BJT Switch Circuits

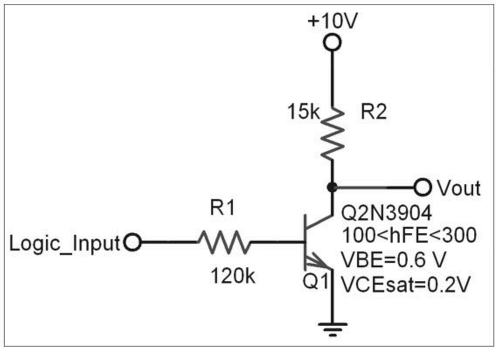
The BJT can be used as either a Logic Switch or as a Current Switch. In either operation, we want the operation to be ***Binary***, in other words, with only two possible outcomes. That means that we don't want to have a range of possibilities, such as would be expected in the Linear Active Region.

That leaves Cut-off and Saturation as the two modes used in switching.

BJT Logic Switch

In this mode, we want the transistor to provide us with a Logic HIGH (e.g. +5 V) and a Logic LOW (e.g. 0 V). To do this, we simply put a resistor in series with the "current source" in the Collector, and ensure that we provide enough Base current to drive it into saturation when it is turned on. It will be in Cut-off when it's turned off.

For this fairly standard circuit, we'll go through a discovery exercise to see how the circuit works, then follow this up with a couple of worked examples to show how you would design BJT Logic Switches.



Notice a few things about this schematic. V_{BE} is given at 0.6 V; β is called h_{FE} and is given as a range of values rather than a single number. This is because transistors are extremely variable from one batch to the next, so manufacturers specify a range within which their devices are guaranteed to fit; V_{in} would best be called V_{BB} for this circuit; and V_{out} is actually V_C.

If the Logic Input was a LOW (assume 0 V):

1. What condition would the transistor be in? Cutoff
2. What would be the current through R2? 0 mA
3. Based on your answer to the previous question, what would the output voltage be? 10 V
4. What logic level would this output voltage be best described as? HIGH

If the Logic Input was a HIGH (assume +5 V):

5. Is Base current possible? Yes
6. If so, replace the transistor with the appropriate transistor model for further analysis. What would the Base current be? 36.7 μA
7. Using the model you chose, determine the lowest possible Collector current predicted for this circuit. 3.67 mA
8. Your answer probably seems reasonable. However, it's always good to do a Load-Line check. What is the maximum current that could exist if the transistor was completely shorted out? 0.667 mA
9. From your last two answers, what transistor model should you be using for this analysis? Saturation
10. What value for V_{CE} does this model predict? 0.2 V

11. What, then, is the output voltage predicted to be? 0.2 V

12. What logic level does this represent? LOW

13. Fill in the following Truth Table for this circuit.

IN, Binary Logic	OUT, Binary Logic
0	1
1	0

14. Which Logic Gate is this? NOT

You'll discover that often, when a resistor is used in a circuit as a current-to-voltage converter, the result is an inversion, as seen in this circuit.

Let's use this circuit to learn a few more things about the transistor switch.

15. Notice that there's considerably more Base current that is needed to put the transistor into saturation. What is the predicted Saturation current, using the Saturation model? (It will be slightly less than the maximum current on the DC Load Line.)

    0.653 mA

16. From this, determine the smallest Base current that would saturate the transistor. 6.53 μA

17. Use this smallest Base current to determine the biggest Base resistor that would allow for saturation.

    673 kΩ

18. With the biggest Base resistor in place, what would the output voltage be, if the input voltage was only 3.3 V?

    3.98 V

19. We'd expect this inverter to produce a Logic LOW. Would the value you just calculated be considered a LOW?

    No

20. With the original resistor, would the output voltage be a clear Logic LOW? Yes

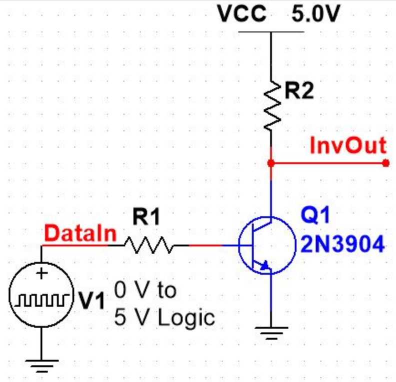
Typically, we pick a Base resistor that's ***one half to one fifth*** of the biggest value for saturation to ensure that the transistor will saturate even if the input voltage levels aren't ideal. That's particularly useful to know if you're using standard TTL Logic ICs, which only guarantee an output HIGH to be 2.4 V or higher. For consistency, in our lab work we'll use approximately ***one half*** in choosing a suitable resistor.

