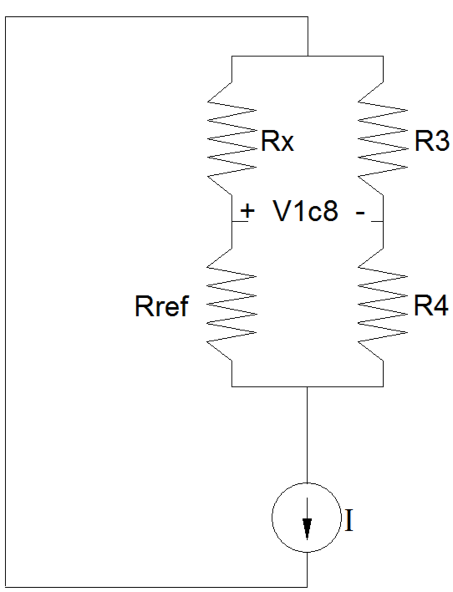
An Ultra Low Resistance Continuity Checker

By R. G. Sparber

Some understanding of electronics is assumed.

Although the title claims this is a continuity checker, its intended use is in machining where it is called an Electronic Edge Finder (EEF). The intended function of the circuit is to detect changes in resistance that are far smaller than can be seen with your regular digital volt-ohm meter. Most of these meters can measure down to a tenth of an ohm. This circuit not only measures down to about 10 milliohms, but it can also detect a change of 0. 2 milliohms. It is beyond the scope of this article to explain why this is useful[2].

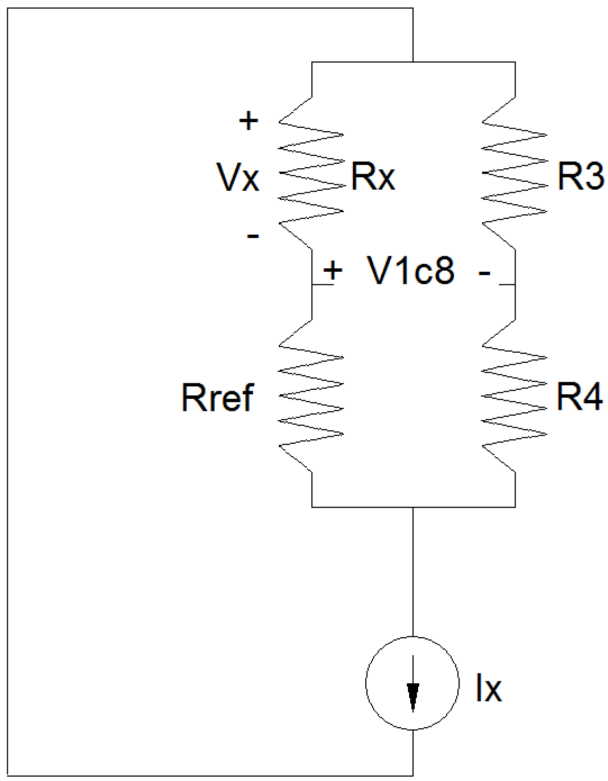
The full circuit is rather complex so let's start at a much higher level and build up to it.



At the heart of the circuit is a Wheatstone bridge. A constant current source, marked "I", feeds the circuit.

R_3 has been chosen to have the same resistance as R_4. When R_x equals R_{ref}, the voltage V_{1c8} is zero. As long as we are in this balanced state, variations in "I" have no effect on V_{1c8}.

[1] You are free to copy and distribute this document but not change it.
[2] See http://rick.sparber.org/rctf.pdf for a similar circuit's operation.



I have defined the voltage across R_x to be V_x plus have replace my constant current source with a Voltage Controlled Current Source.

$$I_x = \frac{10\ mV}{R_x} \qquad (1)$$

I will also select R_3 plus R_4 to be much larger than R_x plus R_{ref}. This means that almost all of I_x flows through R_x and R_{ref}.

