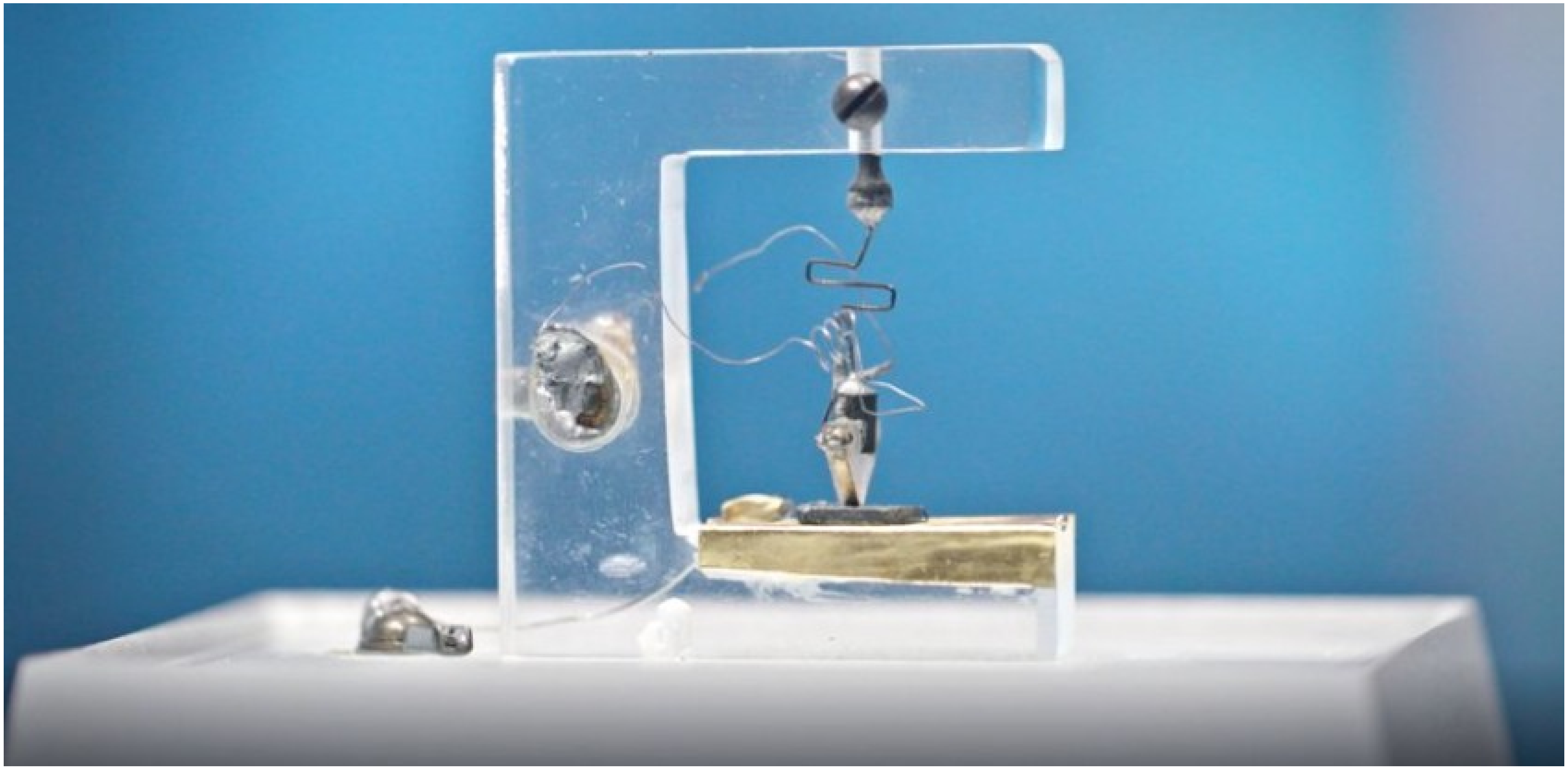
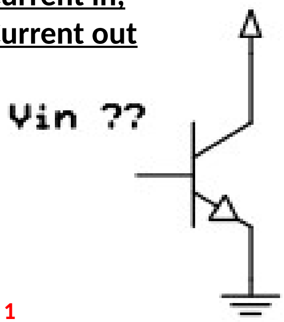
BJT Amplifiers and Switches:
Biasing, Amplifiers, Emitter Followers, and Switching



