Laboratory 11
Transistors

Key Concepts

- Current Amplification
- Follower
- Darlington Connection
- Voltage Amplification

Text Material

- Horowitz & Hill 2nd edition: Sections 2.01 – 2.07, 2.16

Equipment Needed

- +12 V and -12 V Power Supplies
- Oscilloscope
- (2) DVM's
- Function Generator
- Resistor Substitution Box
- High Base Resistance Current Measurement Board

Components Needed

- (2) 2N3904 Transistors
- (2) 1 kΩ Resistors
- (1) 270 Ω Resistor
- (1) 47kΩ Resistor
- (1) 100 Ω Resistor
- (2) 1 μF Capacitors
- (1) 470 Ω Resistor
- (2) 4.7 kΩ Resistors
- (1) 2.7 KΩ Resistor
- (1) 10 kΩ Resistor

Some Background

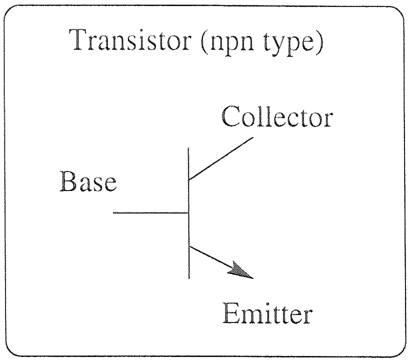
The advent of the transistor marked a turning point in modern day electronics. However, today, the use of discrete transistor circuits is limited, although nearly every integrated circuit is composed of transistors. The use of bipolar transistors as discrete devices where applicable will be explored in this laboratory.

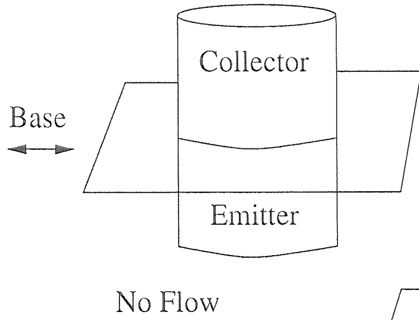
There are five parts to this laboratory as follows:

Part A: Current Amplification
Part B: Transistor Switches
Part C: Voltage Follower
Part D: Voltage Amplifier
Part E: Darlington Connection

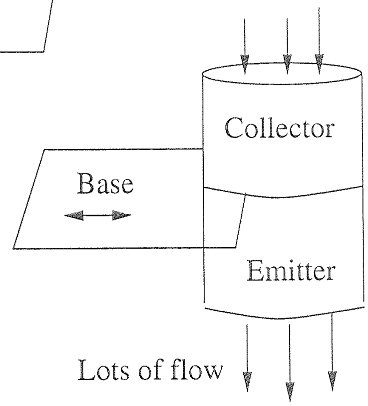
Note on Transistors:

To get you started, think about a transistor as a programmable current valve that comes with a rulebook.





By sliding this base "sheet" back and forth (which is easy to do), we can control the flow of stuff from the collector to the emitter.



Transistor Rule Book: (for you)

1) Set Vbase to NO LESS than about 0.6 V above Vemitter.
2) Vcollector should be a little higher than Vemitter.
3) Don't ask the transistor for more than it's designed for (don't burn it up!)

Transistor Rule Book: (for the transistor)

1) Don't let Vbase be higher than about 0.6 V above Vemitter.
2) Let Icollector ~ Iemitter if Vcollector is a little higher than Vemitter and you obeyed rule 1
3) Limit Icollector to be a maximum of β Ibase

So we get: Vbase = Vemitter + 0.6V Icollector = Iemitter β Ibase = Icollector
Sort of in that order. (β is an intrisic property of the transistor, in the lab, about 200-300)

Parts of the Lab, by the rules:

Part A:

Vbase should be at about 0.6 Volts since Vemitter = 0Volts

The maximum Icollector can be is about 12V/1.0 k ohms or Vcollector will be less than Vemitter and the transistor won't work

Icollector will never be higher than βIbase (It can be less though!)

Part B:

See what happens if you disobey rule 1?

We don't want to burn up the diode or the transistor, so to follow your rule 3, we have to limit Icollector. Note: These rules are made up by the author and are not universal. If there is a lab question, you should answer it in your OWN words...