So let's see. The current flowing through R_x is essentially equal to I_x so

$$V_x = R_x I_x.$$

But $I_x = \frac{10\ mV}{R_x}$ so I can say that

$$V_x = (R_x) \text{ x } \left(\frac{10\ mV}{R_x}\right) = 10 \text{ mV}.$$

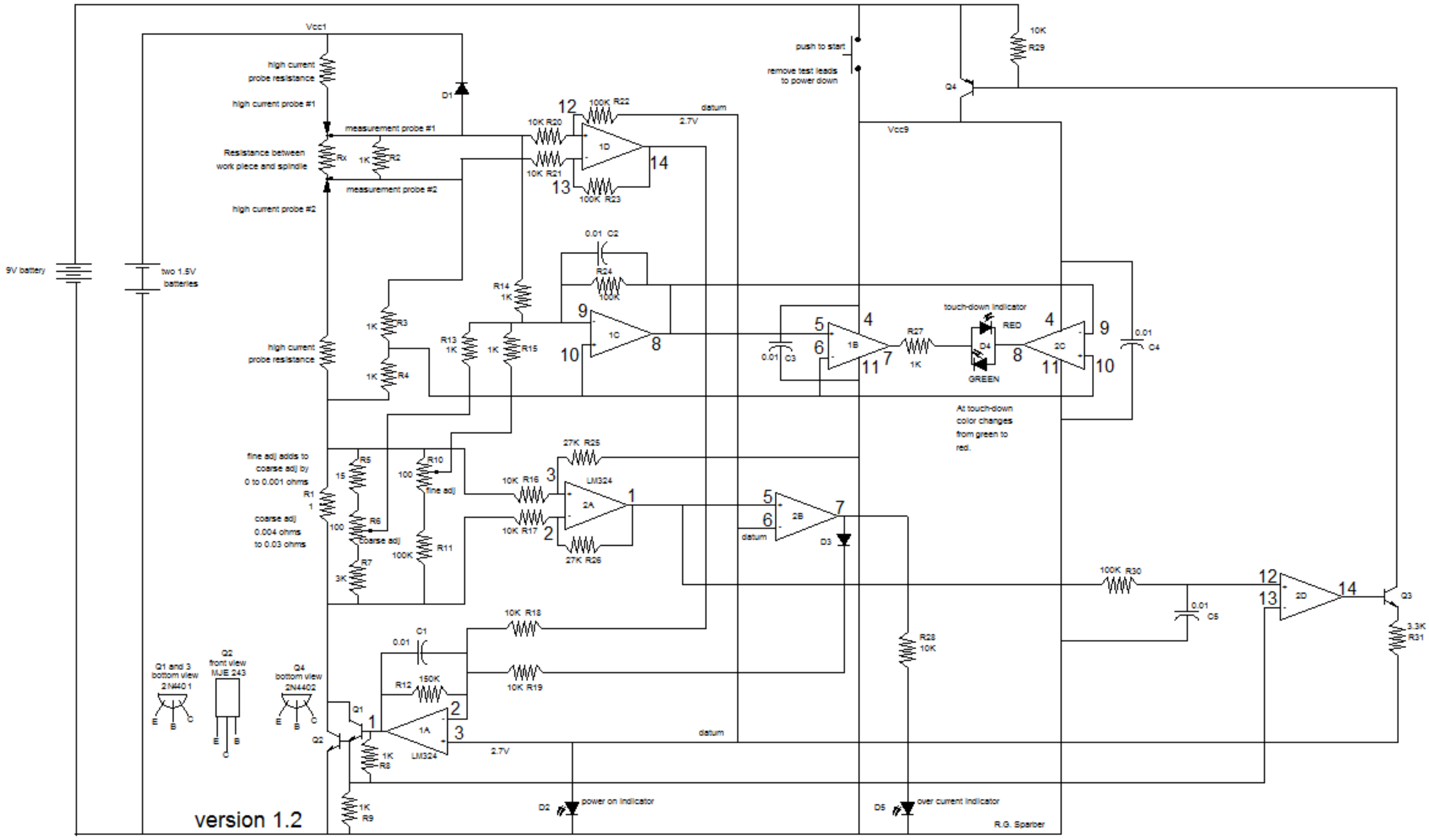
I have forced the voltage across R_x to be held constant at 10 mV. This has no effect on the Wheatstone bridge with its insensitive to I_x when at balance. But it does good things for me as you will soon see.

I_x is free to vary from about 0.25 amps up to 1 amp. Below 0.25 amps, I will turn off power so is part of my automatic power down subsystem. At just above 1 amp, I will reduce the current, wait a bit, and then test to see if I can raise it again. This protects both the circuit and R_x from excessive current.

Given this range for I_x, I can use equation (1) to calculate the range of R_x that I can handle. At 0.25 amps, $R_x = \frac{10\ mV}{0.25\ amps}$ = 40 milliohms. At 1 amp, $R_x = \frac{10\ mV}{1\ amp}$ = 10 milliohms. If I used 0.25 amps all of the time, then when R_x equals 10 milliohms I would have only 2.5 mV across it which is close to the input offset voltage of the op amps I use so would cause excessive error. If I used 1 amp all of the time, then I would sometimes be using more current than I needed. That is not good since this current comes from batteries.