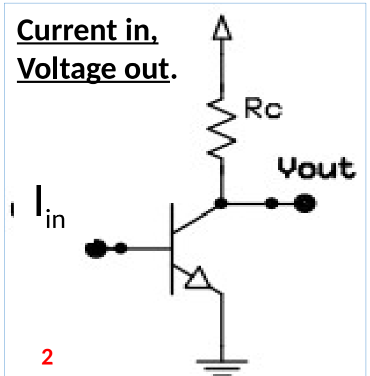
Step-by-Step BJT Amplifier Development

Current in, Current out



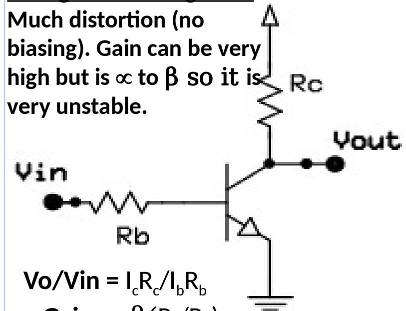
1

Current in, Voltage out.



2

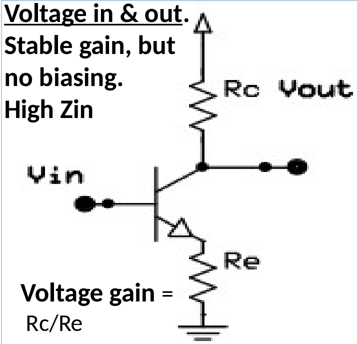
Voltage in & Voltage out.
Much distortion (no biasing). Gain can be very high but is ∝ to β so it is very unstable.



Vo/Vin = I_cR_c/I_bR_b
= Gain ~ $\beta(R_c/R_b)$

3

Voltage in & out.
Stable gain, but no biasing.
High Zin

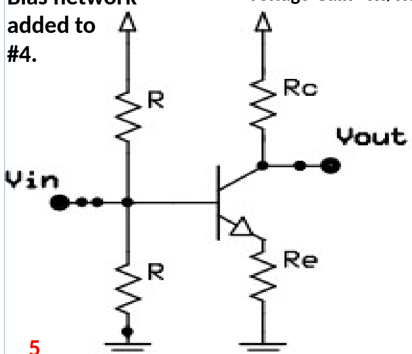


Voltage gain = Rc/Re

4

Bias network added to #4.

Voltage Gain= Rc/Re



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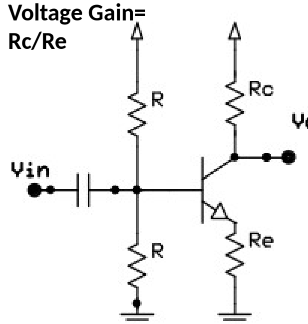
Voltage Gain= Rc/Re



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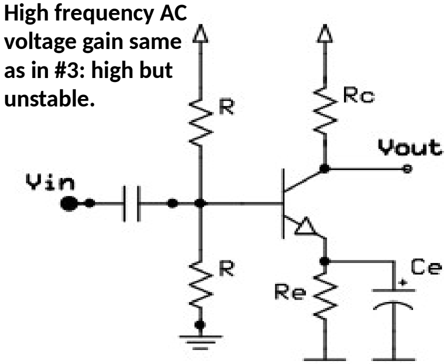
DC blocking capacitor added to #5. Bias voltage (DC) is isolated from input source.

High frequency AC voltage gain same as in #3: high but unstable.



