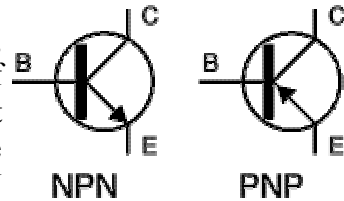


Transistor Circuits

This page explains the operation of transistors in circuits. Practical matters such as testing, precautions when soldering and identifying leads are covered by the [Transistors](#) page.

Types of transistor

There are two types of standard transistors, **NPN** and **PNP**, with different circuit symbols. The letters refer to the layers of semiconductor material used to make the transistor. Most transistors used today are NPN because this is the easiest type to make from silicon. This page is mostly about NPN transistors and if you are new to electronics it is best to start by learning how to use these first.



Transistor circuit symbols

The leads are labelled **base** (B), **collector** (C) and **emitter** (E). These terms refer to the internal operation of a transistor but they are not much help in understanding how a transistor is used, so just treat them as labels!

A [Darlington pair](#) is two transistors connected together to give a very high current gain.

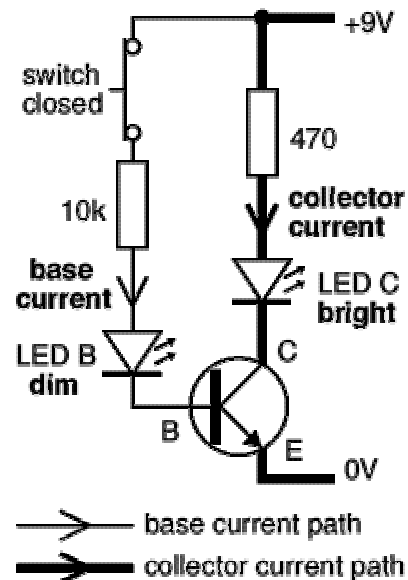
In addition to standard (bipolar junction) transistors, there are **field-effect transistors** which are usually referred to as **FETs**. They have different circuit symbols and properties and they are not (yet) covered by this page.

Transistor currents

The diagram shows the two current paths through a transistor. You can build this circuit with two standard 5mm red LEDs and any general purpose low power NPN transistor (BC108, BC182 or BC548 for example).

The small **base current** controls the larger **collector current**.

When the switch is closed a small current flows into the base (B) of the transistor. It is just enough to make LED B glow dimly. The transistor amplifies this small current to allow a larger current to flow through from



its collector (C) to its emitter (E). This collector current is large enough to make LED C light brightly.

When the switch is open no base current flows, so the transistor switches off the collector current. Both LEDs are off.

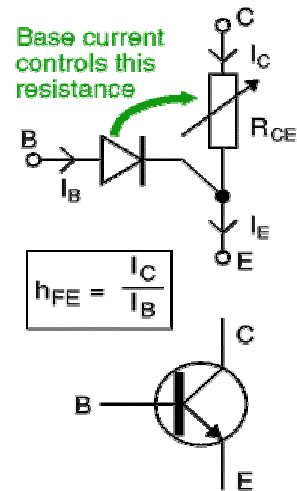
A transistor amplifies current and can be used as a switch.

This arrangement where the emitter (E) is in the controlling circuit (base current) and in the controlled circuit (collector current) is called **common emitter mode**. It is the most widely used arrangement for transistors so it is the one to learn first.

Functional model of an NPN transistor

The operation of a transistor is difficult to explain and understand in terms of its internal structure. It is more helpful to use this functional model:

- The base-emitter junction behaves like a [diode](#).
- A base current I_B flows only when the voltage V_{BE} across the base-emitter junction is 0.7V or more.
- The small base current I_B controls the large collector current I_C .
- $I_C = h_{FE} \times I_B$ (unless the transistor is full on and saturated)
 h_{FE} is the current gain (strictly the DC current gain), a typical value for h_{FE} is 100 (it has no units because it is a ratio)
- The collector-emitter resistance R_{CE} is controlled by the base current I_B :
 - $I_B = 0$ $R_{CE} = \text{infinity}$ transistor off
 - I_B small R_{CE} reduced transistor partly on
 - I_B increased $R_{CE} = 0$ transistor full on ('saturated')



Additional notes:

- A resistor is often needed in series with the base connection to limit the base current I_B and prevent the transistor being damaged.
- Transistors have a maximum collector current I_C rating.

