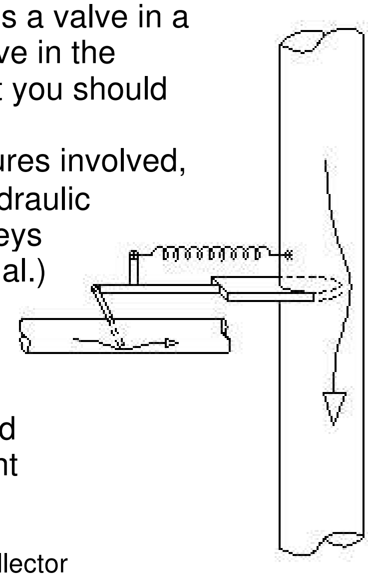
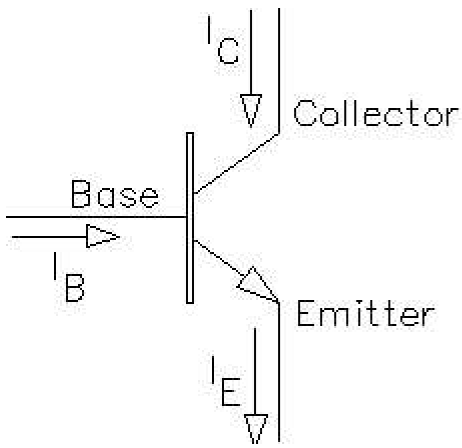
Transistor Notes (BJT) ECE 2210

A.Stolp
3/25/00 rev, 11/21/06

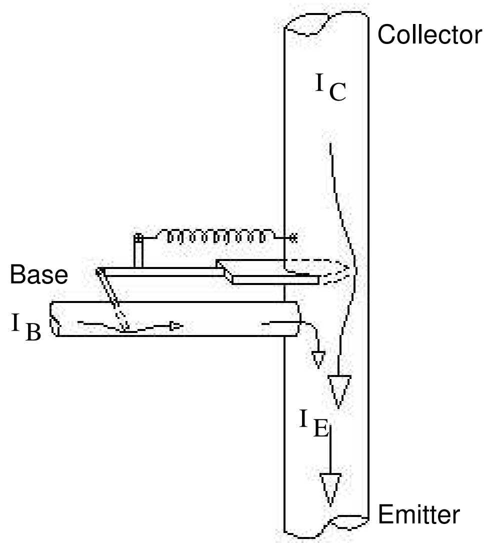


Imagine, if you will, a hydraulic device where the flow in a small pipe controls a valve in a larger pipe. The greater the flow in the small pipe the more it opens the valve in the large pipe. Take a look at the figure to the right. As an engineering student you should immediately see that this could be a useful device. One use might be as a flow-controlled on/off valve (switch). Or, depending on the flows and pressures involved, it could be used as an *amplifier*. That is, it could be used to make some hydraulic signal larger and more powerful. (A signal is a flow or pressure which conveys information and an amplifier is a device which increases the power of a signal.)

The electrical equivalent of this flow-controlled valve is a transistor. Specifically the NPN bipolar junction transistor (BJT). (There are other types.) The symbol for a transistor is shown below. Notice that it's a three-terminal device. That's because the control current (into the base) and the controlled current (into the collector) join together to form a single current out of the bottom (the emitter current). The valve drawn below is a more accurate analogy for the electrical transistor.



NPN transistor

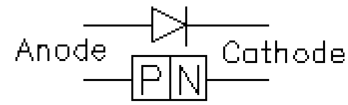


A transistor has three terminals-- the base, the collector, and the emitter. The current flow from the collector to the emitter (through the transistor) is controlled by the current flow from the base to the emitter. A small base current can control a much larger collector current. Often they are related by a simple factor, called beta (β). For a given base current, the transistor will allow β times as much collector current. The key word here is *allow*. The transistor doesn't make the current flow-- some outside power source does that. It simply regulates the current like the valve above. Big power transistors usually have a βs between 20 and 100. For little signal transistors, β is usually between 100 and 400. Darlington transistors (really two transistors in one package) can have βs in the 1000s.

A transistor can be used as a current controlled switch. When there's no base current, it's off, like an open switch. When there is a base current, it's on. If something outside of the transistor is limiting the collector current to less than β times the base current then the transistor will turn on as much as it can, like a closed switch. A transistor that is off is operating in its "cutoff" region. A transistor that is fully on is operating in its "saturation" region. A transistor that is partially on is in active control of its collector current (β times the base current) and is operating in its "active" region. (Note the valve analogy has a problem with the "open" and "closed" terms.)

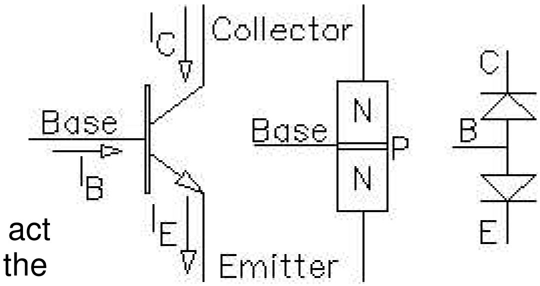
There are many types of transistors. PNP transistors work like the NPN transistors, except that all the currents and voltages are backwards. Field-effect transistors (FETs) are are controlled by voltage instead of current and come in many varieties. In this class we'll only work with NPN transistors.

Silicon diodes are made of two layers of doped silicon, a P layer is the anode and an N layer is the cathode. A P-N junction is a diode.



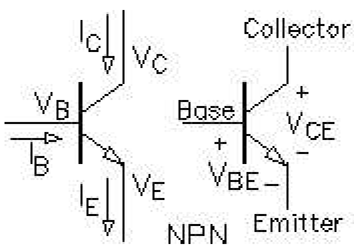
Bipolar junction transistors (BJTs) consist of three layers of doped silicon. The NPN transistor has a thin layer of P-doped silicon sandwiched between two layers of N-doped silicon. Each P-N junction can act like a diode. In fact, this is a fairly good way to check a transistor with an ohmmeter (set to the diode setting).

The base-emitter junction always acts like a diode, but because the base is very thin, it makes the other junction act like a controlled valve (you probably don' t want to know the details, so call it magic).