21. Following that train of thought, pick a suitable resistor from the 10% list of resistors (see the Course Formula Sheet) for this circuit. 330 kΩ (The 120 kΩ in the schematic is about the lowest resistor value we would want to use.)

NPN Design Example

Here's a design example to demonstrate how to make a logic switch to meet particular specifications using a 2N3904 NPN transistor.

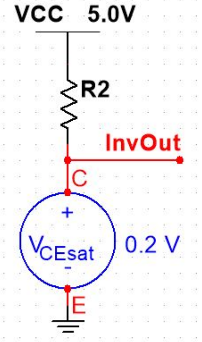
In this case, we're asked to use a 2N3904 transistor as an inverter in a 5 V TTL logic circuit. We'll begin with drawing the basic circuit, then will determine suitable component values.



Notice that the transistor's Emitter is connected to ground. In this configuration, it will be possible to saturate the transistor. If the resistor went to ground with the transistor above it, we would never be able to saturate the transistor -- its Emitter would be 0.7 V below the Base voltage, and there would also be a drop in voltage across the Base resistor, so putting the output at the Emitter would give us a voltage well below 4.3 V, which isn't acceptable. Switching transistors must always have their Emitters connected directly either to ground (NPN) or the power rail (PNP).

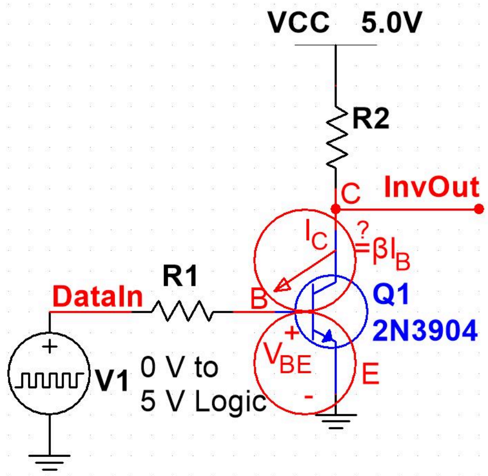
We've got two resistors to pick. Since the actual Collector current isn't specified, we'll start with the pretty typical value of 10 kΩ so that the circuit doesn't draw too much current.

Let's use the Practical Saturation Model to help us determine the saturated Collector Current. The 2N3904 Data Sheet (https://media.digikey.com/pdf/Data%20Sheets/ST%20Microelectronics%20PDFS/2N3904.pdf) shows a maximum V_{CEsat} of about 0.2 V.



From this, we determine that $I_{Csat} = \Delta V_{RC}/R_C = (5 - 0.2)/10\ k\Omega = 480\ \mu A$.

Now, to find a suitable Base resistor, we'll have to switch to the Active Model, but we'll push the circuit into saturation once whe know what that will take.



From this, we can determine the minimum Base current to saturate the transistor. Back to the Data Sheet, we discover that the minimum β for the 2N3904 transistor is 100, so we'll go with that.

$I_B = I_C/\beta = 480\ \mu A/100 = 4.8\ \mu A$

We can now determine the biggest allowable value for R_B. The Data Sheet tells us that V_{BE} could be as high as 0.85 V in the current range we're in, so we'll go with that (we usually just use 0.7 V, though).

$R_B = \Delta V_{RB}/I_B = (5 - 0.85)/4.8\ \mu A = 864\ k\Omega$

We want to make sure that the transistor saturates, so we pick a standard 10% resistor value that's less than half the calculated value -- 390 kΩ. That will allow more than twice the minimum Base current to flow, ensuring that the predicted Collector current will be more than twice the maximum current, therefore saturating the transistor.