- The **current gain h_{FE} can vary widely**, even for transistors of the same type!
- A transistor that is **full on** (with $R_{CE} = 0$) is said to be '**saturated**'.
- When a transistor is saturated the collector-emitter voltage V_{CE} is reduced to almost 0V.
- When a transistor is saturated the collector current I_c is determined by the supply voltage and the external resistance in the collector circuit, not by the transistor's current gain. As a result the ratio I_c/I_B for a saturated transistor is less than the current gain h_{FE} .
- The emitter current $I_E = I_c + I_B$, but I_c is much larger than I_B , so roughly $I_E = I_c$.

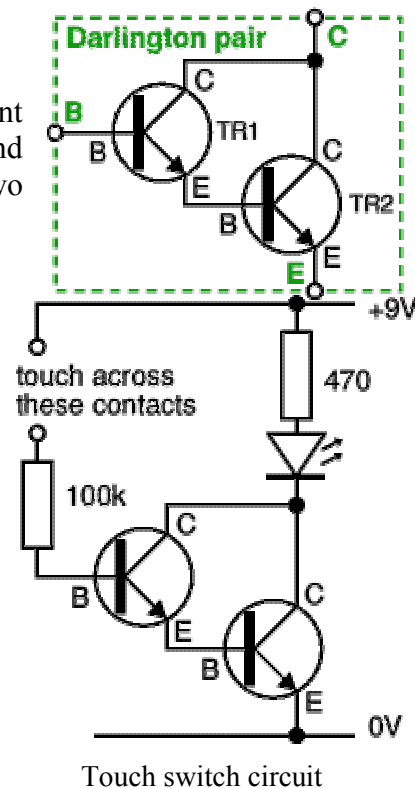
Darlington pair

This is two transistors connected together so that the current amplified by the first is amplified further by the second transistor. The overall current gain is equal to the two individual gains multiplied together:

Darlington pair current gain, $h_{FE} = h_{FE1} \times h_{FE2}$
(h_{FE1} and h_{FE2} are the gains of the individual transistors)

This gives the Darlington pair a very high current gain, such as 10000, so that only a tiny base current is required to make the pair switch on.

A Darlington pair behaves like a single transistor with a very high current gain. It has three leads (**B**, **C** and **E**) which are equivalent to the leads of a standard individual transistor. To turn on there must be 0.7V across both the base-emitter junctions which are connected in series inside the Darlington pair, therefore it requires 1.4V to turn on.

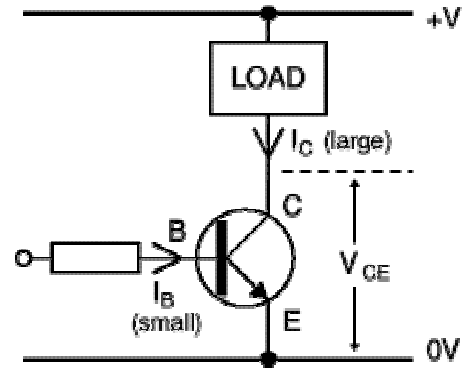


Darlington pairs are available as complete packages but you can make up your own from two transistors; TR1 can be a low power type, but normally TR2 will need to be high power. The maximum collector current $I_{c(max)}$ for the pair is the same as $I_{c(max)}$ for TR2.

A Darlington pair is sufficiently sensitive to respond to the small current passed by your skin and it can be used to make a **touch-switch** as shown in the diagram. For this circuit, which just lights an LED, the two transistors can be any general purpose low power transistors. The 100k Ω resistor protects the transistors if the contacts are linked with a piece of wire.