Part C:

If Vbase = Vemitter + 0.6V, then dVbase = dVemitter, but you still have to obey rule 1: Vbase should be NO LESS than Vemitter + 0.6 V

This is another demonstration of rule 1 for you.

Note on Transistors: (cont'd)
Parts of the Lab, by the rules: (cont'd)

Part D:

Rule 1 is obeyed. And you did a good job of designing a circuit that doesn't force the transistor to limit Icollector. Kind of cool that the collector resistor provides a voltage amplification though since Icollector = Iemitter, and Iemitter is set by Vbase. Think about this: If Vbase goes down, Vemitter goes down and Iemitter goes down, so this means the voltage across the collector resistor goes down, but this means that Vcollector gets CLOSER to +12V (means it LOOKS like Vcollector went UP when Vemitter went DOWN)

Part E:

Here we go. We're setting Ibase of Q1, so the maximum Icollector Q1 can have is the β of Q1 times Ibase of Q1. Now, Icollector = Iemitter of Q1, but this is Ibase for Q2! So the maximum Icollector for Q2 is the β of Q2 times Icollector of Q1. And what is the maximum Icollector for Q1? So what is the maximum Icollector for Q2? Incidentally, V at point B should be around 1.2 V.

If life were so simple, that's all there'd be to transistors, but, alas, there are some extra things you might have discovered in the course of the lab:

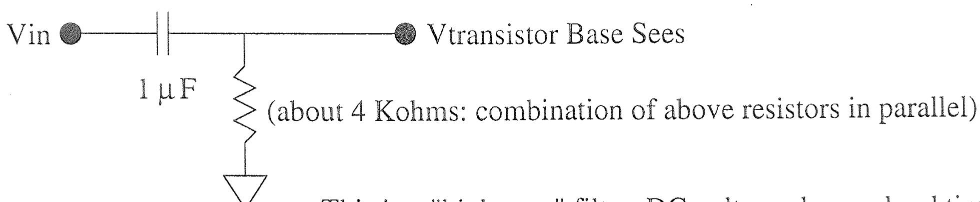
Part A: Transistor characteristics depend on temperature, even more than you found out in the lab. Integrated circuit designers have to really pay attention to this and have elaborate, and simple, solutions to put a lot of transistors in a circuit and not have the performance tank with a temperature change.

Part C: Turns out there's a little bit of resistance in the emitter of a typical transistor and you'll see a smaller voltage on the output of the emitter as a result.

Part D: The comment of part C surfaces here again. You can't ever get that resistance on the emitter to go to zero! So, you have to have a fairly big resistor for the collector to get high gains, but, and here's the killer, this small intrinsic emitter resistance programs the current. Let's say you got rid of the 470 ohm resistor and the intrinsic resistance of the emitter was about 10 ohms, you might expect a gain of -470, but you'd have to be very careful to make sure that Vbase was only about 25mV above the point where the transistor turned on, or Vcollector would be less than Vemitter. And, even worse, that intrinsic emitter resistance depends in Icollector. So, you could make a really high gain circuit, but don't expect the output to look like the input. A safe design has the emitter resistor >> greater than the intrinsic emitter resistance.

A note on frequency response in Part D:

Consider an incoming signal in Part C. It see's a 47 kohm path to ground, a 4.7 kohm path to ground, and current flows into the base of Icollector/β (which is like a path through a resistor of β 470 ohms). So, at low frequencies, the incoming signal "sees" a circuit that looks like:

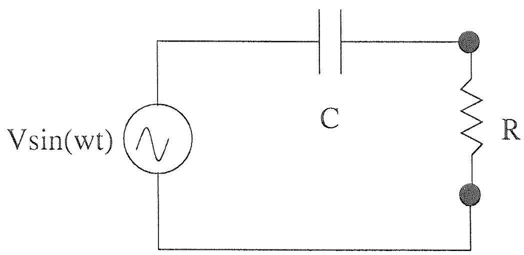


This is a "high pass" filter. DC voltages have a hard time getting past that capacitor. In fact, it acts like a resistor (called impedance) at low frequencies.

