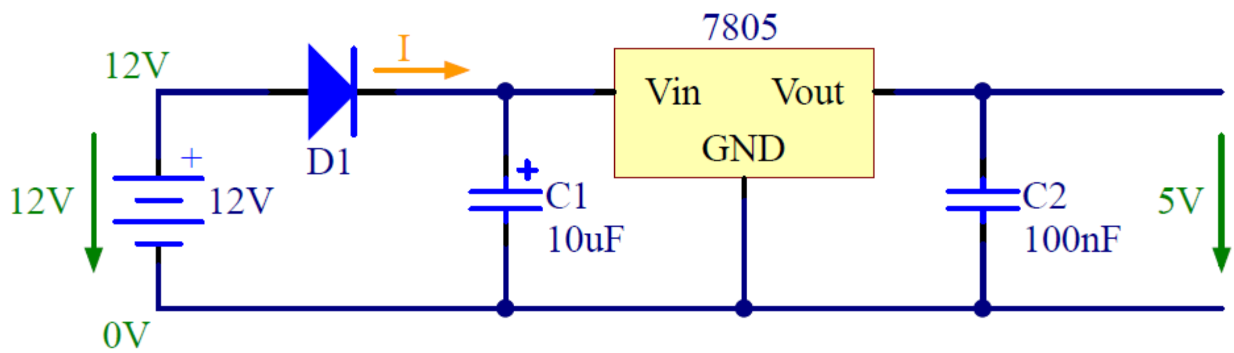

Figure 22 - Power supply with polarity protection, using a diode

Build the protection into the circuit! Make sure the diode is connected properly! On the diode, it is always marked, which terminal is the anode, and which is the cathode: there is a line on its casing closer to the cathode.

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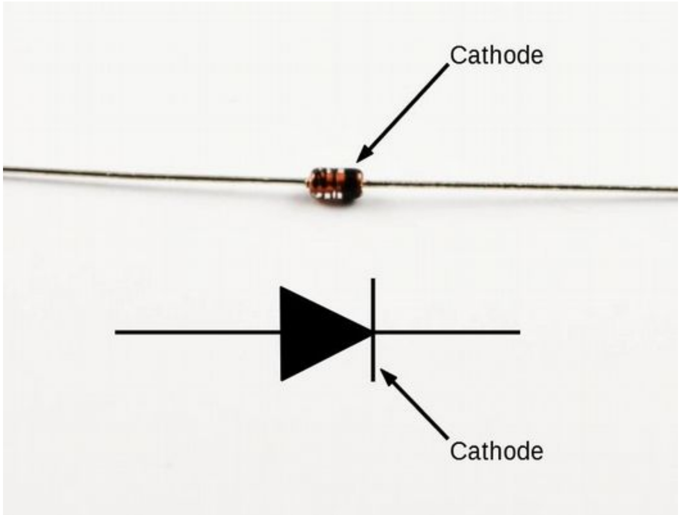

Figure 23 - Diode

If we did everything properly, then the output voltage will be the same as it was previously. (For the sake of curiosity, we can measure the current that flows through the diode.)

Let’s connect our source to the input inversely on purpose! In this case, the diode will block the current, and because of that, our circuit won’t fail. Measure the current that flows through the diode for this case as well!

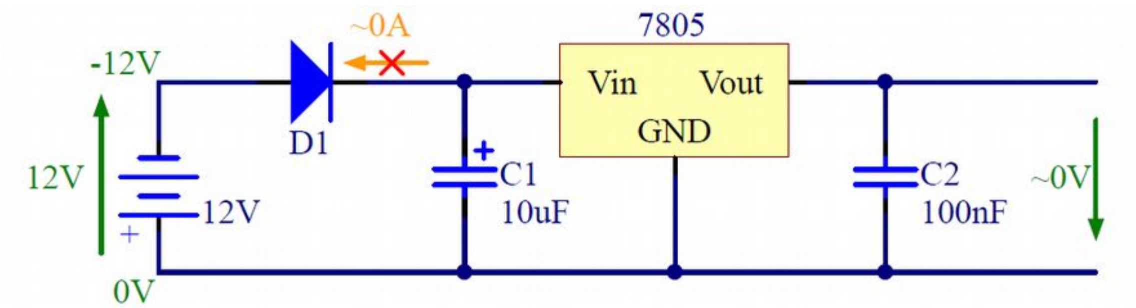

Figure 24 - Power supply protected against reverse polarity

Using this simple component, we managed to prevent our circuit to fail, if we connect the input inversely.

Power Supply with Polarity Independent Input
Let’s examine the circuit below:

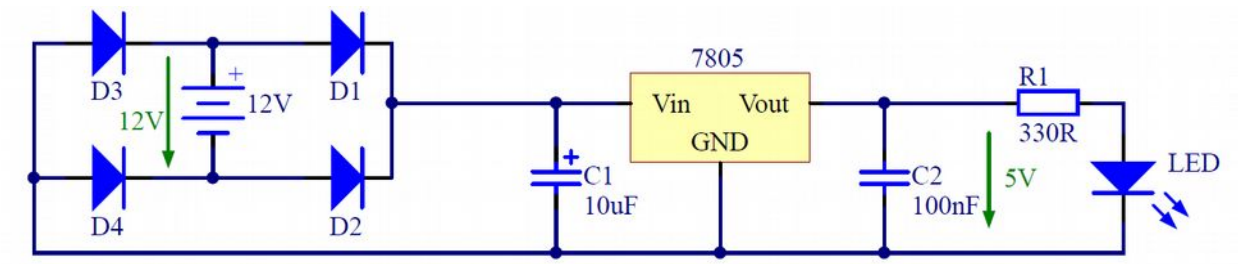

Figure 25 - Polarity independent power supply

Build the circuit and try how it works! Watch out to connect the diodes appropriately! The circuit above is usually called Graetz Bridge, Graetz circuit or Graetz rectifier as well.

