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Experiment: Transistor Circuit Design

You can now explain with confidence what p-doping, n-doping, and depletion layers mean. Now you will put that knowledge to use. You have the transistor in your hand. You stare at it, knowing the power it contains and what it has done for the world. Here you will use your transistor to amplify some spikes.

Time 1-3 Hours

Difficulty Advanced

What will you learn?

In the previous Transistor lesson plan (http://www.backyardbrains.com/experiments/transistorTheory), you learned the theory. Now you will apply it and build your own simple amplifier circuit from scratch using two transistors and some various resistors/capacitors.

Prerequisite Labs

Transistor Theory (http://www.backyardbrains.com/experiments/transistorTheory) - Read how a transistor works before proceeding

SpikerBox (spikerbox) - A familiarity with spikes will make this activity more meaningful

Equipment

Stimulation Cable (/products/stimulationcable)

Cockroaches (/products/cockroaches)

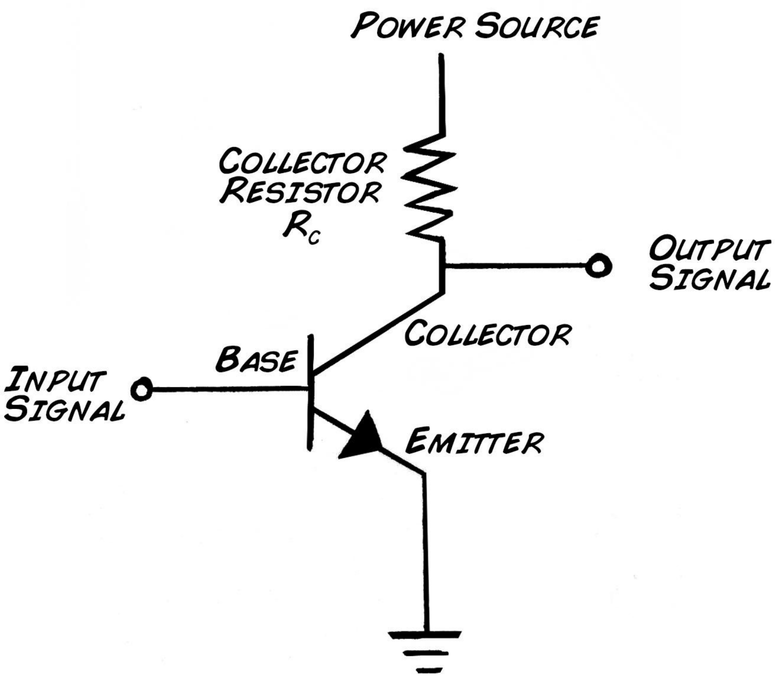
Electrode (/products/recordingelectrode)

Procedure

works (can amplify spikes).

In order to build an amplifier, all you need are a transistor, a power source, some resistors, and some capacitors. There are many ways to mix these together, which is an art (Steve Jobs (http://www.vimeo.com/31813340) often called laying out circuits "digital art"), but we will give you some basic conditions and assumptions to work with and then walk you through the design of your very first simple bio-amp!

There are multiple configurations using NPN transistors, but we will use the "common emitter configuration" because it allows us to have high voltage gain. Why is it called a "common emitter amplifier?" - because the base is the input, the collector is the output, and the "common" or ground is the emitter.



(img/CommonEmitter.jpg)

Like any diligent engineer, let's start with the "requirements" which is a boring way to say: "what we want this machine to actually do." For our bio-amp, we want to "amplify" the very small electrical signals in the cockroach nerves. Let's aim for a "gain" of 150, or increasing the amplitude of the signal 150 times. We also want to limit what we amplify to ensure we are only paying attention to spikes (action potentials) and not other electrical signals like electrical noise from your house. So, like the real SpikerBox, we only want to measure signals with components above 300 Hz (cycles per second). This is also called "high-passing" the signal.

Thus, we have two requirements

1. Gain of 150.
2. Filter setting: high pass filter of 300 Hz.

Now back to the art of electronics design. We base our amp heavily from the very excellent book "Practical Electronics for Inventors" (http://www.amazon.com/Practical-Electronics-Inventors-Third-Edition/dp/0071771336/ref=dp_ob_title_bk) by Paul Scherz.

Parts

In addition to the cockroaches (http://www.backyardbrains.com/products/cockroaches), the cable (http://www.backyardbrains.com/products/stimulationcable), and the electrode (http://www.backyardbrains.com/products/recordingelectrode) mentioned above, you need to visit your local friendly RadioShack (http://www.radioshack.com/storeLocator3/index.jsp?clickid=rsk_header_storeLocator) to obtain:

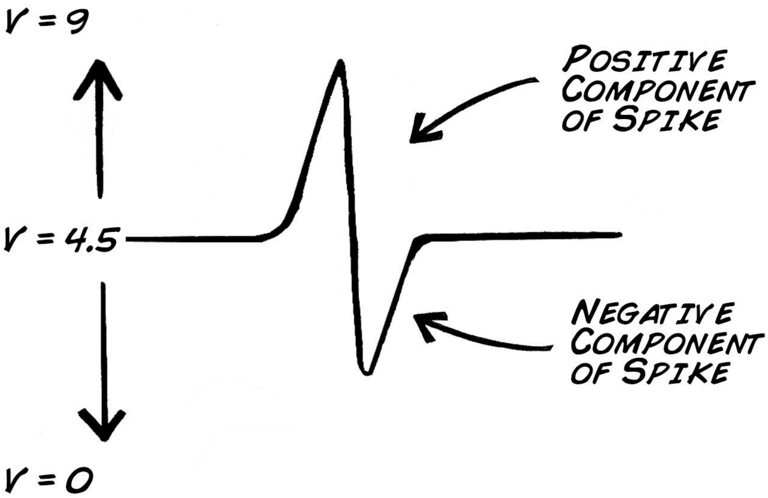
2. four 4.7 kΩ Resistors -from resistor sample pack (http://www.radioshack.com/product/index.jsp?productId=2994585)
3. four 1 kΩ Resistors from same sample pack
4. one 50 Ω Resistor from same sample pack
5. two 1 μF capacitors (http://www.radioshack.com/product/index.jsp?productId=12401431&filterName=Type&filterValue=Ceramic+disc+capacitors)
6. four 10 μF capacitors (http://www.radioshack.com/product/index.jsp?productId=2102481)
7. some jumper wire (http://www.radioshack.com/product/index.jsp?productId=2103801)
8. a solderless breadboard (http://www.radioshack.com/product/index.jsp?productId=12165713)
9. a 9V battery connector (http://www.radioshack.com/product/index.jsp?productId=2062218)
10. a 9V battery (http://www.radioshack.com/product/index.jsp?productId=3897297)
11. an RCA plug (http://www.radioshack.com/product/index.jsp?productId=2103224&filterName=Category&numProdsPerPage=60)
12. a RadioShack Speaker (http://www.radioshack.com/product/index.jsp?productId=2062620) (we love these things)

You also need a small piece of cork or styrofoam to lay the cockroach leg on.

Designing the Circuit

Emitter and Collector Resistors

Since we will be using a 9V battery, and our spikes have both a positive and negative component:



(img/SpikePosNeg.jpg)

We want the neural signal to ride on top of +4.5 V, so we have enough voltage "room" to amplify both the negative and positive parts of the signal. Thus, need the V_c, or voltage at the collector, to be 1/2 V_{cc} (it's confusing, but Vcc means "common current"" or more generally, our 9V power source). We thus need to put a resistor at V_c to set V_c = 1/2 V_{cc}, and we use Ohm's law V=IR, which we can rewrite as:

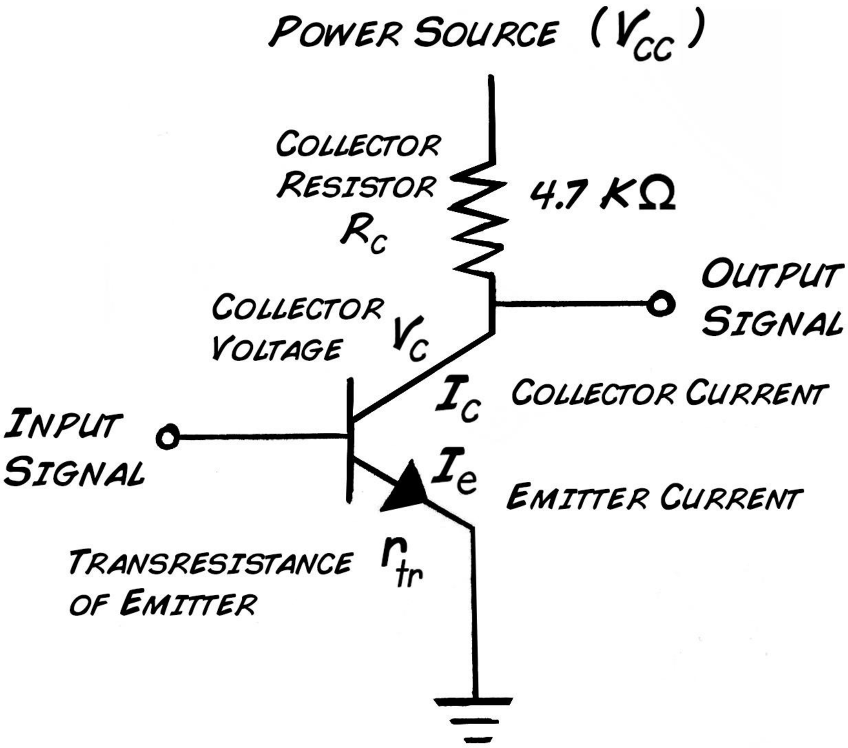
$$R_C = \frac{V_{CC} - V_C}{I_C}$$

(img/RcCalc_1.jpg)

I_c is the current through the collector and function of the transistor (you use the data sheet (http://edge.rit.edu/content/P12005/public/Part%20DataSheets/2N4401NPN.pdf) of the transistor to calculate it). We will use a value of 1 mA for I_c.

$$R_C = \frac{9V - 4.5V}{0.001\ A} = 4500\ \Omega$$

(img/RcCalc_2.jpg)



(img/CommonEmitter2.jpg)

