



Crystal Clear Electronics

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07 - Switching Devices

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INTRODUCTION

This curriculum is about switch devices, in which you can get to know its types, construction, operation and fields of applications.

Before we deep diver into the detailed guide, let's look around at our environment, where these devices can be found. I'll tell you, you don't have to search for it too long, because these devices are part of our everyday life. Think of our home and walk it around, what examples we can see there.

First of all, there are „light switches”, we can turn off or on the lighting inside our house. We use switches for the operation of blender, oven, coffee maker as well, also in the case of vacuum cleaner, hairdryer or computer too. However switching devices aren't only at visible places in our life, because there are several different types and sized switching devices inside our electronic devices. Now you will learn about some of these, because this knowledge is required for your future work.

Let's take a simple example: we would like to make an LED to blink on the breadboard. For this, we need to build the following circuit:

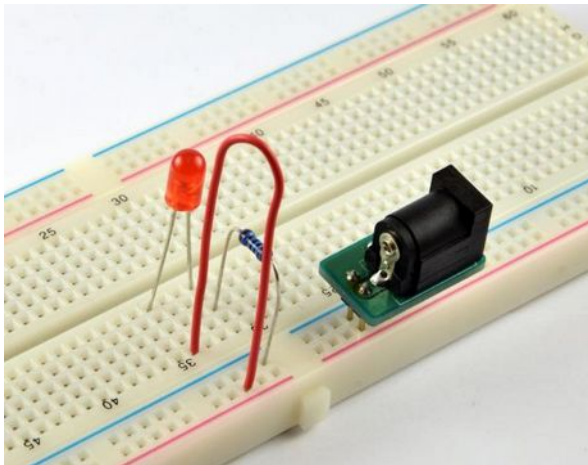
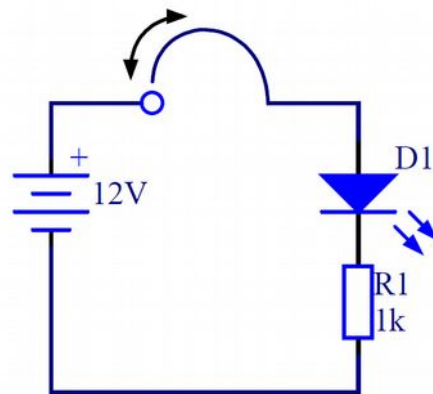


Figure 1 - Simple LED circuit



The free side of the wire, that is connected to the LED's anode, can be connected to any voltage. If you plug the end of the wire into a rail that has positive voltage, then the LED will light up because you close the circuit and current can flow through the LED. If you pull out the previously plugged in wire, then you break the circuit, because of that, current won't flow, and our light source won't light up. Blinking the LED this way is a little bit difficult after all, you have to be careful into which rail you put the right wire, and it takes time until you can do the switch.



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This task should be completed with the help of a kind of switch device to eliminate the previously listed problems.

TYPES OF SWITCHES

Several types of switching devices exist, which vary, depending on the area of application. I will list only those which are important for the later part of the curriculum, those will be presented in detail.

Here is more or less how to group them:

1. Mechanically controlled (can be manually switched)
 - a. switch - bistable
 - b. push button - monostable
2. Electronically controlled
 - a. relay
 - b. bipolar transistor (BJT - Bipolar Junction Transistor)
 - i. NPN type
 - ii. PNP type
 - c. MOSFET (metal oxide semiconductor field effect transistor)
 - i. N channel (enhancement type)
 - ii. P channel (enhancement type)
 - d. Optocoupler (optical coupler)

MECHANICAL SWITCHING DEVICES

The essence of mechanically controlled switch devices is that the state of the switch can be set manually accordingly whether we want to open or close the circuit.

POLES AND CONTACTS

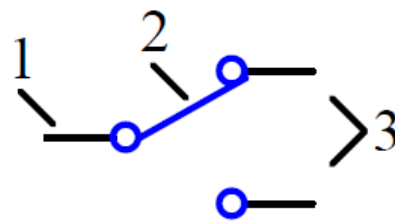


Figure 2 - General switch and its symbol

In the left picture you can see a general switch which I'd like to use in order to show what is depicted in the schematic diagram (figure on the right). The numbers (1) and (3) mark the terminals of the switch device, so these terminals have connection points for us. These terminals can be inserted into our circuit



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to make our switch work. The terminal (in other words leg) marked with (1) is called pole, this is the common output of the switch. This means the following, the output marked with (1) is in contact with one of the outputs of (3) (inside the box), it doesn't depend on the state of the switch. The state of the switch is symbolised by the (2) moving contact, so this can be set by tilting the switch.

In case of switching devices, pole number gives the number of moving contacts, so how many sub-assemblies can be found inside a physical device which are capable for switching.

The number of switches marked with (3) defines how many terminals our pole can connect to. So this is the number of contacts for a single pole.

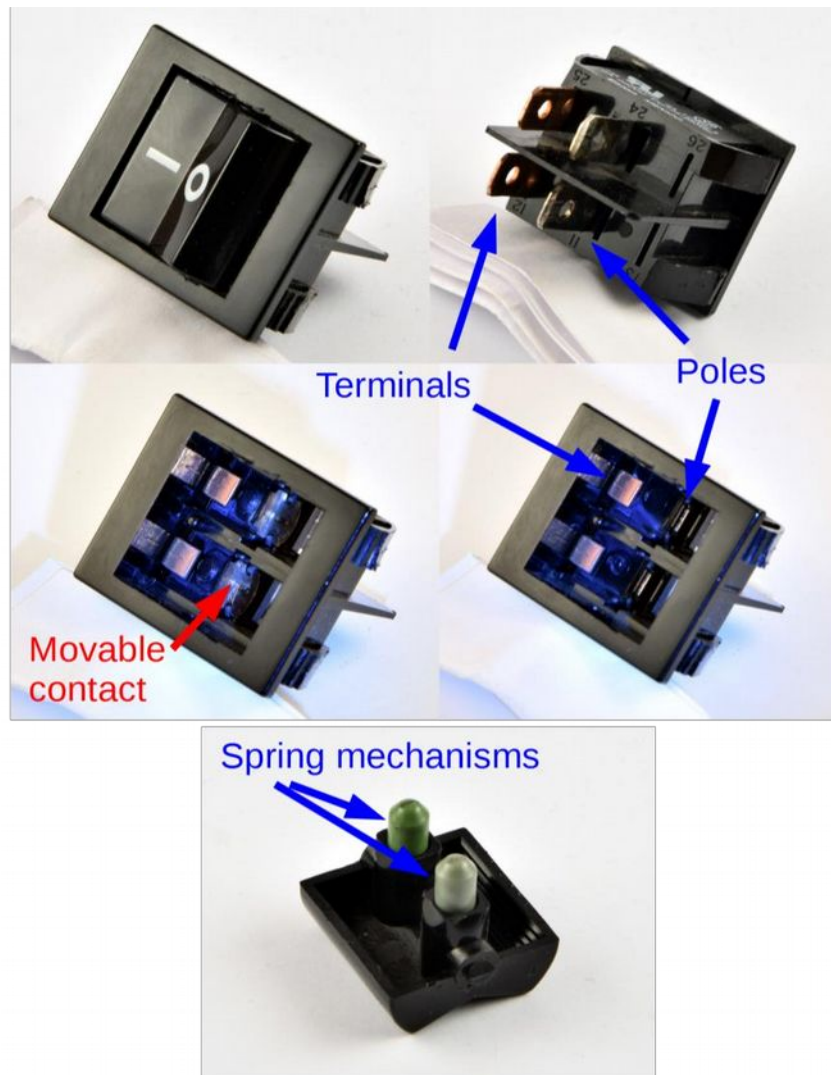


Figure 3 - Internal structure of tilt switch

In the picture above, you can see a mechanical tilt switch at assembled and disassembled state. This switch contains two switching sub-assembly. The switch is realised by a moving switch. When the switch is tilted, the spring mechanism (in the photo, it's green) built in its cover, creates a force in the direction of the moving switch, which tilts the moving switch in the direction of the contactor, so it connects the „pole”

and the „contactor”. If the switch is tilted to the other direction, then the moving contact will move to the other direction and the connection will be interrupted.

It's visible, that the pole number of this switch, is two, because there are two separate switching sub-assemblies in it. The number of contacts is one, because we can see only one contact for each sub-assembly.

HOW MANY STATES DOES MY SWITCH HAVE?

Additional feature of the switches is the number of states they have, i.e. how many stable states the switch can be tilted into. (For example, there is a switch, which has one pole and two contacts, however it is a three-state device, because it has a certain stable state, where it's connected to none of its contacts.)

In case of a device with M poles, and N contacts, M number of poles can connect to N number of contacts. Separate abbreviations are used to indicate the internal design of the switches, which are the following:

Abbreviation	Name	Description
SP	Single Pole	One Input Channel
DP	Double Pole	Two Input Channels
ST	Single Throw	One Output per Input
DT	Double Throw	Two Outputs per Input

These abbreviations have several different combinations in the market (SPST, SPDT, DPDT). I'll use these abbreviations below to simplify the illustration of the internal structures.

BISTABLE AND MONOSTABLE SWITCHES

Another essential feature of the mechanically controlled switches is whether after the switchover the switch remains in the position in which it is set or reverts back to the original position.

Bistable Operating Switches

Our two-contact switch device is bistable, after the switchover, the moving contact remains in the position where we have set it. (It will remain stable after switching over.) Such typical devices can be seen in the following figure.