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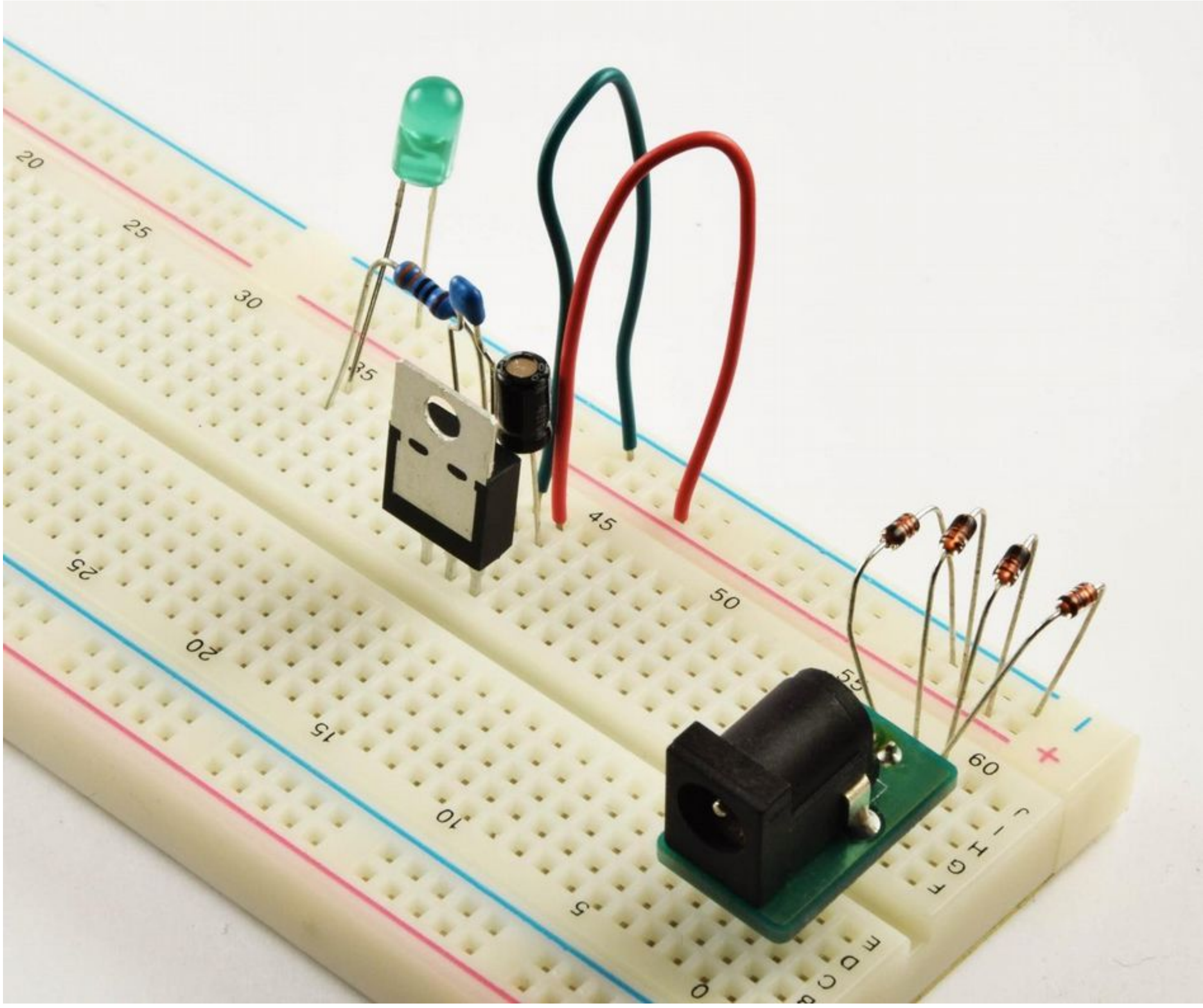

Figure 26 - Wiring breadboard with 4 diodes

We can make our power supply polarity independent by using 4 diodes. This means that, our power supply will work if we connect the voltage to its input in positive way and it will also work if we connect the voltage to its input negatively.

In case of positive connection, the current will flow through the D1 and D4 diodes.

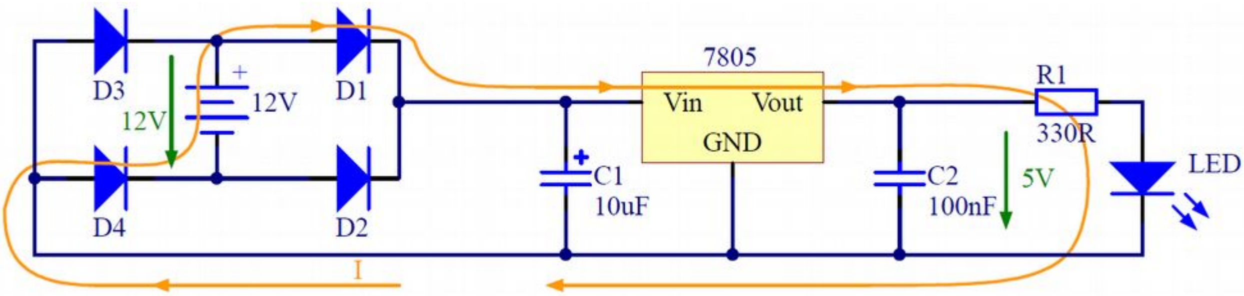

Figure 27 - Operation of polarity independent power supply with positive input

In the case of negative connection, the D2 and the D3 diodes will conduct.