The gain of our circuit as it stands at $\Delta V_c/\Delta V_e$ which is equal to the ratio of R_c/R_e.

$$\text{GAIN} = \frac{R_C}{R_e}$$

(img/GainCalc0.jpg)

We have already set R_c = 4.7 kΩ, and R_e is already built into transistor. Its R_e is called the transresistance, which is calculated as:

$$r_{tr} = \frac{0.026\,V}{I_e}$$

(img/transresistance_1.jpg.jpg)

I_e is approximately the same as I_c, so the transresistance is thus 26 Ω.

$$r_{tr} = \frac{0.026\,V}{0.001\,A} = 26\,\Omega \approx R_e$$

(img/transresistance_2.jpg)

We can calculate the gain as thus:

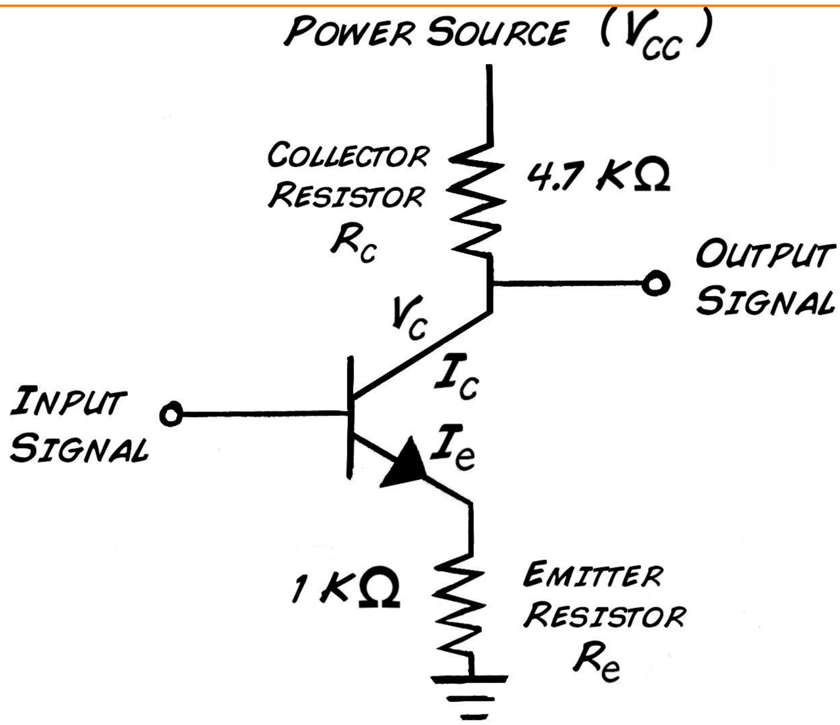
$$\text{GAIN} = \frac{R_C}{R_e} = \frac{4700\,\Omega}{26\,\Omega} = 180$$

(img/GainCalc1.jpg)

However, the transresistance can be unstable in the transistor, so we need to add our own R in addition to the transresistance. Scherz (http://www.amazon.com/Practical-Electronics-Inventors-Third-Edition/dp/0071771336/ref=dp_ob_title_bk) recommends a V_e of 1 V to stabilize the transresistance instability, so via Ohm's law:

$$\text{GAIN} = \frac{R_C}{R_e} = \frac{4700\,\Omega}{1000\,\Omega + 26\,\Omega} = 4.6$$

(img/GainCalc3.jpg)



(img/RcRe_Known.jpg)

We will have a change in gain. The new gain is:

$$\text{GAIN} = \frac{R_C}{R_e} = \frac{4700\,\Omega}{1000\,\Omega + 26\,\Omega} = 4.6$$

(img/GainCalc3.jpg)

Oh no! Our original gain of 180 disappeared! And our gain is now much smaller than we need! But, have no fear, we can add a capacitor in parallel with the 1 kΩ resistor that will effectively make the 1 kΩ disappear for our spike signal. We want to add the capacitor anyway, as we need to make a:

High Pass Filter

A resistor and capacitor in parallel act as high pass filters, and, as stated above, we want our high pass to 300 Hz. This is easy to calculate.

$$f = \frac{1}{2\pi RC}$$

(img/HighPassCapacitor_1.jpg)