At this point, we could verify our circuit to ensure that it saturates:

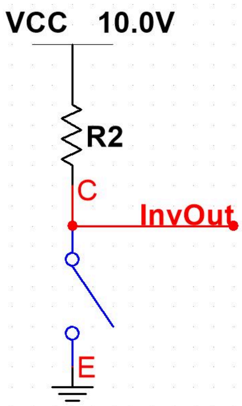
$I_B = \Delta V_{RB}/R_B$ = (5 -0.85)/390 kΩ = 10.6 μA

The Active Model predicts $I_C = \beta I_B$ = 100 * 10.6 μA = 1.06 mA

...but the maximum possible I_C is 5V/10 kΩ or 500 μA, so the transistor will be saturated.

Let's check to make sure the transistor goes into Cutoff at the other extreme, and determine the expected output voltage:

When the DataIn signal is LOW (0.0 V), there is not possibility of current flowing through the Base, so the transistor is in Cutoff. Here's the Cutoff model:



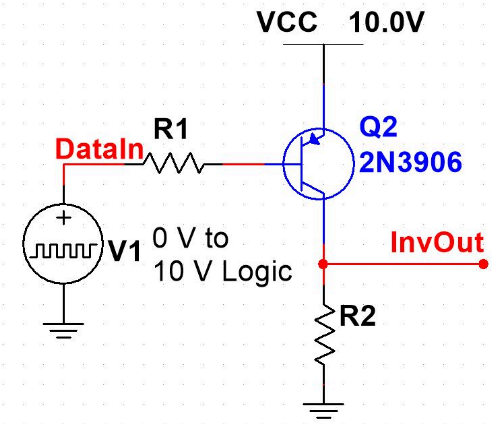
With no current flowing through R2, InvOut will be +10 V, or Logic HIGH.

Here's a summary:

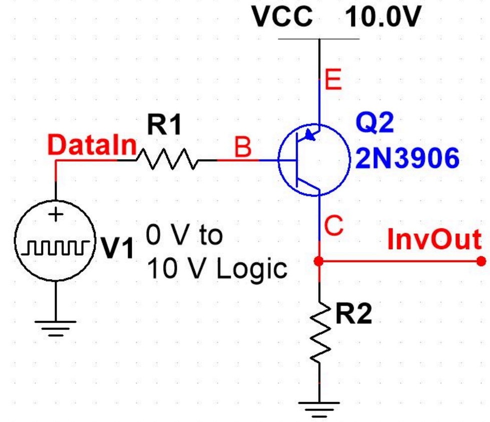
DataIn	InvOut
0.0 V	10.0 V
10.0 V	0.2 V

PNP Design Example

Let's do a PNP switch design example. At the end of this, we'll investigate why most simple transistor switches are made using NPN transistors instead of PNP transistors. As with the NPN transistor, we need to connect the Emitter directly to a constant voltage. In this case, since the Emitter needs to be more positive than the Collector, we'll connect it directly to the power supply, provided as +10 VDC.



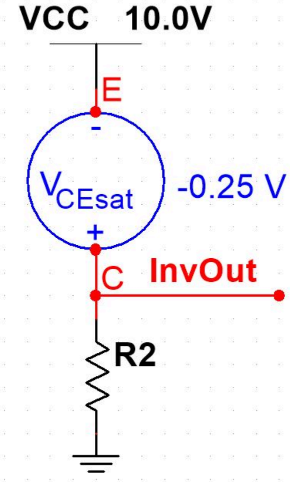
Since we're not as accustomed to working with PNP transistors, let's make sure we label the pins before we go any further.



Notice, again, that the power supply is incorrectly named -- it really should be V_{EE}, but Multisim doesn't let us change the label on a net to suit the component we're working with, so we're stuck with V_{CC}.