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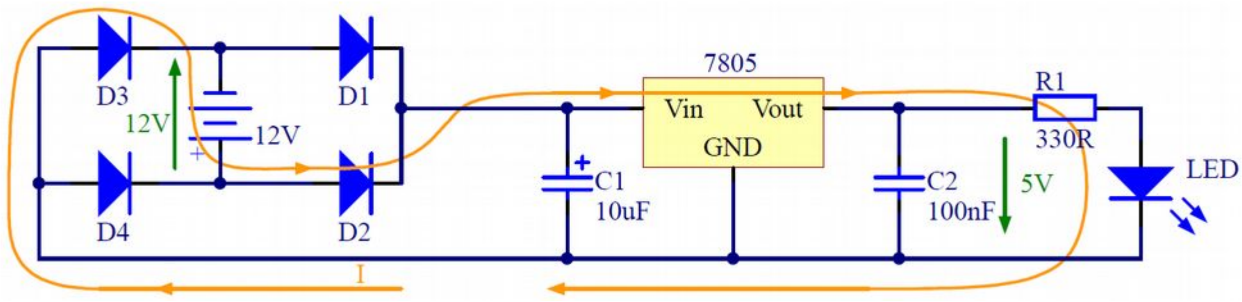

Figure 28 - Operation of polarity independent power supply with negative input

With this simple trick, we don't just make a protection for our circuit, we added a new feature as well: the circuit will always work, no matter how the input is connected to our circuit, in terms of polarity.

However, we still haven't made our circuit protected, if we connect a voltage, that is too big.

Overvoltage Protection of Power Supplies

For our power supply's overvoltage protection, we need a component, which is able to absorb a dangerously high voltage.

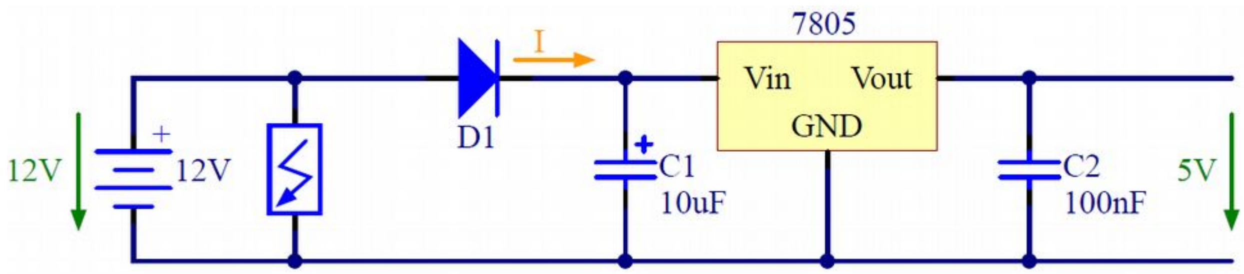

Figure 29 - Power supply with overvoltage protection

For this problem, a quite good solution is a Zener diode. This component is also a kind of diode, it can be greatly used for overvoltage protection, thanks to its special property. You can read more about this in a later chapter too. For now, it is enough to know, that, if there is a higher voltage on it, than the threshold voltage, it can conduct inversely too, i.e. from the cathode to the anode.

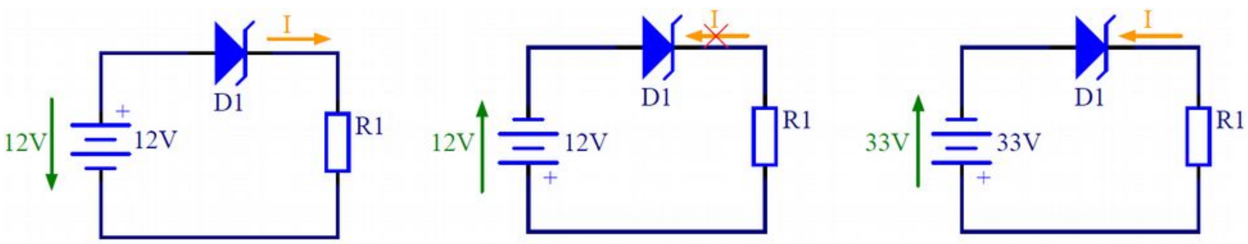

Figure 30 - Operation of Zener diode

We can protect our power supply against overvoltage by using a component like this. There are several diodes with different threshold voltages. For us, the 33 V Zener diode is the best to build our protection. Furthermore, we'll need to build a fuse into the circuit too, so that neither the Zener diode nor the voltage source connected to the input can be damaged.

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Let's examine this issue theoretically! If the voltage of the input is higher than 33 V, then a current will start to flow through the Zener diode, as the figure below shows that too, by using an imaginary 40 V voltage source.