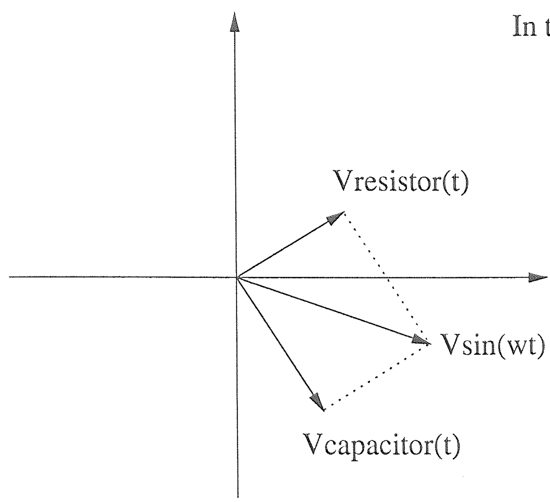
Note on Transistors: (cont'd)

A note on frequency response in Part D: (cont'd)

Consider this case:



The current through the circuit is the same I(t), so the voltage across the resistor is RI(t). Now, since V=q/c, the voltage across the capacitor is out of phase with the voltage across the resistor. In fact, we think of the voltages across the capacitor and the resistor as vectors (called phasors), and the vector sum of the Vresistor(t) vector and the Vcapacitor(t) vector = Vsin(wt).



In this diagram, the Vsin(wt) vector rotates about counter-clockwise with angular velocity of w. The resistor and capacitor vectors rotate too at w. The resistor leads the applied voltage by a phase angle of invTan((I(t)/wC) / (I(t)R)) or invTan (1/(wCR))

So what?

Practically, this means you'll really start seeing effects in the response of the circuit of Part D at f = 1/(2pi C R) or about 40 hz, give or take.

This isn't the only game in town though. Think for a second. A transistor is conductors separated by a dielectric, not a real good one, but you can see effects at high frequencies if this capacitance is of the order of 10 pf or so. At lower frequencies, the impedance from this capacitance is high so you don't see it. (Recall Impedance is like 1/wC for a capacitor) At high frequencies, this capacitance robs your gain. You might see this effect if your frequency is set high enough. It will look a lot like the behavior you saw at low frequency, but it's tougher to fix (in fact it gets enhanced because the capacitance, primarily between the base and the collector, gets boosted by a factor of β like the emitter resistance got boosted when we were looking at the resistance the signal source saw.

Procedure

Part A: Current Amplification

What makes the transistor so useful? The answer is that the transistor is a current amplifier. Figure 11-1 shows an NPN transistor, the common 2N3904, connected to measure the current into its base (B) and its collector (C). By varying R with the resistor substitution box, we can vary the current into the base, I_B, and measure the current that flows into the collector (I_C). The current that flows out of the emitter, I_E, to ground is, by Kirchoff's Current Law, equal to the sum of I_B and I_C.

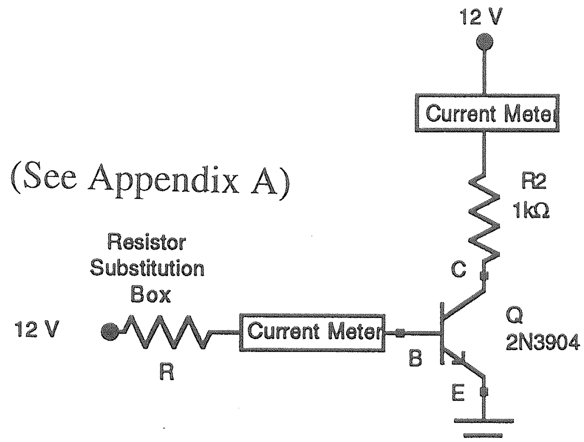


Figure 11-1 Transistor Current Gain Circuit

I. Vary R from 1 kΩ to 10 MΩ in increments listed in the table below and record I_C and I_B. Calculate the current gain $\beta = I_C / I_B$. CAUTION: **Make certain that R never falls below 1 kΩ or else the transistor will be destroyed.**

R	I_B	I_C	β
1k			
5k			
10k			
50k			
100k			
500k			
1 M			
5 M			
10 M			

<u>Question One:</u> Is the current gain β constant over the rang of I_B used above? Explain.

II. Set R = 1 MΩ. If you have a soldering iron in your lab, heat it up and touch the tip to the transistor thus warming the transistor. How does β vary? Does it increase or decrease? If you don't have a soldering iron, try warming the transistor with your hand, the effect is much smaller, but it may be able to be seen.