Since no current requirements have been provided, let's aim for about a half a milliamp again. From a 10 V supply, that would require roughly a 20 kΩ resistor, so we'll go just a bit bigger to help force this into saturation. *(A bigger resistor at the Collector means a bigger voltage drop for the same current, leaving less of a drop across the transistor, so that pushes us into saturation; a smaller resistor at the Base provides more Base current, also driving us further into saturation.)*

Using the Saturation model and the 2N3906 Data Sheet (https://www.mccsemi.com/pdf/Products/2N3906(TO-92).pdf), we can determine the saturation current at the Collector. The data sheet tells us that V_{CEsat} could be as big as -0.25 V in the current range we're working in.



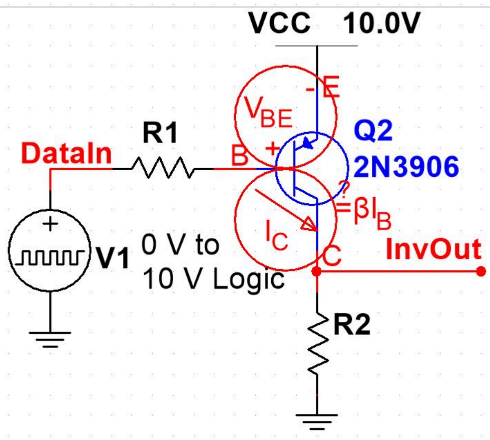
The "upside down" supply that's negative just means a voltage drop from V_{CC}. Mathematically, inverting a negative makes it positive; electrically, there's always a voltage drop across a transistor, so V_C has to be lower than the supply voltage.

We can calculate I_{Cmax} by shorting out the transistor: I_{Cmax} = 10/22 kΩ = 455 μA.

The saturation current, I_{Csat} = (10 - 0.25)/22 kΩ = 443 μA, which makes sense -- it's less than the maximum possible.

From the Saturation Model, we can see that the output voltage, $V_{InvOut} = V_{CC} - (-V_{CEsat})$ = 9.75 V. This would be a Logic HIGH.

Now, to find out what we need for the Base resistor, we'll have to use the Active Model, but we'll use it to help us force the transistor into saturation.



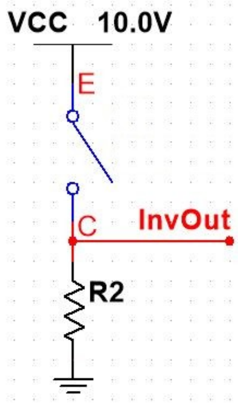
Using the Transfer function, we determine that the smallest Base current that can saturate this transistor is $I_B = I_C/\beta$. The Data Sheet tells us that the minimum value for beta in our current range is 80, so I_B = 443 μA/80 = 5.54 μA.

The Data Sheet says V_{BE} could be as big as -0.85 V, so we'll go with that again.

To make the transistor saturate, there needs to be Base current. We can only get Base current if the input voltage is lower than the Emitter voltage, so that happens when DataIn is LOW, or 0 V. So, KVL tells us that the biggest value for R_B = (10 - 0.7)/5.54 μA = 1.679 MΩ. So, we'll pick a resistor a bit less than half that size from our standard 10% values, arriving at 820 kΩ.

As a double-check, we can determine I_B = (10 - 0.7)/820kΩ = 11.3 μA. So the Collector current predicted by the Active Model is $I_C = \beta I_B$ = 80*11.3 μA = 907 μA. Since this is about twice the maximum current that could exist in this circuit, the transistor is saturated.

Now, let's check what happens when the input is HIGH. The voltage supplying the Base is the same as the voltage supplying the Emitter, so there's no way Base current can flow, meaning there will be no Collector current, and the transistor will be in Cutoff. Here's the Cutoff Model to help us predict the output voltage:



With no current flowing through R_C, the output voltage will be 0.0 V. This is a Logic LOW.

Here's a summary:

DataIn	InvOut
0.0 V	9.75 V
10.0 V	0.0 V

Why choose NPN over PNP for a switch?

Now, as promised, we'll look at why the NPN circuit is a better choice as a simple logic switch.