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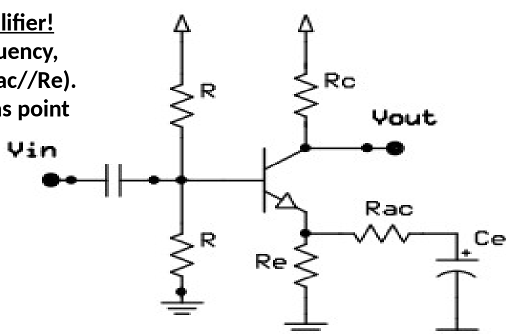
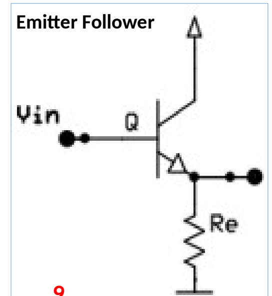
Perfect Amplifier!
At high frequency, Gain =Rc/(Rac//Re). Gain and bias point are stable.



8

Emitter Follower
Valuable as a buffer. Gain is exactly one. Z_{in} is extremely high and Z_{out} is low. V_{out} is always less than Vin by an offset of ~ 0.6 V. Can only source current.

Emitter Follower



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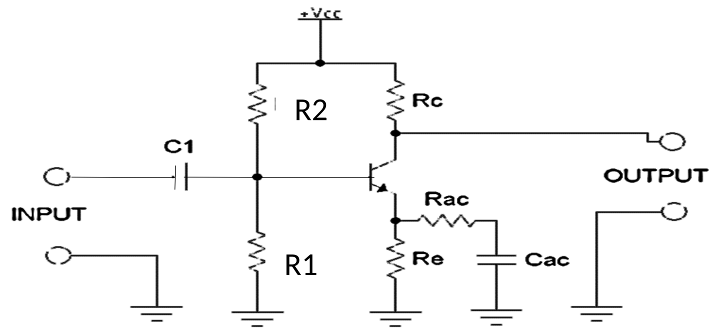
The Cookbook BJT Amplifier

“Common Emitter” Amplifier



This design approach is valid for operation <~500kHz.

Note: “$R_X//R_Y$” means “R_X in parallel with R_Y”

This very quick design approach is useful for low-frequency applications that do **not** require an optimized design. See Notes.

1. **Select quiescent collector current I_{cQ}**. This is the DC collector current flowing when there is no input signal, and the collector voltage is equal to about one-half the supply. Consider power drain, input and output impedance, day of the week, etc; 10 mA is OK for many applications.

2. **Select quiescent collector voltage, V_{cQ}.** Assuming that your supply voltage, Vcc, is predetermined, let $V_{cq} \sim (V_{cc}/2)$. Making V_{cq} roughly equal to ½ the supply maximizes the AC signal swing at the output. See Note 2 on the next slide.

3. **Select $R_c = (V_{cc} - V_{cQ}) / I_{cQ}$.**

4. **Set $R_e = R_c / 10$.** This will set the DC gain to 10. See Note 3.

5. **Select divider current, I_d**, which is the current through the voltage divider comprised of R1 and R2; make $I_d \sim I_{cQ}/20$ so divider is not heavily loaded by base current.

6. **Set R_1 and R_2.** Knowing I_d and the fact that the voltage at the node of $R_1R_2 = ((I_{cQ} \times R_e) + 0.6V)$, calculate values for R_1 and R_2.

7. **Select C_1, the input coupling capacitor**. It must pass the lowest required frequency, F_{low}. Let $C_1 >> 1/[2\pi R_{in} F_{low}]$ where $Rin \sim R_1//R_2$. See Note 4.

8. **For maximum AC gain**, make $R_{ac} = 0$. and make C_{ac} huge, ~ 470 uFd? R_{ac} may be added to improve AC gain stability, reduce distortion, and increase Zin. See Note 5

Notes on BJT amplifier design:

This design approach is useful for straightforward applications that do not require an optimal design. It will usually provide a quick, reasonable circuit when the supply voltage is at least 10 V, the collector current is between 1 mA and 100 mA, and the frequency under 500 kHz.

