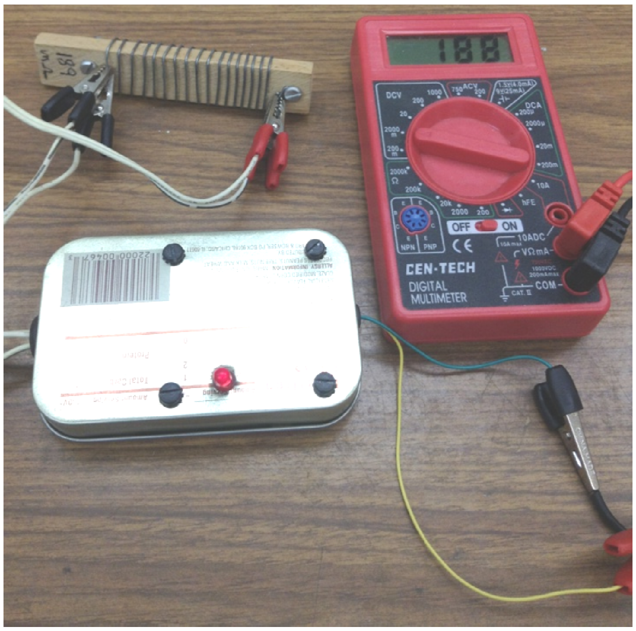
A Resistance Amplifier, version 1.2

By R. G. Sparber



Most Digital Volt-ohms-Meters (DVMs) can measure down to 1 ohm. But what if you want to measure smaller resistances, say 0.001 ohms? This can be useful if trying to find a short on a circuit board or for measuring the electrical resistance of bearings in order to select the proper Lathe Electronic Edge Finder model. This article details a low cost device that amplifies the unknown resistance so a common DVM can measure it. Call it a Resistance Amplifier.

Here you see the Resistance Amplifier being used to measure a 189 milli ohm (mΩ) resistor. The DVM is set to read milli Volts (mV) and is read directly as mΩ.

If your meter can read to the nearest mV, then the circuit will let you read down to 1 mΩ. The largest resistance the circuit can handle is around 2 ohms. Most DVMs can read down to 1 ohm so there is some overlap here.

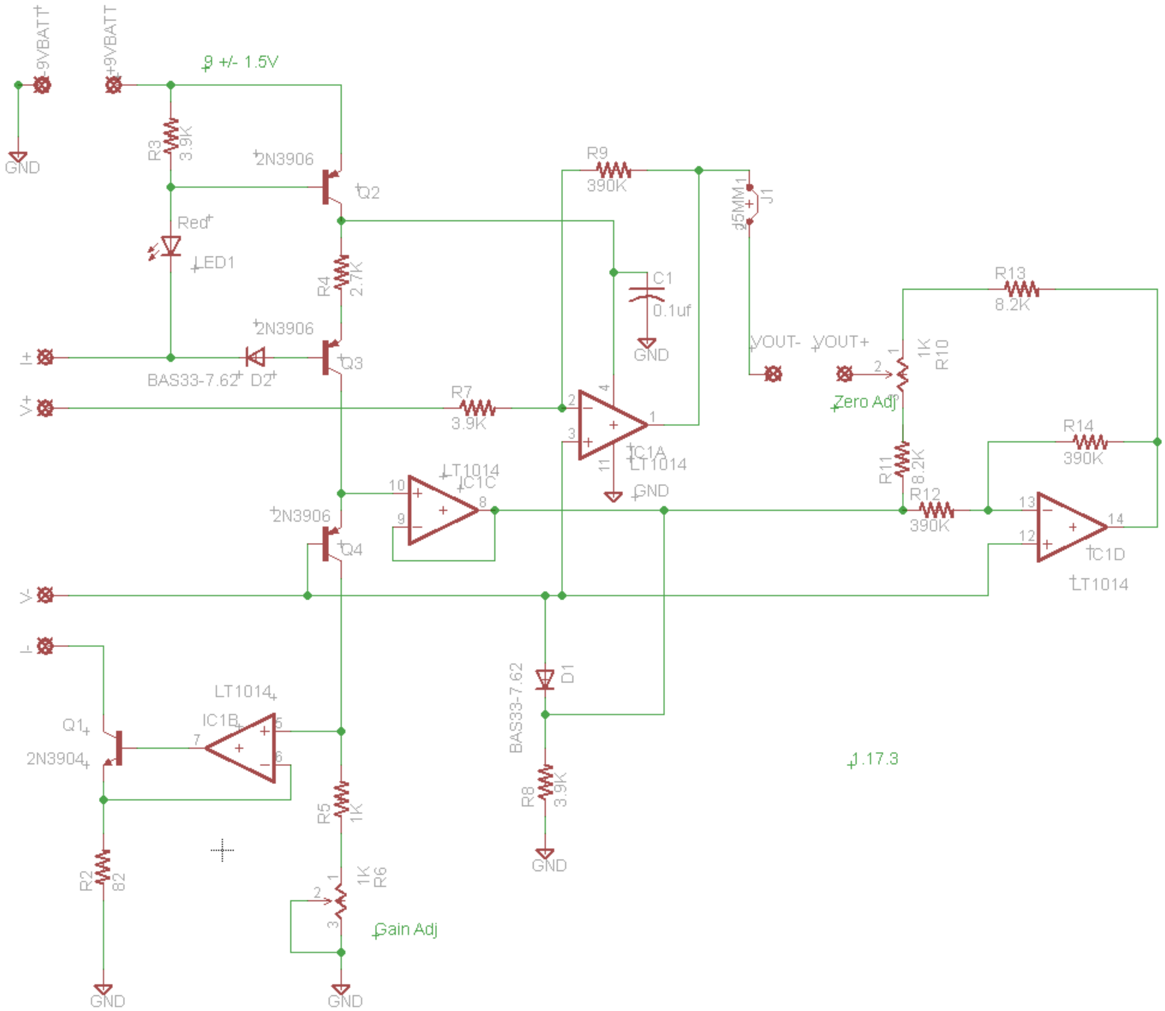
If you look closely, you will see that four connections are made to the resistor under test. This measurement method, called a Kelvin Connection[2], enables the circuit to measure even the smallest resistance regardless of the contact resistance of the probes.

[1] You are free to copy and distribute this document but not change it.
[2] See http://en.wikipedia.org/wiki/Four-terminal_sensing

To use the Resistance Amplifier, you first connect its output to your DVM. Set your DVM to read either 200 mV full scale or 2000 mV full scale depending on the expected result. Then you connect two black clips to one end of the unknown resistor and the two red probes to other end of the unknown resistor. This both powers up the circuit and measures the unknown. When done, remove the probes and the circuit powers down.

Pictured here is a measurement of a short length of copper wire which reads 4.0 mΩ.

Normally, if you wanted to develop 1 mV across a 1 mΩ resistor, you would need to pass 1 amp through it. That high a current would not be practical for the little 9V battery used to power the resistance amplifier. In some cases it might even damage the resistor. So instead I pass 10 milli amps (mA) through the unknown resistor and then amplify the resulting voltage by a factor of 100.



The Circuit

The circuit uses one quad op-amp IC, one LED, four transistors, two diode, and 13 resistors[3] including 2 trim pots. There is also a single bypass capacitor. That is a lot of resistors but they don't cost much. The diodes and transistors are nothing special. However, the IC, a LT1015 is special and costs around $4.

I built the circuit on a single sided circuit board but a 2" x 2" piece of perf board would work too. All resistors can be 1/8W but since I had 1/4W resistors, that is what I used.

The circuit must first have the two black clips (I- and V-) connect to the unknown resistance and then the two red clips (I+ and V+) connected. Connecting in the wrong order causes the LED to be dim and the voltmeter to read negative.

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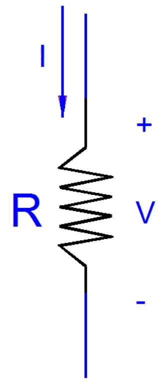
[3] Due to a last minute circuit change, there is no R1.

The Basic Theory

Let's start with Ohms Law:



$V = I \times R$ (b1)

This equation says that the voltage measured across an unknown resistance equals the current flowing through the resistance times the resistance. If I use a 1 amp current, then

V = 1 amp x R
Where R is in ohms and V is in volts. (b2)

Given a DVM able to read milli volts, this same arrangement gives me

V = 1 amp x R
Where R is in milli ohms and V is in milli volts. (b3)

I really didn't change anything.