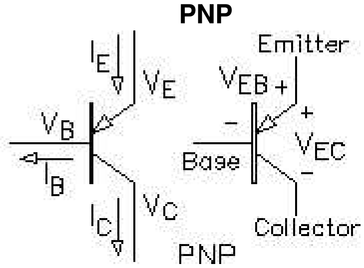


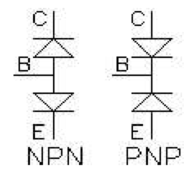
A bipolar junction transistor contains two diode junctions

Transistor Symbols



PNP





Cutoff	Active	Saturation
reverse	reverse	forward
reverse	forward	forward

Junction bias

Notice the subscripts

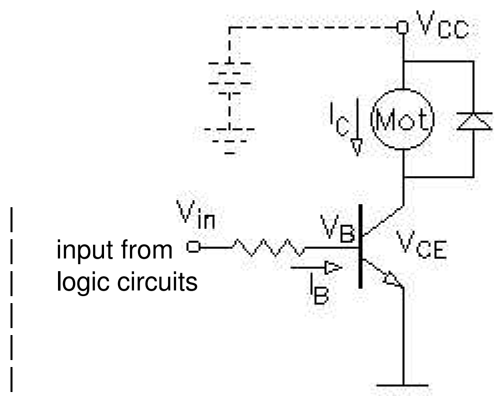
$v_{BE} = v_B - v_E$

$v_{CE} = v_C - v_E$

Replace v_{BE} with v_{EB} and v_{CE} with v_{EC} in equations below

Modes or regions of operation
(v_{BE} and v_{CE} are approximate)

Cutoff (off)	Active (partially on)	Saturation (fully on)
$v_{BE} < 0.7V$	$v_{BE} \simeq 0.7V$	$v_{BE} \simeq 0.7V$
$i_B = 0$	$i_B > 0$	$i_B > 0$
	$v_{CE} \geq 0.2V$	$v_{CE} \simeq 0.2V$
$i_C = 0$	$i_C = \beta i_B = \alpha i_E$ $\alpha \simeq 1$ controlled by the transistor	$i_C < \beta i_B$ limited by something outside of the transistor



Motor Driver

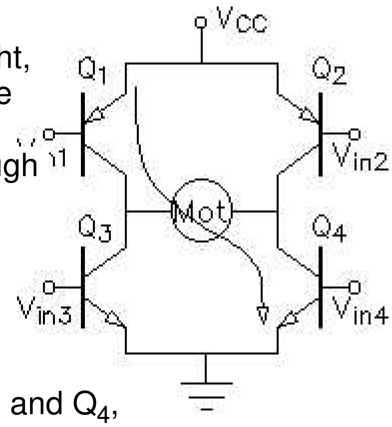
The Transistor as a switch

One of the most common uses of a transistor is as a current-controlled switch. Transistor switches are the basis for all digital circuits, but that' s probably not where you' ll use the transistor. More likely, you' ll want to control a high-current device, like a motor, with arintegrated-circuit output from a computer or logic circuit . The small integrated circuit won' t be able to supply enough current to run the motor, so you' ll use a transistor to switch the larger current that flows through the motor. The input is hooked to the base of the transistor. (Often through a current limiting resistor, since V_B will only be 0.7V when the transistor is on.) A small I_B can switch on the much larger I_C and V_{CE} can be as low as 0.2V.

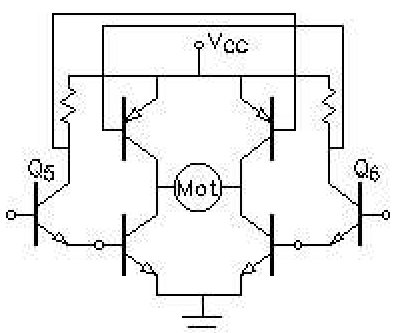
V_{CC}: The terminal marked V_{CC} above is just a circuit terminal hooked to a power supply, drawn in dotted lines here, but usually not shown at all. Power supply wires, like ground wires are often not shown explicitly on schematics. It makes the schematics a little less cluttered and easier to read.

Diode: If you' re switching an inductive load, like a motor, you should add a diode so that you' re not trying to switch off the motor current instantly. The diode (called a *flyback* diode when used like this) provides a path for the current still flowing through the motor when the transistor is switched off.

H-bridge: Of course, if you want to make the motor turn in both directions you' ll need a more complex circuit. Look at the circuit at right, it' s has the shape of an H, hence the name. If transistors Q_1 and Q_4 are on, then the current flows as shown, left-to-right through the motor. If transistors Q_2 and Q_3 are on, then the current flows the other way through the motor and the motor will turn in the opposite direction. (The motor here is a permanent-magnet DC motor.) In my circuit, the top two transistors are PNPs, which makes the circuit more efficient. The H-bridge could also be made with all NPNs or with power MOSFET transistors.



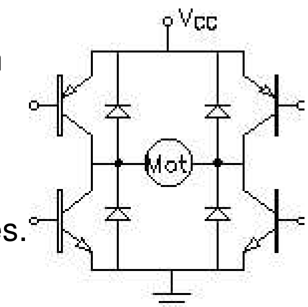
An H-bridge requires four inputs, all operated in concert. To turn on Q_1 and Q_4, as shown, V_{in1} would have to be low and V_{in4} would have to be high. At the same time, the other two transistors would have to be off, so V_{in2} would have to be high and V_{in3} would have to be low.



If the control circuit makes a mistake and turns on Q_1 and Q_3 (or Q_2 and Q_4) at the same time you' ll have a toaster instead of a motor driver, at least for a short while.

The circuit at left requires only two inputs. Transistors Q_5 and Q_6 work as *inverters*, when their inputs are high, their outputs are low and vice-versa. The resistors are known as *pull-up* resistors.

The H-bridge should also include flyback diodes.



Linear Amplifiers

The objective of a linear amplifier is to output a faithful reproduction of an input signal, only bigger. A voltage amplifier makes the signal voltage bigger. A current amplifier makes the signal current bigger. Many amplifiers do both. All amplifiers should make the signal power bigger (depends somewhat on the load). Of course that means that they need a source of power, generally DC power from a battery or power supply. The signals are usually AC.

Unlike transistor switches, which operate in cutoff and saturation, linear amplifiers must operate in the active region.

Important relations: (active region)

$v_{BE} = v_B - v_E = 0.7 \cdot V \qquad v_{CE} = v_C - v_E > 0.7 \cdot V$ ($\simeq$ 0.2V if saturated)

$i_C = \beta \cdot i_B \qquad i_C = \alpha \cdot i_E \simeq i_E$

Bias:
Outside of the active region the input (base current) doesn' t linearly control the output (collector current). To work as an linear amplifier, a transistor must operate in the active region. That means that the transistor must be turned on part way even when there' s no signal at al Look back at the valve analogy, if small fluctuations in the horizontal pipe flow (i_B) should produce larger but similar fluctuations in the vertical pipe flow (i_C), then there must always be *some* flow. If either flow ever stops, the horizontal pipe flow (i_B) is no longer in control.

To work in the active region i_B and i_C must be positive for all values of the AC signals. i_B and i_C must be *biased* to some positive DC value. We use capital letters (I_B and I_C) for these DC bias values and lower case letters (i_b and i_c) for the AC signals that will appear as fluctuations of these DC values

All voltages and currents can be shown in three different ways

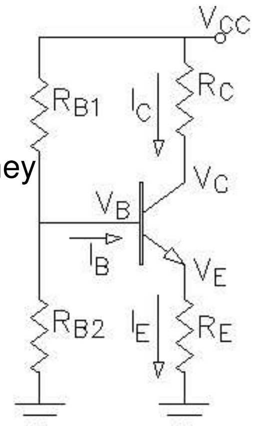
	examples		meaning
CAP_{CAP}	V_B	I_C	DC, Bias
sm_{sm}	v_b	i_c	AC, signal
sm_{CAP}	v_B	i_C	DC and AC Together

The objective of bias then, is to partially turn on the transistor, to turn it, sort-of, half-way on. Now if I twiddle i_B, i_C will show a similar, but bigger, twiddle-- that' s the whole idea. The transistor should never go into cutoff for any expected input signal, otherwise you' ll ge*clipping* at the output. Clipping is a form of distortion, where the output no longer looks like the input.