With the NPN circuit, when the voltage drops to zero, the transistor is in Cutoff; when the voltage goes high, the transistor saturates. But what if the input signal doesn't go all the way "to the top"? Let's say it only goes to 2.8 V, which is an acceptable TTL HIGH input. I_B would be (3.3 - 0.85)/390 kΩ = 6.28 μA, so I_C is predicted to be 100*6.28 μA or 628 μA, which is still enough to saturate the transistor and produce a clear Logic Low.

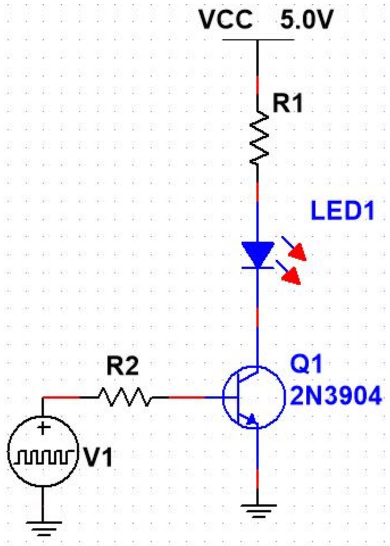
However, with the PNP transistor, things are different. When the input is LOW, at 0.0 V, things look OK, as the transistor will still saturate, giving us a clear Logic HIGH at the output. But if an input HIGH doesn't go all the way to 10 V, the transistor won't go into Cutoff. Let's say the Input HIGH was just 7.0 V instead of a full 10 V. Current would still be able to flow from Emitter to Base, so the transistor wouldn't go into Cutoff, and the output wouldn't be 0.0 V as expected. In fact, (and you can check this) the voltage would be about 5.95 V -- not even close to the expected Logic Low!

So, the NPN circuit is much more forgiving of varying input voltages, and is therefore usually used when a simple inverter is required.

BJT Current Switch

Since transistors are, by nature, current amplifiers, it makes sense to use them to turn current on or off. In this case, the circuit will ***NOT*** be an inverter in terms of the existence or absence of current.

One typical application is the ***LED Driver***, shown below.



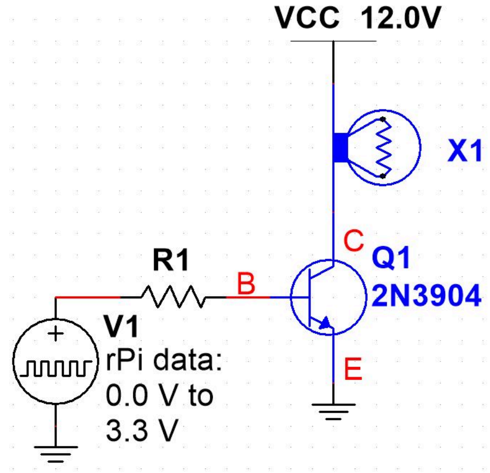
If the RED LED has a forward barrier potential of 1.8 V, the 2N3904 has a V_{CEsat} of 0.2 V, a V_{BEon} of 0.7 V, and a minimum β of 100, and the LED requires about 10 mA to glow well:

22. Choose a suitable 10% value resistor for the Collector resistor. 330 Ω (We usually choose a bigger resistor on the Collector side of a transistor circuit.)
23. If the input signal switches between 0 V and +5 V, determine the theoretical maximum resistance for the Base resistor. 43 kΩ
24. Using our previous guidelines, choose a suitable 10% value resistor for the Base resistor. 18 kΩ (We usually choose a smaller resistor at the Base side of a transistor circuit.)
25. When is the LED on? When the input is HIGH

Note: as indicated before, a bigger resistor at the Collector forces the transistor into saturation sooner, and a smaller resistor at the Base provides more current, ensuring saturation, hence the choices indicated above.