You can buy ohm meters like this with 1 amp test currents. But I want to run on a small 9 volt battery and keep the test current at something reasonable, like 10 milli amps (mA). I can do that by introducing a voltage amplifier with a gain of G

$V_{out} = G \times V_{in}$ (b4)

The input, V_{in}, is multiplied by G in order to generate V_{out}. With V_{in} equal to the V across out resistor we get

V = G x (10 mA x R)
Where V is in milli volts, G is a number, and R is in milli ohms. (b5)

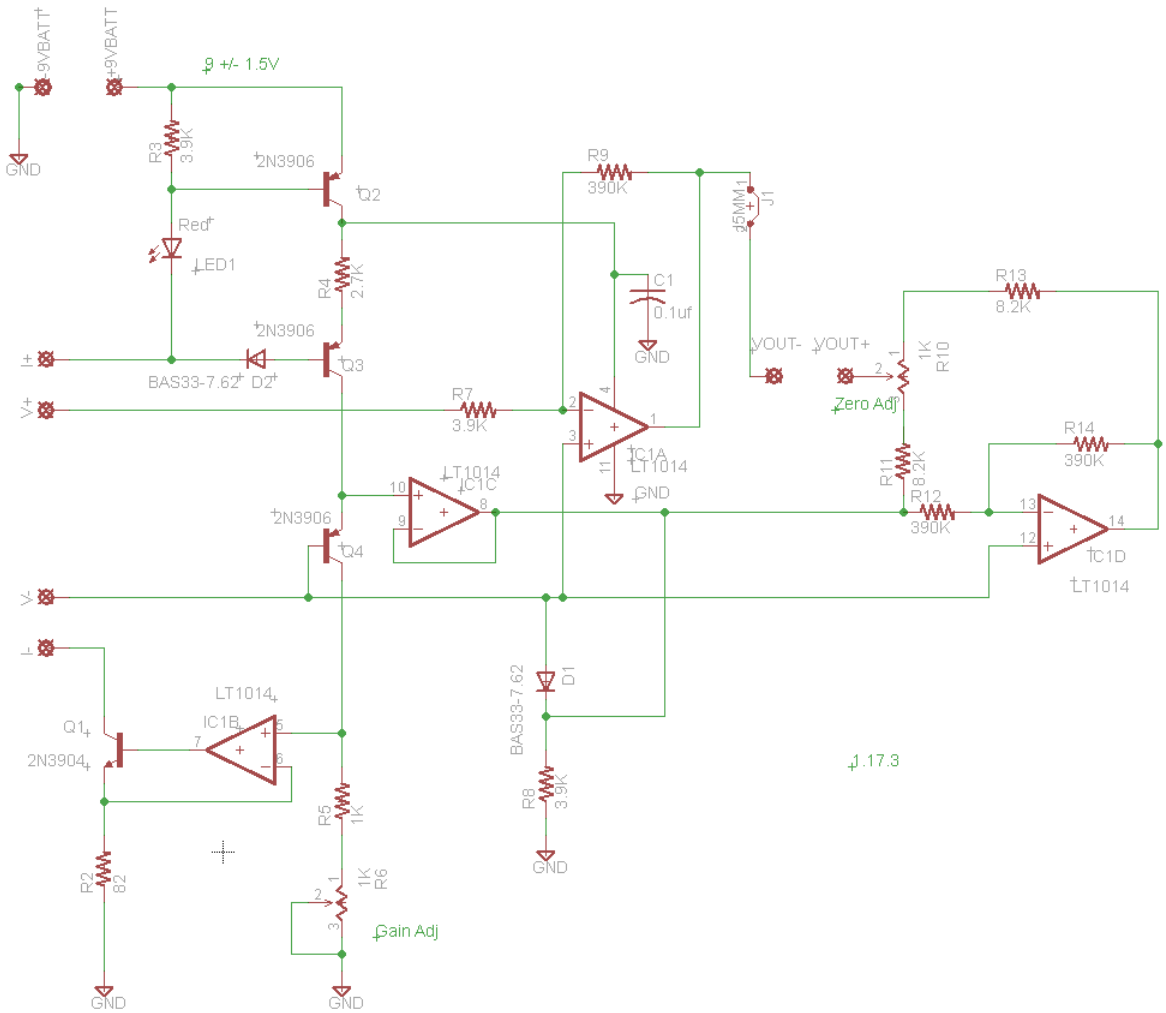
Say I set G equal to 100. I then get

V = 100 x (10 mA x R)
V = 100 x (10 mA x R)
V = 1000 mA x R
V = 1 amp x R (b6)

So with the use of a voltage amplifier with a gain of 100, I am able to have an actual test current of just 10 mA but have it look like 1 amp. This is the essence of the resistance amplifier. The rest of the circuit is involved in either generating the 10 mA test current or compensating for the non-ideal behavior of my voltage amplifier.

The rest of this article requires an understanding of electronics. But you do not have to understand the circuit in order to build and use it.

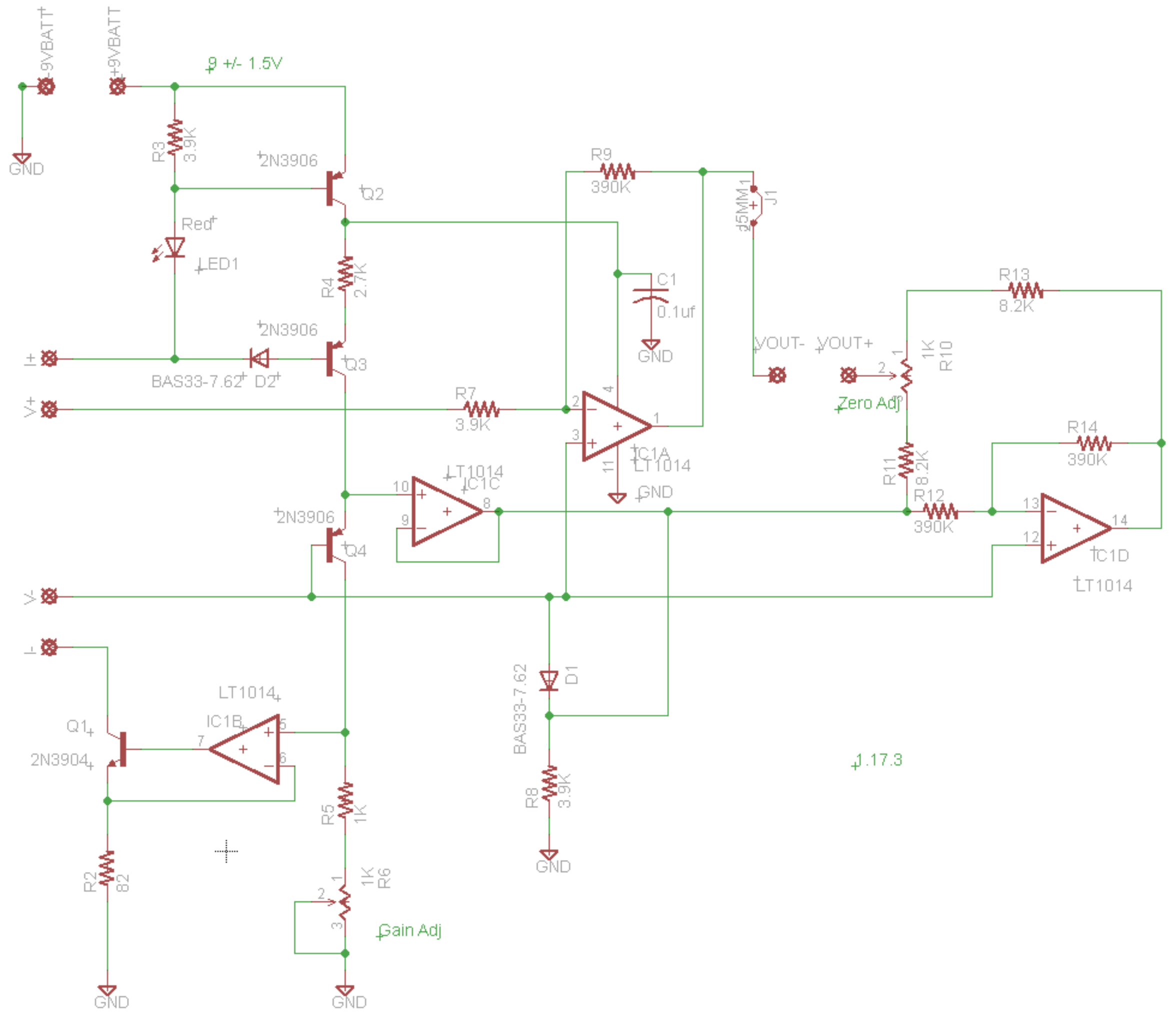
High Level Circuit Description



Power is controlled by Q2 which senses when the test current is flowing out of the I+ lead. When this current is present, Q2 saturates and LED1 lights. It then applies power to the quad op-amp IC.

When the probes are first connected, in the correct order, the current flowing out of the I+ probe flows into the V- probe, down D1 and R8, and into ground. Once the op amps are powered up, D1 is turned off by op amp C. This removes any large current flow into V- and therefore removes most of the voltage drop across its contact resistance.