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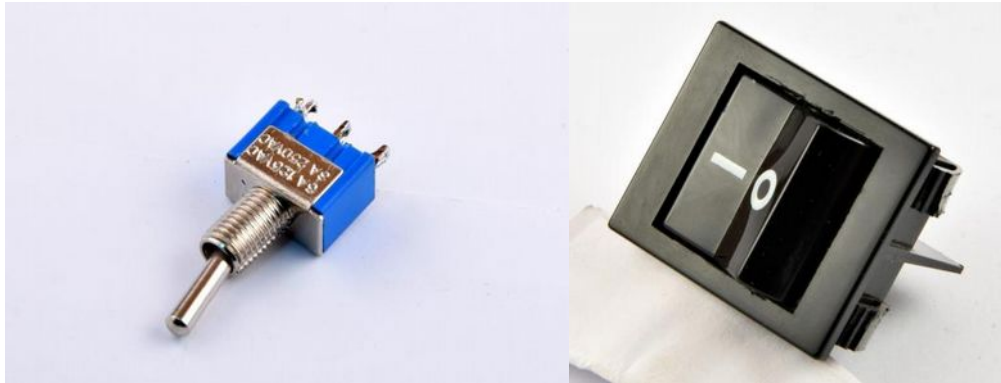


Figure 4 - Bistable switches

Bistable operating devices can have two, three, or even more outputs too.

The SPST switch is a component with two outputs, which conducts current (in this case, it closes the circuit), or not (in this case, it breaks the circuit).

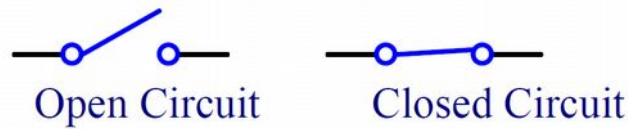


Figure 5 - Symbols of the two state of the SPST switch

The SPDT, or three output devices can be called toggles as well, because we can choose which output should be connected to the pole.

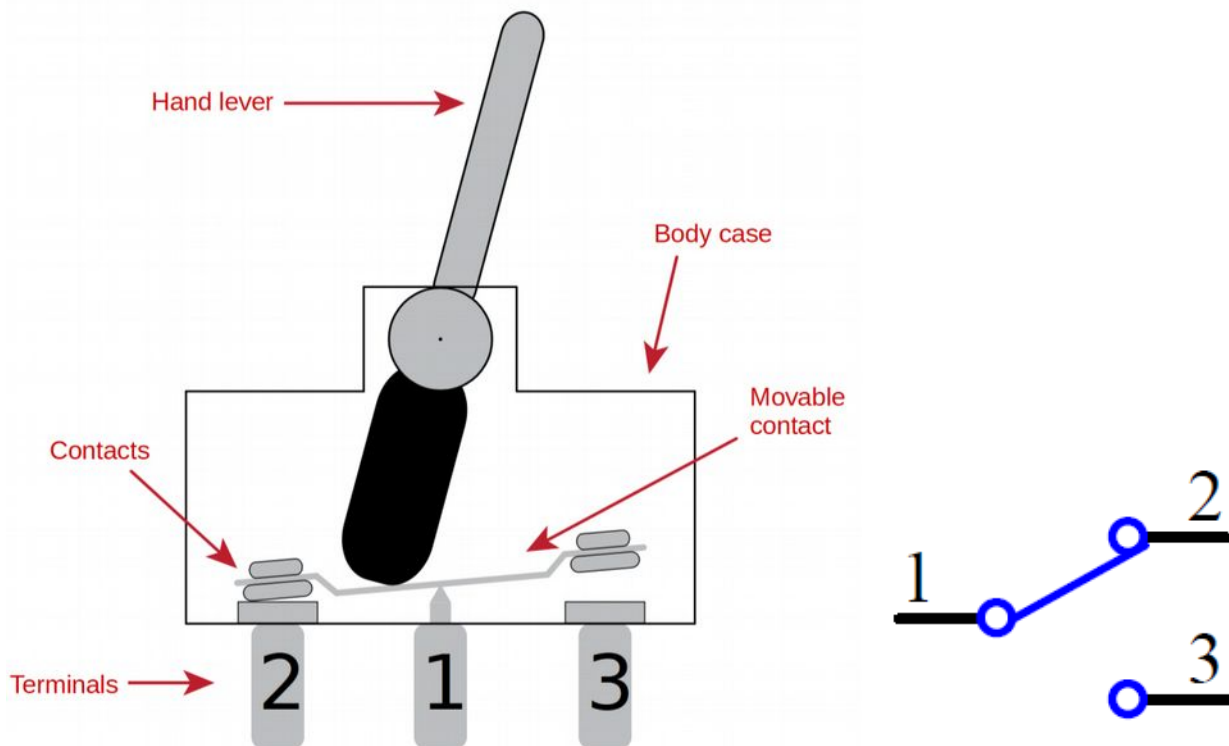


Figure 6 - Internal structure of SPDT switch



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The number (1) marks the pole (we call it common contactor as well), the numbers (2) and (3) mark the other two terminals. In the figure, you can see that, practically the inside of the switches is only mechanically constructed.

The rotary switch is a subtype of multiple output switches. Using our learnt markings, these devices are single-pole N contact components. We have a common pole, which can be connected to N contacts.

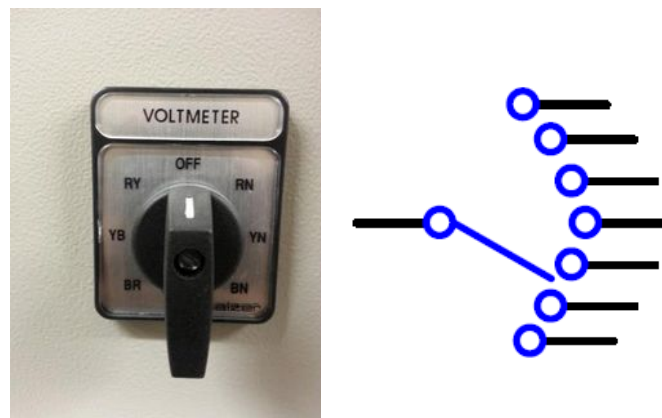


Figure 7 - Rotary switch and its symbol

Author: Balurbala [CC BY-SA 3.0 (<https://creativecommons.org/licenses/by-sa/3.0/>)
https://commons.wikimedia.org/wiki/File:Selector_switch.jpg

DPDT switches also belong to the group of multiple terminal switches. The figure shows that, this type of switch is like two SPDT (single pole two terminals) switches within one component, except the fact that we can control the two poles at once, i.e. the positions of the switches depend on each other.

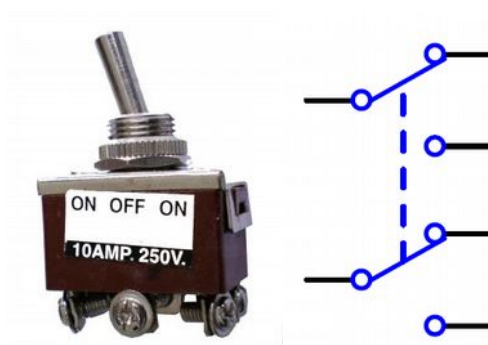


Figure 8 - DPDT switch and its symbol

Author: Suyash Dwivedi [CC BY-SA 4.0 (<https://creativecommons.org/licenses/by-sa/4.0/>)
https://commons.wikimedia.org/wiki/File:Dpdt_10amp_switch.jpg

Of course, there are such components, which have several switches integrated into, i.e. several switches can be found inside a single component and these are independent from each other.

Such device as an example is the DIP switch, which is none other than building multiple SPST switches into a single component.

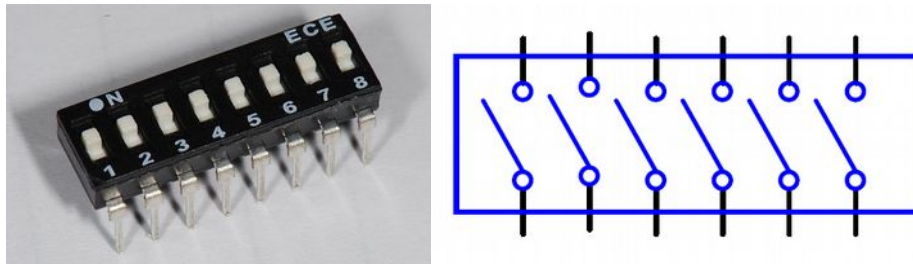


Figure 9 - DIP switch and its symbol

Author: Peter Halasz. (User:Pengo) [CC BY-SA 2.5 (<https://creativecommons.org/licenses/by-sa/2.5>)]
https://commons.wikimedia.org/wiki/File:DIP_switch_01_Pengo.jpg

Push Buttons or Monostable Operating Switches

Those devices belong to the monostable group which return to their original state after switchover. The reason for this, if we stop pushing the button (i.e. the button has been released), then a small spring pushes back the contact to a stable state and it holds there as well. In the figure, number (4) marks the spring, number (6) marks the push button of the device, number (3) marks the contacts, which closes the two outputs (1,2) when the push button is pressed.

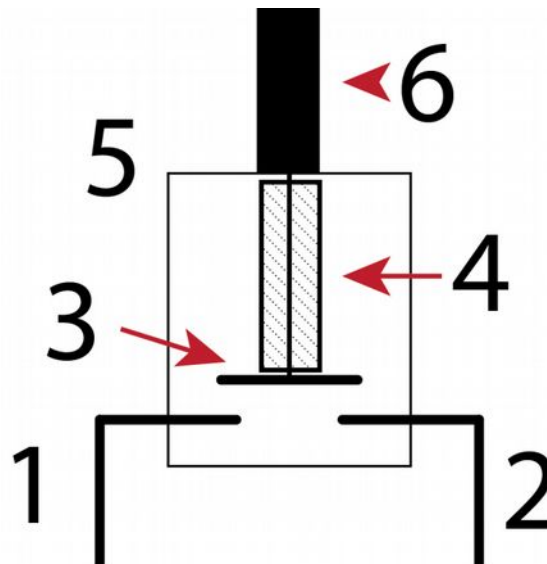


Figure 10 - Internal structure of push button

This is how a simple push button works, if it is pressed, then it conducts, after releasing it, it will become open again.

The switches, shown by the figure above, are so-called normally open switches (NO - normally open). That means, in case of stable state, there is a break between the two outputs, so the circuit is open.