Note 2: Allow for effect of V_e if DC gain is < ~10. This is because a high V_e (resulting from low gain) will prevent the output from swinging close to ground and limit collector voltage swing). So, at low gains you may wish to make V_{cQ} one or two volts greater than ½ V_{cc} for this reason.

Note 3. Note that too much DC gain will lead to bias point instability. However, if the gain is very low, R_e will tend to be large and the signal-swing will be limited as discussed in Note 2 above. (Sometimes, especially in the case of an early stage, your signal-swing will be quite small, and you may not require a carefully centered V_{cQ}.) A DC gain of about 10 usually works well. Remember that the AC gain can be made much greater than the DC gain by adding a large capacitor across R_e. See Note 5 below.

Note 4: The input impedance to the amplifier is $Z_{in,}$ where $Z_{in} = (R_1//R_2)//(R_e x\beta) =\sim R_1//R_2$. The output impedance of the amplifier is $Z_{out} = R_c$. This is because the transistor collector circuit is simply a current source, and current sources have very high parallel resistance.

Note 5: Adding C_{ac} in parallel with Re effectively reduces R_e for AC signals and, therefore, increases AC gain while maintaining low DC gain which will stabilize the bias point. Unfortunately, whereas the AC gain will now be very high (maybe as great as 100 or more), distortion will be high, and the gain will vary with transistor characteristics. R_{ac} may be added to incorporate some AC negative feedback and stabilize AC gain. At $F >> 1/(2\pi R_{ac}C_{ac})$, AC gain $= R_c/(R_e//R_{ac})$. Note that this approximation of the AC gain is only valid for values of R_e and R_{ac} in the range of hundreds of ohms or greater.

If C_{ac} and R_{ac} are present, Z_{in} drops because R_e has been effectively reduced for AC signals. Now, $Z_{in} = (R_1//R_2)//(R_e//R_{ac})\beta$ at $F >> 1/(2\pi R_{ac}C_{ac})$. Also, C_1 must be increased since Z_{in} has dropped. At high frequencies where C_{ac} is a short, $C_1 = 1/(2\pi Z_{in} F_{cutoff})$.

2. The Esteemed Emitter Follower

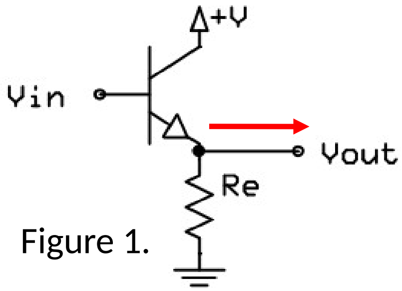


Figure 1.

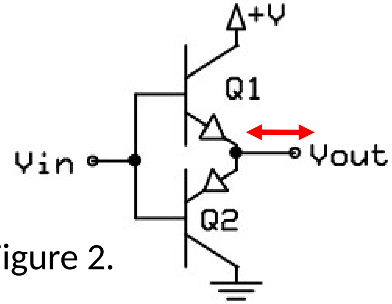


Figure 2.

The BJT emitter follower is a simple, yet particularly valuable circuit. With a stable and accurate AC gain of almost exactly 1.0, extremely high input resistance, and very low output resistance (sort of), the emitter follower makes an excellent "buffer" that can be used, for example, to drive a heavy load from a high resistance source.

Looking at the input characteristics, Vout will always equal Vin, less one diode drop. As a result, as Vin increases, Vout will increase the same amount and the gain will be 1.0. To the voltage source at then base, there is always a "following" voltage source at the emitter. Because of this "tracking" action, an increase in voltage at Vin will only produce a very small increase in base current. Therefore, the resistance looking into the base (Zin) will be very high: (Zin = β x Re)

Remember, however, that the output will always be about 0.6 volt less than the input. Fortunately, this is a fairly constant offset voltage and can often be ignored -especially with AC signals.