Furthermore, the transistor must not saturate. That will also cause clipping at the output.

Because β can vary widely from transistor to transistor of the same part number and V_{BE} changes with temperature, achieving a stable bias can be a bit of a problem. Usually an emitter resistor (R_E) is needed to stabilize the bias.

DC Analysis in the active region



DC analysis applies to both switching and bias, although the circuits we' ll look at here will include an R_E and we' ll be working in the active region, meaning they are bias circuits. The key to DC analysis with an R_E is usually finding V_B.

The circuit at right shows a typical bias arrangement. The equations below are for that circuit, adapt them as necessary to fit your actual circuit.

If you can neglect I_B:

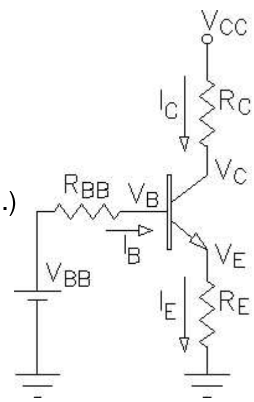
Often in quick-and-dirty analysis you can neglect the base current, I_B. In that case:

$$V_B = V_{CC} \cdot \frac{R_{B2}}{R_{B1} + R_{B2}} \qquad V_E = V_B - 0.7 \cdot V \qquad I_E = \frac{V_E}{R_E} \simeq I_C \qquad V_C = V_{CC} - I_C \cdot R_C$$

This assumption is OK if: $R_{B1} \| R_{B2} << \beta \cdot R_E$

Quick check: $R_{B1} < 10 \cdot R_E$ and/or $R_{B2} < 10 \cdot R_E$ Should result in <10% error if β =100

If you can't neglect I_B:

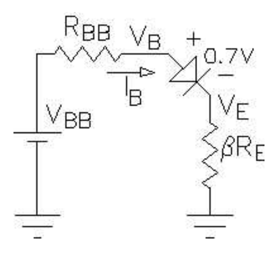


Then you need to make a Thevenin equivalent of the base bias resistors.

$$V_{BB} = V_{CC} \cdot \frac{R_{B2}}{R_{B1} + R_{B2}} \qquad R_{BB} = \frac{1}{\frac{1}{R_{B1}} + \frac{1}{R_{B2}}}$$

(Thevenin Eq.)

From the base' s point-of-view, the emitter resistor will look β + 1) times bigger than it really is. This is because (β + 1) times as much current flows through R_E than into the base. We can ignore the fact that the current is bigger if we pretend that the resistor is bigger. That leads to the simplified circuit. (Usually we use β as the factor rather than (β + 1), after all β just isn' t that well known anyway.)



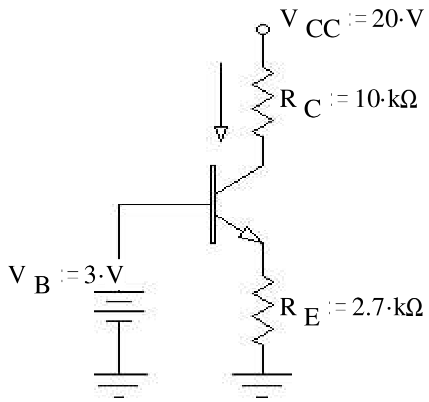
$$I_B = \frac{V_{BB} - 0.7 \cdot V}{R_{BB} + \beta \cdot R_E} \qquad I_C = \beta \cdot I_B \simeq I_E \qquad V_E = I_E \cdot R_E \simeq I_C \cdot R_E \qquad V_B = V_E + 0.7 \cdot V$$

$$V_C = V_{CC} - I_C \cdot R_C$$

OR: $V_B = I_B \cdot \beta \cdot R_E + 0.7 \cdot V$ $\qquad V_E = V_B - 0.7 \cdot V$ $\qquad I_E = \frac{V_E}{R_E} \simeq I_C$ $\qquad V_C = V_{CC} - I_C \cdot R_C$

Examples, DC (Bias) Analysis

1)



Given:

$V_B := 3 \cdot V$, regardless of current into base

$V_{CC} := 20 \cdot V \quad R_C := 10 \cdot k\Omega \quad R_E := 2.7 \cdot k\Omega$

Find I_C, V_C, V_{CE}, and P_Q:

Solution:

$V_E := V_B - 0.7 \cdot V \qquad V_E = 2.3 \cdot V$

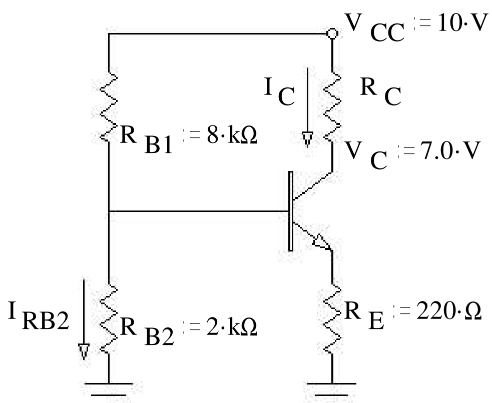
$I_E := \frac{V_E}{R_E} \qquad I_E = 0.852 \cdot mA \quad \simeq \quad I_C := I_E$

$V_C := V_{CC} - I_C \cdot R_C \qquad V_C = 11.48 \cdot V$

$V_{CE} := V_C - V_E \qquad V_{CE} = 9.18 \cdot V$ > 0.2V, OK, is in active region

$P_Q := V_{CE} \cdot I_C \qquad P_Q = 7.82 \cdot mW$

2)



Given: may neglect I_B

$V_{CC} := 10 \cdot V \quad V_C := 7.0 \cdot V \quad R_{B1} := 8 \cdot k\Omega \quad R_{B2} := 2 \cdot k\Omega \quad R_E := 220 \cdot \Omega$

Find V_B, V_E, I_C, R_C, V_{CE}, I_{RB2}, and P_Q:

Solution:

$V_B := V_{CC} \cdot \frac{R_{B2}}{R_{B1} + R_{B2}} \qquad V_B = 2 \cdot V$

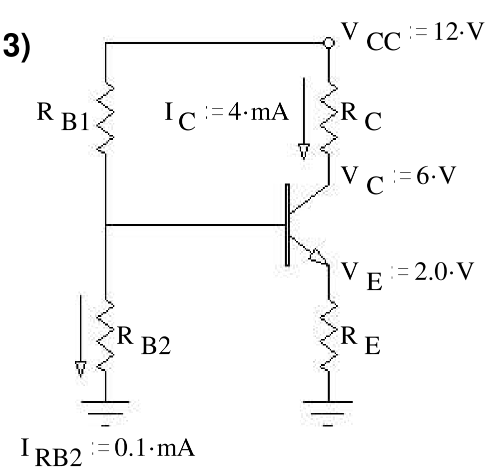
$V_E := V_B - 0.7 \cdot V \qquad V_E = 1.3 \cdot V$