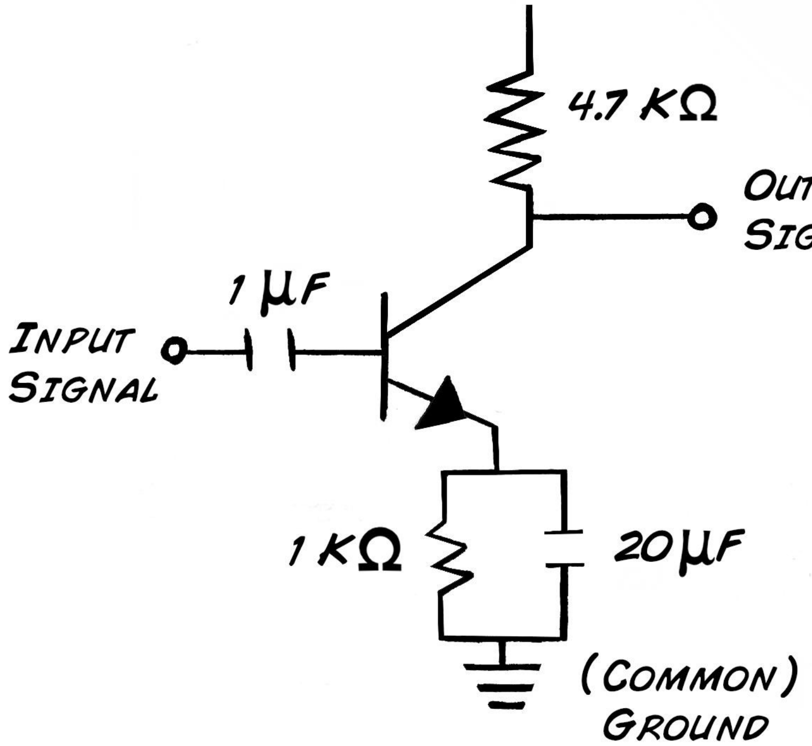
We already have R = 1 kΩ, and the f should be 300 Hz, so the capacitor is thus 20 uF.

$$300\ Hz = \frac{1}{(2\pi)(1000\,\Omega)C}$$

$$C = 0.000020\ F$$
$$= 20\ \mu F$$

(img/HighPassCapacitor_2.jpg)

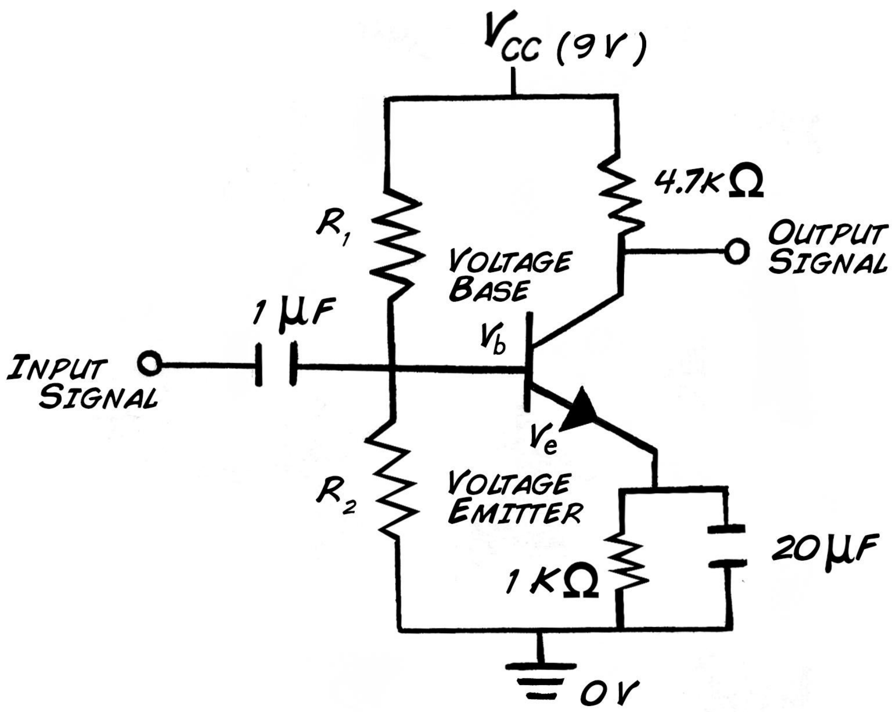
All that remains is the input capacitor to remove any DC offset on the input signal and keep our circuit stable. Let's just set it to 1 uF.



(img/CommonEmitter_CapsIN.jpg)

Setting the Bias Voltages

Remember from our transistor theory (http://www.backyardbrains.com/experiments/transistorTheory) that the transistor will not switch on without a lower limit voltage push, and this is approximately 0.6 V for silicon-based circuits. We need to add bias resistors.



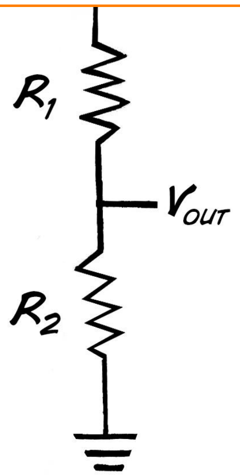
(img/NeedR1R2.jpg)

We want V_b, the voltage at the base, to be 0.6 V higher that the Voltage at V_e, so

$$V_b = V_e + 0.6\,V$$
$$V_b = 1\,V + 0.6\,V = 1.6\,V$$

(img/Vbase.jpg)

We know V_e to be 1V due to the voltage drop calculated above, so V_b should be 1.6V. We will make a voltage divider!