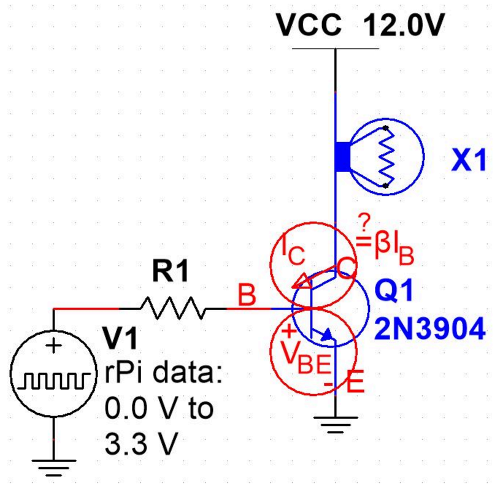
Note also that, as a current switch, the transistor is not an inverter -- it's a ***Buffer***, which is something that provides the required output while protecting the controlling signal at the input. A logic-generating device, such as a microcontroller or PLD, cannot produce a lot of current at its outputs. Our MC9S12XDP512 is capable of driving 10 mA at each of its output pins, but its total current output cannot exceed about 50 mA. So, if more than four or five LEDs are to be driven by this device, the outputs need to be buffered using transistors or other current drivers. And, clearly, if the intent is for the microcontroller to drive something that requires an amp or two, a transistor buffer is a necessity.

Here's a short worked example of a Current Switch. A 12 V lamp that draws 125 mA is to be turned on and off using a Raspberry Pi, a 3.3 V logic device. Let's start with a schematic. Again, notice that the Emitter is connected directly to one of the power rails, in this case Ground, since we're using an NPN transistor. A quick check of the Data Sheet (https://media.digikey.com/pdf/Data%20Sheets/ST%20Microelectronics%20PDFS/2N3904.pdf) indicates that a 2N3904 can handle currents up to 200 mA, so we'll use that.



Notice that there's no Collector resistor -- in this case, the lamp is the current-limiting device.

Since we already know the Collector current (125 mA), we can go straight to the Active Model to start working out the Base resistor. Let's assume V_{BE} = 0.7 V, since we've seen that in our practical exercises, and that β = 100 at a minimum.



$I_B = I_C/\beta$ = 1.2 mA

The biggest value for R_B = (3.3 - 0.7)/1.2 mA = 2.17 kΩ, so pick something a bit smaller than half, which leaves us with 1.0 kΩ.

Design complete! A quick check: I_B = (3.3 - 0.7)/1.0 kΩ = 2.6 mA, so the Active Model predicts 260 mA. Since the lamp limits the current to I_C = 125 mA, the transistor will be saturated.

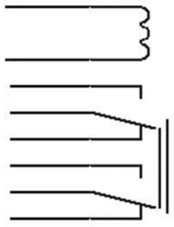
Level Translator

Transistors can also be used as Level Translators -- devices that convert logic at one set of voltage levels, for example 3.3 V TTL, to another set of voltage levels, for example 5 V TTL. In our first example, the transistor was used to convert 5 V TTL to 10 V CMOS. The output voltages may be stepped up or down to whatever values are desired.