If the push button conducts by default and the circuit can be interrupted by pushing the button, then we're talking about a normally closed (NC) switch. The following figure shows possible designs of a button.



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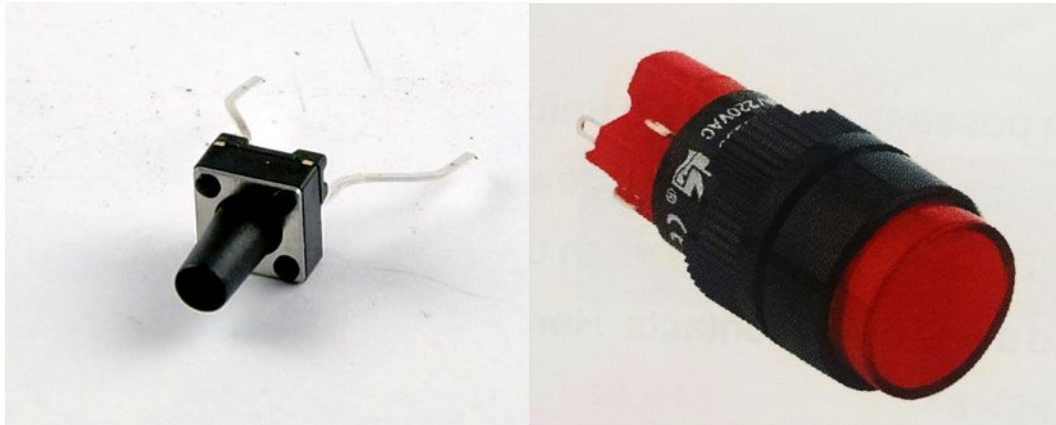


Figure 11 - Push buttons

Author: Achalshanth [CC BY-SA 4.0 (<https://creativecommons.org/licenses/by-sa/4.0/>)
https://commons.wikimedia.org/wiki/File:Push_button_switch.jpg]

BOUNCE OF CONTACTS

For each mechanical switch, care must be taken to ensure that the contacts, when pressed together, first for a very short period of time, with an imperceptibly small amplitude to the eye, can start bouncing on each other, and then the state of constant contact is set. This is what we call a bounce, which may cause some circuits to fail. The problem is illustrated below with a push button.

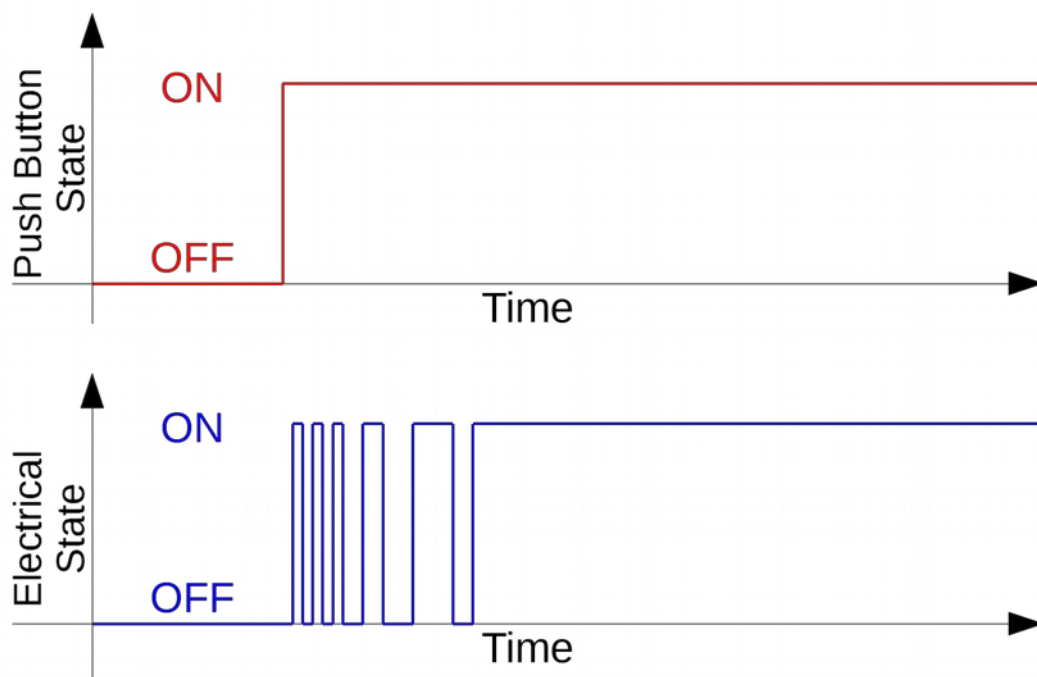


Figure 12 - Bounce of push button

At the beginning of the picture, the button is not pressed, so there is no contact between the two contacts (NO, normally open switch). At the moment marked with red, you press the button, which starts to flicker, so the contacts inside the button will come into contact for a little while, and then they won't come into contact again. This occurs several times until the final stable contact occurs between the two terminals



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(the status at the end of the figure). It is important to note that this action takes very little time, usually a few ten milliseconds. This unwanted phenomenon will play a role in the rest of the curriculum, where we will build a protection against it.

This brings us to the end of the overview of manually operated switches, moving to a slightly more exciting area.

ELECTRONICALLY CONTROLLED SWITCHES

Electronically controlled switch devices, of which operation is more complex than mechanically controlled ones, but explained by a sufficiently simplified model, should not be a problem with their understanding.

The first important thing we have to mention is how this type of devices can be switched. Their names contain that some kind of electric quantity is needed for their control, this can be current or voltage. Let's look at these devices in detail, one by one.

RELAYS

There are three main parts of a relay: the coil, the iron core and the contacts. Let's discuss the coil first, which you may not know yet.



Figure 13 - Coil

Author: Peripitus [CC BY-SA 4.0 (<https://creativecommons.org/licenses/by-sa/4.0/>)]
https://commons.wikimedia.org/wiki/File:Toroidal_inductor.jpg

The relay is formed out of long wire which is wound around a geometric shape (usually cylinder). For this, we use one of the wire's feature, if current flows through the wire, then magnetic field will appear around it. If we wind up the wire, then in a given volume, there will be several wires, and all of them will bear a part in creating the magnetic field. In that given volume, the strength of the magnetic field will increase, because the effect will appear multiple times. The magnetic field, which is created like that, is proportional to the coil's number of turns. The magnetic effect can be increased, if the coil is around some kind of iron core. (To understand the operation of relays, you don't need to know the physics behind the magnetic phenomenon, because of that, I won't talk about it.)

Returning to the relays, our coil with iron core, has two terminals, which forms part of our input stage. We are able to move the moving contact by this control circuit. The output stage (which we can switch) consists of terminals and contact(s).



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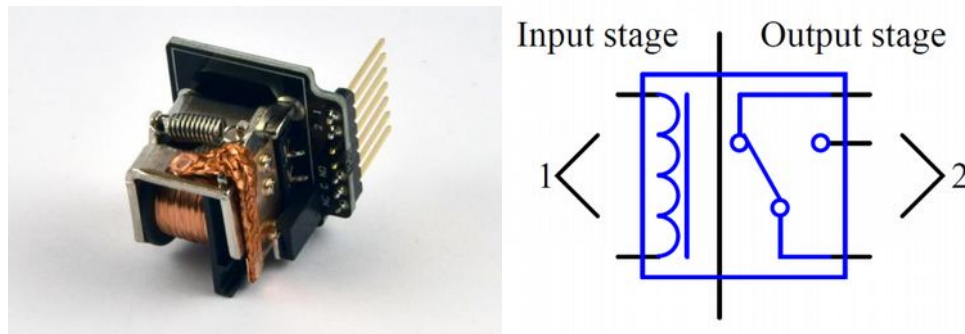


Figure 14 - Relays and its symbol

The left side of the picture shows the input stage, the right side shows the output stage. The number (1) marks the terminals of the input, the number (2) marks the terminals of the output. Its operation is very simple, if we connect proper voltage to the input stage, then the tilt switch of the output stage will draw to the other terminal because of the magnetic field which is created by the current, that flows through the coil.

The relay used in the curriculum, can be seen quite clearly in the individual parts. If you look for the datasheet of the relay, you will find the following internal structure.

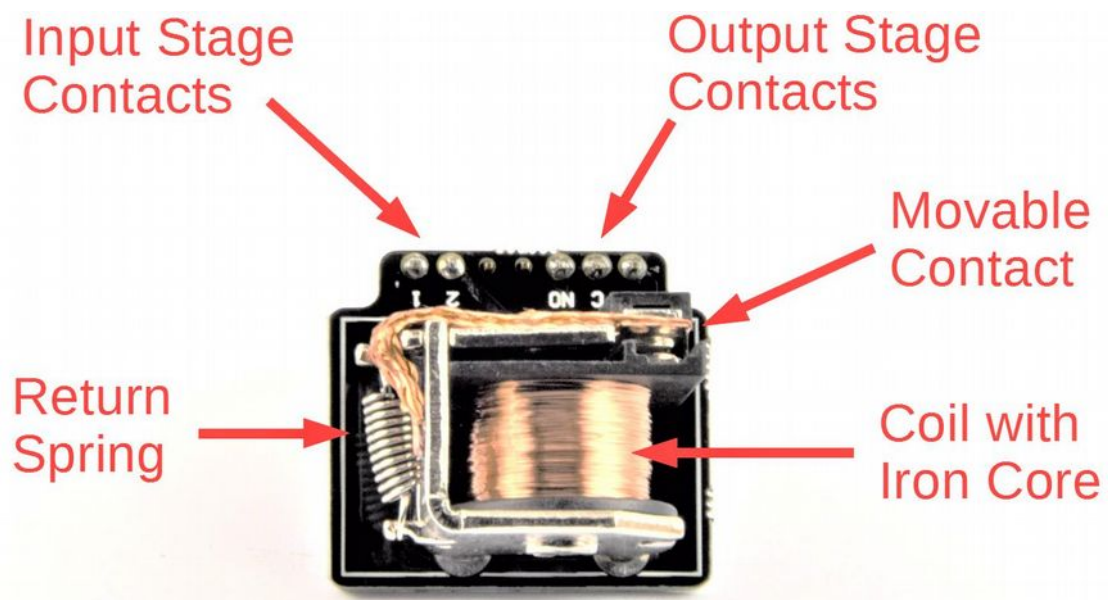


Figure 15 - Structure of relay

Latching Relays

Relay has bistable and monostable variants too, depending on, how the moving contact behaves, if the voltage on its input is aborted.