$I_E := \frac{V_E}{R_E} \qquad I_E = 5.91 \cdot mA \quad \simeq \quad I_C := I_E$

$R_C := \frac{V_{CC} - V_C}{I_C} \qquad R_C = 508 \cdot \Omega \qquad V_{CE} := V_C - V_E \qquad V_{CE} = 5.7 \cdot V$ > 0.2V, OK, is in active region

$I_{RB2} := \frac{V_B}{R_{B2}} \qquad I_{RB2} = 1 \cdot mA \qquad P_Q := V_{CE} \cdot I_C \qquad P_Q = 33.68 \cdot mW$

3)



Given: may NOT neglect I_B $\quad \beta := 150$

$V_{CC} := 12 \cdot V \quad V_E := 2.0 \cdot V \quad V_C := 6 \cdot V \quad I_{RB2} := 0.1 \cdot mA \quad I_C := 4 \cdot mA$

Find R_E, R_C, V_B, I_B, R_{B2}, and R_{B1}:

Solution:

$V_{CE} := V_C - V_E \qquad V_{CE} = 4 \cdot V$ > 0.2V, is in active region

$I_E \simeq I_C \quad I_E := I_C \qquad R_E := \frac{V_E}{I_E} \qquad R_E = 500 \cdot \Omega$

$R_C := \frac{V_{CC} - V_C}{I_C} \qquad R_C = 1.5 \cdot k\Omega$

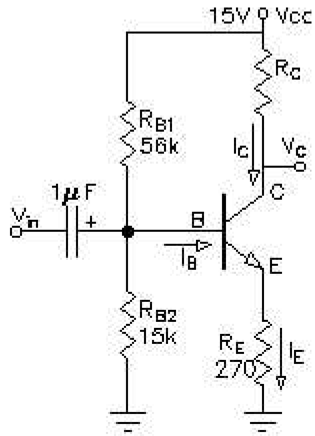
$V_B := V_E + 0.7 \cdot V \qquad V_B = 2.7 \cdot V \qquad I_B := \frac{I_C}{\beta} \qquad I_B = 0.027 \cdot mA$

$R_{B2} := \frac{V_B}{I_{RB2}} \qquad R_{B2} = 27 \cdot k\Omega \qquad R_{B1} := \frac{V_{CC} - V_B}{I_{RB2} + I_B} \qquad R_{B1} = 73.4 \cdot k\Omega$

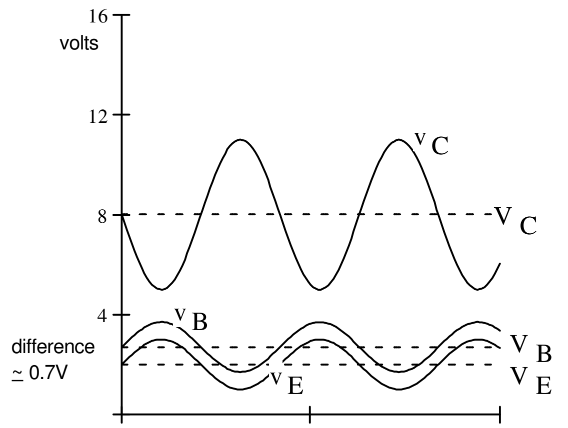
AC Analysis of Common emitter (CE) amplifier

With an R_E, any AC signal applied to the base will then also appear just as big at the emitter (just lower by 0.7V DC). The AC signal current through R_E, will be about the same as through R_C, so the AC signal voltage across R_C will be bigger than that across R_E by the ratio of R_C/R_E. Recalling that the signal at the emitter is about the same as the signal at the base...

base to collector AC gain $= \dfrac{v_c}{v_b} = \dfrac{R_C}{R_E}$



Signals



v_E follows v_B, just 0.7V DC lower

If a capacitor is placed in parallel with R_E then the effective AC resistance in the emitter goes way down and the gain goes way up. In that case we need a way to estimate the AC resistance within the base-emitter junction itself.

This is called the small-signal emitter resistance: $r_e = \dfrac{25\cdot mV}{I_C}$

To find the gains when the input has a source resistance and the output is connected to a load resistor, the calculations become a little more complex. YOU DON' T NEED TO KNOW THE FOLLOWING MATERIAL.

R_E is the DC resistance from emitter to ground

R_e is the AC signal resistance from emitter to ground, may be zero

Input impedance: $R_i = R_{B1} \| R_{B2} \| \beta\cdot(r_e + R_e)$

Output impedance: $R_o = R_C \| r_o$ <-- r_o Often neglected

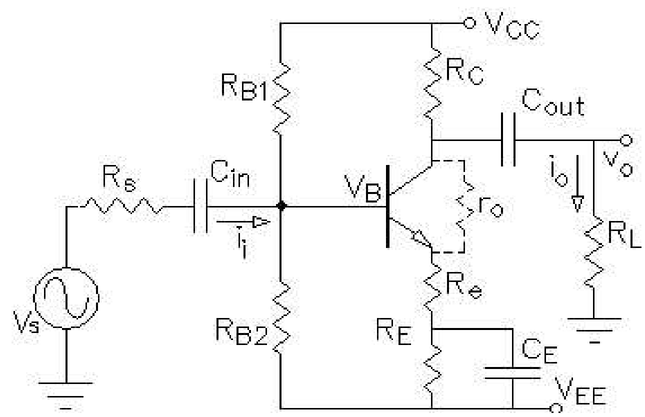
AC collector resistance: $r_c = R_C \| R_L \| r_o$

r_o is a characteristic of the transistor, and is often neglected

Voltage gain: $A_v = \dfrac{v_o}{v_b} = \dfrac{r_c}{r_e + R_e}$

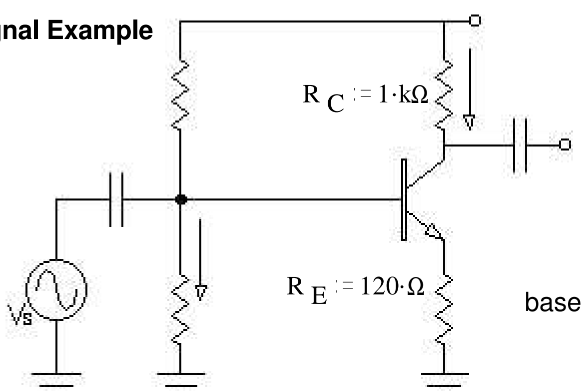
OR: $\dfrac{v_o}{v_s} = \dfrac{R_i}{R_S + R_i}\cdot\dfrac{r_c}{r_e + R_e}$

Current gain: $A_i = \dfrac{i_o}{i_i} = \dfrac{r_c}{r_e + R_e}\cdot\dfrac{R_i}{R_L} = A_v\cdot\dfrac{R_i}{R_L}$



There are several other types of transistor amplifiers, but we won' t look at them here.