Part B: Transistor Switches

One of the main uses of a discrete transistor is that of a switch. Often one needs to control a large current source from a small current source. Otherwise stated, a high impedance source needs to drive a low impedance circuit. As a current amplifier the transistor is suited to accomplish this task.

Consider the circuit shown in Figure 11-2. Here a high impedance source is simulated with a 10 V peak-to-peak square wave signal fed through a 10 kΩ resistor. The maximum current input to the transistor is thus 5V / 10 kΩ or 0.5 mA. A light emitting diode, or LED, requires more that 0.5 mA to light. To light the diode we use a transistor switch which turns the diode on and off. When current is fed into the base of the transistor, the transistor conducts and is said to be ON. The LED lights. When the base receives no current, the transistor is in the non-conducting state and no current flows from collector to base.

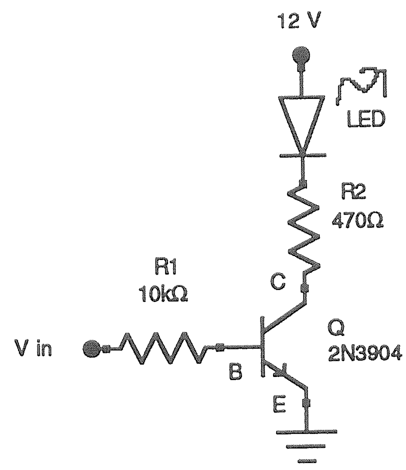


Figure 11-2 Transistor Switch

Construct the circuit shown in Figure 11-2 and drive it with a 10V peak-to-peak square wave centered at zero volts with a frequency of less than 1 Hz. Using an oscilloscope or DMM, note when the LED is on and when it is off (V_C high or low).

Question Two: Explain the operation of the above circuit-namely why doesn't the LED turn on when the signal is low and what is the purpose of the 470Ω resistor?

Part C: Voltage Follower

In Part B we looked at how the transistor can be used to amplify current in digital (ON or OFF) situations. The transistor can amplify the current of analog signals as well. The circuit shown in Figure 11-3 does just that. The input impedance of the circuit is much larger than the output impedance and this the driving signal is buffered (not loaded down) by whatever output circuitry is connected to the output. This circuit is useful when a feeble signal must drive some device that requires more that current than the signal itself can produce.

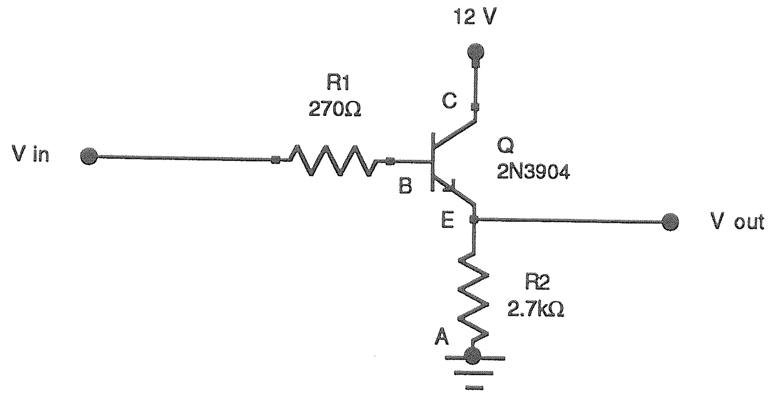
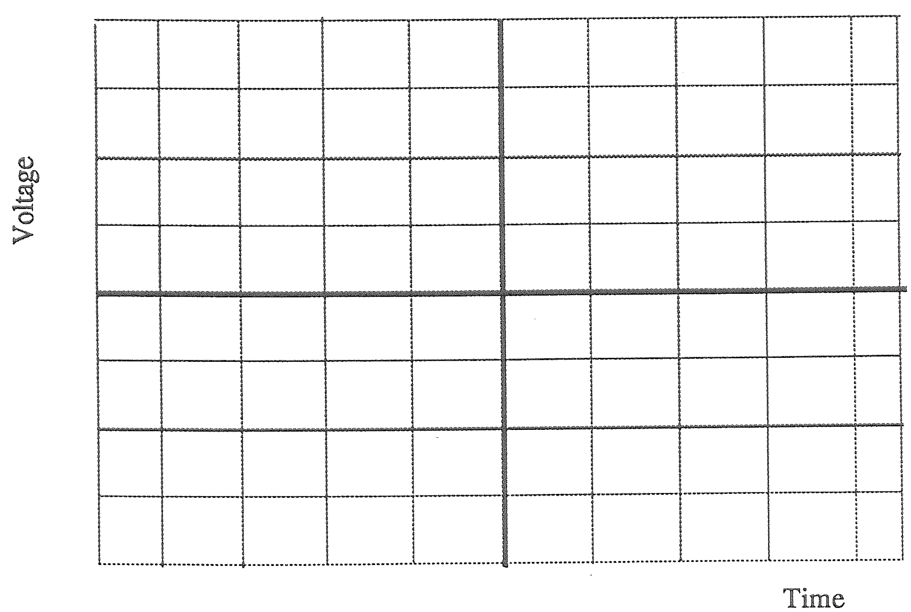