Regarding the output characteristics, If we load the circuit with a resistor to ground (in parallel with, or replacing, Re), it will tend to pull down the emitter (which is the cathode of the E-B diode). However, if the base is driven by a stiff (low series- resistance) voltage source, as the emitter is pulled down with a load to ground, the E-B diode will be "stretched", resulting in more base current. This additional base current results in greater collector current (remember β), which will flow out the emitter. The emitter voltage will rise until E-B voltage is again equal to one diode drop. As a result, the emitter voltage is constant even as the load increases, which provides very low output resistance and the ability to drive heavy loads.

This excellent performance is achieved because the circuit has almost 100% negative feedback.

Note, however, that the circuit has one important limitation: With the NPN circuit shown in figure 1, the output can only actively SOURCE current in the direction shown; it can only pull **up** on a load that is connected to ground. There is no active transistor affect when pulling down on a load (such as a resistor connected to the positive rail). Due to β, the transistor will provide very high currents when sourcing current; however, sinking current will only be provided by the emitter resistor. Therefore, when sourcing current, Zout ≅ (resistance driving the base) x β. When sinking current, Zout = Re.

If it is necessary to both source and sink current, the "push-pull" double emitter-follower shown in Figure 2 may be used. In this circuit the NPN provides high source current as in Figure 1, but the bottom PNP can and pull down on a load and sink heavy currents.

Always remember to include an emitter resistor to make the emitter follower "work". For example, with an NPN emitter-follower a resistor to ground is required so that an oscilloscope or other high resistance load can be properly driven. The output must never float (which is, of course, true for every point in every circuit).

3. Multi-Stage Amplifiers

The maximum voltage gain that can be achieved with a single stage amplifier is limited by b. At higher frequencies, the problem is magnified as b drops with frequency (f_t). To provide suitable overall gain, additional amplifier stages are often needed. Just as important, however, is the need for high input impedance and low output impedance so that successive stages do not cause loading. This requirement will, also, often result in the need for additional stages. See **Figure 1** below.

Simple "direct-coupling" of amplifier stages will work if the bias point of the first stage is carefully set so it can be directly coupled, and provide dc bias, to the second stage. See **Figure 2**; a PNP is used in the second stage to facilitate DC level-shifting. The use of capacitor coupling resolves this issue, with the capacitor chosen to provide adequate low-frequency response; see **Figure 3**. Note that the addition of a 2nd stage will load the first stage and <u>always</u> reduce the gain and signal swing of the first stage. DC amplifiers cannot, of course, be AC coupled.

An emitter- follower is often a good approach to obtaining low output resistance and high output current. See **Figure 4**, where an emitter- follower is used to "buffer" the output of the amplifier to provide low output resistance and the ability to drive a heavy load. In this direct- coupled circuit, the emitter- follower is properly biased at about ½ the supply via the collector of the first transistor. Remember, however, that an NPN emitter-follower has non-symmetrical output that can only actively source current; this may result in much distortion when driving a load. See Slide 3.

As discussed in Slide 3, the output emitter-follower will have a low Z_{out} (very roughly: R_c/β) when it is going positive and sourcing current; however, its Z_{out} will be much higher ($=R_e$) when it is going low (sinking current) and significant distortion may result. If you need to sink a lot of current, you can use a double emitter- follower. You could also choose a relatively low value for the follower's R_e, but be careful of power dissipation.

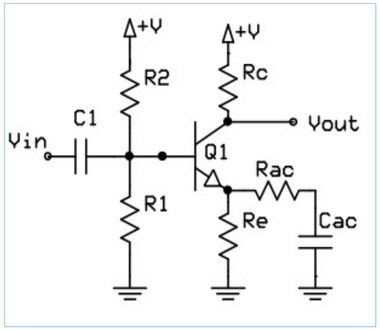


Figure 1. Single stage amplifier.