Using a transistor as a switch

When a transistor is used as a switch it must be either **OFF** or **fully ON**. In the fully ON state the voltage V_{CE} across the transistor is almost zero and the transistor is said to be **saturated** because it cannot pass any more collector current I_C . The output device switched by the transistor is usually called the 'load'.



The power developed in a switching transistor is very small:

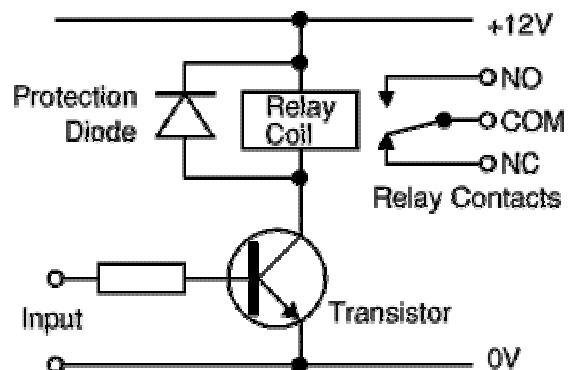
- In the **OFF** state: power = $I_C \times V_{CE}$, but $I_C = 0$, so the power is zero.
- In the **full ON** state: power = $I_C \times V_{CE}$, but $V_{CE} = 0$ (almost), so the power is very small.

This means that the transistor should not become hot in use and you do not need to consider its maximum power rating. The important ratings in switching circuits are the **maximum collector current $I_C(\max)$** and the **minimum current gain $h_{FE}(\min)$** . The transistor's voltage ratings may be ignored unless you are using a supply voltage of more than about 15V. There is a table showing technical data for some popular transistors on the [transistors](#) page.

For information about the operation of a transistor please see the [functional model](#) above.

Protection diode

If the load is a **motor**, [relay](#) or **solenoid** (or any other device with a coil) a [diode](#) must be connected across the load to protect the transistor from the brief high voltage produced when the load is switched off. The diagram shows how a protection diode is connected 'backwards' across the load, in this case a relay coil.



Current flowing through a coil creates a magnetic field which collapses suddenly when the current is switched off. The sudden collapse of the magnetic field induces a brief high voltage across the coil which is very likely to damage transistors and ICs. The protection diode allows the induced voltage to drive a brief current through the coil (and diode) so the magnetic field dies away quickly rather than instantly. This prevents the induced voltage becoming high enough to cause damage to transistors and ICs.

When to use a [relay](#)

Transistors cannot switch AC or high voltages (such as mains electricity) and they are not usually a good choice for switching large currents ($> 5A$). In these cases a [relay](#) will be needed, but note that a low power transistor may still be needed to switch the current for the relay's coil!



Advantages of relays:

- Relays can switch **AC and DC**, transistors can only switch DC.
- Relays can switch **high voltages**, transistors cannot.
- Relays are a better choice for switching **large currents** ($> 5A$).
- Relays can switch **many contacts** at once.



Disadvantages of relays:

- Relays are **bulkier** than transistors for switching small currents.
- Relays **cannot switch rapidly**, transistors can switch many times per second.
- Relays **use more power** due to the current flowing through their coil.
- Relays **require more current than many ICs can provide**, so a low power transistor may be needed to switch the current for the relay's coil.

Relays

Connecting a transistor to the output from an IC

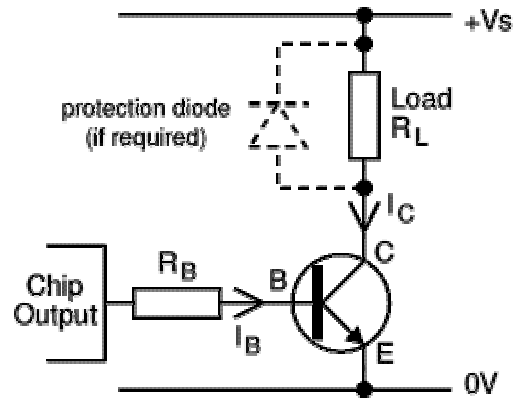
Most ICs cannot supply large output currents so it may be necessary to use a transistor to switch the larger current required for output devices such as lamps, motors and relays. The 555 timer IC is unusual because it can supply a relatively large current of up to 200mA which is sufficient for some output devices such as low current lamps, buzzers and many relay coils without needing to use a transistor.