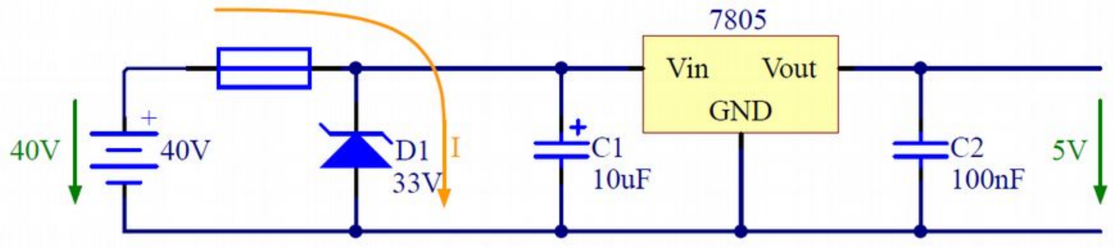


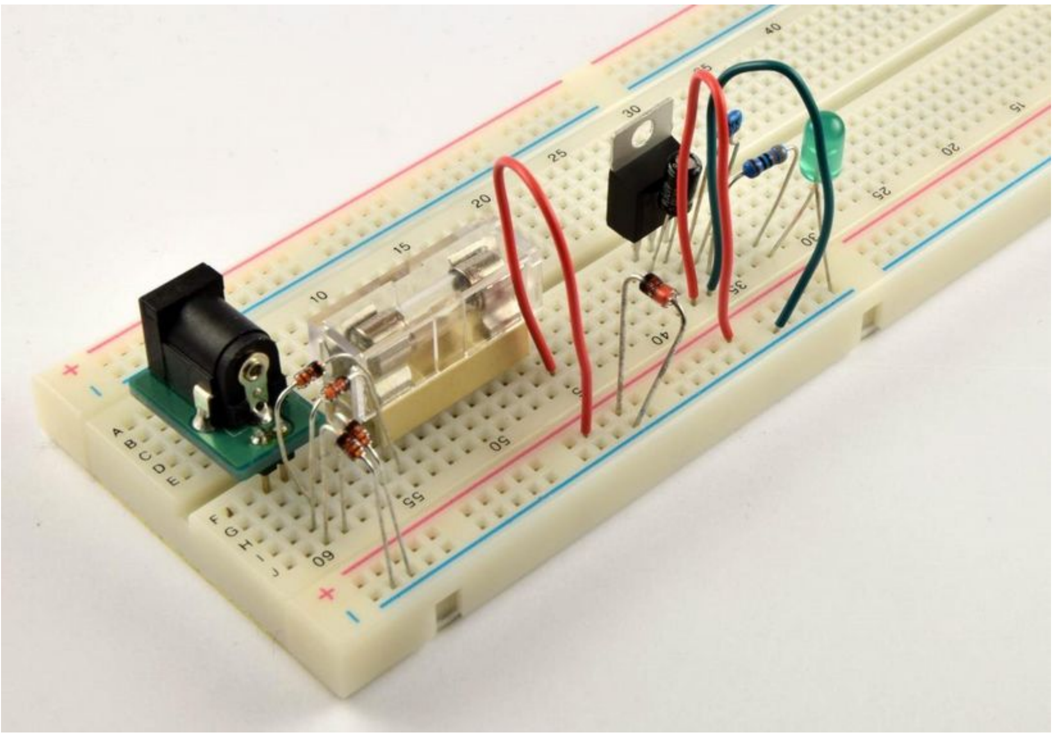
Figure 31 - Power supply protected against overvoltage

The fuse would burn by this current, so the too big input voltage would „come off" from our circuit.

Like all parts, the Zener diode has a maximum allowed power too, if which is exceeded, it can be damaged. We have to choose the fuse in a way that its fusible fibre should burn before the Zener diode can be damaged. By using the components in the component list, you can't try this operation. You would need a fuse with lower value or a Zener diode with higher power.

Summary of Power Supplies

If we combine the previously learnt protections, then we'll get a power supply which is protected against the input voltage's polarity and overvoltage as well, and the LEDs, that are connected to the circuit's output, give information about the operation of the circuit.



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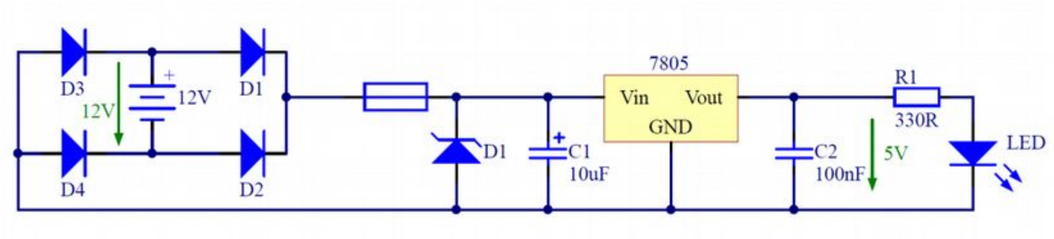

Figure 33 - Polarity independent power supply with overvoltage protection

Additional features

The power supplies, which are in electronic devices, are more complicated than this, and have complex protections in them as well. For example, overheat protection, which means that, the power supply monitors its own temperature, and if the temperature is close to the dangerous value then the power supply turns off its output. There are power supplies which can tolerate a short circuit on their output.

A power supply can become complicated not only with complex protections. A power supply can have multiple channels, different voltage outputs too. The power supplies, which are built into personal computers, can be controlled as well: like this, a PC can be turned on remotely, and for that reason, a personal computer from nowadays can shut down itself completely after turning off the operating system

The Diode

The diode is an electronic component, which allows the current to flow one direction only. Because of this important feature, it can be used for several things, we saw examples for this in the previous chapters.

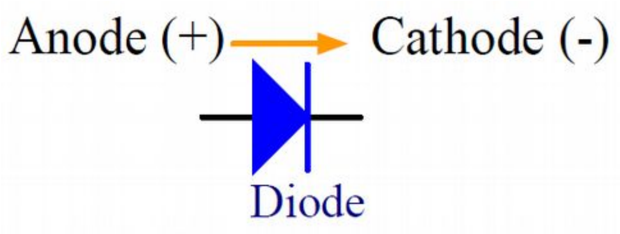

Figure 34 - Symbol of diode

Comment

It's easy to remember which side the anode is and which the cathode is. The symbol of the diode consists of a triangle and a line. The line with the triangle's two edge form a letter „K", and that's exactly the cathode's terminal.