Latching is also called the phenomenon where the contacts retain their status after the magnetic phenomenon has stopped to exist. This is how bistable relays works, which have two types, depending on what control they require.

In the first case, our control circuit also has two terminals (as before), and the direction of the current, that flows through the coil, defines to which stable state will our output stage be set. In the second case,



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the structure of the input stage is different, because in the present case, it contains two coils which can be seen in the schematic figure below.

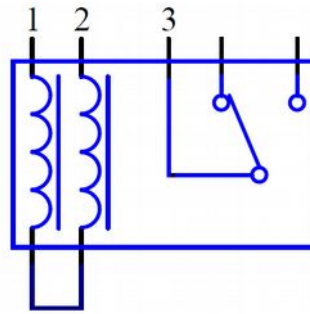


Figure 16 - Symbol of latching relay

The coil (1) is capable of moving the controlled contact in one direction, as previously known. To set our contact to its default place, we need to connect proper voltage to the coil (2), which is capable of pulling in the contact to the other direction. You could consider it as we have a setter (set, S) and a resetter (reset, R) coil. Usually, in the datasheet of latching relays, the manufacturers use the markings S and R, and because of that I'll refer to them the same way.

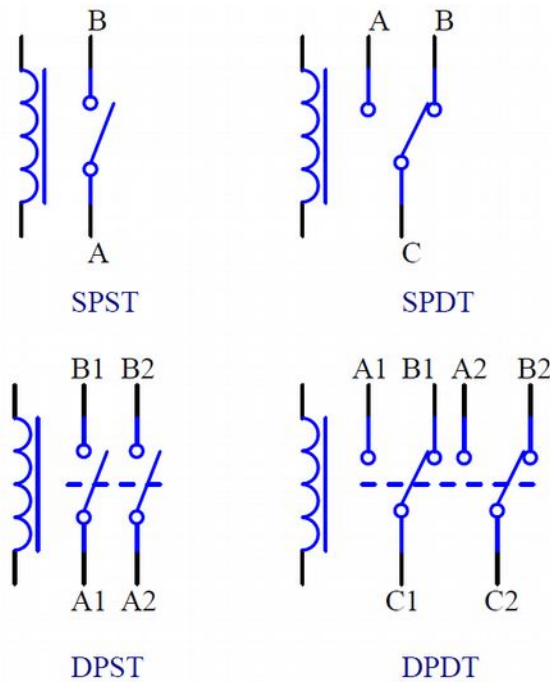


Figure 17 - Symbols of different relays

The symbols known for mechanical switches can also be found in the case of relays for output stages. If we combine the bistable and DPDT output stages, then the internal structure will look the following way.



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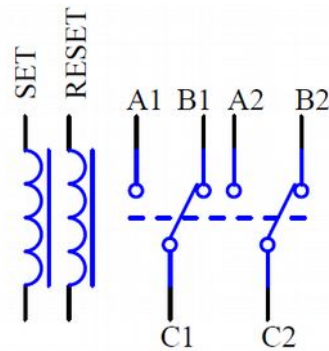


Figure 18 - Latching DPDT relay

Let's look at this device's operation to help understanding it. The (C1) and (C2) terminals are common contacts (poles), these can come in contact with pin (A) or (B). As we can see (dotted line in the figure), (C1) and (C2) depend on each other, so they can be switched at once to direction (A) or (B). So, this is our output stage. Our input stage contains two coils because of its bistable operation, a Set and a Reset coil.

Suppose that the (C) pins are in contact with the (A) pins by default. If we connect appropriate voltage to the Set coil, then the (C1) and (C2) contacts draw to contacts (B1) and (B2). After eliminating the voltage, the contacts (C) will stay in stable state by still in contact with pins (B). If you want the terminals (A) and (C) to come into contact again, you will need to connect appropriate voltage to the Reset coil. Once the voltage has been removed, the contacts remain similarly stable.

Operation	Contact of C1	Contact of C2
Voltage, connected to the Set coil	B1	B2
Termination of voltage on the Set coil	B1	B2
Voltage, connected to the Reset coil	A1	A2
Termination of voltage on the Reset coil	A1	A2

What Is The Relay For?

We often use relays if we would like to switch higher voltage (24-230 V) by small voltage (for example 12 V). There are such relays, which are able to switch tens and hundreds of amps as well, while we only have to transfer a fraction of the power through their coil.

Another important role of relays is the galvanic separation, which is used for electrical isolation of parts of electronic devices. It is important when separating parts. When separating parts, it's important, that an electric charge carrier should not be transferred from one unit to another unit. A typical area of application can be, if a low voltage circuit (for example 12 V) switches several networks (230 V AC) consumers (for example lighting). The interface (buttons, touchscreen), which can be touched by anybody, is placed on the low voltage side of the circuit. We don't want these interfaces to be exposed to the high voltage in any way, as this will increase the risk of electric shock. It's solvable with the help of relays, that the high voltage parts are isolated from the low voltage side.



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There are several other solutions for galvanic separation, which will be discussed in the later part of the curriculum.

BIPOLAR JUNCTION TRANSISTOR (BJT)

The following switch device we will get to know, is the bipolar transistor. We can look at this device as the basic component of nowadays electronics. Their discovery bought a big breakthrough to the history of electronics, with the help of them, the size of electronic components has reduced by leaps and bounds, while their reliability has increased too. Currently we can find bipolar transistors on their own or rather as the basic components of integrated circuits.

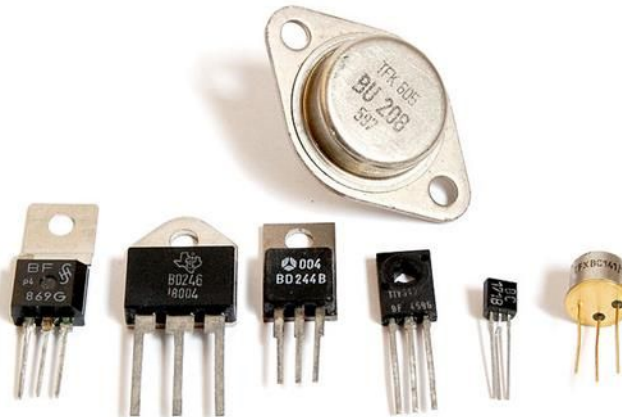


Figure 19 - Bipolar transistor

We're talking about semiconductor devices, the physics behind their operation goes beyond the limits of these curriculum, so I won't describe it in detail.

Symbol

The bipolar transistor has three terminals which are named as the base (B), collector (C) and emitter (E). In wiring diagrams, they are marked the way the figure below shows it.

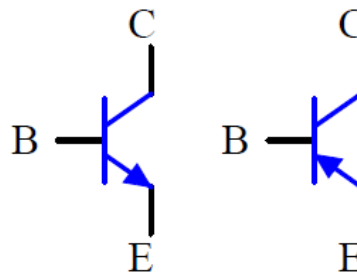


Figure 20 - Symbols of n-p-n type and p-n-p type transistors

Two types of transistor exist, according to the figure above, the first one is referred as „nnp” type, the other is referred as „pnp” type. As we mentioned before, transistors are made out of semiconductor material, the „n” and the „p” indicate that each semiconductor layer is formed from a semiconductor type „n” or „p”. Certainly, the behaviour of the npn transistor is different to the behaviour of pnp type, for the time being, let's stick to the npn type, later we will examine the differences.



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Operation of NPN Transistors

If we would like to demonstrate the operation of transistors, using a **simplified** model, a current controlled current source is the best approach. We can imagine that, we have a current source of which output current can be controlled by the input current.

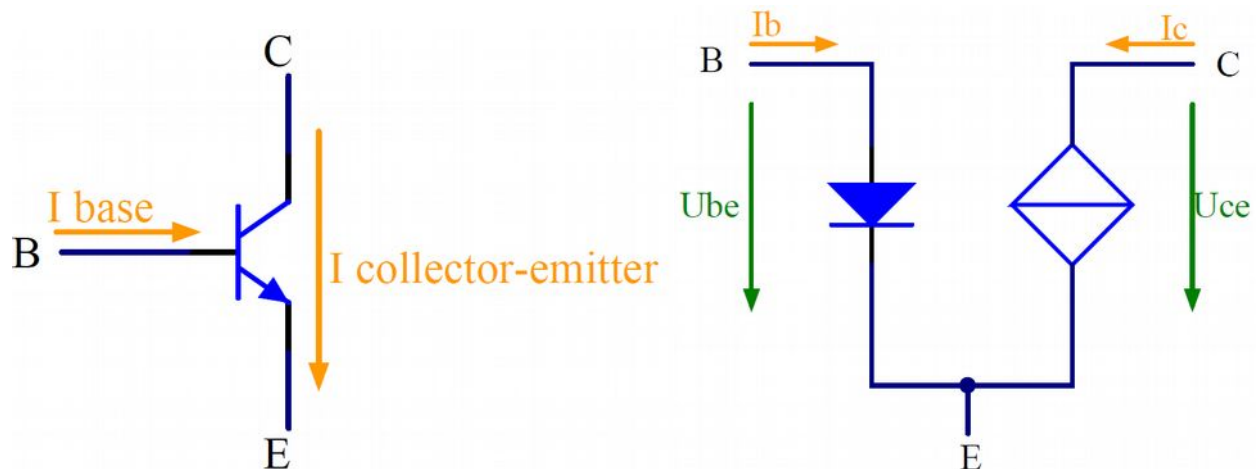


Figure 21 - Simplified replacement circuit of npn transistor

In case of transistors, the current (I_C), that flows between the collector and emitter, can be affected by the current of the base (I_B), where the current amplification factor determines the connection of the two current values.

$$I_C = \beta \cdot I_B$$

You may find it strange, that we drew a diode between the emitter and the base of the current controlled current source model. Due to the design of the BJT transistors, there is a p-n junction between the base and the emitter, which, if you think back, is practically a diode. If we connect a voltage, properly high enough, to the base-emitter diode, then the diode will open, therefore, current will start to flow through the base. (the forward voltage is usually around 0.7 V).