AC Signal Example



If the v_s signal were applied at the base, an AC signal would also appear at the collector. How much larger would it be? (Voltage gain).

base to collector AC gain $= \dfrac{v_c}{v_b} = \dfrac{R_C}{R_E} = 8.33$ times bigger

ECE 2210 Transistor Switching Circuit Examples

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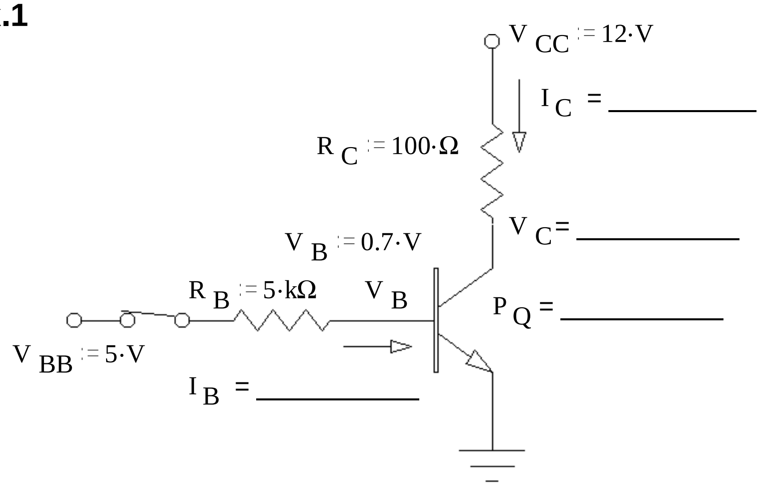
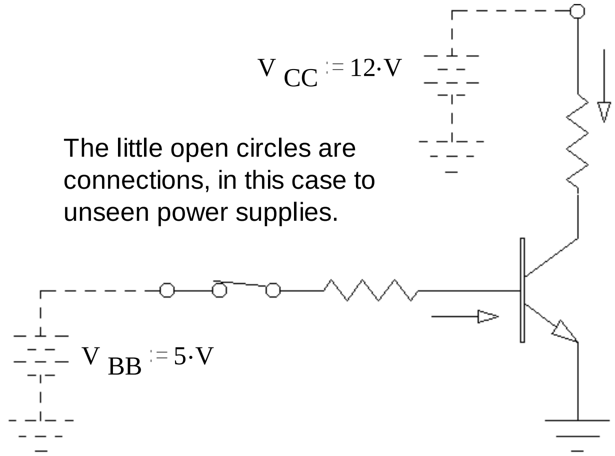
rev 12/3/14

Ex.1





The little open circles are connections, in this case to unseen power supplies.

If: $\beta := 100$ $\quad I_B := \frac{V_{BB} - 0.7\cdot V}{R_B}$ $\quad I_B = 0.86\cdot mA$ $\quad I_C := \beta\cdot I_B$ $\quad I_C = 86\cdot mA$

$V_C := V_{CC} - R_C\cdot I_C$ $\quad V_C = 3.4\cdot V$

$P_Q := V_C\cdot I_C$ $\quad P_Q = 292.4\cdot mW$

If: $\beta := 200$ $\quad I_B := \frac{V_{BB} - 0.7\cdot V}{R_B}$ $\quad I_B = 0.86\cdot mA$ $\quad I_C := \beta\cdot I_B$ $\quad I_C = 172\cdot mA$

$V_C := V_{CC} - R_C\cdot I_C$ $\quad V_C = -5.2\cdot V$

must be in saturation: $\quad V_C := 0.2\cdot V$

$I_C := \frac{V_{CC} - V_C}{R_C}$ $\quad I_C = 118\cdot mA$

$P_Q := V_C\cdot I_C$ $\quad P_Q = 23.6\cdot mW$

Since saturation can depend on β, You usually assume a small β when designing a circuit that should saturate (a switching circuit).

If: $R_C := 50\cdot\Omega$ $\quad I_C := \beta\cdot I_B$ $\quad I_C = 172\cdot mA$ $\quad V_C := V_{CC} - R_C\cdot I_C$ $\quad V_C = 3.4\cdot V$

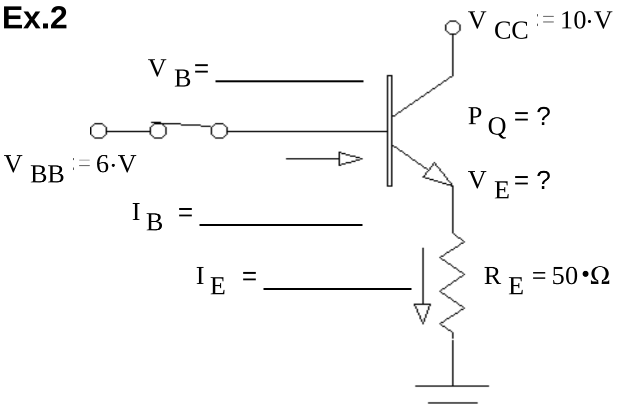
same $\beta := 200$ $\quad P_Q := V_C\cdot I_C$ $\quad P_Q = 584.8\cdot mW$

Saturation also depends on R_C and V_{CC}.

What is the largest value that R_B could be and still keep the transistor in saturation?

$I_{Csat} := \frac{V_{CC} - 0.2\cdot V}{R_C}$ $\quad I_{Csat} = 236\cdot mA$ $\quad I_B := \frac{I_{Csat}}{\beta}$ $\quad I_B = 1.18\cdot mA$ $\quad R_{Bmax} = \frac{5\cdot V - 0.7\cdot V}{I_B} = 3.644\cdot k\Omega$

Ex.2



$V_B := 6\cdot V$ $\quad V_E := 5.3\cdot V$ $\quad R_E := 50\cdot\Omega$

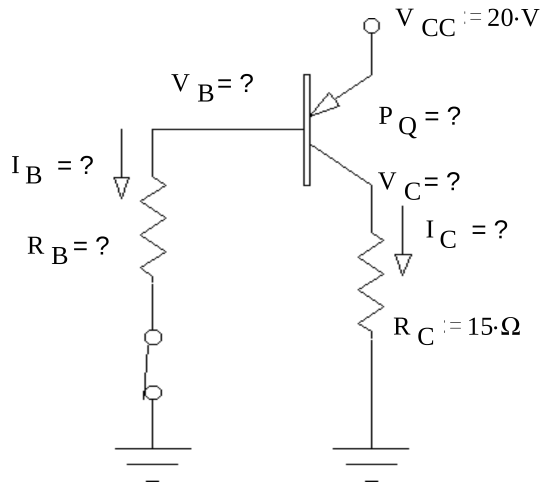
$I_E := \frac{V_E}{R_E}$ $\quad I_E = 106\cdot mA$ Doesn't depend on β

$I_B := \frac{I_E}{\beta + 1}$ $\quad I_B = 0.5\cdot mA$ $\quad \simeq \frac{I_E}{\beta} = 0.53\cdot mA$

If β is big enough.

$P_Q := (V_{CC} - V_E)\cdot I_E$ $\quad P_Q = 0.498\cdot W$

Ex.3 If the load must be connected to ground, a PNP transistor is often a better choice.