Operation of the Diode

The most used diodes nowadays are built up from semiconductors. The semiconductors are materials which can poorly conduct current and they aren't good as an insulator either. A material as an example is silicon. Out of semiconductors, type P and type N semiconductors are made by a special process, you can read more about this process in the following outlook.

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If a type P and type N semiconductor are fitted together, we call this a P-N junction. For now, let's accept that „the diode is a semiconductor device which contains a P-N junction". The type P side is called anode, the type N side is called cathode.

Its special feature, that it only conducts, if we connect positive voltage to it, i.e. the anode's (the type P side) voltage is greater than the voltage of the cathode (the type N side). We call the likely connected positive voltage as forward direction voltage.

The diode doesn't conduct if the voltage is negatively connected, so we call this reverse direction voltage, if the voltage of the cathode (the type N side) is bigger than the anode's (the type P side) voltage.

Semiconductors and P-N junction

A semiconductor crystal can be produced with a special method, in which the material is constructed up in a special grid where there isn't any free valence electron.

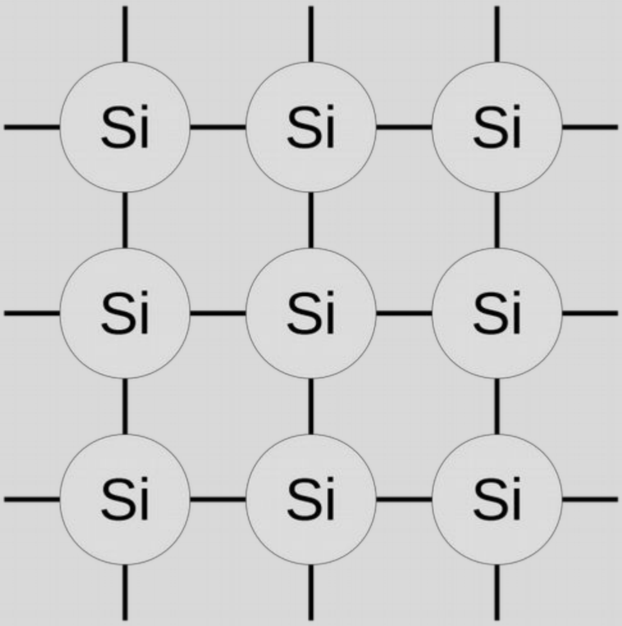

Figure 35 - Silicon in atomic grid

If we mix a material to this semiconductor by chemical way (this is called pollution, or doping), which has more valence electron than the semiconductor, then, in the final material, there will be an electron which won't take part in the construction of the atomic grid, i.e. it will remain free. We call this material as type N semiconductor. The N means the negative, the presage of overplus electron's charge. A material like this will be created if we put phosphorus between silicon atoms.

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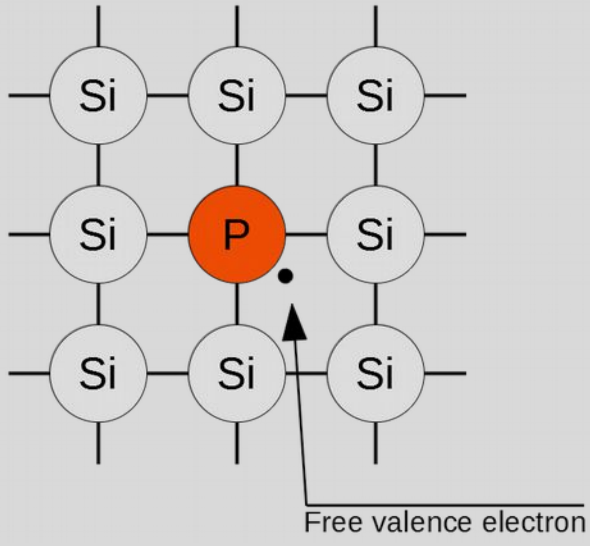

Figure 36 - Silicon in phosphorus polluted atom grid

It’s important to remember, that the material remains neutral in terms of electricity, i.e. the number of protons and electrons in the material are the same. In a chemical way, it has an electron overplus, it has an electron, which can take part in conducting current. It will become a positively charged material, if the electron peels off from this.

If we mix a material to the semiconductor, which has less valence electrons, then in the final material, an electron will be missing to create a complete atom grid, i.e. an electron absence will be created, in other words, a hole. We call these materials as type P semiconductors; this is what is created if we put boron between silicon atoms. The letter P implies to positive, the presage of the electron deficit.

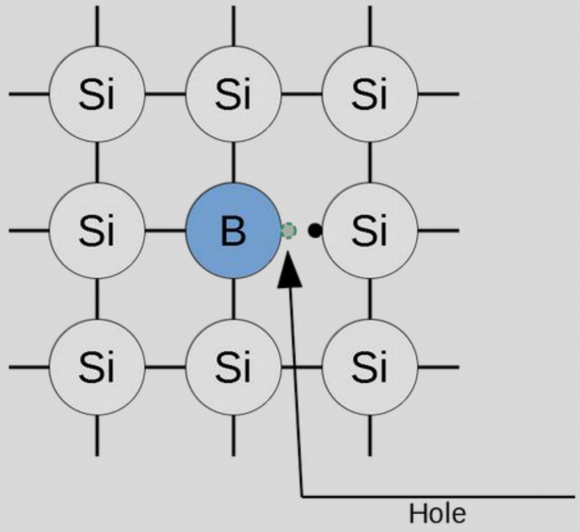

Figure 37 - Silicon in atom grid, polluted with boron

In this case it’s also important, that the final material won’t be positively charged, the number of protons and electrons will be the same. From a chemical point of view, the material is able to accept an additional electron. If this hole is filled by an electron, then the material will become negatively charged.