Figure 11-3 Transistor Follower (Emitter Follower)

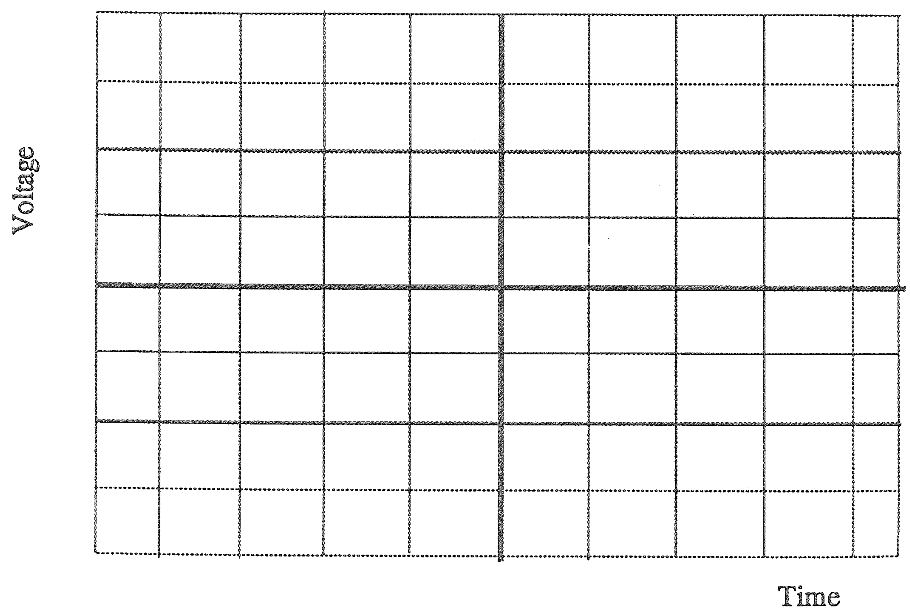
I. Construct the circuit shown in Figure 11-3 and drive it with a 5 V peak-to-peak sine wave with frequency 1 kHz centered at zero volts. Sketch the input and output below.



Question Three: Is there a phase change between the output and the input signals?

Question Four: Does the output signal replicate the input signal? Explain why or why not in terms of the transistor's function.

II. Remove the ground connection from point A and connect point A to -12 V. Use the same input signal and observe the output signal. Sketch both below.



Question Five: Explain why changing the voltage on the emitter changes the output of the emitter follower.

Part D: Voltage Amplifier

The transistor can be used as a somewhat suitable voltage amplifier, however for low frequency circuits commonly found in instrumentation, the transistor is usually avoided. The design of a solid transistor amplifier is somewhat more of an art than a science. More suitable, easily designed amplifiers will be studied in the next laboratory.

A common-emitter amplifier is shown in Figure 11-4. Construct the circuit and drive it with a 0.2 V peak-to-peak sine wave. Vary the frequency from 1 Hz to 1 MHZ in decade intervals and plot the output voltage on the graph below. Note any phase change on the graph as well.