A transistor can also be used to enable an IC connected to a low voltage supply (such as 5V) to switch the current for an output device with a separate higher voltage supply (such as 12V). The two power supplies must be linked, normally this is done by linking their 0V connections. In this case you should use an NPN transistor.

A resistor R_B is required to limit the current flowing into the base of the transistor and prevent it being damaged. However, R_B must be sufficiently low to ensure that the transistor is thoroughly saturated to prevent it overheating, this is particularly important if the transistor is switching a large current ($> 100mA$). A safe rule is to make the base current I_B about five times larger than the value which should just saturate the transistor.

Choosing a suitable NPN transistor

The circuit diagram shows how to connect an **NPN transistor**, this will switch on the load when the IC output is **high**. If you need the opposite action, with the load switched on when the IC output is **low** (0V) please see the circuit for a [PNP transistor](#) below.



The procedure below explains how to choose a suitable switching transistor.

1. The transistor's maximum collector current $I_{c(max)}$ must be greater than the load current I_c .

NPN transistor switch
(load is on when IC output is high)

$$\text{load current } I_c = \frac{\text{supply voltage } V_s}{\text{load resistance } R_L}$$

Using units in calculations
Remember to use V, A and Ω or V, mA and $k\Omega$. For more details please see the [Ohm's Law](#) page.

2. The transistor's minimum current gain $h_{FE(min)}$ must be at least **five** times the load current I_c divided by the maximum output current from the IC.

$$h_{FE(min)} > 5 \times \frac{\text{load current } I_c}{\text{max. IC current}}$$

3. Choose a transistor which meets these requirements and make a note of its properties: $I_{c(max)}$ and $h_{FE(min)}$. There is a table showing technical data for some popular transistors on the [transistors](#) page.
4. Calculate an approximate value for the base resistor:

$$R_B = \frac{V_c \times h_{FE}}{5 \times I_c} \quad \text{where } V_c = \text{IC supply voltage} \quad \text{(in a simple circuit with one supply this is } V_s)$$

5. For a simple circuit where the IC and the load share the same power supply ($V_c = V_s$) you may prefer to use: $R_B = 0.2 \times R_L \times h_{FE}$
6. Then choose the nearest standard value for the base resistor.
7. Finally, remember that if the load is a motor or relay coil a **protection diode** is required.

Example

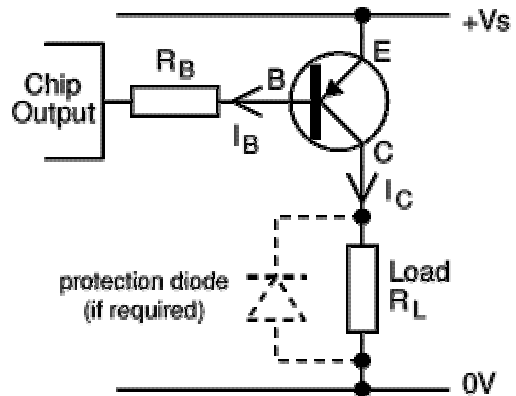
The output from a 4000 series CMOS IC is required to operate a relay with a 100Ω coil. The supply voltage is 6V for both the IC and load. The IC can supply a maximum current of 5mA.

1. Load current = $V_s/R_L = 6/100 = 0.06\text{A} = 60\text{mA}$, so transistor must have $I_{c(\text{max})} > 60\text{mA}$.
2. The maximum current from the IC is 5mA, so transistor must have $h_{FE(\text{min})} > 60$ ($5 \times 60\text{mA}/5\text{mA}$).
3. Choose general purpose low power transistor **BC182** with $I_{c(\text{max})} = 100\text{mA}$ and $h_{FE(\text{min})} = 100$.
4. $R_B = 0.2 \times R_L \times h_{FE} = 0.2 \times 100 \times 100 = 2000\Omega$. so choose $R_B = 1\text{k}\Omega$ or $2\text{k}\Omega$.
5. The relay coil requires a **protection diode**.