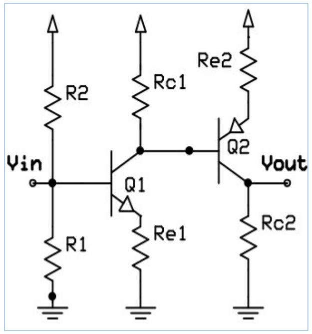


Figure 2. Two-stage, direct-coupled amplifier.

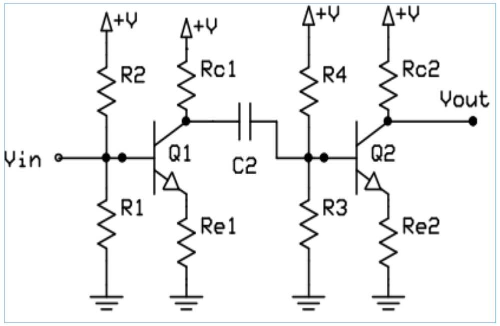


Figure 3. Two-stage, capacitor-coupled amplifier.

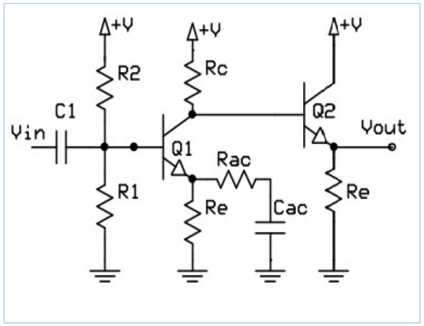


Figure 4. Single amplifier stage with emitter-follower output.

4. Transistors in Switching Applications

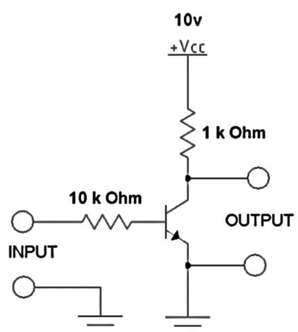
Transistors can be used as signal amplifiers since a small change in base current will result in a large change in collector current. When used as amplifiers they are operated in their ***linear*** mode, biased between “OFF’ and saturated. However, for many amplifier applications you may choose to use operational amplifiers rather than transistors; they are simpler to apply and far more precise for use in instrumentation.

However, transistors are indispensable for use in ***switching*** applications- when they are always either “OFF” or “ON” (saturated). As switches, transistors are typically used as interface devices (“drivers”) between low-current devices, such as op-amps and sensors, and high-current loads such as relays and motors. A transistor that is saturated or OFF dissipates very little power.

In **Fig. 1**, the input voltage is initially zero; the transistor is OFF, and the collector voltage is equal to the supply. If a slowly- varying voltage is applied to the base of a transistor, base current will start to flow when the input voltage approaches 0.6 volt. This current will be limited by the 10K resistor and will equal (Vin-0.6)/10K. A large collector current will begin to flow which will be equal to the base current multiplied by b (100 or so). As the collector current increases, the voltage at the collector will drop. Since b is large, the collector voltage will rapidly drop with a small increase in base voltage. When the collector voltage is near zero, collector current will reach its maximum value (10V/10K) and we say the transistor is *saturated*. A saturated transistor will have a very low collector-emitter voltage: typically a few hundred millivolts.

It is important to note that as the 10K base resistor is decreased, the voltage gain of the switch will increase, and the slope of the output curve will be much sharper. Of course, if this resistor is too low, it might load the source, or the base current might be destructive to the transistor.

In **Fig. 2**, a light-sensitive resistor will decrease in resistance when illuminated, shunting base current to ground and turning the lamp OFF. In a darkness, the photo resistor will increase in resistance and R1 will bias the transistor ON. At intermediate light levels, the lamp will glow at medium brightness. You should generally avoid circuits as shown in Figure 1 and Figure 2. These lack **hysteresis**, so they will switch gradually, resulting in intermediate states and unacceptable operation.