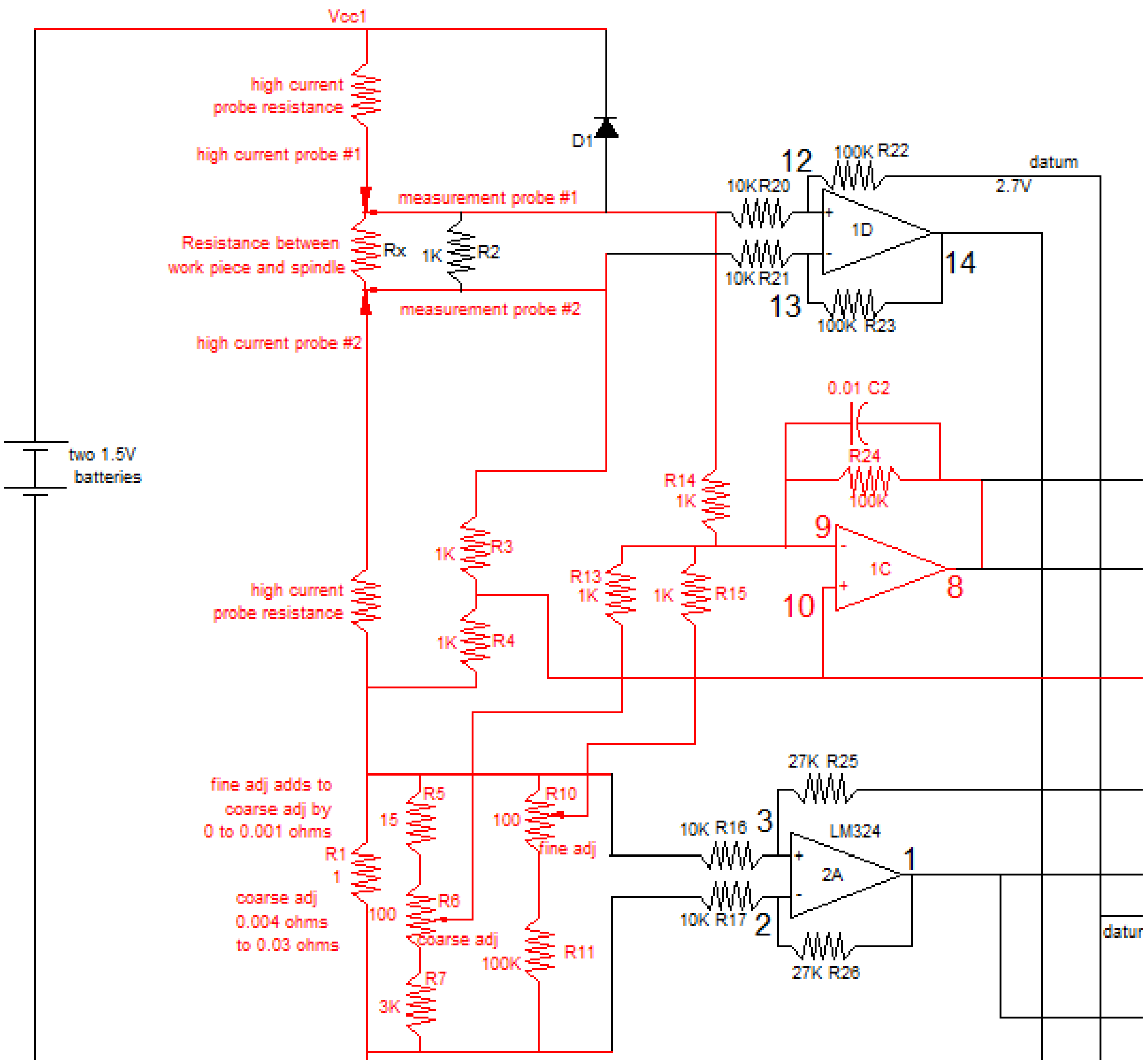
Circuit Details

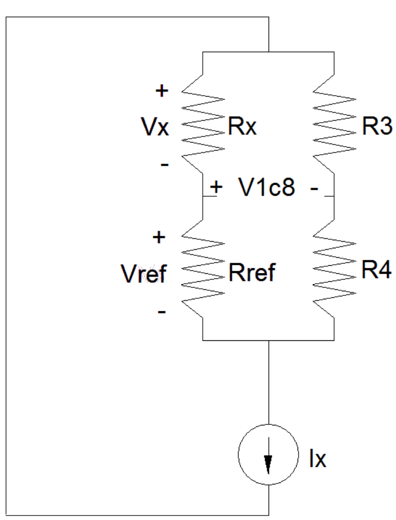
I will drop the entire circuit into your lap but then focus on each subsystem to make it more comprehensible.