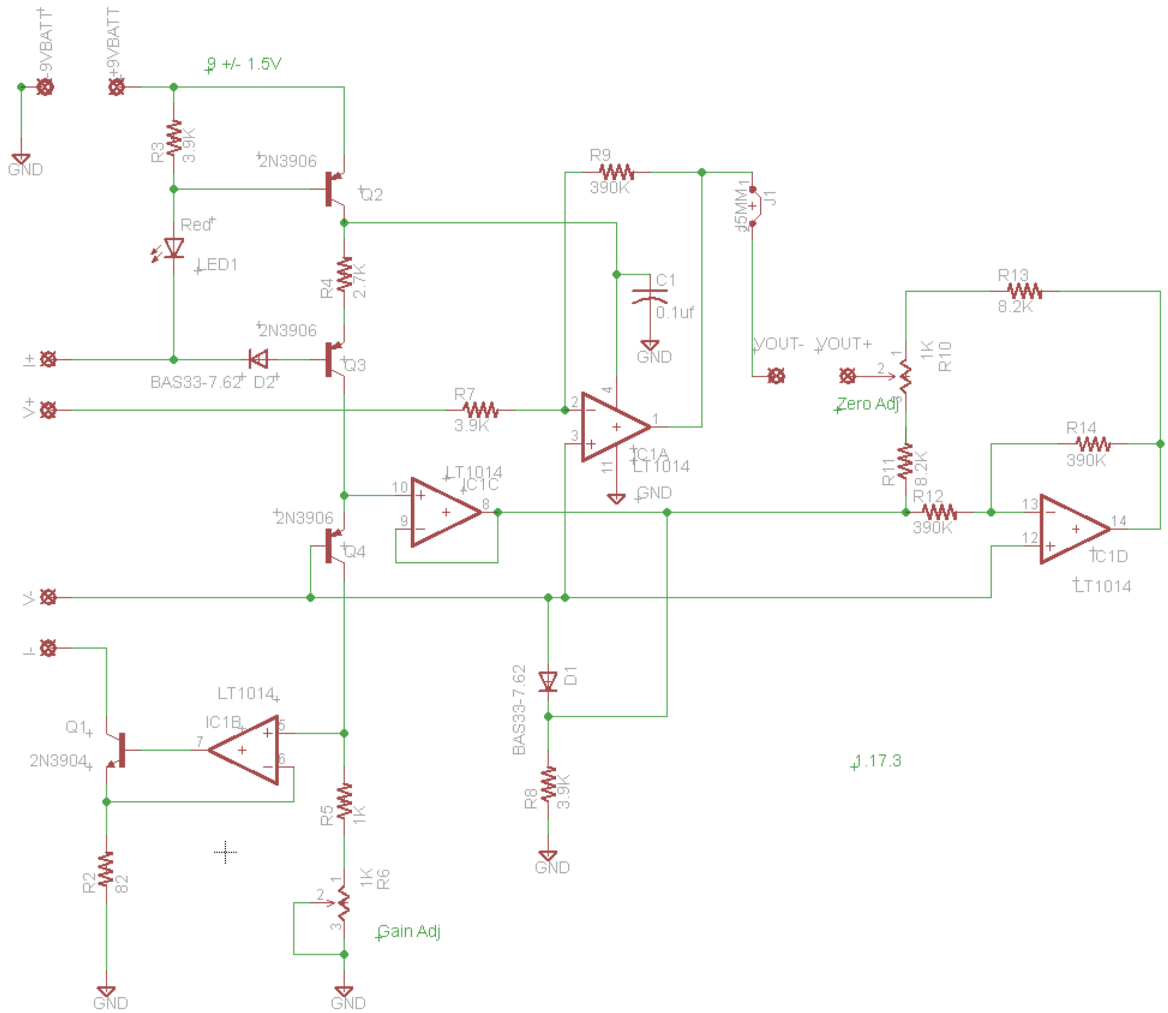
Power up is not complete yet. We still must get Q1 to turn on and sink the real test current.



When Q2 is saturated and the LED is on, a voltage is developed across R4. This causes a current to flow into the emitter of Q3 and about 98% of it flows out of its collector. This collector current then flows into the emitter of Q4 and about 98% flows out the collector. The Q4 collector current flows through R5 and trim pot R6 to define the voltage at pin 5 of op amp B. This voltage is then applied across R2.

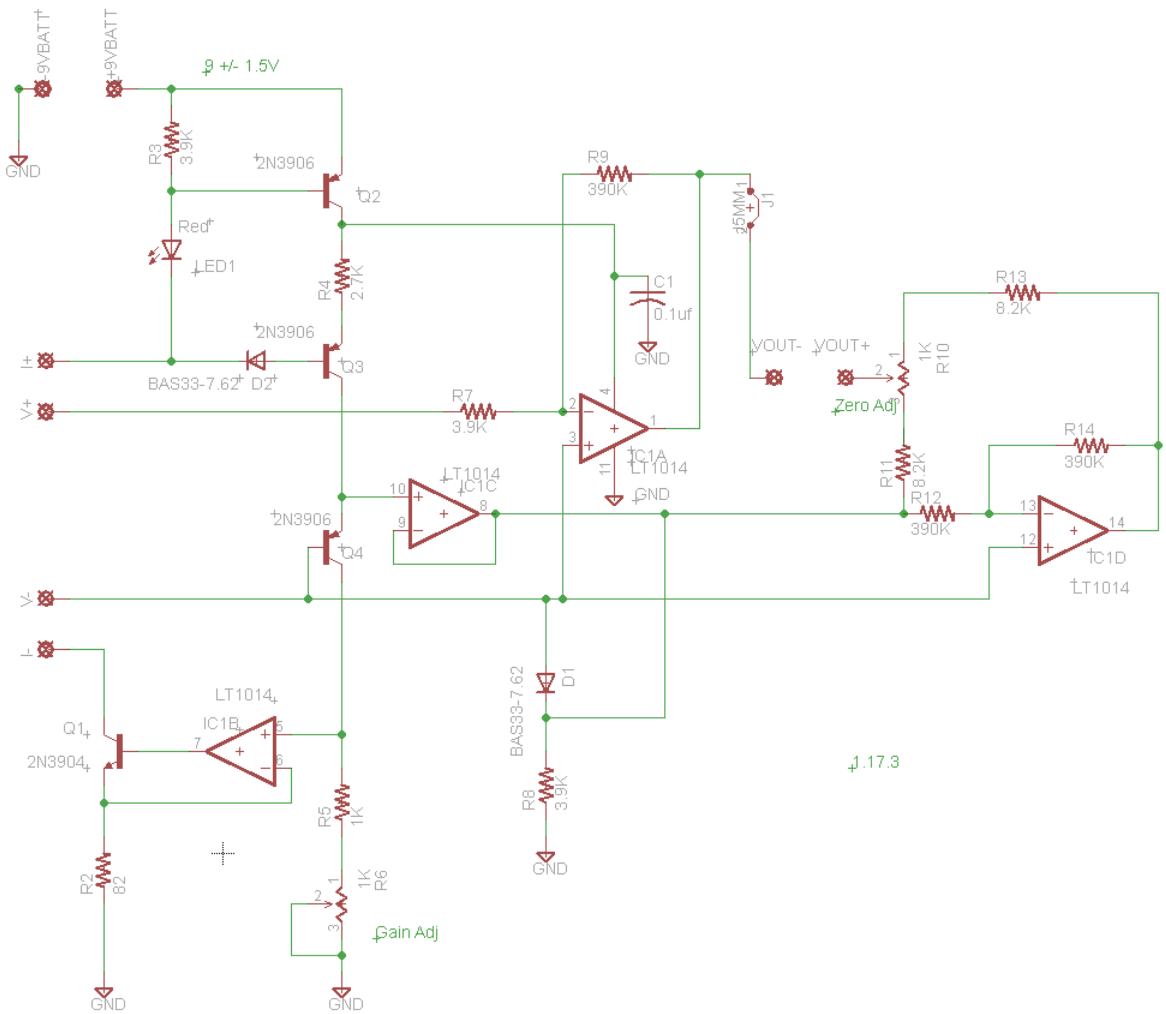
The voltage across R2 causes a current to flow in it. This current is draw from the emitter of Q1. About 98% of this current flows into the collector of Q1and is our test current. It flows out the bottom of the unknown resistance connected between the I+ and I- nodes. As long as the test current is flowing out of I+, power remains on. Any disruption of this flow automatically turns off power. In this way the user is not bothered with powering up or down.

If the red leads, V+ and I+ are connected first, the op amps can go into "latch-up" causing them to not operate correctly even when full power is applied.



You may have figured out that there is no R1. Late in the development I discovered a subtle design error. When the circuit is supposed to be off, the base of Q3 is pulled up to near 9V because no current is flowing. But the collector of Q2 is pulled near ground due to the op amps trying to turn on. This applies greater than -5V to the emitter-base junction of Q3. That causes this junction to break down and conduct. The result is that Q2 partially turns on. I saw about 0.2 mA flowing from the battery when it should have been zero. The fix I chose was to put D2 in series with the base of Q3. This prevents current flowing into the base of Q3 when off and raises the voltage on the base of Q3 when on. This voltage rise prevents Q3 from saturating due to the emitter-base voltage of Q4. With such a tiny current flowing in D2, I measured its voltage drop at 0.38V.

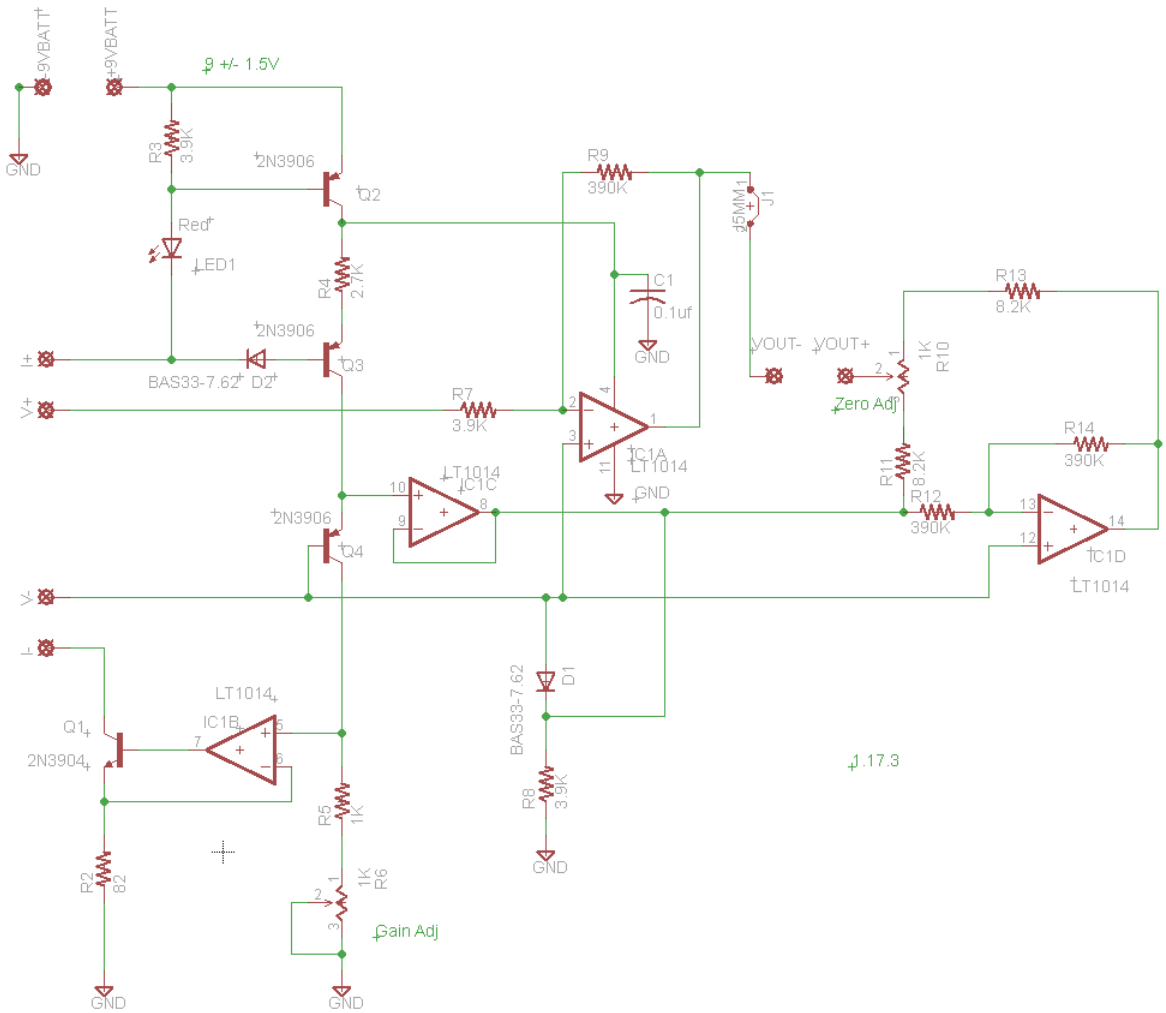
The voltage developed across the unknown resistance is sensed by the V+ and V- leads. It is fed into the inverting amplifier formed by R7, R9, and op amp A.