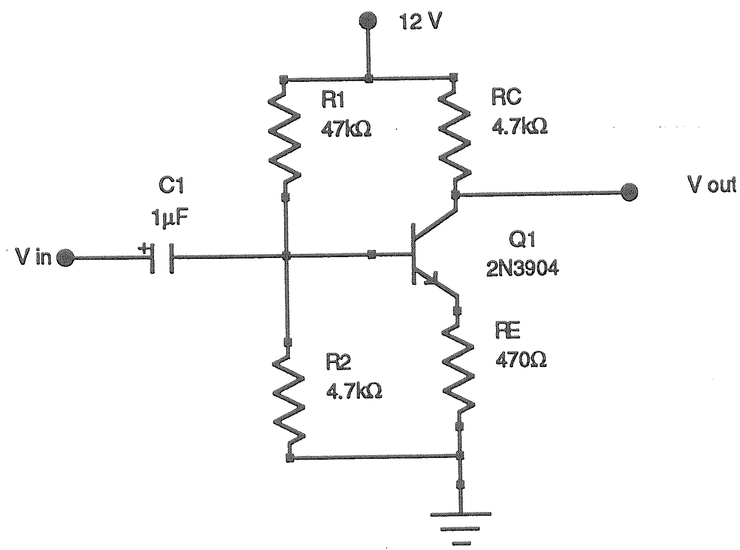
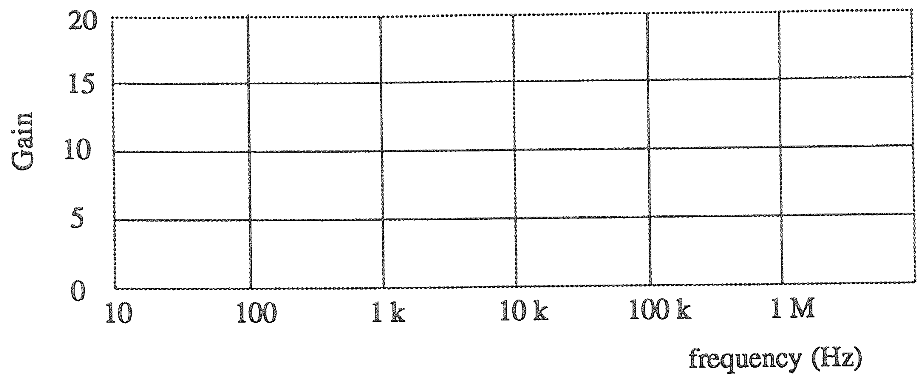
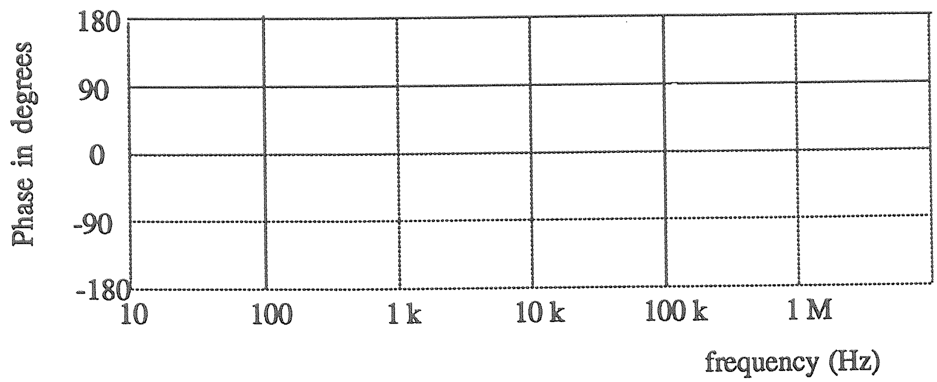


Figure 11-4 Common-Emitter Amplifier

V vs. frequency



phase vs. frequency



Question Six: Is the voltage gain what you expected? Explain.

Question Seven: Explain any frequency dependence of the voltage gain.

Question Eight: Is it possible to modify the circuit to produce a gain of 1000?. Explain.

Question Nine: Does the output signal look like the input signal, or is there distortion? Comment on any distortion. Is it avoidable?

Part E: Darlington Connection

Most transistors have relatively modest current gains. By connection our transistors in a Darlington configuration as shown in Figure 11-5, high gains are possible. Construct a circuit similar to that in the figure and measure I_B, I_C and β as you did in part A.