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In a P-N junction, free electrons and holes get close to each other at the edges of the two materials. These electrons start to fill the holes near the edge line (in this case, we're talking about micrometres in terms of scale). In this range, free electrons and holes disappear, we call this empty range.

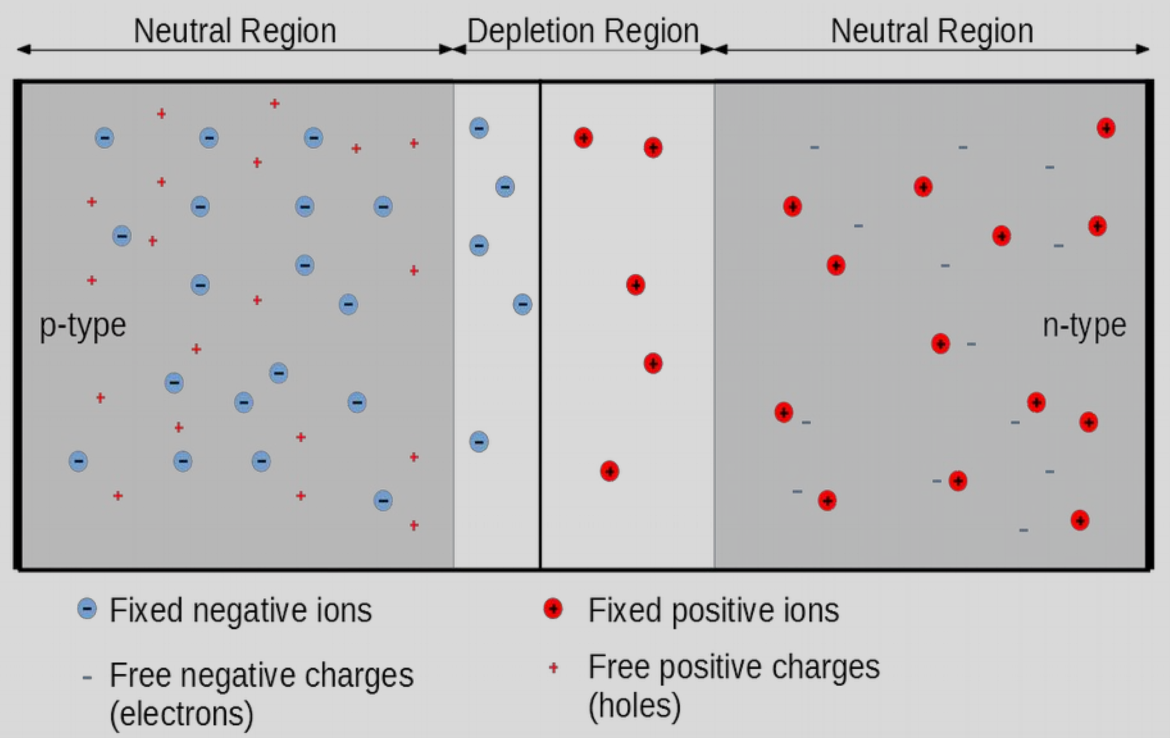

Figure 38 - P-N junction

With that, the electrons were moved from the type N area to the type P area, at the edge of type P, the material became negatively charged, while on the edge of type N area, the material became positively charged.

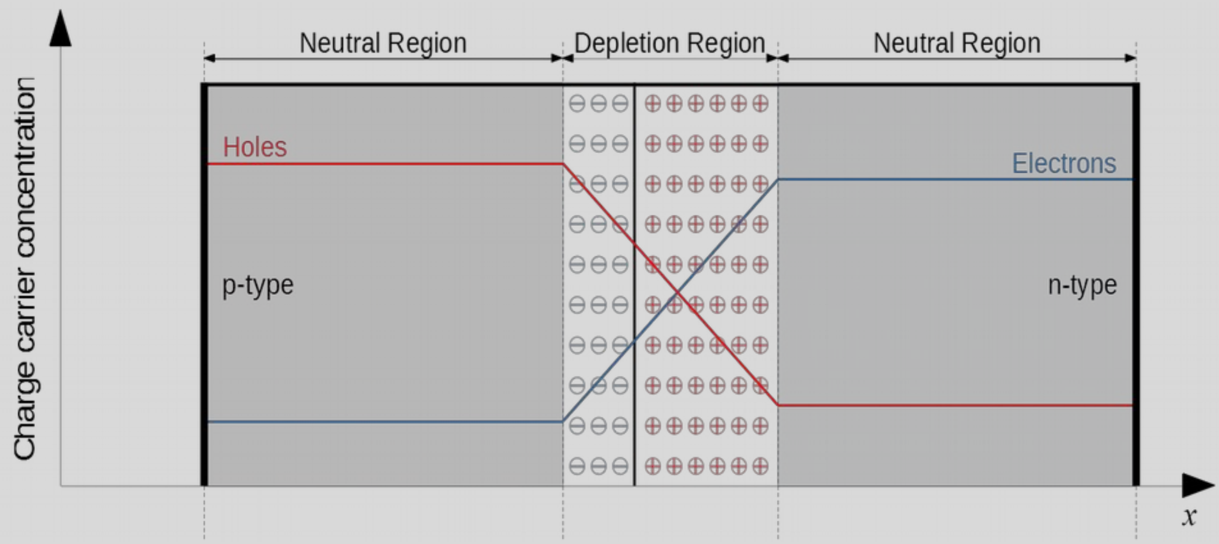

Figure 39 - Empty range of P-N junction

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Let's examine what happens if we connect positive voltage to this P-N junction!