Although the quad op amp LT1014 is very good, there is still up to ± 0.3 mV of input offset voltage present. With the amplifier set for a gain of $-\frac{R11}{R10} = -100$, this means that the output can be ± 30 mV due to input offset. If ignored, this would contribute an uncertainty in the output equal to the equivalent of ± 30 mΩ.

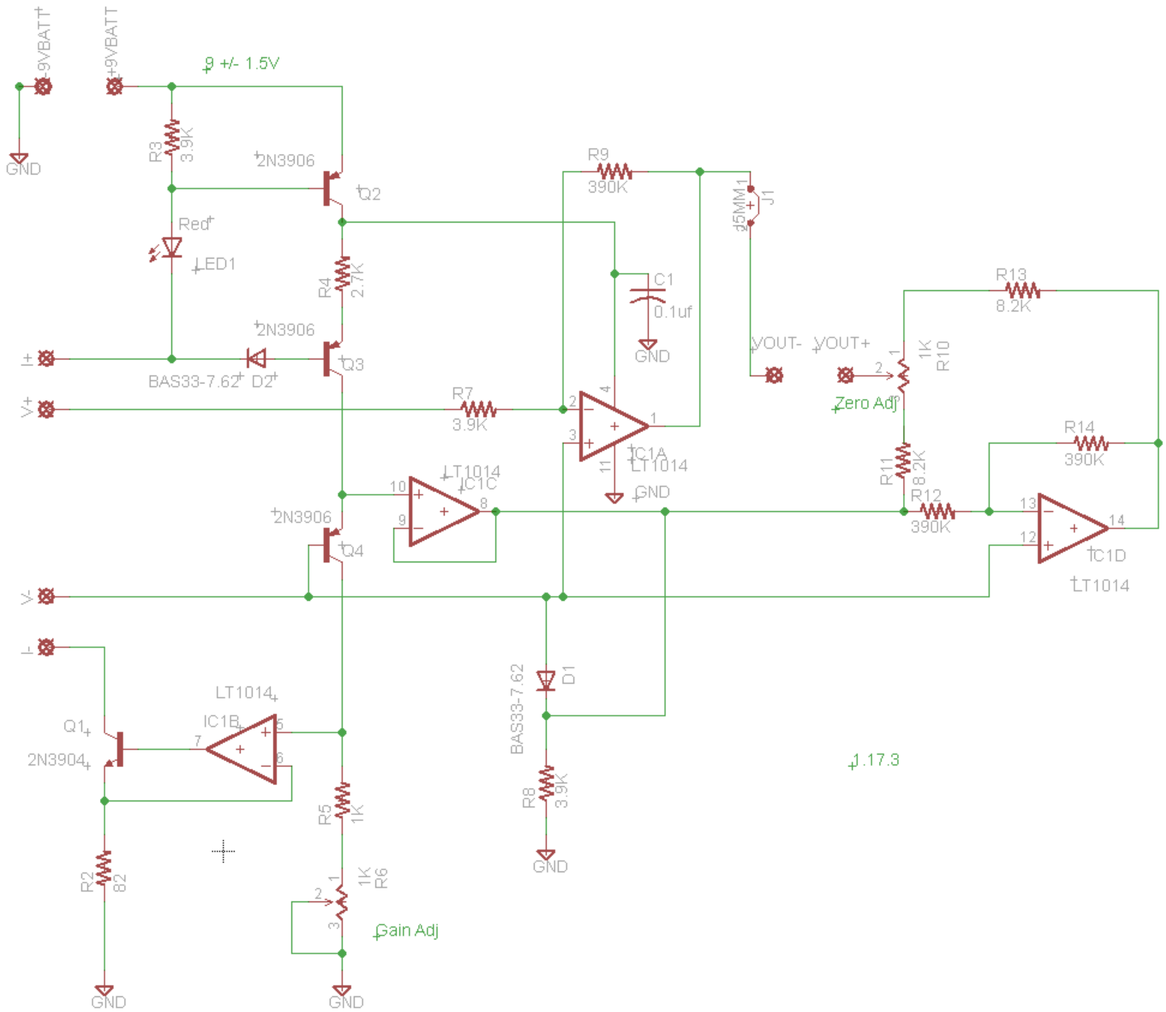
I solved this problem by adding a voltage source that can put out up to ± 35 mV. R10 is adjusted with test probes all shorted together. When Vout reaches zero, all offset has been nulled. I have seen a drift of around ±1 mV so far which translates to ± 1 mΩ.

Since your typical DVM is equivalent to a 10 meg ohm resistor on its input, there is no loading of this offset circuit.



I used a 22 turn trim pot which means one full turn causes a change of about 3 mV. It is therefore rather easy to adjust it to within 1 mV of the desired value.

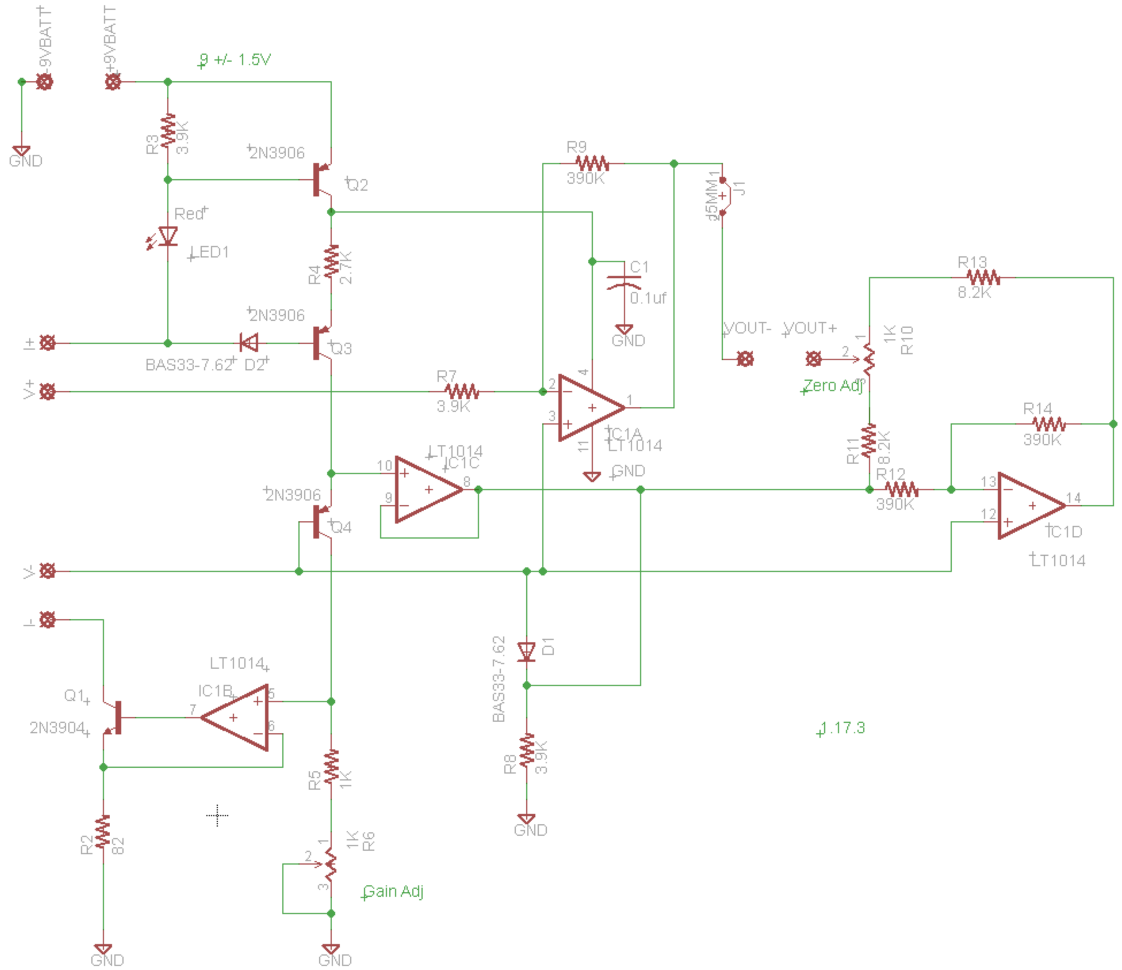
The reference voltage used to feed the R10 trim pot comes from the emitter-base junction of Q4. I buffer this voltage with op amp C and use it to drive one end of the voltage divider formed by R10, R11, and R13. The other end of the voltage divider is fed from a unity gain inverting stage formed by R12, R14, and op amp D. In this way, I only need one reference voltage.