(img/VoltageDivider.jpg)

Our V_{in} is course 9V, and our V_{out} is 1.6 V, and we use the classic voltage divider equation:

$$V_{OUT} = \frac{R_2}{R_1 + R_2} V_{IN}$$

(img/VoltageDividerEquation.jpg)

We can rearrange the equation and calculate...

$$\frac{R_1}{R_2} = \frac{V_{IN} - V_{OUT}}{V_{OUT}} = \frac{V_{CC} - V_B}{V_B} = \frac{9V - 1.6V}{1.6V} = 4.6$$

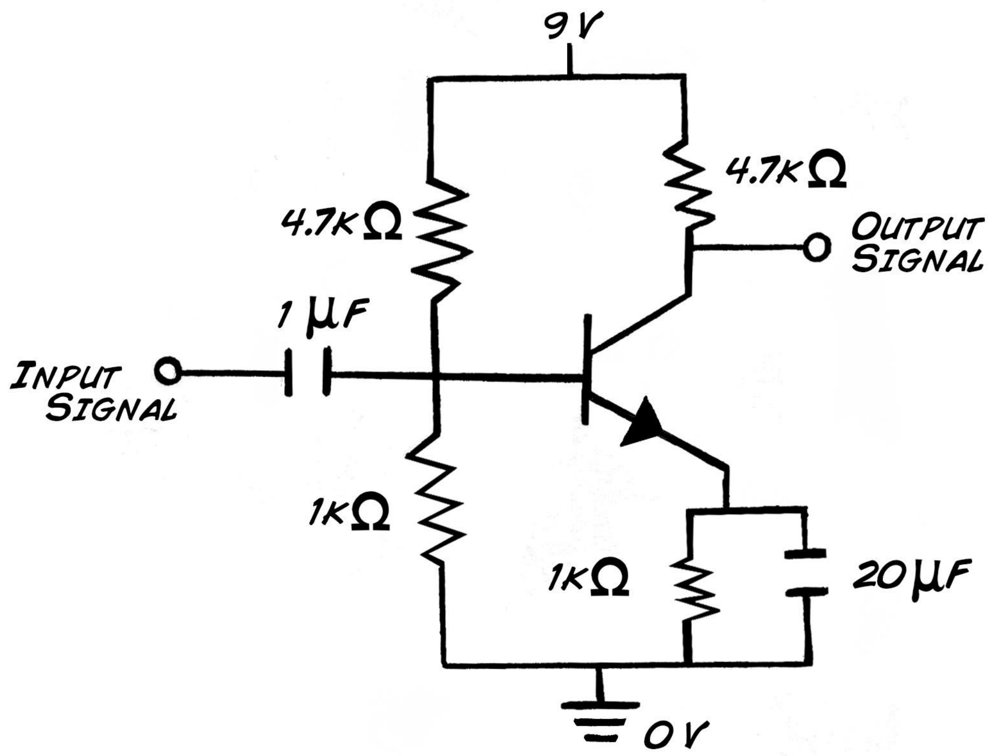
(img/R1vR2.jpg)

Thus, R1 needs to be ~4.6x larger than R2. Sounds simple enough, but, as a rule of thumb for this transistor design:

$$\frac{R_1 R_2}{R_1 + R_2} \leq 25{,}000$$

(img/minimumR1R2.jpg)

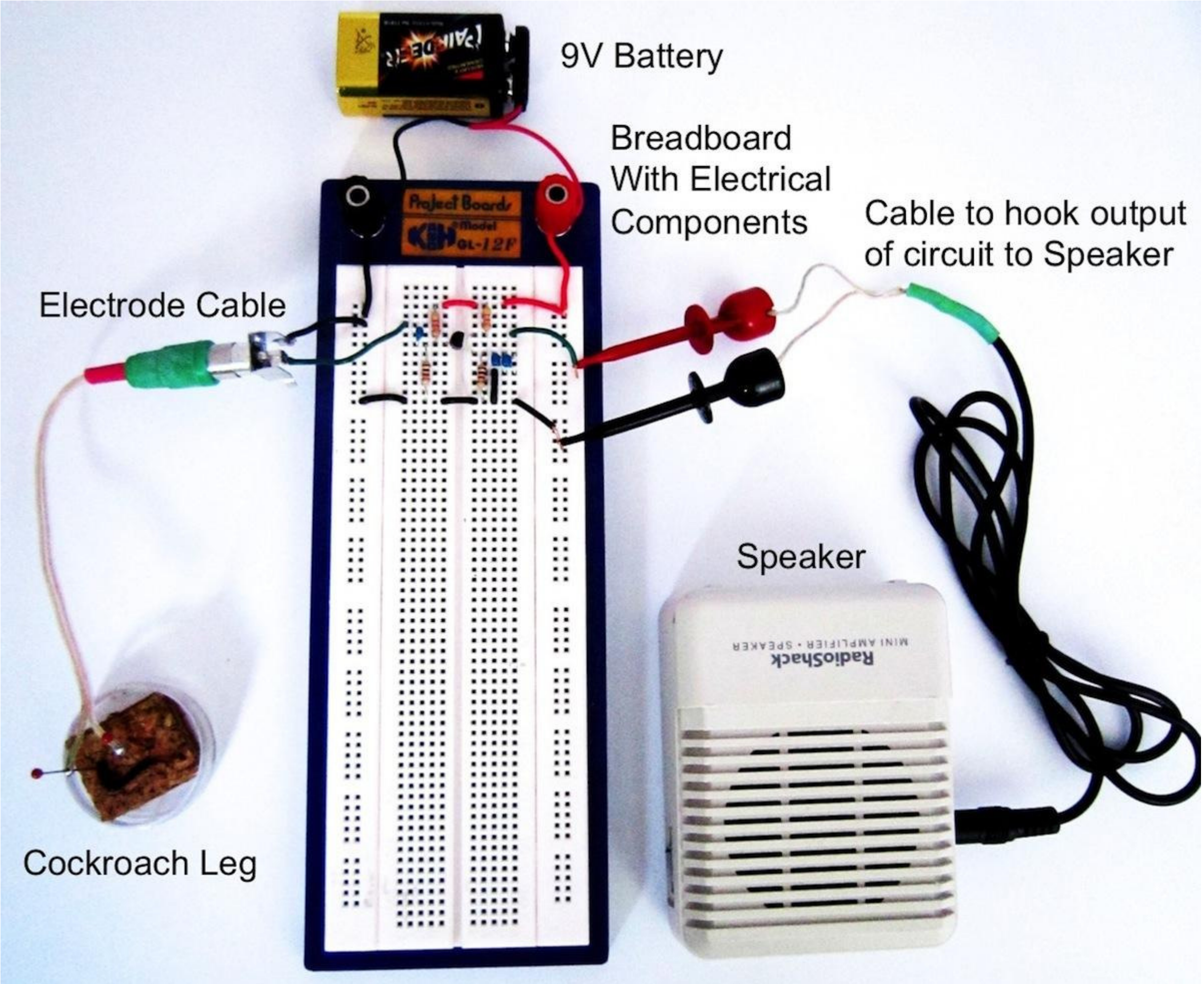
So, we'll just select R2 = 1 kΩ, and R1 = 4.7kΩ as values, since we are already using these resistor values and have them on hand.