Due to the current of base, current is able to flow through the collector, maximum beta factor of base current. In this case, we say that the transistor is closed. If we don't open the diode, current doesn't flow through the base, and like this, current won't flow between the collector-emitter either, i.e. it will behave as a break. In the present, we say that the transistor is open.

To conduct current between the collector and the emitter, it is required, that the voltage of the emitter has to be lower, compared to the voltage of the base. In case of proper voltages, the following current directions will be true.



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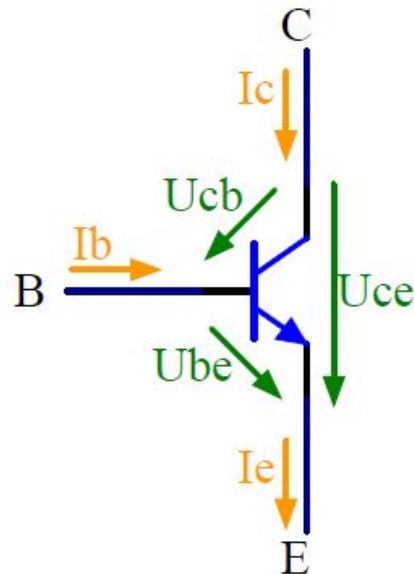


Figure 22 - Voltage of the npn transistor and its currents

The BJT Transistor as a Switch

With the help of the following connections, we can examine the operation of the BJT transistor in a circuit.

The current of the emitter has to be the sum of the current that flows through the base and the collector.

$$I_E = I_B + I_C$$

As we noted before, every BJT transistor has a parameter, which shows that, in case of closed state, how many times the current on the collector is bigger than on the base. This parameter is usually called beta.

$$I_C = \beta \cdot I_B$$

Let's look at a practical example, which can be used to understand the operation of a BJT transistor as a switch. On the breadboard, assemble the circuit, shown below! As a little help, look at the figure that shows the terminals of the transistor.



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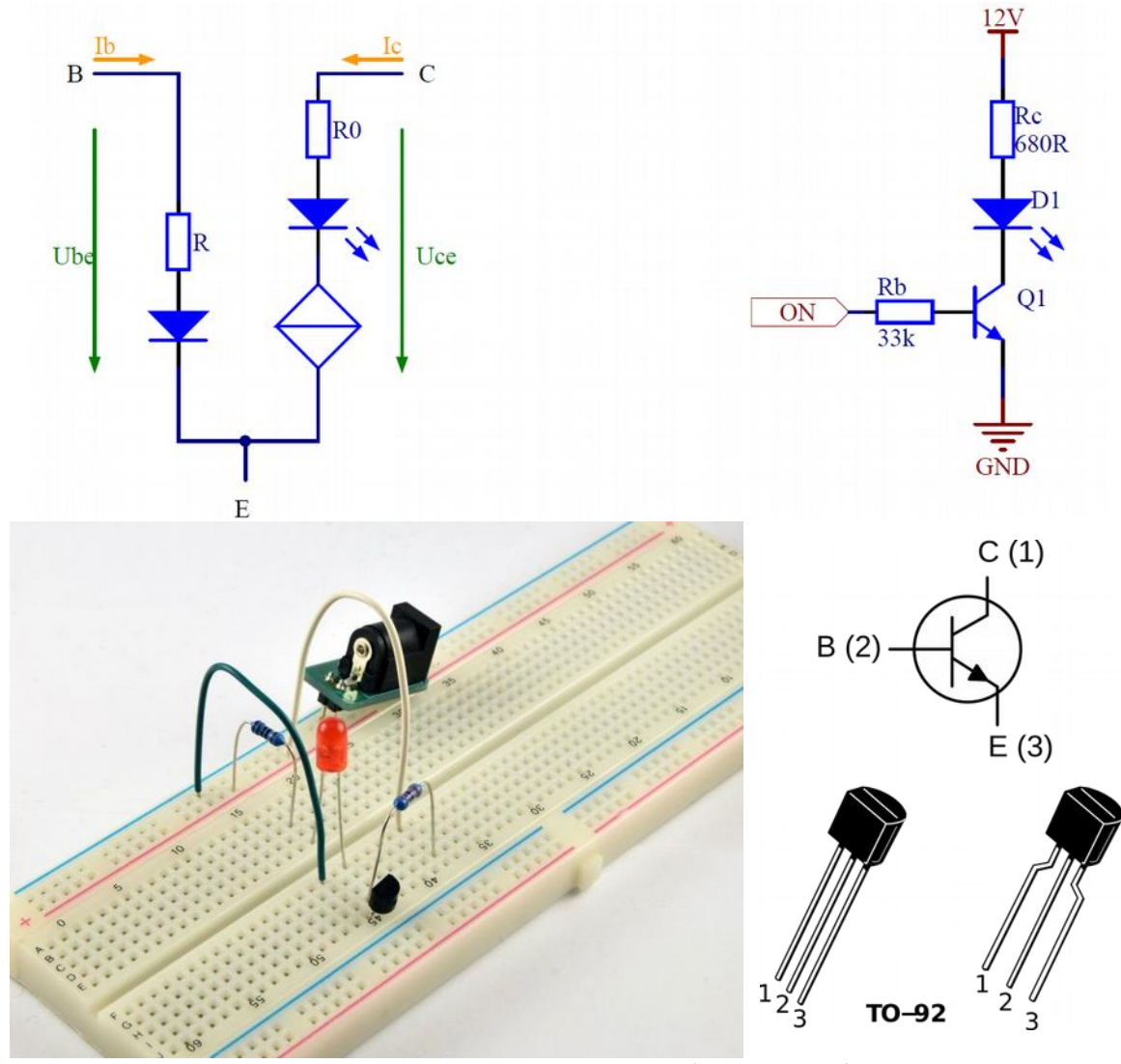


Figure 23 - Using the transistor as a switch (ON/OFF control)

ON/OFF Control

If you connect the „ON” point to 12 V, then the LED will light up. In this case, a current will start to flow through the R_B resistor, which will flow through the transistor’s base-emitter diode. The value of the base current can be calculated the following way:

$$I_B = \frac{U_{ON} - 0.7[V]}{R_B} = \frac{12[V] - 0.7[V]}{33[k\Omega]} = 0.34 [mA]$$

Ideally, the collector current can be beta-times the base current (the beta of BC546B transistor is around 180), i.e.

$$I_C = \beta \cdot I_B = 180 \cdot 0.34[mA] = 61 [mA]$$

Calculate what would happen if we simply connected the cathode of the LED diode to the GND! If the LED’s forward voltage is 2 V then the voltage of the R_C resistor will be 10 V, i.e. its current will be



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$$I_{RC} = \frac{10 \text{ [V]}}{680 \text{ [\Omega]}} = 14.7 \text{ [mA]}$$

If you measured the current of the diode in the transistor circuit, you would measure around 14 mA. You could ask that how this is possible, because we calculated that the collector current could be 61 mA as well. Truly, the calculated collector current is a maximum value. This means that, if a current flows through the collector of the transistor, which is smaller than the calculated value, then the transistor, between its collector and emitter, acts like a short circuit, i.e. it is fully turned on. If we would like to use a BJT transistor as a switch, then we will always have to choose the base current as its beta multiplied value will have to be way bigger than the switched current.

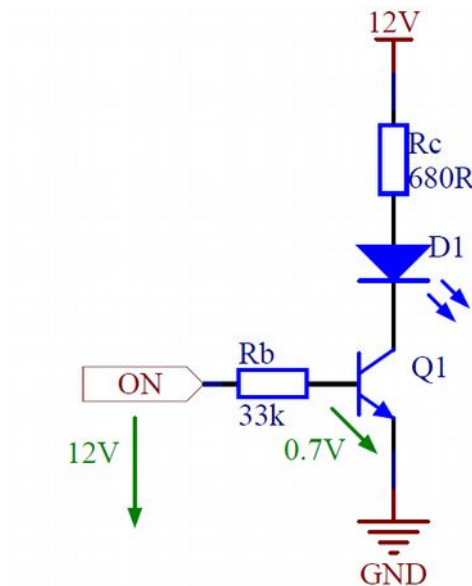


Figure 24 - Sizing of transistor switch

Let's look at how a BJT switch should be sized.

First of all, we have to know the transistor's beta. It's important to notice, that, the beta of devices can have values on a wide scale, and it depends on various things. Before they come out from the manufacturer, their features are already different, not to say, the β depends heavily on the temperature of the transistor as well. So we have to size the circuit like the transistor have to be open enough in every operational status. We can provide that if we calculate using the smallest occurred β value, because this is the worst case. So you have to find the smallest β for your type of transistor, which you will find as h_{fe} in the datasheet, and you choose the smallest. In our case, it's

$$\beta = 150$$

We know that, we need to provide properly high voltage between the base-emitter in order to make sure our transistor is in forward mode, that voltage is about 0.7 V.

$$U_{BE} = 0.7 \text{ [V]}$$

In our circuit, our consumer is an LED, through which we would like to drive, say, 15 mA of current. Our collector current is 15 mA.



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$$I_C = 15 \text{ [mA]}$$

$$I_C = \beta \cdot I_B \Rightarrow I_B = \frac{I_C}{\beta} = \frac{15 \text{ [mA]}}{150} = 0.10 \text{ [mA]}$$

We can write down the following equation for the base resistor

$$R_B = \frac{U_{ON} - U_{BE}}{I_B} = \frac{12 \text{ [V]} - 0.7 \text{ [V]}}{0.10 \text{ [mA]}} = 113 \text{ [k}\Omega\text{]}$$

Obviously, the calculated resistance value is a maximum value. If we used a larger one, the base current would be too small for the required collector current.