Going back to the power and current source circuit, you can now see that Q4 passes the current coming from Q3 which is set mostly by the voltage across the LED and D2. Since the current through Q4 is stable, its voltage will only be a function of temperature. Variations in battery voltage have a minimal effect.

A limited positive feedback loop exists in the power circuit. The voltage across the LED is set by the intrinsic voltage drop of the silicon plus the voltage drop of its bulk resistance. As the current rises, the voltage rises. An increase in LED voltage causes an increase in voltage across R4. This causes a rise in Q3's emitter current and ultimately a rise in the voltage at the emitter of Q1. That causes a rise in Q1's collector current. The system is stable because the rise in voltage due to the LED's bulk resistance dominates over the equivalent of a negative resistance of the feedback path involving op amp B.

Detailed Equations



When the circuit is first starting up, the current out of the I+ node is less than the full amount. This current is

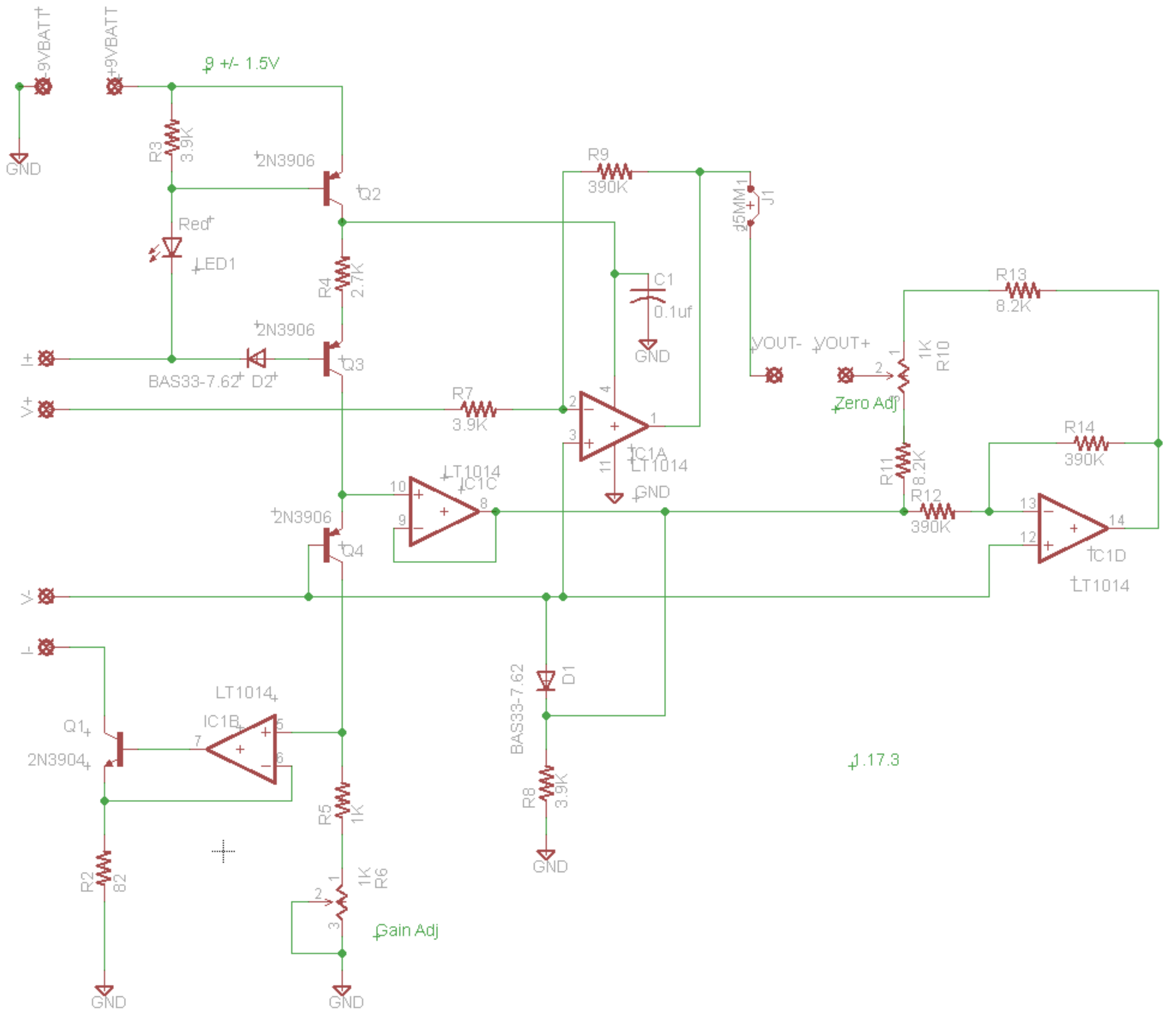
$$I_{start} = \frac{V_{battery} - V_{eb2(sat)} - V_{LED1} - V_{D2} - V_{D1}}{R_1 + R_8} \qquad \text{(d1)}$$

At low battery, and worst case maximum silicon drops this is about

$$I_{start} = \frac{7.5V - 0.8V - 2.5V - 0.4V - 0.8V}{2.7K}$$

$$I_{start} = \frac{3.0V}{2.7K} = 1.11\ mA$$

Even with a β_2 of 20, this is plenty to saturate Q2 and power up the IC. Once the IC is up, Q1 comes up and the normal test current flows.



The normal test current does not depend on battery voltage as long as no transistors saturate.

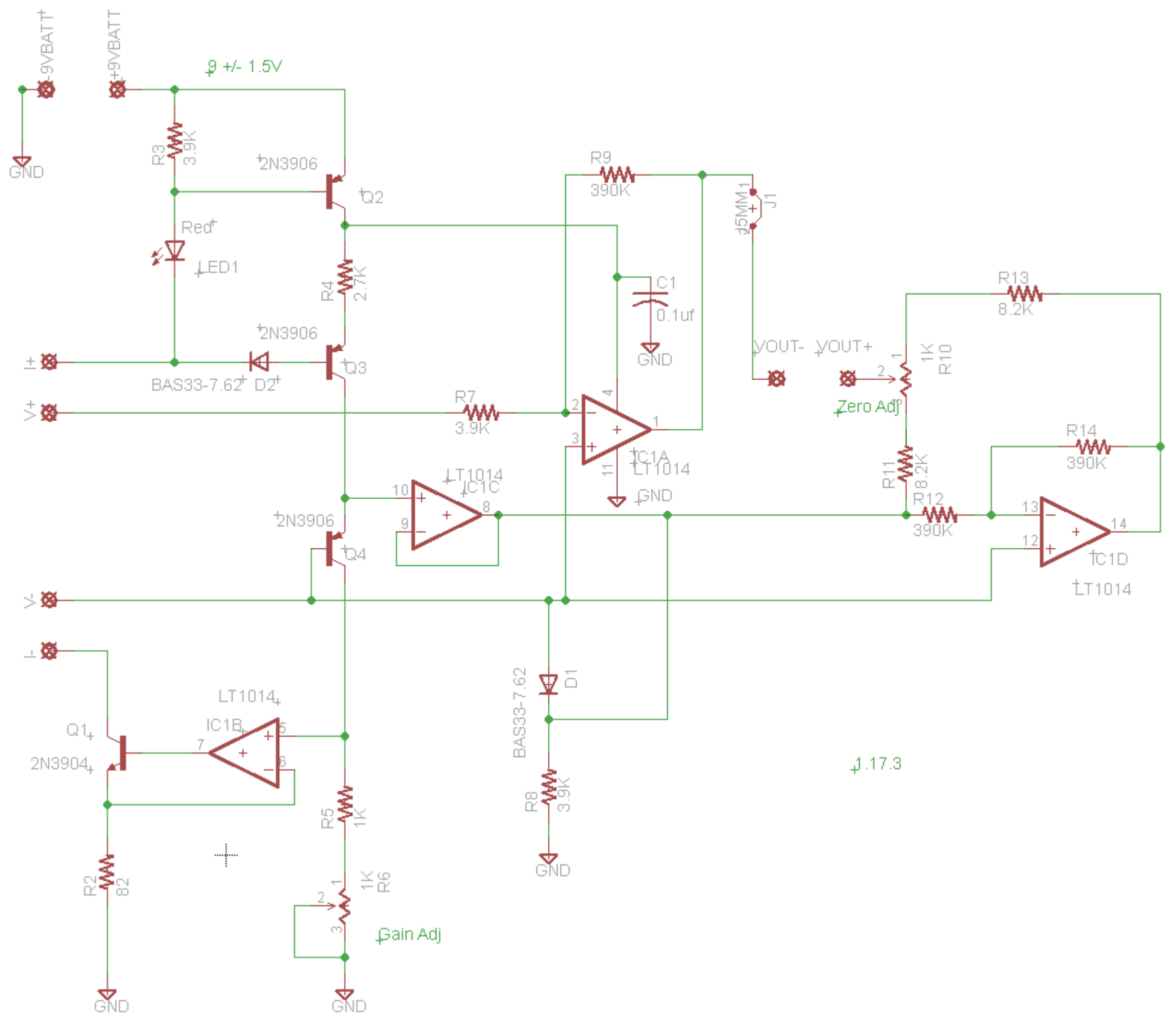
$$I_x = \frac{V_{LED1} - V_{D2} + V_{eb2(sat)} - V_{ec2(sat)} - V_{eb3}}{R_4} \times \alpha_3 \times \alpha_4 \times \frac{R_5 + R_6}{R_2} \qquad \text{(d2)}$$

With nominal values this is

$$I_x = \frac{2.1V - 0.4V + 0.8V - 0.01V - 0.65V}{2.7K} \times 0.98 \times 0.98 \times \frac{1K + 0.5K}{82\ ohms}$$

$$I_x = 12.0\ mA$$

With nominal values but trim pot R6 at minimum we get $I_x = 8.0\ mA$ and with R6 at maximum we get $I_x = 16.0\ mA$. This is a range of approximately ±30%. All resistors are 5% which leaves about ±15% for variations in silicon voltage drops. If this is not enough, R2 might need to be changed to re-center the range.