Let's assume a a small β and saturation and find the R_B necessary.

a small β: $\beta := 20$

$V_C := V_{CC} - 0.2 \cdot V$ $\quad V_C = 19.8 \cdot V$

$R_C := 15 \cdot \Omega$

$I_{Csat} := \dfrac{V_C}{R_C}$ $\quad I_{Csat} = 1.32 \cdot A$

$I_B := \dfrac{I_{Csat}}{\beta}$ $\quad I_B = 66 \cdot mA$

$V_B := V_{CC} - 0.7 \cdot V$ $\quad V_B = 19.3 \cdot V$

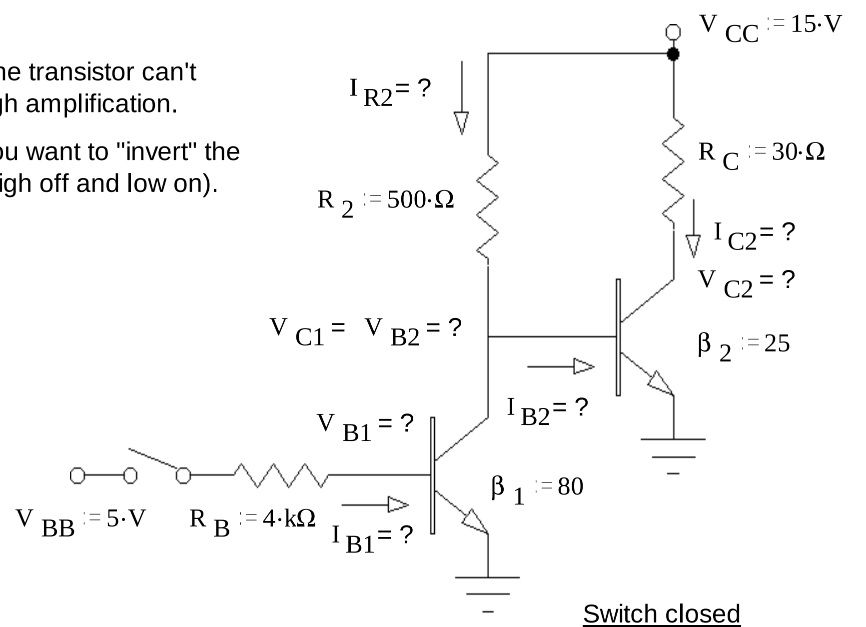
$R_B := \dfrac{V_B}{I_B}$ $\quad R_B = 292 \cdot \Omega$

$P_Q := 0.2 \cdot V \cdot I_{Csat}$ $\quad P_Q = 264 \cdot mW$

Ex.4

Sometimes one transistor can't provide enough amplification.

Sometimes you want to "invert" the input (make high off and low on).



<u>Switch open</u>

$I_{B1o} := 0$ $\quad V_{B1o} := 0 \cdot V$

$V_{B2o} := 0.7 \cdot V$

$I_{B2o} := \dfrac{V_{CC} - 0.7 \cdot V}{R_2}$ $\quad I_{B2o} = 28.6 \cdot mA$

$I_{R2o} := I_{B2o}$ $\quad I_{R2o} = 28.6 \cdot mA$

$I_{C2o} := \beta_2 \cdot I_{B2o}$ $\quad I_{C2o} = 715 \cdot mA$

$V_{C2o} := V_{CC} - R_C \cdot I_{C2o}$ $\quad V_{C2o} = -6.45 \cdot V$

Q_2 must be in saturation: $\quad V_{C2o} := 0.2 \cdot V$

$I_{C2o} := \dfrac{V_{CC} - V_{C2o}}{R_C}$ $\quad I_{C2o} = 493.3 \cdot mA$

<u>Switch closed</u>

$I_{B1c} := \dfrac{5 \cdot V - 0.7 \cdot V}{R_B}$ $\quad I_{B1c} = 1.08 \cdot mA$

assume Q_1 is in saturation $\quad V_{C1c} := 0.2 \cdot V$

$I_{C1c} := \dfrac{V_{CC} - V_{C1c}}{R_2}$ $\quad I_{C1c} = 29.6 \cdot mA$

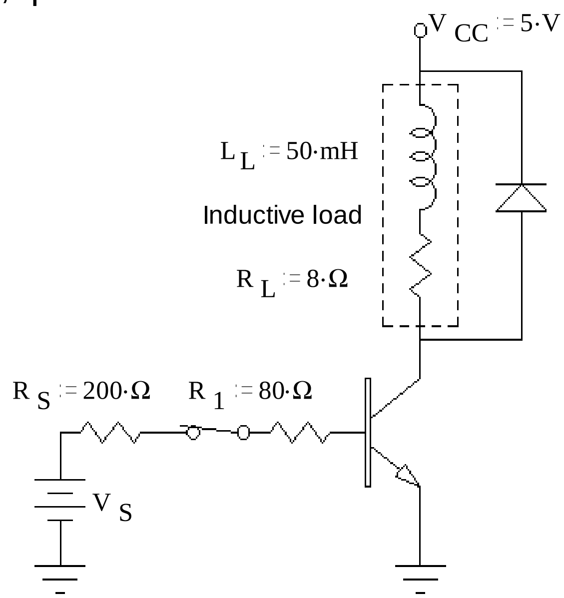
$\beta_1 \cdot I_{B1c} = 86 \cdot mA$ $\quad I_{C1}$ is controlled by R_2

$V_{B2c} := V_{C1c}$ $\quad V_{B2c} = 0.2 \cdot V$

$I_{B2c} := 0$ $\quad I_{C2c} := 0 \;=\; I_{RCc}$

When the switch is open, current flows in through the load resistor, R_C, When it is closed, no current flows though the load. This is an example of logical "inversion".

Ex.5 Modified from F07 Final



A transistor is used to control the current flow through an inductive load (in the dotted box, it could be a relay coil or a DC motor).

a) Assume the transistor is in saturation (fully on) and that switch has been closed for a long time. What is the load current?

$I_C = ?$

$$I_{Csat} := \frac{V_{CC} - 0.2 \cdot V}{R_L} \qquad I_{Csat} = 600 \cdot mA$$

b) $\beta := 80$ find the minimum value of V_S, so that the transistor will be in saturation.

$$I_{Bmin} := \frac{I_{Csat}}{\beta} \qquad I_{Bmin} = 7.5 \cdot mA$$

$$V_{Smin} := I_{Bmin} \cdot (R_S + R_1) + 0.7 \cdot V \qquad V_{Smin} = 2.8 \cdot V$$

Use this V_S for the rest of the problem.

c) Does the diode in this circuit ever conduct a significant current? If yes, when and how much?

When the switch opens. $I_{Dmax} = I_{Csat} = 600 \cdot mA$ from part a)

d) You got a bad transistor. $\beta := 60$ Find the new I_C, and V_{CE} and P_Q.