The minimum base resistance value can be determined from the maximum permissible base current, but this value is not always specified in the transistors' datasheet. In this case, the maximum base current can be estimated using the h_{fe} and the maximum collector current, using the following formula

$$I_B^{max} = \frac{I_C^{max}}{\beta} = \frac{100 \text{ [mA]}}{150} = 0.66 \text{ [mA]}$$

$$R_B^{min} = \frac{U_{ON} - U_{BE}}{I_B^{max}} = \frac{12 \text{ [V]} - 0.7 \text{ [V]}}{0.66 \text{ [mA]}} = 17.12 \text{ [k}\Omega\text{]}$$

So the resistance of the base has to be between 17.12 k Ω and 113 k Ω for safety operation. In our practical example, we used 33 k Ω resistor, which falls within this range.

Now, measure the transistor's collector voltage using your multimeter compared to the GND, when the transistor is turned on. If everything works well, you will measure a value underneath 1 V, i.e. the transistor will truly turn on, it will connect its collector to the emitter.

Now change the R_B to a 680 k Ω resistor. What kind of change did you experience in the collector voltage and what could be the reason for that?

The bigger base resistance results smaller base current. The 680 k Ω reduces the base current so much, that the transistor can no longer drive the LED, therefore, the collector voltage increases, no longer works as an „ideal” switch!

Feel free to try other resistance values as well, but be careful not to use less resistance than the calculated minimum resistance!

Use of PNP Transistors

The sequence of layers is different, but what is the difference when a circuit is implemented with these devices?



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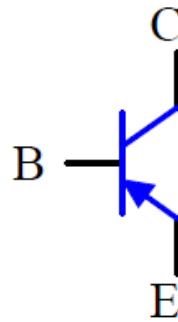


Figure 25 - Symbol of pnp transistor

If you have a better look at this kind of transistor, a p-n junction can be also found between its base and emitter, which is equivalent to a diode, however it is an opposite direction diode compared to the npn transistor. The proper wiring can be seen in the following figure:

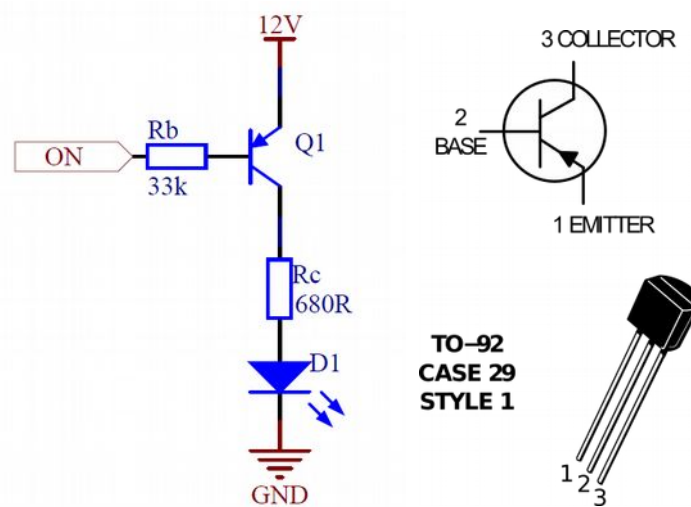


Figure 26 - Switch circuit using pnp transistor

At this type, the emitter will be higher than the collector, in terms of voltage, and current directions will be the following.

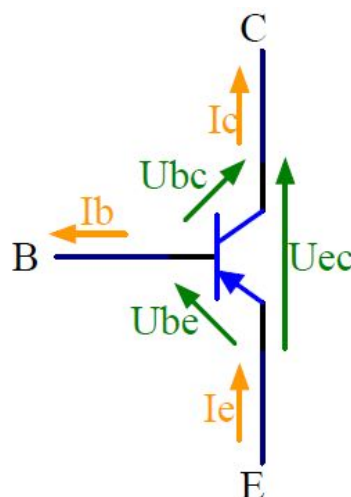


Figure 27 - Voltage and current conditions of pnp transistor



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The equations, learnt during npn transistors, also apply to pnp transistors, only the directions of currents and voltages have changed.

The only difference, in its operation is that, the LED will only light up if you connect the „ON” point to the GND, not when you connect it to the 12 V.

NPN and PNP transistors are manufactured as well, but the NPN switches are faster and their production cost is lower as well, thus this one is used more often in control and switch circuits. In case of amplifier circuits, NPN and PNP transistors are used together.

MOSFET

The following switch type, at which we will have a look, is the MOSFET. These components can be called as insulator layer field effect transistors, which originates from its structure and operation.

Don't be afraid! It isn't complicated!

The MOS acronym is the short form of the English words Metal Oxide Semiconductor, the FET consists of Field Effect Transistor, which refers to the fact that it is field-controlled. Also, the MOSFET has different types, we will examine the one, which operates in enhancement mode.

Similarly, to bipolar transistors, these switch devices also have 3 terminals, which are the Drain (D), Source (S) and Gate (G). Its symbol used on wiring diagrams can be seen in the following figure.

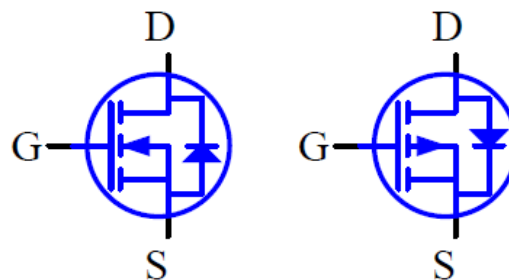


Figure 28 - Symbol of N channel and P channel MOSFETs

On the left side, you can see the so-called N channel, on the right side, the so-called P channel variant of enhancement type MOSFET. Their operation is very similar to bipolar transistor's operation, the biggest difference is that we control these with voltage, not with current.

We can pull something down to ground with the N channel MOSFET, so the Source's voltage has to be lower compared to the Drain's voltage.

(In case of connecting inversely the Drain-Source terminals, then the Source will be on higher potential and because of its structure, the so-called body-diode will open, through which current will be able to flow.)

With the help of P channel MOSFET, we can pull something up to supply voltage (In reverse case, the body diode will open.)

The control electrode of the device is the Gate terminal and the current conduction between the Drain-Source can be affected with it. In case of N channel MOSFET, between Drain-Source, a current conductive



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channel appears because of the controlling, and charges are able to flow through this channel from the Drain to the Source.

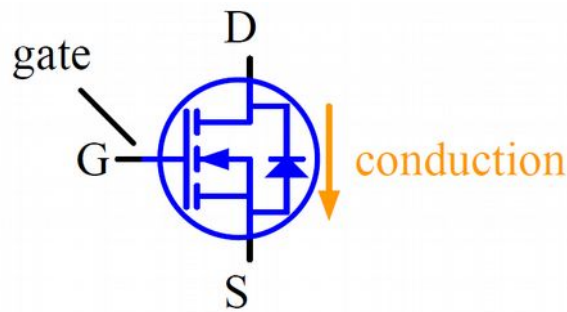


Figure 29 - Control electrode and current conduction, in case of N-channel MOSFET

Between the Gate-Source terminals, because of its internal structure, there is a so-called Gate-capacity, and we can control the channel by charging or discharging this capacitor. Short-time current impulse flows through the capacitor when charging or discharging it, but if the Gate-capacitor has been charged already, then current won't flow from the direction of the Gate terminal.

It is important that the Gate terminals should not be left freely „float”, because the capacitor will charge up, because of leaking charges, which come through the Gate electrode, and in spite of our will, the MOSFET will open. To make sure, that the capacitor doesn't charge up unintentionally, we have to insure the discharge of the capacitor, in case of uncontrolled Gate electrode. A solution for this is the pull up/down resistor, which I will present later.

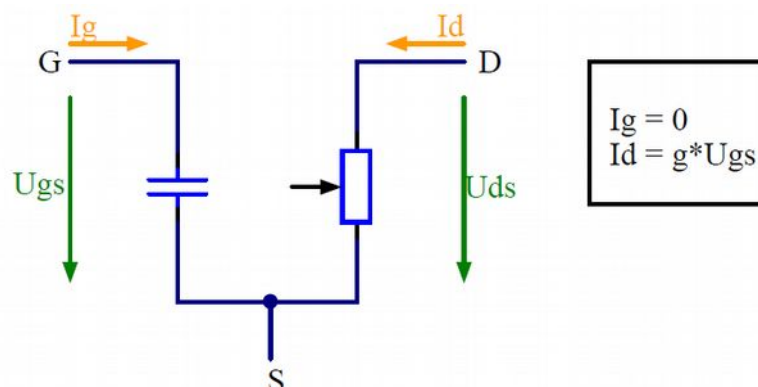


Figure 30 - Simplified replacement circuit of MOSFET

THE GATE-CAPACITOR AND THE CONTROLLED RESISTOR IN THE MODEL OF MOSFET

We will examine the MOSFET as a switch element, so its simplified model is a voltage-controlled resistor, which we use in order to approach its operation. The Drain current (I_D) depends on the Drain-Source voltage (U_{DS}).

You can find the Drain-Source resistance in the datasheet with the $R_{ds(on)}$ marking, which gives its value, when the MOSFET is fully open. Considering its operation, if we increase the gate-source voltage (U_{GS}), then the drain-source resistance will decrease and the I_D will increase. The amount of heat, the FET creates during current conduction, depends on the resistance value, the lower the $R_{ds(on)}$ resistance, the lower the heat loss (dissipation) will be.



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We have to look for the following data in the datasheet:

Symbol in the datasheet	Description
U_{DS}	Permissible drain-source voltage
i_D	Permissible continuous drain current
U_{GS}	Permissible gate-source voltage
P_D	Permissible largest heat loss
$U_{GS} (th)$	Gate-Source threshold voltage - that's when the conductive layer will start to appear between the drain source

You already know its essential operation, controlling, now let's examine the two types of MOSFET.