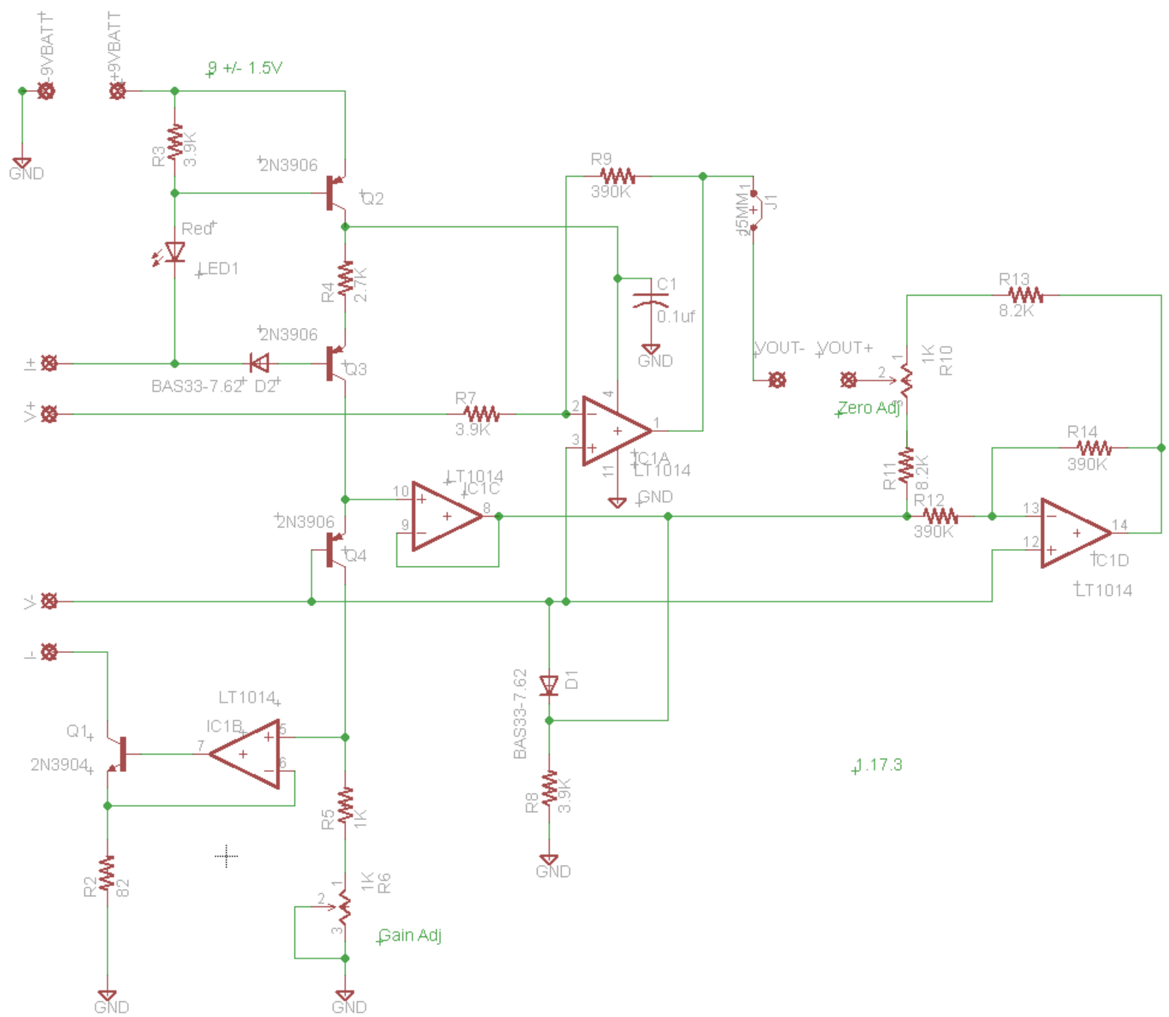
This test current passes through the unknown resistance to generate V_x which feeds the voltage amplifier

$$V_{out-} = -\frac{R_9}{R_7} \times V_x \qquad \text{(d3)}$$

This ignores the finite gain of op amp A , its input bias current, and its input offset voltage. The bias current and offset voltage will be canceled by the circuit to be described next. Nominally

$$V_{out-} = -\frac{390K}{3.9K} \times V_x$$

$$V_{out-} = -100 \times V_x$$



The worst case variation in gain is - 90 to -110 or ±10% because I am using 5% resistors.

Using equations (d2) and (d3) we can see the entire circuit performance assuming all DC offset has been nulled:

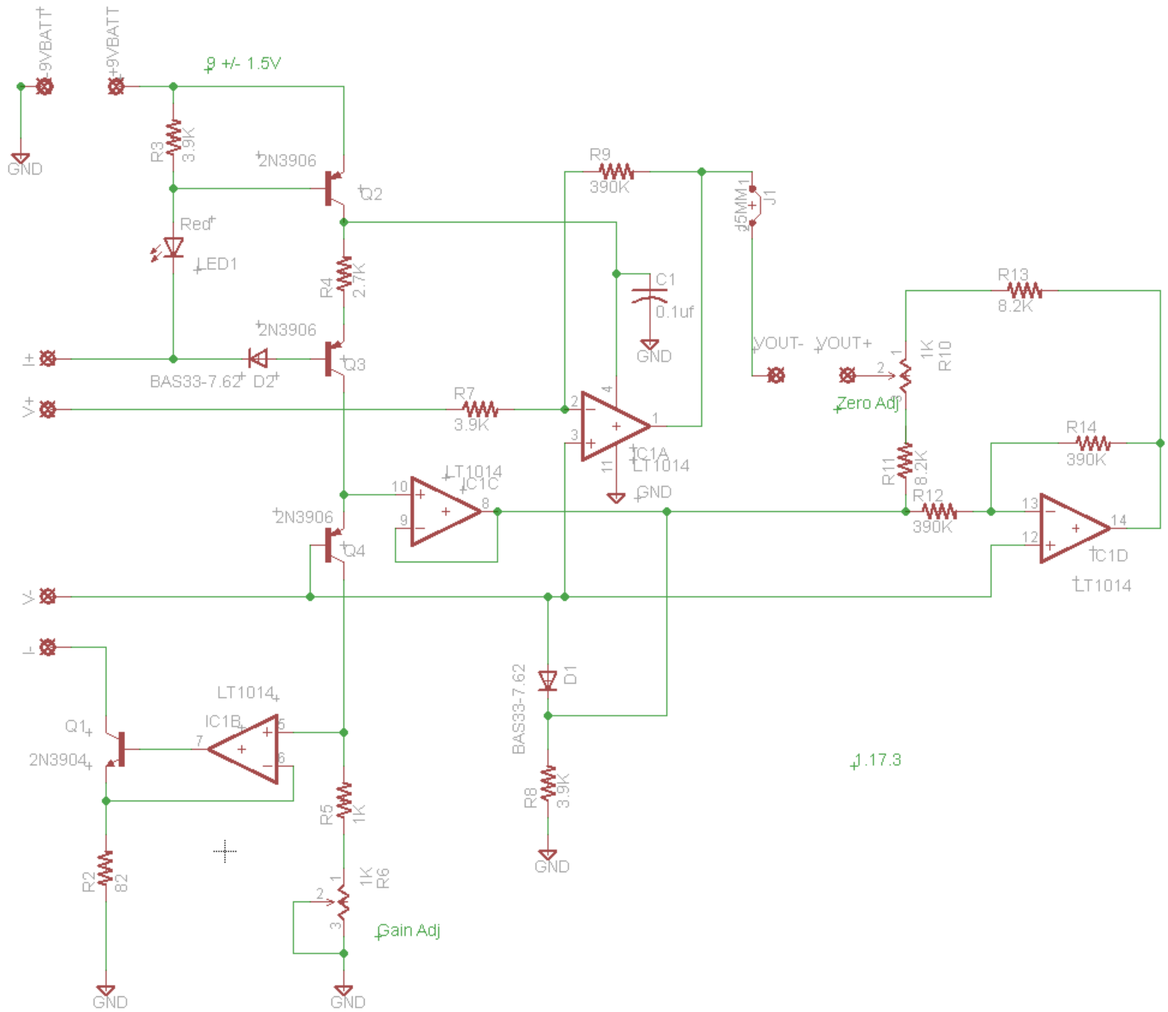
$$I_x = \frac{V_{LED1} - V_{D2} + V_{eb2(sat)} - V_{ec2(sat)} - V_{eb3}}{R_4} \times \alpha_3 \times \alpha_4 \times \frac{R_5 + R_6}{R_2} \qquad \text{(d2)}$$

$$V_{out-} = -\frac{R_9}{R_7} \times V_x \qquad \text{(d3)}$$

Recall that $V_x = R_x \times I_x$ (b1)