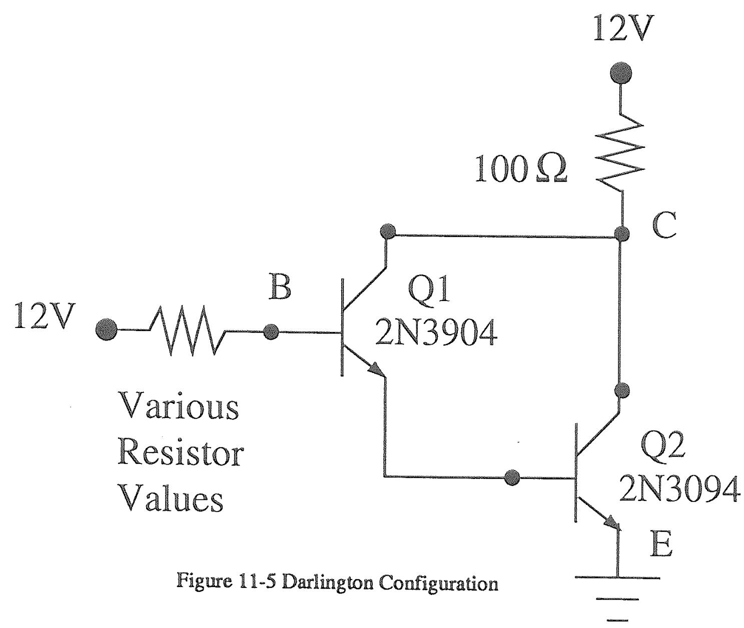


Figure 11-5 Darlington Configuration

Vary R from 1 kΩ to 10 MΩin increments listed in the table below and record I_C and I_B. Calculate the current gain $\beta = I_C / I_B$. **CAUTION: Make certain that R never falls below 1 kΩ or else the transistor will be destroyed.**

Note:

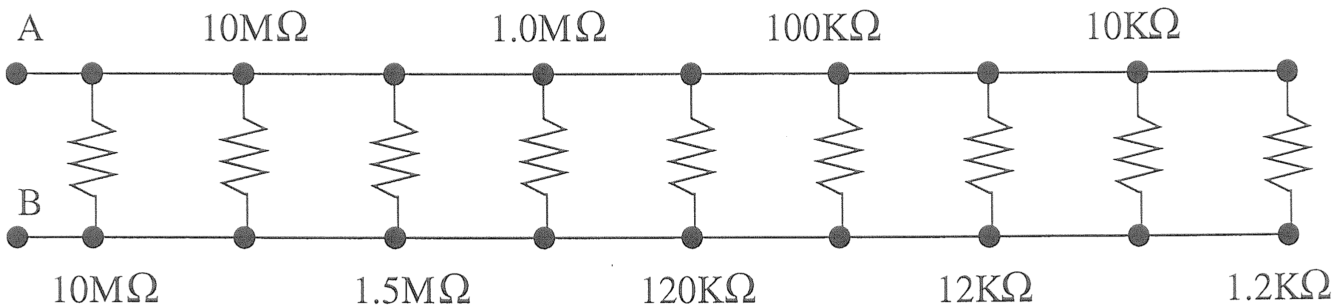
You may need to use very different resistor values in Part E. That current measurement gets really tough at the 10 Meg resistance. There's a technique explained in Appendix B that explains a different method for measuring current at very high resistance values.

R	I_B	I_C	β
1k			
5k			
10k			
50k			
100k			
500k			
1 M			
5 M			
10 M			

Question Ten: Is the gain of the two transistor circuits equal to twice the gain of a single transistor? Explain.

Appendix A: Make your own Resistance "Box"

Examine the circuit below:



Together in parallel, the resistance between points A and B is 964 Ohms.