The circuit uses two quad op amp ICs, one power NPN, a few small signal transistors and diodes, and a bunch of resistors and capacitors. It is powered by a 9V battery and two 1.5V batteries.

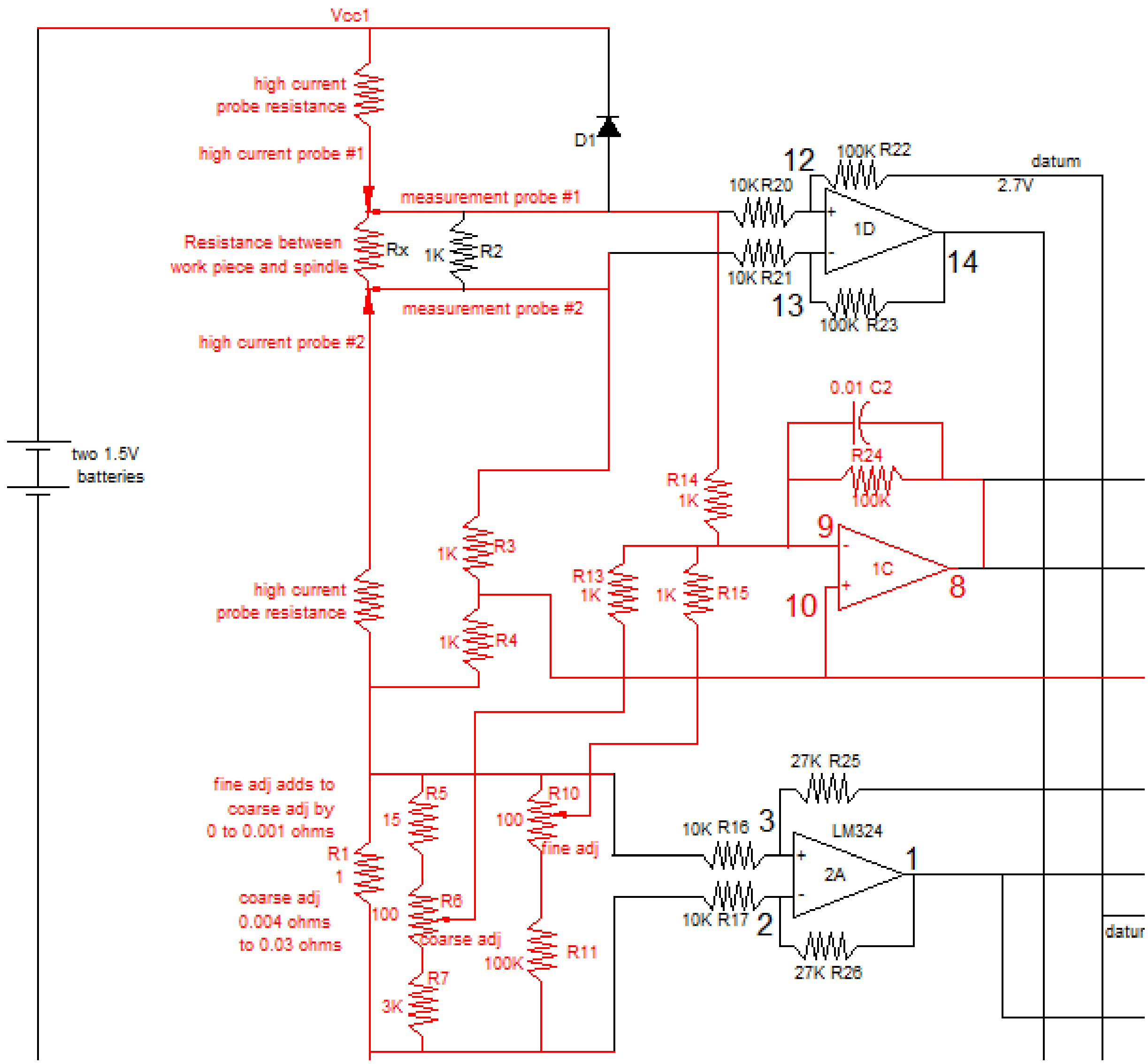
The Wheatstone Bridge





The circuitry in red may not look like a Wheatstone Bridge but it follows the same logic. R14 in the schematic corresponds to R3 in the simplified diagram. R1, R5, 6, 7, 10, 11, 13, and 15 are represented by R4 in the simplified diagram. And the voltage out of op amp 1C, pin 8 is my V_{1c8}.