(img/Finished1stage.jpg)

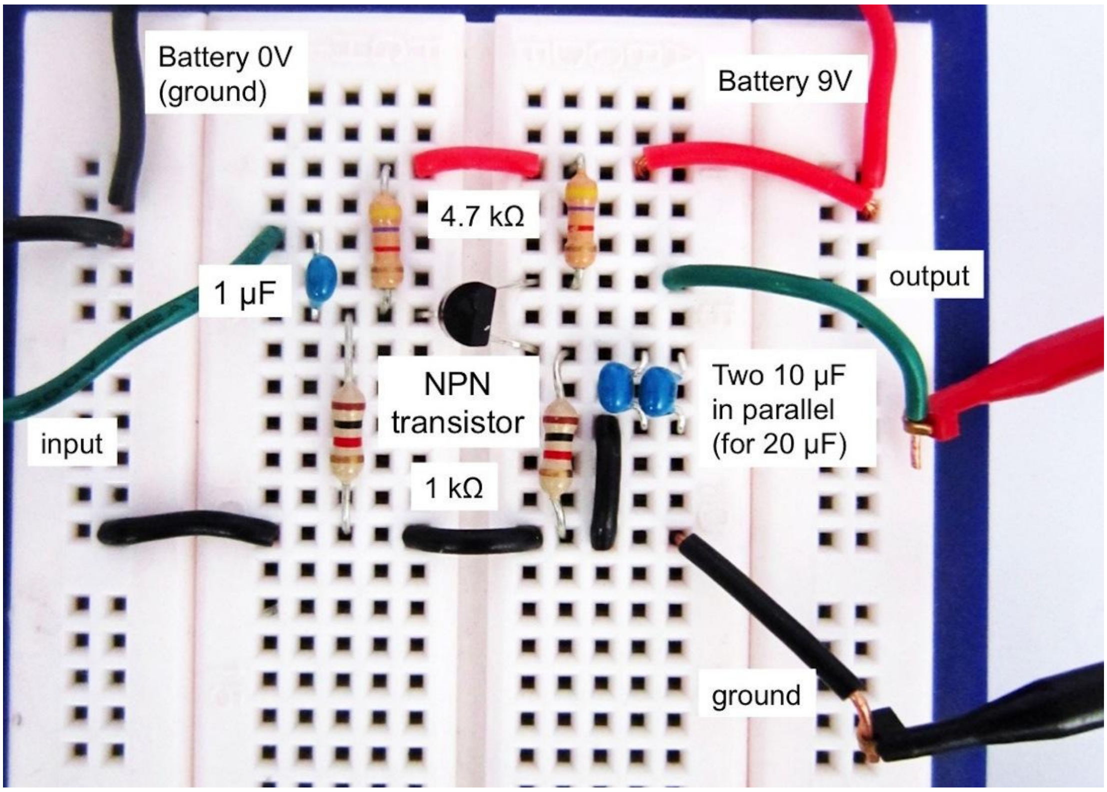
And that's that! Now it's time to...