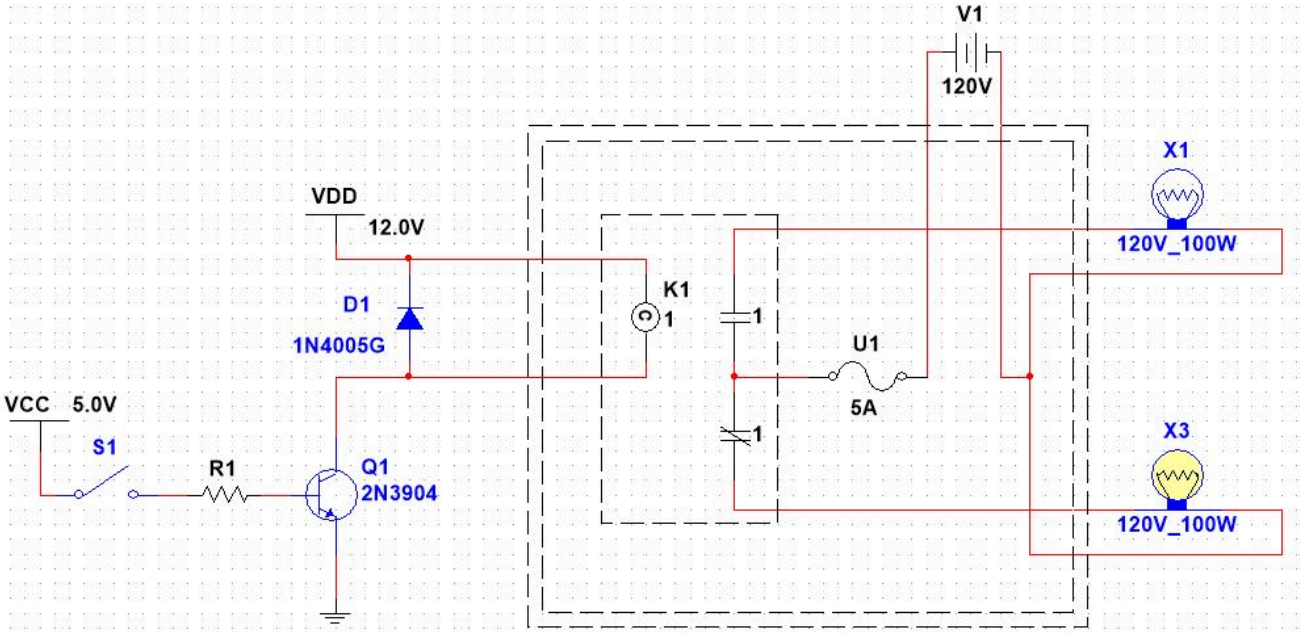
You'll get lots of experience with Level Translators in one of the Self Assessments.

Relay Driver

A Relay is an electromechanical device in which current through an electromagnet is used to activate a mechanical switch, usually in another electrically-isolated circuit. The relay coil introduces a new problem: inductive current and the voltage spikes generated when a switch is suddenly opened. The following is a picture of a relay you should have in one of your kits, along with a schematic of what's inside. This is a fairly complicated relay, with two independent double pole switches controlled by a single coil (DPDT switch).



Here's a typical relay circuit, using 5 V TTL to control a 12 V relay coil which activates a switch in a 120 VAC circuit.



Notice two things to begin with: The 120 VAC circuit is electrically-isolated from the logic circuit -- there are no electrical connections between them, and activation occurs entirely by means of an electromagnet closing a switch; there's a diode in the circuit that we hadn't mentioned before -- more on that to come!

26. The relay coil draws 18 mA when powered from 12 VDC. How much Base current is required, if the worst β for this transistor is 100? 180 μA
27. Given that V1 represents 5 V logic and assuming a V_{BEon} of 0.7 V for the transistor, what is the biggest value allowed for R1? 23.9 kΩ Pick a suitable 10% resistor value, given our previous guidelines. 10 kΩ
28. Given that the upper set of contacts in the relay switching side is normally-open (N.O.), when the input is HIGH the 120 VAC lamp connected to that switch will be ON

Now, for the diode in the schematic.

29. Given its orientation, it is normally reverse biased , and therefore has no effect on the transistor circuit.

30. In an inductor, such as the electromagnet in the relay, which electrical characteristic cannot be instantly changed?

Current

When the transistor suddenly goes into Cut-off, there is no path for the current from the coil, and the coil, acting as a nearly-ideal current source, will instantly increase the voltage to the point at which it will find a path for the current. If the relay was in a circuit controlled by a regular switch instead of a transistor, there would be a spark or series of sparks across the contacts of the switch as the relay coil current dissipated. However, in our case, the only path for that current is through the transistor. Without the diode, the voltage would rise until it reaches the transistor's reverse breakdown volt… , at which point the current would flow under the influence of a high voltage, resulting in considerable power since $P = IV$. If the current surge lasts long enough, the transistor will be damaged or destroyed.

If, however, the diode is present, the voltage generated by the coil current will rise until the diode is forward biased , which will put the anode of the diode at a voltage of 12.7 V in this circuit. The transistor will be protected, and the diode will provide a path for the current at a very small voltage drop across the diode of 0.7 V, and little power will be generated.

As there's really no difference, other than the diode, between the relay driver and the Current Switch, there isn't much point in another worked example.

Key take-away: always put a protection diode across the coil of a relay or any other inductive load that's being switched by a transistor!