$I_C = ?$ $\quad I_C := \beta \cdot I_{Bmin}$ $\quad I_C = 450 \cdot mA$ Now operating in active region

$V_{CE} = ?$ $\quad V_{CE} := V_{CC} - R_L \cdot I_C$ $\quad V_{CE} = 1.4 \cdot V$

$P_Q = ?$ $\quad P_Q := V_{CE} \cdot I_C$ $\quad P_Q = 0.63 \cdot W$

$\beta = 60$ Use this for the rest of the problem.

c) Find the minimum value of R_L so that the transistor will be in saturation.

$$I_B := \frac{V_{Smin} - 0.7 \cdot V}{R_S + R_1} \qquad I_B = 7.5 \cdot mA$$

$$I_{Cmax} := \beta \cdot I_B \qquad I_{Cmax} = 450 \cdot mA$$

$$R_{Lmin} := \frac{V_{CC} - 0.2 \cdot V}{I_{Cmax}} \qquad R_{Lmin} = 10.7 \cdot \Omega$$

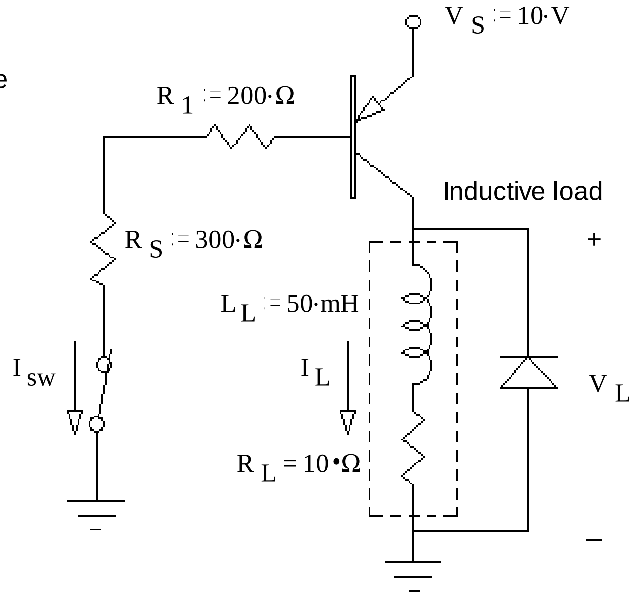
d) R_L, can't be changed, so find the maximum value of R_1 so that the transistor will be in saturation.

$I_{Csat} = 600 \cdot mA$ from part a)

$$I_{Bmin} := \frac{I_{Csat}}{\beta} \qquad I_{Bmin} = 10 \cdot mA$$

$$R_{1max} = \frac{V_{Smin} - 0.7 \cdot V}{I_{Bmin}} - R_S = 10 \cdot \Omega$$

Ex.6 From F05 Final with modifications from F06 Final



A transistor is used to control the current flow through an inductive load (in the dotted box, it could be a relay coil or a DC motor).

a) $\beta := 25$ Assume the transistor is in the active region, find I_{sw}, I_L, V_L, V_{EC} and P_Q.

$I_B := \dfrac{V_S - 0.7 \cdot V}{R_S + R_1}$ $\qquad I_B = 18.6 \cdot mA = I_{sw}$

$I_L := \beta \cdot I_B$ $\qquad I_L = 465 \cdot mA$

$R_L := 10 \cdot \Omega$

$V_L := I_L \cdot R_L$ $\qquad V_L = 4.65 \cdot V$

$V_{EC} := V_S - V_L$ $\qquad V_{EC} = 5.35 \cdot V$

$P_Q := V_{EC} \cdot I_L$ $\qquad P_Q = 2.488 \cdot W$

b) Was the transistor actually operating in the active region? yes no (circle one) yes

How do you know? (Specifically show a value which is or is not within a correct range.)

$V_{EC} = 5.35 \cdot V \quad > \quad 0.2 \cdot V$

c) Find the maximum value of R_1, so that the transistor will be in saturation.

If saturated: $V_{EC} := 0.2 \cdot V$

$I_{Csat} := \dfrac{V_S - 0.2 \cdot V}{R_L}$ $\qquad I_{Csat} = 0.98 \cdot A$

$I_{Bmin} := \dfrac{I_{Csat}}{\beta}$ $\qquad I_{Bmin} = 39.2 \cdot mA$

$R_{1max} = \dfrac{V_S - 0.7 \cdot V}{I_{Bmin}} - R_S = -63 \cdot \Omega$ **NOT POSSIBLE**

d) $R_1 = 200 \cdot \Omega$ and can't be changed, find the minimum value of β so that the transistor will be in saturation.

$I_{Csat} = 0.98 \cdot A$ $\qquad \beta_{min} := \dfrac{I_{Csat}}{I_B}$ $\qquad \beta_{min} = 52.7$

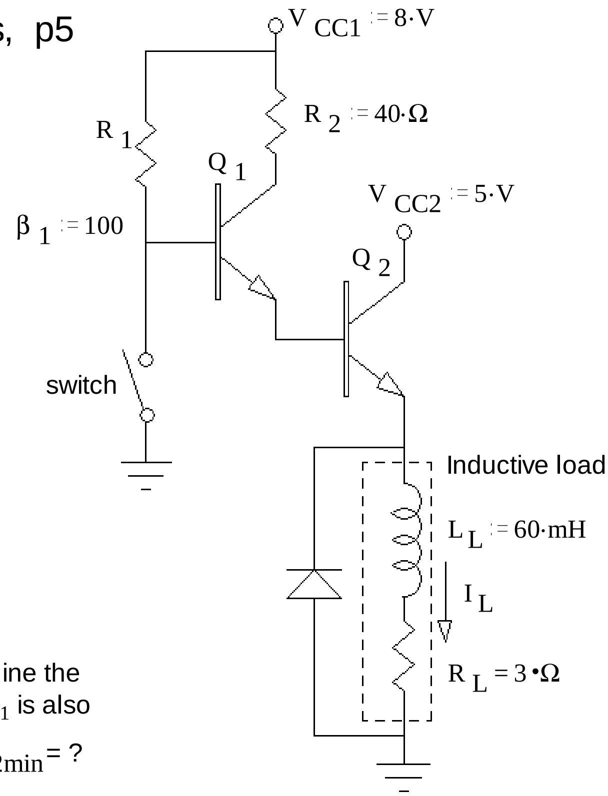
e) How much power is dissipated by the transistor if it has the β you found in part d)

$P_Q := 0.2 \cdot V \cdot I_{Csat}$ $\qquad P_Q = 0.196 \cdot W$

f) Does the diode in this circuit ever conduct a significant current? If yes, when and how much?

When the switch opens. $I_{Dmax} = I_{Csat} = 0.98 \cdot A$ from part a)

g) The switch is open for a while. What is the load current (I_L) now? 0



Ex.7 From F13 Final

A transistor is used to control the current flow through an inductive load (in the dotted box, it could be a relay coil or a DC motor).

a) In order for current to flow in through the load, the switch should be: i) closed or ii) open (Circle one)

b) Assume the switch has been in the position you circled above for a long time. I_L is 1.3A. Find the power dissipated by transistor Q_2 (neglect base current and V_{BE}).