N-channel Enhancement Type MOSFET as a Switch

In the following figure, you can see the current and voltage directions of the N-channel MOSFET.

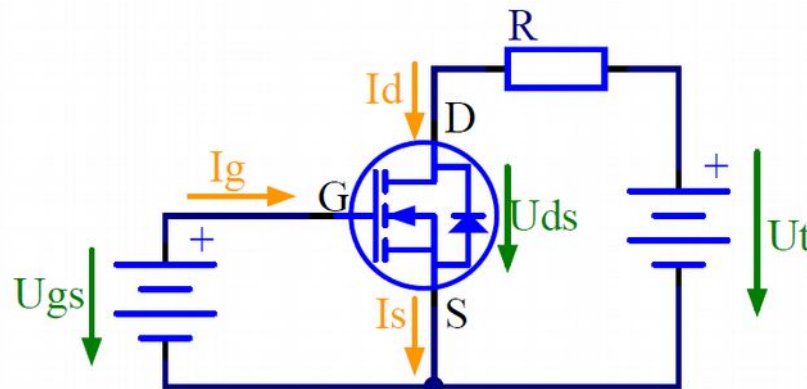


Figure 31 - Voltage and current directions of N channel MOSFET

Let's look at our well-known example again, in order to inspect our switching element during its operation.

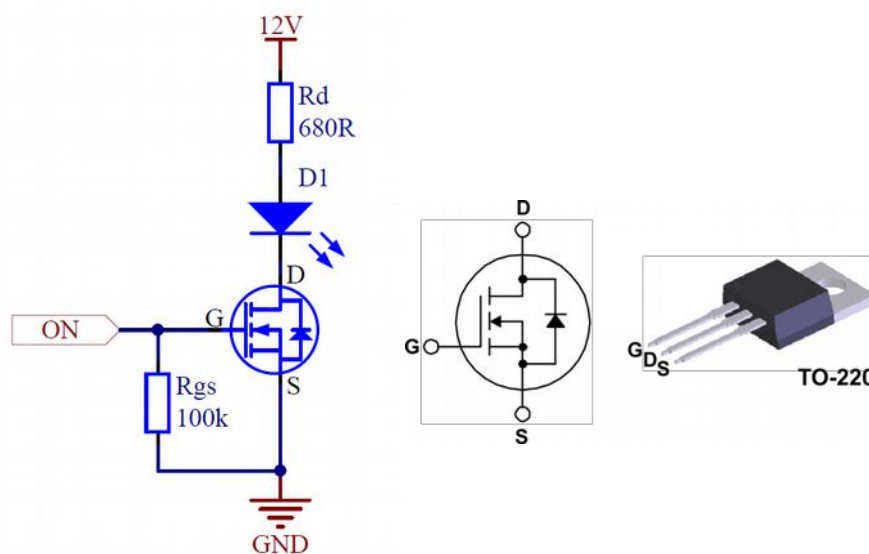
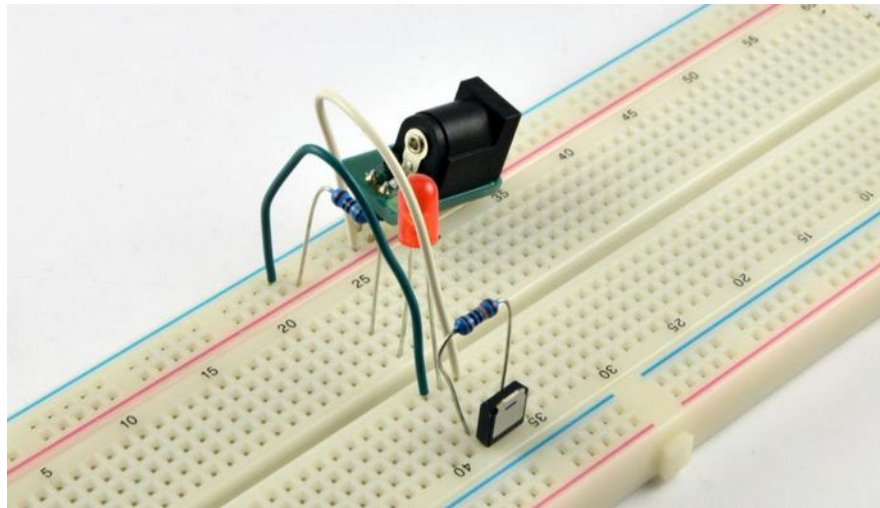


Figure 32 - Using the N-channel MOSFET as a switch

After the assembly of our circuit, let's look at each component's function in the circuit. The LED goes into the higher voltage drain branch with the associated R_D resistor. We connect the source terminal of the MOSFET to the ground, so in case of conduction, our circuit will be closed, and our LED will need to light up. There is a parallel R_{GS} , so-called pull down, resistor between the gate-source terminals, so if we don't drive the gate with a control signal, it won't even float, it will be on fixed GND potential, i.e. it will stay in turned off state.

The pull-down resistor is a solution where we connect the terminal to a lower voltage point, through a resistor, so in case of uncontrolled electrode, it will be on constant voltage, and the operation of the device won't be uncertain. Typically, we „draw” the terminal to the ground.

In the circuit, we have to connect proper voltage to the „ON” point, which will turn on the FET and the LED will start to light up. This is the minimum layout required for proper operation.



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P-channel Enhancement Type MOSFET

Current and voltage directions of the P-channel MOSFET will be the following.

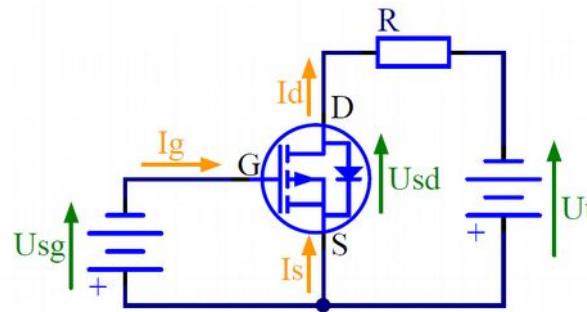


Figure 33 - Current and voltage directions of P-channel MOSFET

The LED circuit built with MOSFET is possible the following way.

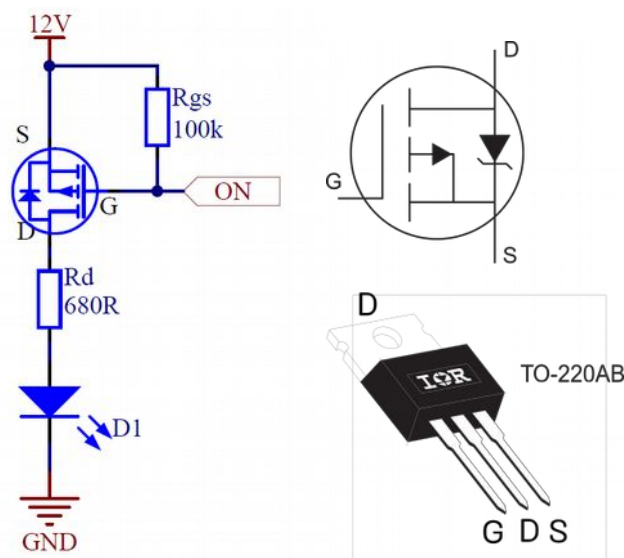


Figure 34 - Using P-channel MOSFET as switch

The given components' role is the same as it was in the N-channel LED circuit. The only difference is the R_{GS} resistor, which now acts as a pull up resistor.

The pull up resistor connects a certain terminal to a higher voltage point, as its name suggests this. Similarly to the pull-down resistor, the input of the controller is on a defined potential all the time.

OPTOCOUPLER

The optical coupler, or its everyday name, optocoupler, can be classified as a switch. You will learn more about this switch type during a later part of curriculum.



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MEASUREMENT OF SWITCHING DEVICES USING A MULTIMETER

In the next section, we will see how our multimeter can easily and quickly check that the devices described so far (for example, during previous use) have failed.

During these measurements, it's important to measure these switches as independent components, i.e. it has to be disconnected from everything, because you will get false results for the measurement. So you will only need your multimeter and component which you would like to measure. It's practical to find the measured component's datasheet on the internet at first, in order to know, what you should measure on each and what the wiring of the device is. Let's look at the measures for each component.

BIPOLAR TRANSISTORS

Examination of NPN Transistors - Base Terminal Short Circuit

We have to do this measurement by using the multimeter's diode measure option, so switch the device into this function.

If you would like to decide whether there's a short circuit between the base and one of its terminals (collector or emitter), then at first, you will have to find the pin assignment of the transistor. In case of BC546B, you will find the following:

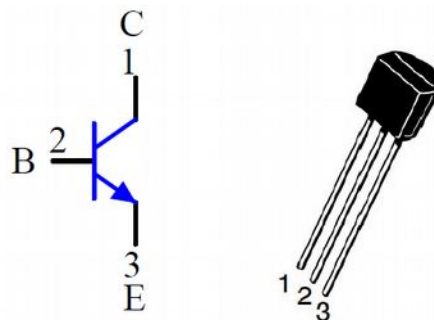


Figure 35 - Pin assignment of BC546B

If this is completed, then, you connect the red measuring cable to the base, the black measuring cable to the collector, the way the figure below shows that.

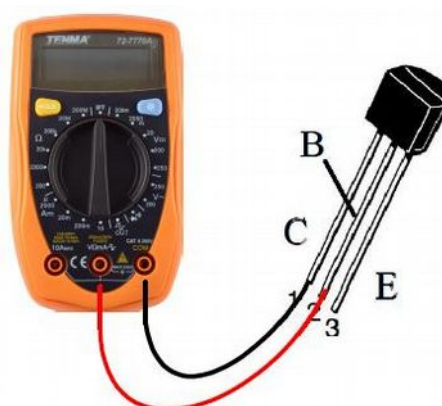


Figure 36 - Measuring the base-collector p-n junction of BC546B



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What does the multimeter show? If you can see a value around 600-680 (forward voltage of p-n junction) on the display, then your transistor's two terminals are proper, they aren't wrong. If the multimeter shows a very small or 0 value, then probably there's a short circuit between the two terminals. If you see a value of 1 on the display, then there's a break between the base-collector. In the last two cases, our parts are faulty.