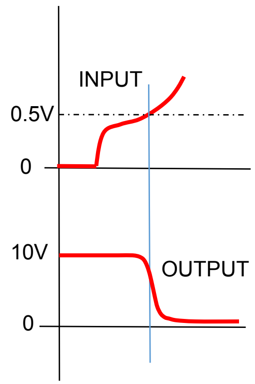


Figure 1

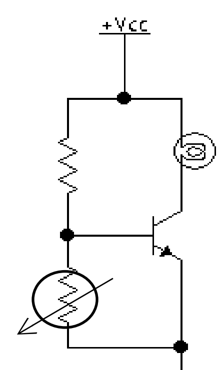
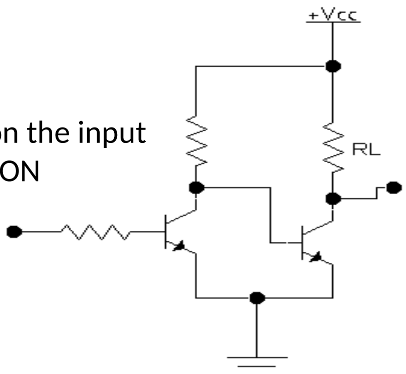


Figure 2

EXAMPLES OF TRANSISTOR *SWITCHING* CONFIGURATIONS

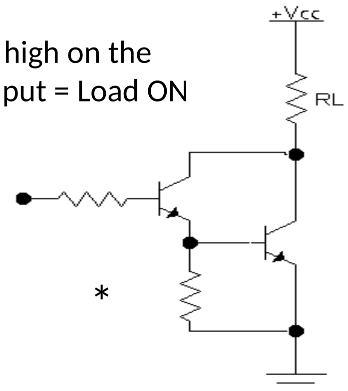
Except where shown, these circuits use a saturating transistor to drive a load.

A low on the input = Load ON



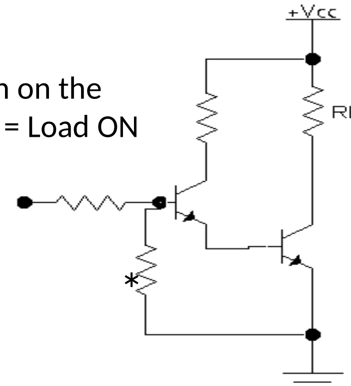
Non-Inverting

A high on the input = Load ON



Darlington (NOT saturating)

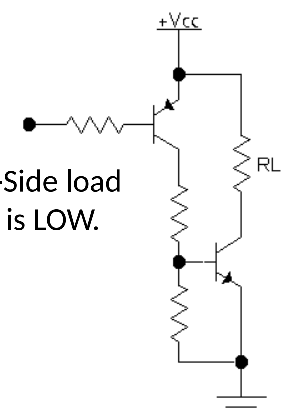
A high on the input = Load ON

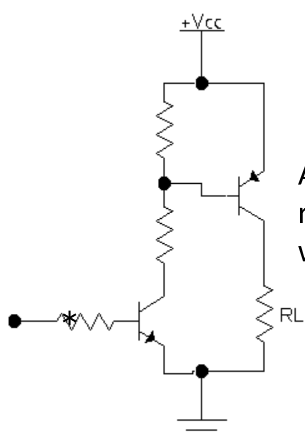


Not a Darlington

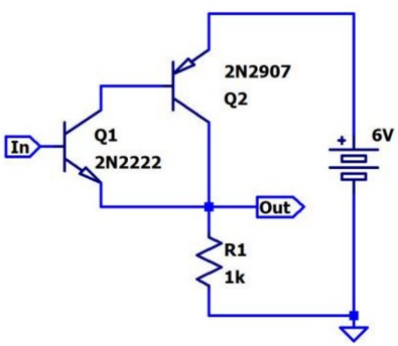
Compound Transistor Circuits

An NPN drives a Hi-Side load ON when the input is LOW.





A PNP drives a ground-referenced load ON when the input is HIGH.



Sziklai Compound Circuit (Linear)

*Emitter-Base shunt resistor -Necessary!!

May be used in linear circuits with the incorporation of negative feedback