$I_L := 1.3 \cdot A$ $\quad P_{Q2} = ?$ $\quad R_L := 3 \cdot \Omega$

$V_{CE2} := V_{CC2} - I_L \cdot R_L$ $\quad V_{CE2} = 1.1 \cdot V$

$P_{Q2} := V_{CE2} \cdot I_L$ $\quad P_{Q2} = 1.43 \cdot W$

c) This is an unacceptable power loss, so you would like to determine the minimum β_2 needed so that Q_2 will be in saturation. Assume Q_1 is also in saturation. You may assume $I_E = I_C$ for both traistors. $\quad \beta_{2min} = ?$

$$I_L := \frac{V_{CC2} - 0.2 \cdot V}{R_L} \qquad I_L = 1.6 \cdot A \ = \ I_{C2}$$

$V_{E2} := V_{CC2} - 0.2 \cdot V$ $\quad V_{E2} = 4.8 \cdot V$

$V_{B2} := V_{E2} + 0.7 \cdot V$ $\quad V_{B2} = 5.5 \cdot V$

$V_{C1} := V_{B2} + 0.2 \cdot V$ $\quad V_{C1} = 5.7 \cdot V$

$$I_{C1} := \frac{V_{CC1} - V_{C1}}{R_2} \qquad I_{B2} := I_{C1} \qquad I_{B2} = 57.5 \cdot mA \qquad \beta_{2min} = \frac{I_L}{I_{B2}} = 27.826$$

Better answer $\quad$ $$I_{B2} := I_{C1} \cdot \left(\frac{\beta_1 + 1}{\beta_1}\right) \qquad I_{B2} = 58.075 \cdot mA \qquad \beta_{2min} = \frac{I_L}{I_{B2}} - 1 = 26.551$$

You replace Q_2 with a new transistor that has a β greater than what you just calculated.

d) How much power is dissipated by the new transistor Q_2 (neglect base current and V_{BE})? $\quad P_{Q2} = ?$

$P_{Q2} := 0.2 \cdot V \cdot I_L$ $\quad P_{Q2} = 320 \cdot mW$

e) What is the maximum value of R_1 needed to saturate Q_1? $\quad \beta_1 = 100$

$$I_{B1min} := \frac{I_{C1}}{\beta_1} \qquad I_{B1min} = 0.575 \cdot mA \qquad V_{B1} := V_{B2} + 0.7 \cdot V \qquad V_{B1} = 6.2 \cdot V$$

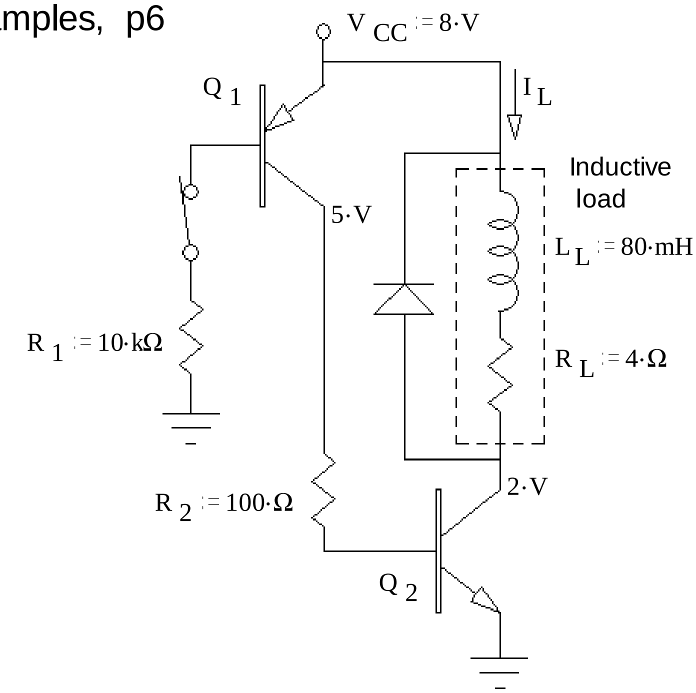
$$R_{1max} := \frac{V_{CC1} - V_{B1}}{I_{B1min}} \qquad R_{1max} = 3.13 \cdot k\Omega$$

f) Does the diode in this circuit ever conduct a significant current? If yes, when and how much?

When the switch closes. $\quad I_{Dmax} = I_L = 1.6 \cdot A$ $\quad$ from part c)

Ex.8 From F12 Final

A couple of transistors are used to control the current flow through an inductive load. The switch has been closed, as shown, for a long time.



a) You measure the voltage at each collector (referenced to ground) as shown on the drawing. Find the power dissipated by transistor Q_2 .

$V_{C1} := 5 \cdot V$ $\qquad V_{C2} := 2 \cdot V$

$$I_L := \frac{V_{CC} - 2 \cdot V}{R_L} \qquad I_L = 1.5 \cdot A$$

$$P_{Q2} := V_{C2} \cdot I_L \qquad P_{Q2} = 3 \cdot W$$

b) Find the β of transistor Q_2 .

$$V_{R2} := 5 \cdot V - 0.7 \cdot V \qquad V_{R2} = 4.3 \cdot V$$

$$I_{R2} := \frac{V_{R2}}{R_2} \qquad I_{R2} = 43 \cdot mA$$

$$\beta_2 := \frac{I_L}{I_{R2}} \qquad \beta_2 = 34.884$$

c) Find the β of transistor Q_1 .

$$I_{R1} := \frac{V_{CC} - 0.7 \cdot V}{R_1} \qquad \beta_1 := \frac{I_{R2}}{I_{R1}} \qquad \beta_1 = 58.9$$

d) Find the minimum β for transistor Q_1 to be in saturation. $\beta_{1min} = ?$

If Q_1 is saturated: $V_{R2} := V_{CC} - 0.2 \cdot V - 0.7 \cdot V \qquad V_{R2} = 7.1 \cdot V$

If Q_1 is saturated: $I_{R2} := \dfrac{V_{R2}}{R_2} \qquad I_{R2} = 71 \cdot mA \qquad \beta_{1min} := \dfrac{I_{R2}}{I_{R1}} \qquad \beta_{1min} = 97.3$

You replace Q_1 with a different transistor so that now: $\beta_1 := 200$ Use this from now on.

e) Find the new load current (I_L) assuming transistor Q_2 is in the active region.

Q_1 is saturated: $I_{R2} = 71 \cdot mA \qquad I_L := I_{R2} \cdot \beta_2 \qquad I_L = 2.477 \cdot A$

f) Check the assumption that Q_2 is in the active region and recaculate I_L if necessary.

$I_{R2} \cdot \beta_2 \cdot R_L = 9.907 \cdot V \qquad V_{CE2} := V_{CC} - I_{R2} \cdot \beta_2 \cdot R_L \qquad V_{CE2} = -1.907 \cdot V$ **Not possible**

Q_2 is saturated: $I_L := \dfrac{V_{CC} - 0.2 \cdot V}{R_L} \qquad I_L = 1.95 \cdot A$

g) Does the diode in this circuit ever conduct a significant current? If yes, when and how much?

When the switch opens. $I_{Dmax} = 1.95 \cdot A$ from part f)