If we remove the 1.2 K ohm resistor, R tot = 4.91 K

If we then remove the 10 K ohm resistor, R tot = 9.66 K

And then we remove the 12 K ohm resistor, R tot = 49.5 K

And then we remove the 100 K ohm resistor R tot = 98 K

And then we remove the 120 K ohm resistor R tot = 536 K

And then we remove the 1.0 M ohm resistor R tot = 1.15 M

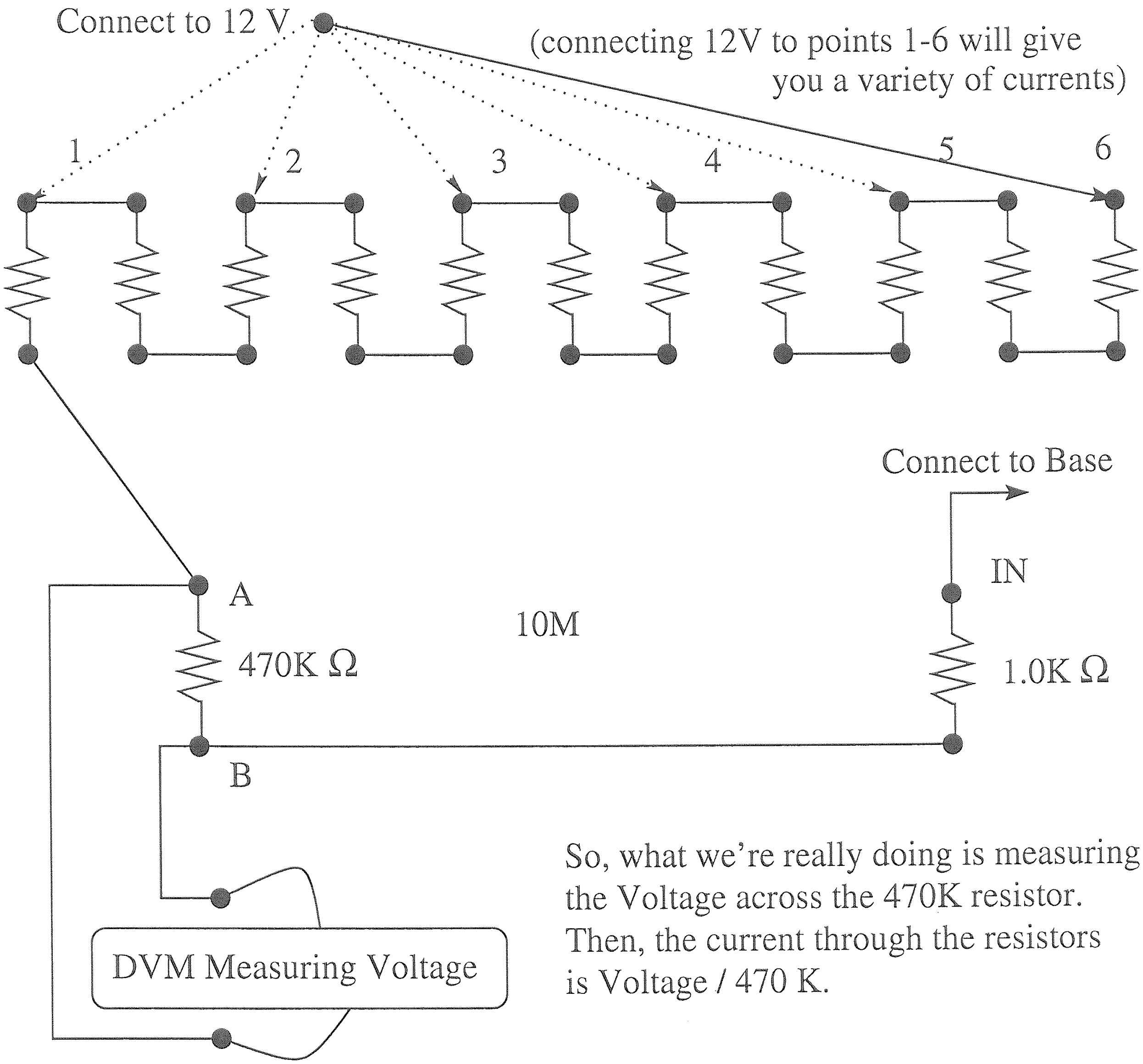
And then we remove the 1.5 M ohm resistor R tot = 5 M

And then we remove the 10 M ohm resistor R tot = 10 M

Well, you get the idea. All we're really trying to do is to vary the base current over a reasonable range: the actual resistance values aren't that important. You will probably have trouble getting a good current reading at 5 M ohm and higher. Hopefully, for part A, you won't need these values. If, however, these current values are important for your measurement, proceed to Appendix B for another trick. (You'll probably need it in any case for part E)

Appendix B: Measure Base Current when Base Resistance is high

Examine the circuit below:
(Resistors are 5.0M unless indicated)



So, what we're really doing is measuring the Voltage across the 470K resistor. Then, the current through the resistors is Voltage / 470 K.

We can't just measure the voltage across a 5 M resistor since there is a resistance inside the DVM of about 10M ohms. By putting this 10M ohm in parallel with the 470k ohm resistor though, we have significantly reduced this effect.