On the type P semiconductor, the voltage will be greater than on the type N semiconductor, therefore the electric field will start to move the holes to the same direction as the field (from the type P to the type N), and it will start to move the electrons in the opposite direction of the field (from the type N to the type P). Both holes and free electrons will start to move in the direction of empty range, which makes it narrower. If the field reaches a certain level, the empty range will become so narrow that electrons will able to jump it over and they will able to wander at large, i.e. the current will start to flow.

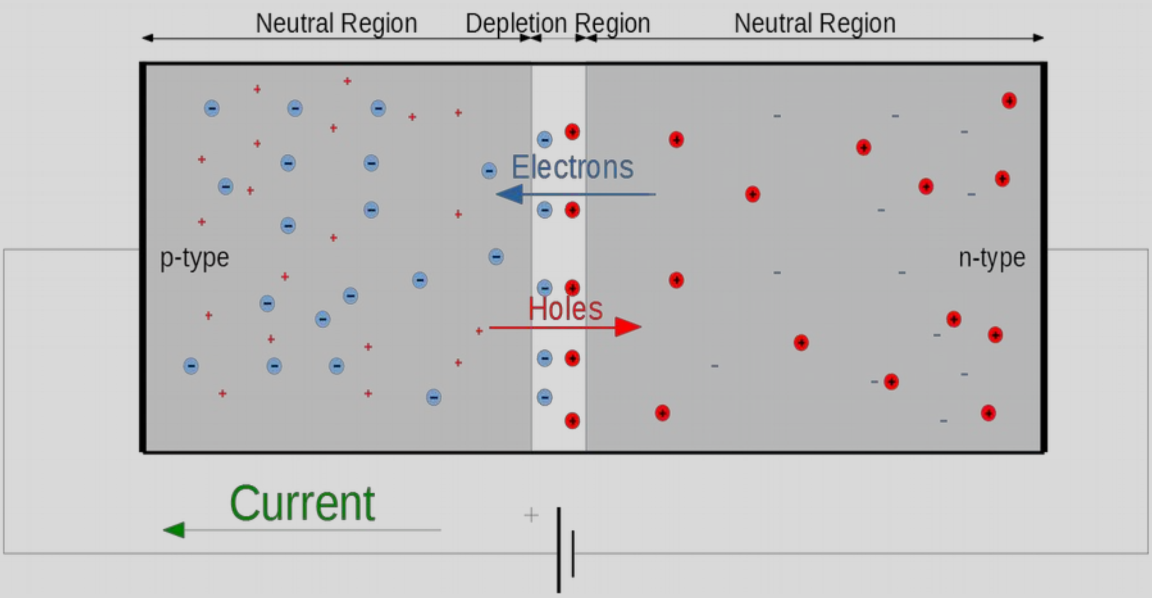

Figure 40 - Positively charged P-N junction, with reduced empty layer, current flows

However, if we connect the voltage to the P-N junction reversely, i.e. connecting higher voltage to the type N semiconductor than the type P semiconductor, then the holes and electrons will start to move to the opposite direction, with that, the empty range will grow in size, the current won't flow. For that reason, the P-N junction doesn't conduct in reverse way.

Properties of Diodes

In the previous part, we saw that the diode conducts to one direction only. Now let's get a better look at this!

Forward Bias Voltage of the Diode

The diode becomes a conductor only if we connect a voltage high enough to it in forward direction. We usually call this minimal voltage as forward voltage.

Comment

The forward voltage is a voltage, which is needed for the empty range to pull together and to make the electrons to able to jump across this to create current.

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Connecting voltage to the diode, which is smaller than the forward voltage, current doesn't flow. In every diode's datasheet, we can find the value of this forward voltage. In the case of silicon diodes, this value is around 0.7 V.

ELECTRICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)						
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
Forward voltage	I_F = 10 mA	V_F			1	V
Reverse current	V_R = 20 V	I_R			25	nA
	V_R = 20 V, T_j = 150 °C	I_R			50	µA
	V_R = 75 V	I_R			5	µA
Breakdown voltage	I_R = 100 µA, t_p/T = 0.01, t_p = 0.3 ms	$V_{(BR)}$	100			V

Figure 41 - Forward voltage of 1N4148 diode

The forward voltage of the 1N4148 can be 1 V at most, according to the datasheet. This value is given by the manufacturer for the temperature of 25 °C and the current of 10 mA, in case of these conditions, the forward voltage will never be bigger than 1V.

Forward voltage

Why does the datasheet give the maximum of the forward voltage? The exact number for each diode can vary because of the manufacturing process's inaccuracy. So, in most cases, the manufacturers give a range, which can be established by the manufacturing process.

Characteristic of the Diode

If we connect greater voltage to the diode than the forward voltage in positive direction, then it will conduct. How does the diode's current depend on the connected voltage?

In the datasheet, we can find the diode's forward way characteristic, i.e. a curve, where we can read out what forward current will flow through the diode, in case of a given forward voltage.