So we can say

$$V_{out-} = -\frac{R_9}{R_7} \times R_x \times \frac{V_{LED1} - V_{D2} + V_{eb2(sat)} - V_{ec2(sat)} - V_{eb3}}{R_4} \times \alpha_3 \times \alpha_4 \times \frac{R_5 + R_6}{R_2} \qquad \text{(d4)}$$



You will see in the next section that V_{out+} is just a DC voltage that cancels the offset present in V_{out-}. Therefore, I can assume this adjustment has been made and say

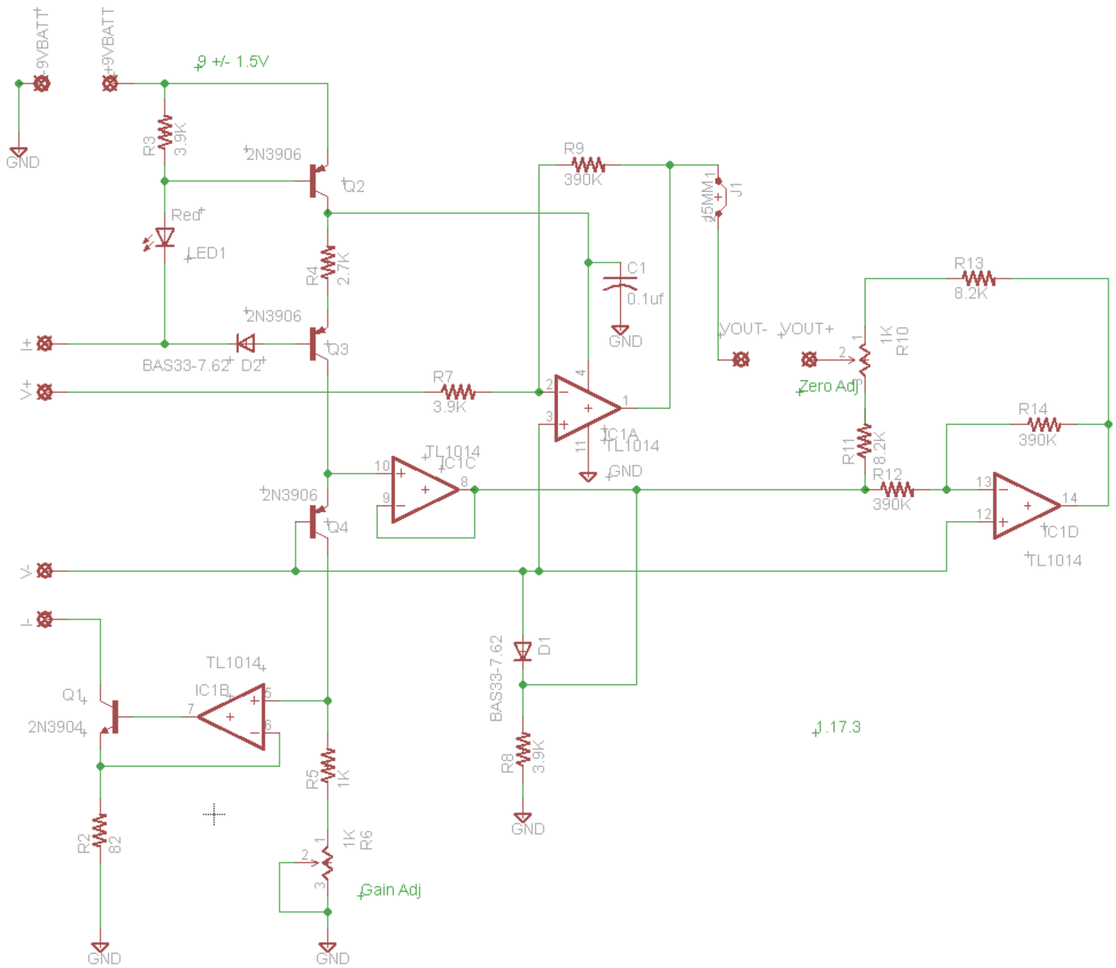
$V_{out} = V_{out+} - V_{out-}$

$$V_{out} = \frac{R_9}{R_7} \times R_x \times \frac{V_{LED1} - V_{D2} + V_{eb2(sat)} - V_{ec2(sat)} - V_{eb3}}{R_4} \times \alpha_3 \times \alpha_4 \times \frac{R_5 + R_6}{R_2} \qquad \text{(d5)}$$

Using nominal values, I get

$$V_{out} = (100) \times 12.0\, mA \times R_x$$
$$V_{out} = 1200\, mA \times R_x$$

A 20% reduction in R6 brings this down to



$V_{out} = 1000\ mA \times\ R_x$

or

$V_{out} = 1\ amp \times\ R_x$

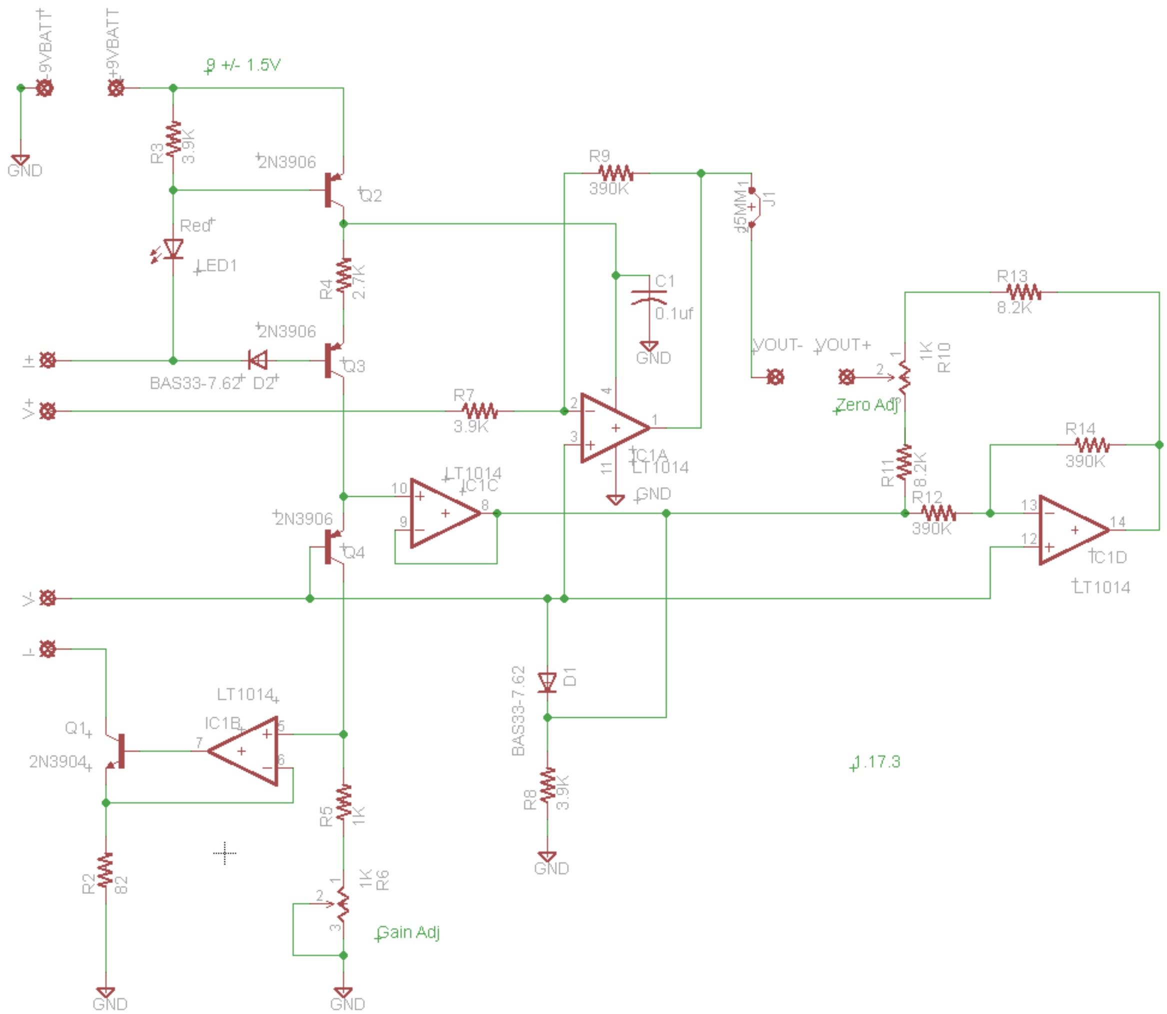
So with the DVM set to mV, the resistance amplifier reads mΩ directly.