Choosing a suitable PNP transistor

The circuit diagram shows how to connect a **PNP transistor**, this will switch on the load when the IC output is **low** (0V). If you need the opposite action, with the load switched on when the IC output is **high** please see the circuit for an [NPN transistor](#) above.

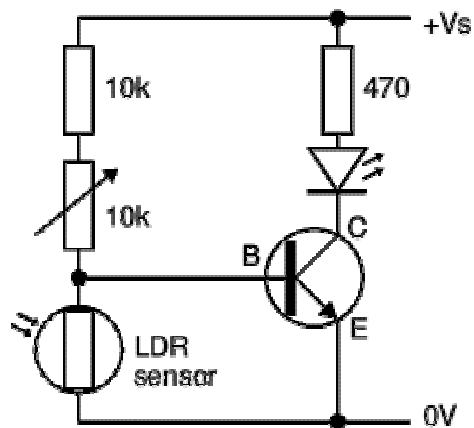
The procedure for choosing a suitable PNP transistor is exactly the same as that for an NPN transistor described above.



PNP transistor switch
(load is on when IC output is low)

Using a transistor switch with sensors

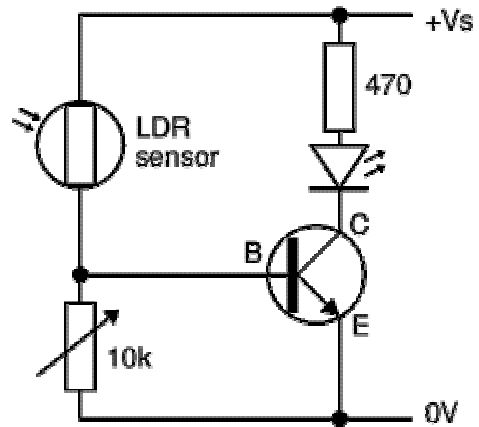
The top circuit diagram shows an [LDR](#) (light sensor) connected so that the LED lights when the LDR is in darkness. The variable resistor adjusts the brightness at which the transistor switches on and off. Any general purpose low power transistor can be used in this circuit.



LED lights when the LDR is dark

The $10k\Omega$ fixed resistor protects the transistor from excessive base current (which will destroy it) when the variable resistor is reduced to zero. To make this circuit switch at a suitable brightness you may need to experiment with different values for the fixed resistor, but it must not be less than $1k\Omega$. If the transistor is switching a load with a coil, such as a motor or relay, remember to add a [protection diode](#) across the load.

The switching action can be inverted, so the LED lights when the LDR is brightly lit, by swapping the LDR and variable resistor. In this case the fixed resistor can be omitted because the LDR resistance cannot be reduced to zero.



LED lights when the LDR is bright

Note that the switching action of this circuit is not particularly good because there will be an intermediate brightness when the transistor will be **partly on** (not saturated). In this state the transistor is in danger of overheating unless it is switching a small current. There is no problem with the small LED current, but the larger current for a lamp, motor or relay is likely to cause overheating.

Other sensors, such as a [thermistor](#), can be used with this circuit, but they may require a different variable resistor. You can calculate an approximate value for the variable resistor (R_v) by using a [multimeter](#) to find the minimum and maximum values of the sensor's resistance (R_{min} and R_{max}):

Variable resistor, $R_v = \text{square root of } (R_{min} \times R_{max})$

For example an LDR: $R_{min} = 100\Omega$, $R_{max} = 1M\Omega$, so $R_v = \text{square root of } (100 \times 1M) = 10k\Omega$.

You can make a much better switching circuit with sensors connected to a suitable IC (chip). The switching action will be much sharper with no partly on state.

A transistor inverter (NOT gate)

Inverters (NOT gates) are available on logic ICs but if you only require one inverter it is usually better to use this circuit. The output signal (voltage) is the inverse of the input signal:

- When the input is high (+Vs) the output is low (0V).
- When the input is low (0V) the output is high (+Vs).