You've done the math, and now it's time to physically build your circuit. Put your battery, transistor, resistors, capacitors, and input/output components into place on your breadboard, as below:



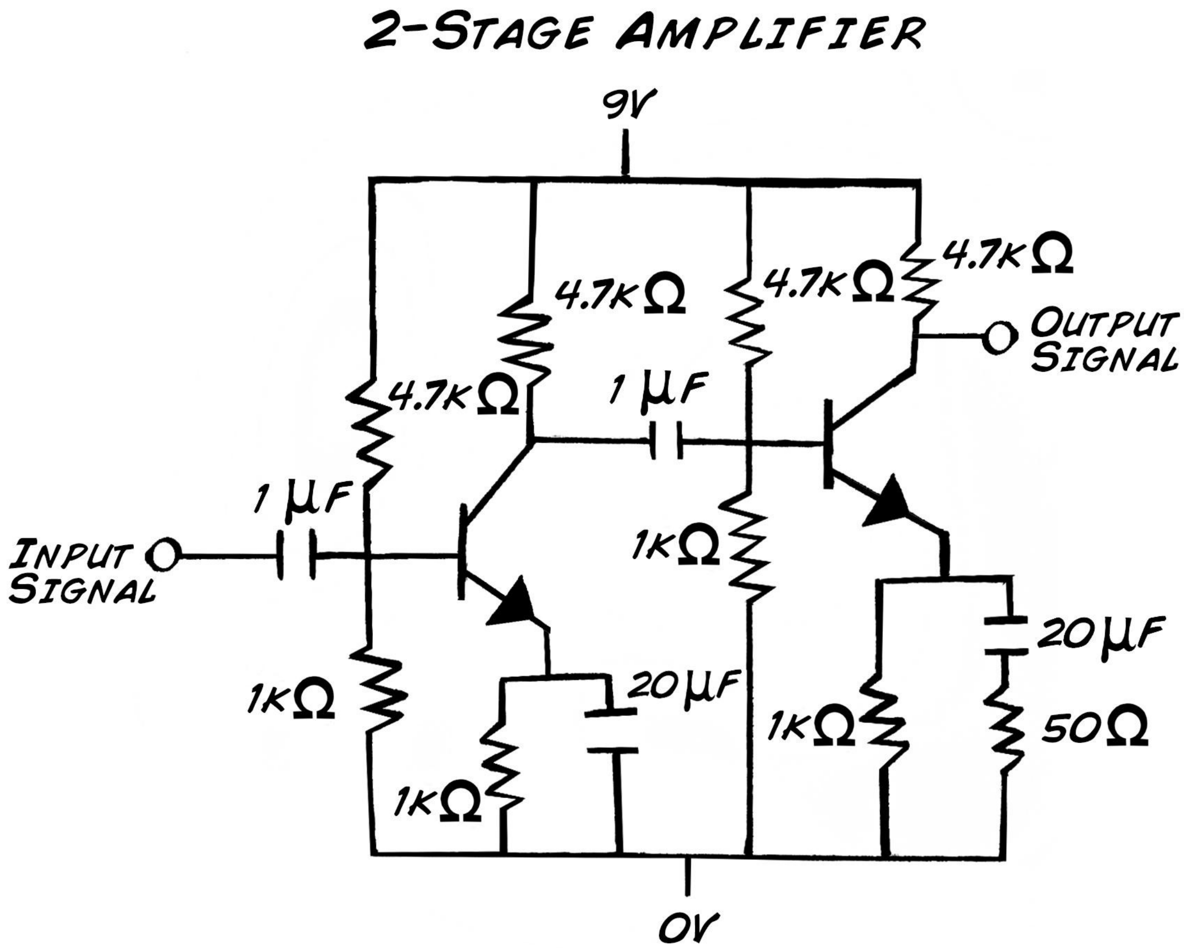
(img/1StageBig.jpg)

A closer look at the circuit on the breadboard:

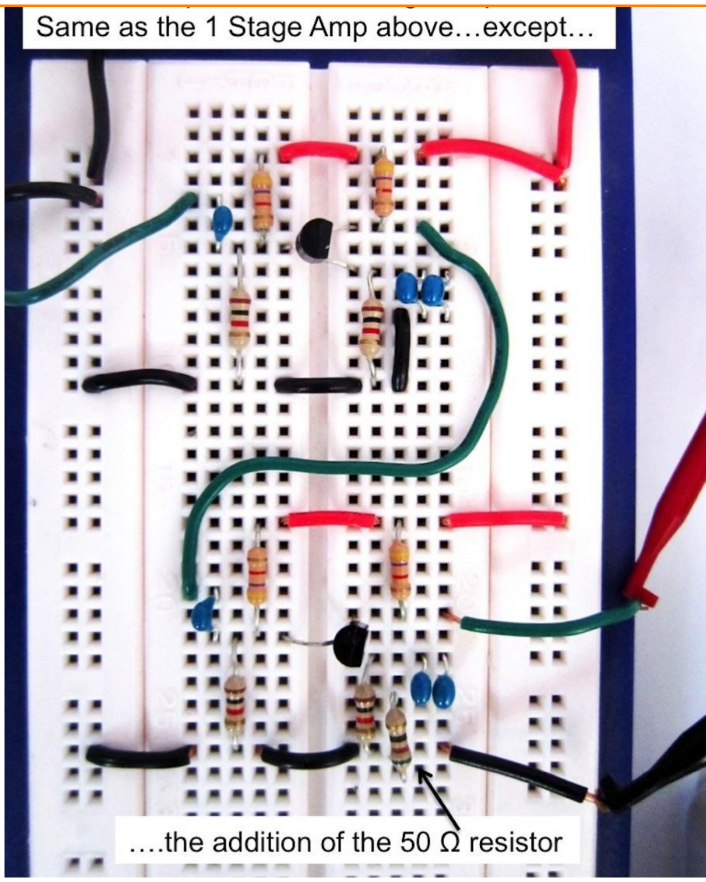


(img/1StageSmall.jpg)

and brush the cockroach leg with a toothpick. You may hear a very faint response, but it will be buried in the noise. Let's amplify the spikes some more. You can create a "second stage" of amplification, much like we do with our normal SpikerBox, where you have output of the circuit go into the input of another copy of the circuit, as below:

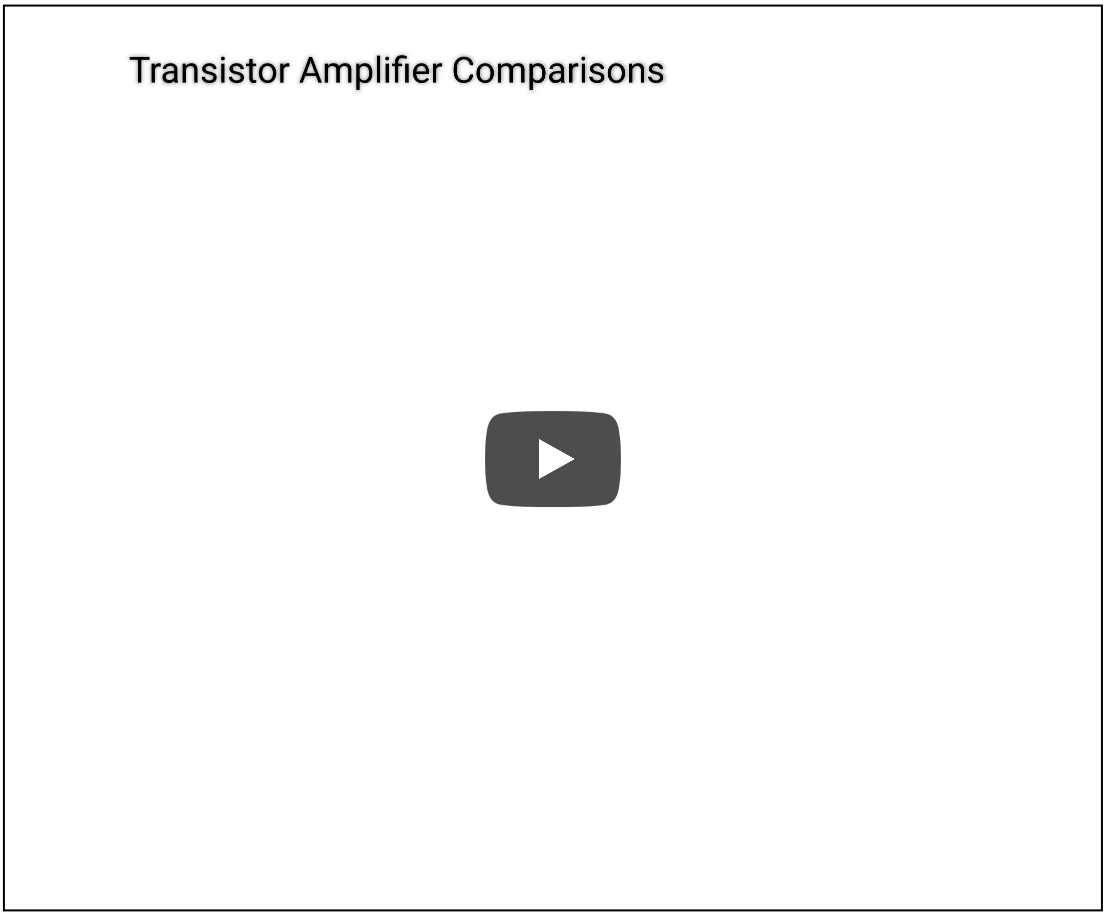


(img/2StageAmp.jpg.)



(img/2StageSmall.jpg)

However, you will find this "doubling up" makes the circuit slightly unstable, so let's drop the gain a bit on the second stage. We've added a 50 Ω resistor in parallel with R_e to lower the gain of the second stage a bit, but will still make for louder spikes when you hook up up this circuit to your cockroach leg. See video below.



You have now built your very own amplifier with transistors! Congratulations! Let us know (mailto:info@backyardbrains.com) if you have figured out a way to make the circuit simpler, cleaner, and with more amplification.

You are on your way to inventing many more wonderful things. The history of science is defined by the invention of new equipment in the hands of imaginative minds. The telescope allows you to see things very far away. The microscope allows you to see the very small. The PCR machine allows you to measure molecules of DNA, and the transistor allows you to observe tiny electrical signals. With these tools we can see and attempt to understand the world beyond the ability of our naked senses. Now begin discovering.

Discussion Questions

1. Why are the spikes from our simple two-transistor bioamp "noisier" than the SpikerBox? What does the SpikerBox do? Hint: the SpikerBox has many more transistors and uses them to build operational amplifiers (http://en.wikipedia.org/wiki/Operational_amplifier), which are then further mixed into instrumentation amplifiers (http://en.wikipedia.org/wiki/Instrumentation_amp). Welcome to the Art of Electronics!