Next we will look at the maximum resistance the circuit can measure. The worst case is when the battery is almost dead, all silicon is at maximum drop, and the test current is at maximum.

$$V_{I+} = V_{battery} - V_{eb2(sat)} - V_{LED1} - V_{D2} \qquad \text{(d6)}$$

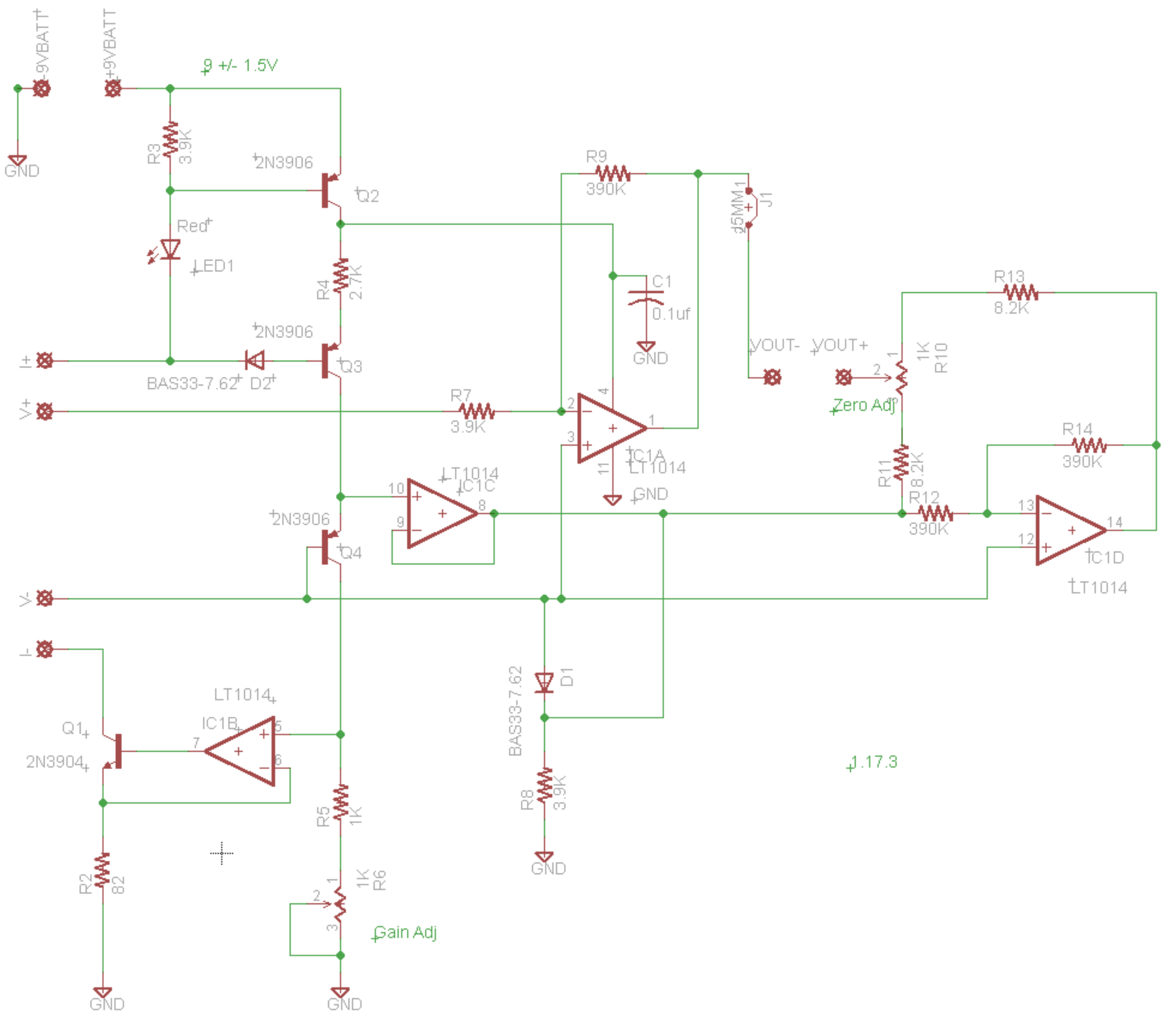
$$V_{I+} = (9\text{V} - 1.5\text{V}) - 0.8V - 2.5V$$

$$V_{I+} = 4.2\text{V}$$



For now, assume that V_x is small compared to 4.2V. We will check it later. This lets us say that $V_{V-} \cong 4.2V$. The LT1015 can swing its output to almost ground but only when the output current is very small. Let me assume it goes down to 0.6V. Then the output swing is 4.2- 0.6 = 3.6V. We have a gain of 100 so this means that V_x is $\frac{3.6V}{100} = 36\ mV$. This says our assumption about V_x being small compared to 4.2V is correct. It also lets us calculate the maximum unknown resistor since we know that $R_x = \frac{V_x}{I_x} = \frac{36\ mV}{16\ mA} = 2.25\ ohms$. This value gets us into the lowest range of the DVM so when the resistance amplifier runs out of gas, the regular ohm meter function of the DVM can take over.

We will now wrap things up by analyzing the circuit that cancels all DC offsets in the voltage amplifier.



The worst case offset voltage at V_{out-} is canceled by the voltage at V_{out+}. The voltage divider string formed by R10, R11, and R13 is fed by V_8 and V_{14} which are outputs of op amp C and D respectively.

$$V_8 = V_{eb4} \qquad \text{(d7)}$$

and nominally,

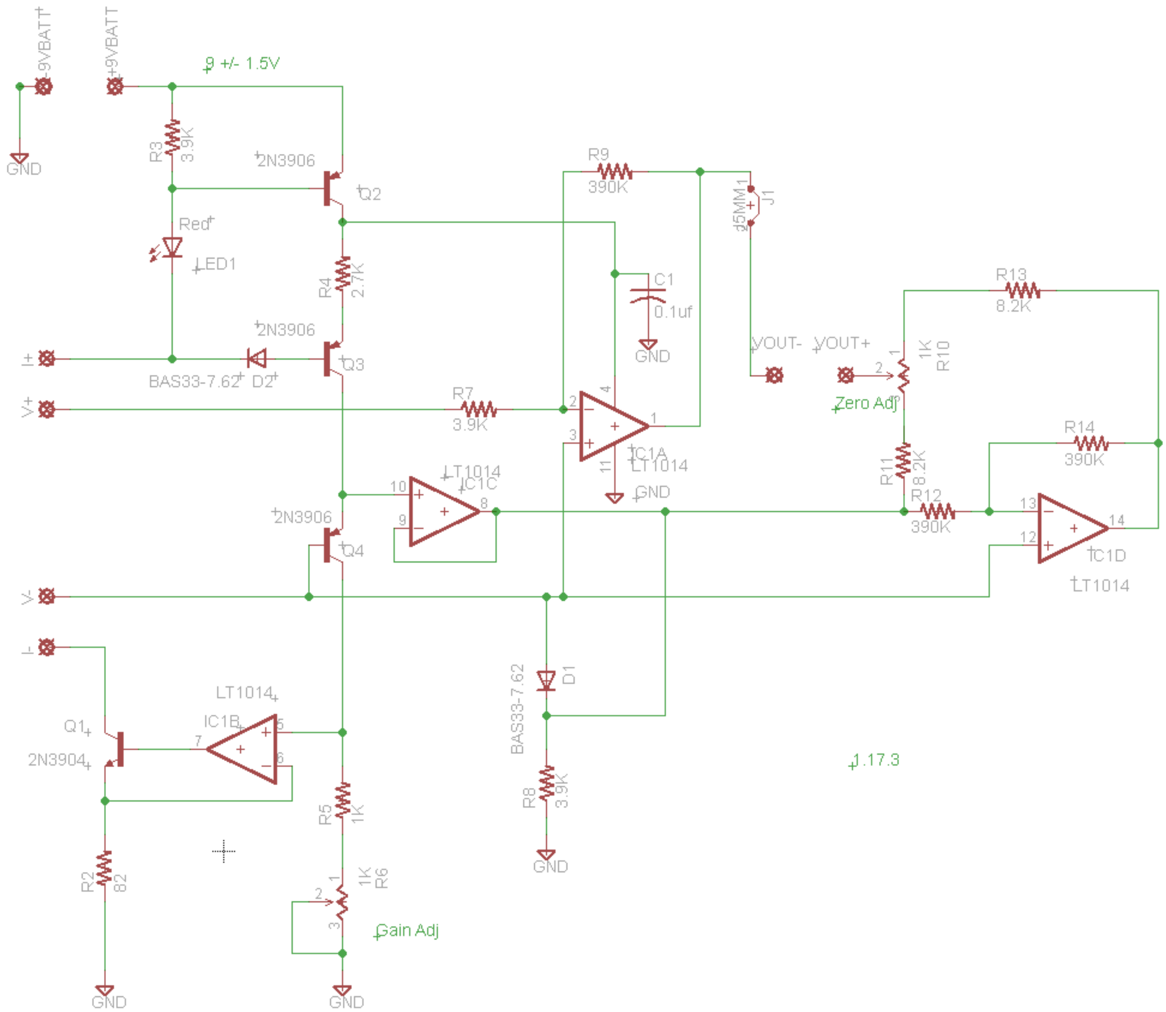
$$V_{14} = -V_{eb4} \qquad \text{(d8)}$$

When the Zero Adjust trim pot, R10 is at center, V_{out+} is zero independent of the value of V_{eb4}. When at minimum,

$$V_{out+} = \frac{(2 \times V_{eb4}) \times R_{11}}{R_{10}+R_{11}+R_{13}} - V_{eb4} \qquad \text{(d9)}$$

and nominally,

$$V_{out+} = \frac{(2 \times 0.65V) \times 8.2K}{1K+8.2K+8.2K} - 0.65V$$



$$V_{out+} = -37.4\,mV$$

When the maximum,

$$V_{out+} = -\frac{(2 \times V_{eb4}) \times R_{13}}{R_{10}+R_{11}+R_{13}} + V_{eb4} \qquad \text{(d10)}$$

and nominally,

$$V_{out+} = -\frac{(2 \times 0.65V) \times 8.2K}{1K+8.2K+8.2K} + 0.65V$$

$$V_{out+} = +37.4\,mV$$

Therefore, I can nominally compensate for up ±37 mV of offset. If this is not enough range, R11 and R13 can be reduced.

R10 is a 22 turn pot which means that one turn causes about a 3 mV change. It is easy to adjust V_{out+} to a voltage within 1 mV of the desired value.

I welcome your comments and questions.

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