We do the same investigation between the base-emitter, but now, we connect the red measuring cable to the base, the black measuring cable to the emitter.

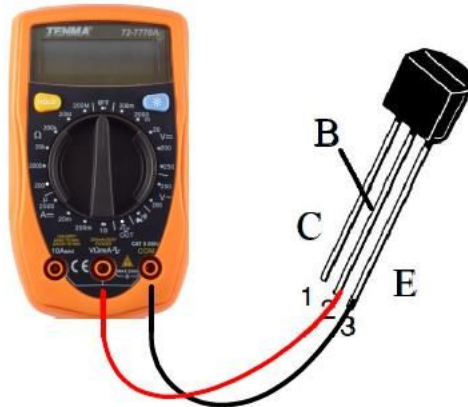


Figure 37 - Measurement of base-emitter p-n junction of BC546B

The feedback will be the same as it happened previously.

Examination of PNP transistors - Base Terminal Short Circuit

If we would like to measure a short circuit between the base and other terminals of a PNP transistor, then it will be different, the way we connect the black measuring cable to the base, the red measuring cable to the other two terminals. From now on, the way we measure, is the same as it was before. Don't forget that, the pin assignment of PNP transistors can be different, so you need to find the pin assignment in its datasheet.

Checking Collector-Emitter Short Circuit

The measures are the same for the NPN and PNP transistors, but the pin assignment can be different. Our multimeter should be switched to the diode measure option.

In our example, we will measure a collector-emitter short-circuit using an NPN transistor. Actually, we would like to measure the connection between the collector and emitter terminals, so we have to connect our measuring cables to these two electrodes. In this case, we don't really care about the colour of measuring cables. For example, let's connect the black measuring cable to the Collector, the red one to the Emitter.



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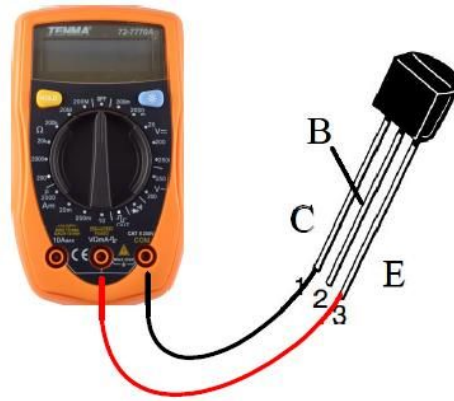


Figure 38 - Examination of short circuit between collector-emitter of BC546B

If the multimeter shows 1, then there's a break between the collector-emitter, which means that it's perfect. However if it's 0, or the device shows a very small value, then unfortunately the two terminals of the transistor are shorted.

MOSFET

Measurement of Gate-Source and Gate-Drain Resistance

This measurement can be done with the multimeter's resistance measure option, so you have to switch the device to this state.

The measurement can be done to both N-channel and P-channel MOSFETs as well (you have to be careful, because the polarities are inverse on these devices). In the example, I will use the N-channel MOSFET.

In the datasheet, look up the pin assignment again.

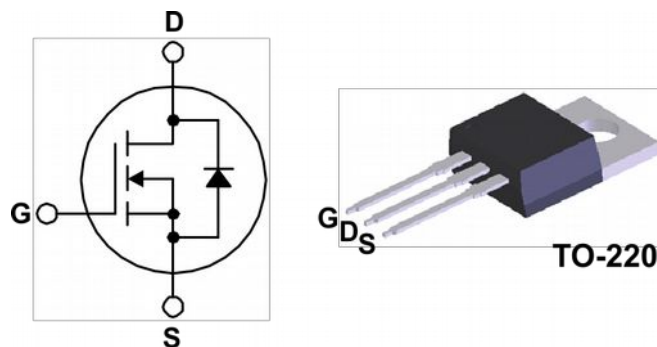


Figure 39 - Pin assignment of an N-channel MOSFET

First, we connect the two measuring cables, of the multimeter, to the gate and source terminals.

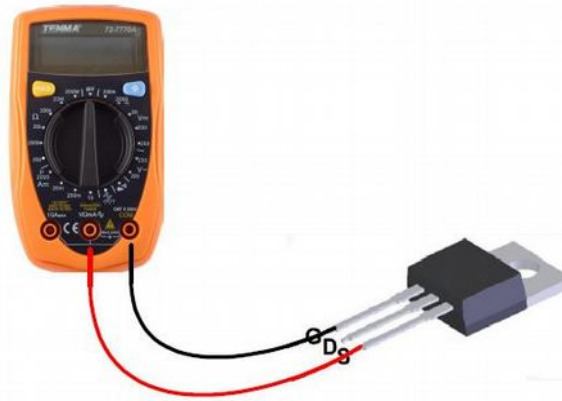


Figure 40 - Examination of gate-source short-circuit, in case of N-channel MOSFET

If the ohmmeter indicates a break (1), then the device likely works, inversely, if you get a measurable resistance, then it's sure, that the FET is faulty, i.e. the gate has punched through.

Repeat the measurement between the gate and drain terminals as well, in order to find out if there's a punch through. In this case as well, if you're able to measure resistance between the two contacts, then the device can't be used for switching henceforward.



Figure 41 - Examination of gate-drain short circuit, in case of N-channel MOSFET

Measurement of Conduction Between the Drain and Source When the FET is Open

During the measurement, you have to switch the multimeter to the diode measure option. Be careful not to touch the terminals of the device with your hand, because it will affect the result. Connect the negative pole to the MOSFET's source pin, during the measurement this will stay unchanged. Connect the multimeter's positive cable to the drain of the MOSFET. In this case, it can happen, that the multimeter will show a short-circuit or break. This depends on the state of the gate capacitor which we don't know. Now let's discharge the gate capacitor with the help of your finger, like so, you touch the gate and the source terminals at once. If you are done with this, there should be a break between the drain and the source. Now take off the positive measuring cable from the drain terminal, and connect it to the gate leg. Wait a few seconds and carefully put back the red cable to the drain terminal. If all true, you will have to experience a short-circuit between the drain-source. The question is, why it is like that? When your positive cable was on the gate terminal, the gate capacitor was charged up by the small current of the multimeter, so the FET became open. After the displacement of the measuring cable, our device indicated conduction between the drain and source.



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Measurement of the Body (Drain-Source) Diode

During the measurement, we short-circuited the gate and the source terminals, and we have to switch the multimeter to diode measurement mode:

drain - red measuring cable
source - black measuring cable

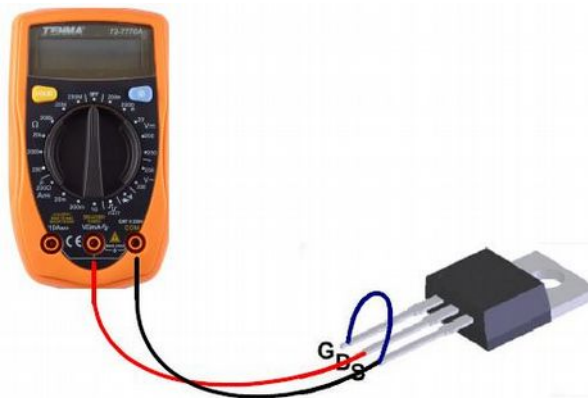


Figure 42 - Measure of N-channel MOSFET's body diode in reverse direction

During this measurement, we have to measure a break, i.e. we have to see a number 1 on the multimeter's display. The reason for this is that we don't charge the gate capacitor because of the short-circuit, so the FET isn't open. In case of connecting the drain-source properly, current won't flow, i.e. you can consider it as a break.

Let's replace the measuring cables:

source - red measurement cable
drain - black measurement cable

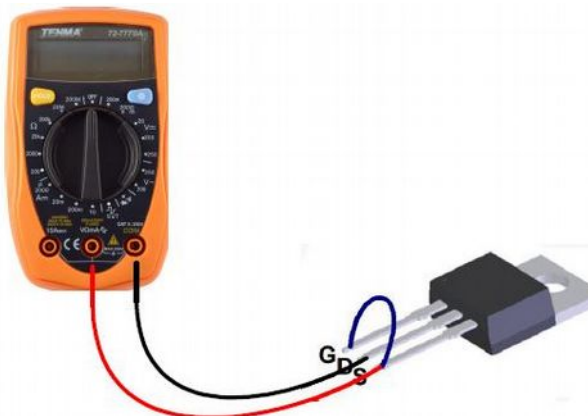


Figure 43 - Measure of N-channel MOSFET's body diode in forward direction

In this case, we should see a value around 500-600, if it works properly. The reason for this is that, the gate capacitor is not charged up again, so the FET isn't open. We have changed the drain-source voltage levels. If you remember, previously, I mentioned the body diode in the MOSFET, which will conduct in case of inverse connection. We presented this phenomenon and you successfully managed to measure the body-diode.



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These are typical measurements, which we can do with a multimeter, in order to check the components.

WHY DO WE MEASURE THE FAULTS THIS WAY?

In all cases, we start from the internal structure and the expected operation. For example, we measure, whether a p-n junction, or body diode, the expected value of 0.6 V falls and leads only in one direction. We can test if it actually opens a MOSFET or if it has to be a break somewhere, then there is a break.

WHAT CAN YOU DO IF THE COMPONENT IS FAULTY?

If you don't receive the expected result during one of the measurements, even after multiple tries, then the component is faulty. In this case, place it selectively in electronic waste bin immediately, because it will only give you a headache if it doesn't produce the expected behaviour later.

This is the end of our work together. I'm glad I was able to guide you through your studies, and I hope I've made it easier to understand the switching devices. I wish you good luck for the rest!



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