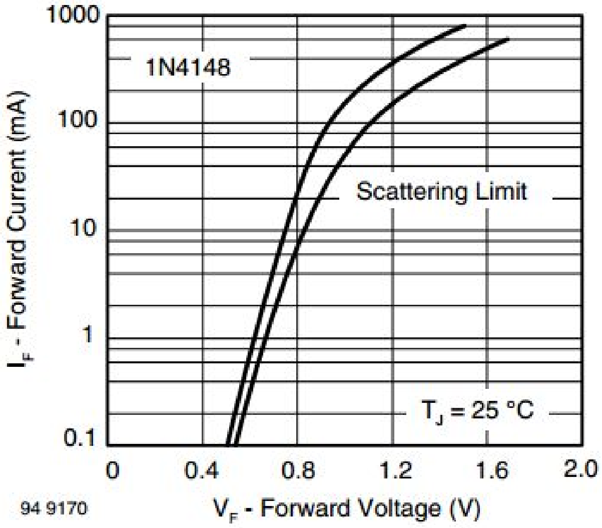

Figure 42 - Forward characteristic of 1N4148

In the figure, it's visible, that under the forward voltage, current doesn't flow (it isn't plotted), then reaching this, the current starts to rise quickly (exponentially).

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Reverse Bias of the Diode

If we examine the datasheet in details, we can see that, the diode is able to conduct in reverse way a little bit as well! We call this current as reverse current.

ELECTRICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)						
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
Forward voltage	I_F = 10 mA	V_F			1	V
Reverse current	V_R = 20 V	I_R			25	nA
	V_R = 20 V, T_j = 150 °C	I_R			50	µA
	V_R = 75 V	I_R			5	µA
Breakdown voltage	I_R = 100 µA, t_p/T = 0.01, t_p = 0.3 ms	$V_{(BR)}$	100			V

Figure 43 - Reverse current of 1N4148 diode

The value of this leaking current is very small: In case of 20 V reverse voltage, the leaking current is 25 nA, i.e. 0.000000025 A.

The leaking current grows slowly as the voltage rises. If the reverse voltage exceeds a certain value, then suddenly, a great current will start to flow through the diode. This is what we call breakdown of the diode, and this voltage value is the breakdown voltage of the diode.

ELECTRICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)						
PARAMETER	TEST CONDITION	SYMBOL	MIN.	TYP.	MAX.	UNIT
Forward voltage	I_F = 10 mA	V_F			1	V
Reverse current	V_R = 20 V	I_R			25	nA
	V_R = 20 V, T_j = 150 °C	I_R			50	µA
	V_R = 75 V	I_R			5	µA
Breakdown voltage	I_R = 100 µA, t_p/T = 0.01, t_p = 0.3 ms	$V_{(BR)}$	100			V

Figure 44 - Breakdown voltage of 1N4148 diode

The breakdown voltage of the 1N4148 diode is at least 100V, which is significantly bigger than its forward voltage.

Breakdown

When reaching the breakdown voltage, the field in the P-N junction is so big, that the electrons, that are able to wander, will start to move so fast and hitting other electrons, it will be able to rip that electron from the grid. Like that, there will be two electrons which wander, which can rip new electrons from the grid. An avalanche starts, when more and more electrons become free.

Special Diodes

There are lots of special diodes, which have unique features apart from the basic ones. For example, such diodes are the LED, the Zener diode or the Schottky diode.

LED

The LED or the Light-Emitting Diode is a diode which is made out of special semiconductors, that emits light during conduction.

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Light Emitting Diode

In the P-N junction, the holes and the electrons „melt together" during conduction, which results energy emission. In case of LEDs, this emission happens in form of light.

Figure 45 - Symbol of LED

The symbol of the LED is based on the symbol of diode: the outflowing light is marked with small arrows. The LEDs have the same features as diodes have, they conduct in forward direction only, their characteristics are similar, and they have reverse direction breakdown as well.

LEDs emit colour of their light specific to their material, i.e. it depends on the material of the semiconductor, whether it lights up as red or green. Every LED is able to emit a single colour light, for multi-coloured LEDs they use more, different coloured LEDs

White LEDs

The white LED is a little bit different than the others, because of its colour. White is a colour, that contains all the other colours, therefore, there isn't any semiconductor, which is able to emit white colour on its own. However, there is solution to make an LED which emits white light. A blue light LED is covered with fluorescent material, which emits yellowish green light because of the blue light. A mixture of these colours will result white light.

Zener Diode
You already heard about the Zener diode previously, where it was used for overvoltage protection. It's the Zener diode's characteristics, that, its breakdown voltage can be determined very accurately, unlike the normal diode's break down voltage.

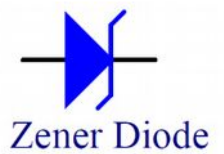

Figure 46 - Symbol of Zener diode

The symbol of the Zener diode is based on the symbol of the diode: only the line that marks the cathode looks differently.

Avalanche in Zener diode

The process in the Zener diode differs from the avalanche effect in that the large amount of free electrons are released not by impact, but by the dissolution of chemical bonds.

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Schottky Diode

The Schottky-diode is a diode which consists of a junction of a metal and a type N semiconductor.

Figure 47 - Symbol of the Schottky diode

The symbol of the Schottky diode is also based on the symbol of the diode: the only difference is the line that marks the cathode. This diode also has all the features that basic diodes have. Conducts well in forward direction, however its forward voltage is significantly smaller than the forward voltage of the normal diode, and its reverse direction leaking current is excessively low. Schottky diodes are fast switch devices, because in them, charge storing doesn't happen. Because of this feature, they are commonly used in high frequency devices for rectifying, for example in switching power supplies.

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