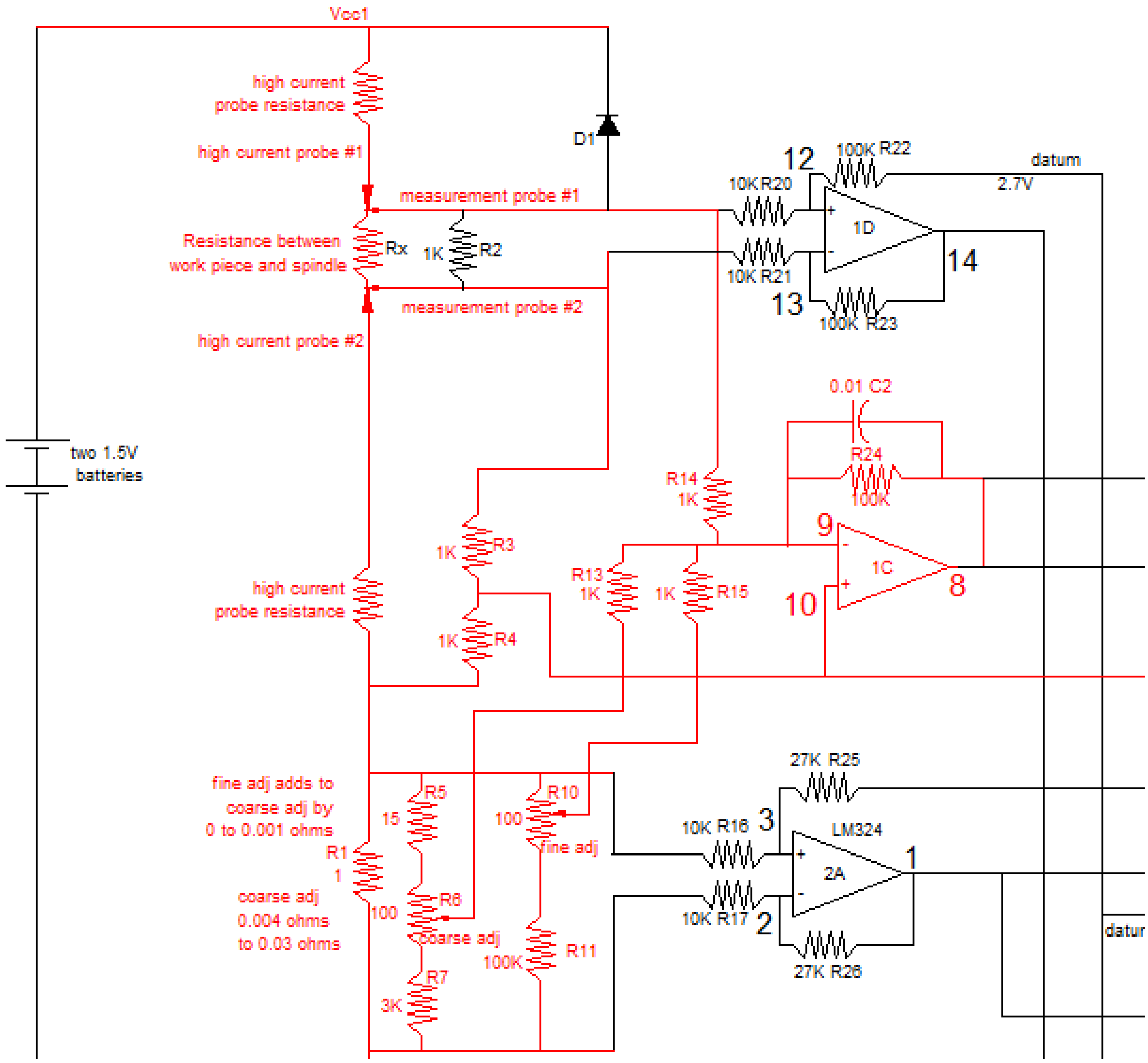
One minor difference with my approach is that I am comparing the voltage drop across R_x to the voltage drop across R_{ref}. When they are equal, I am at balance. Functionally, there is no difference.



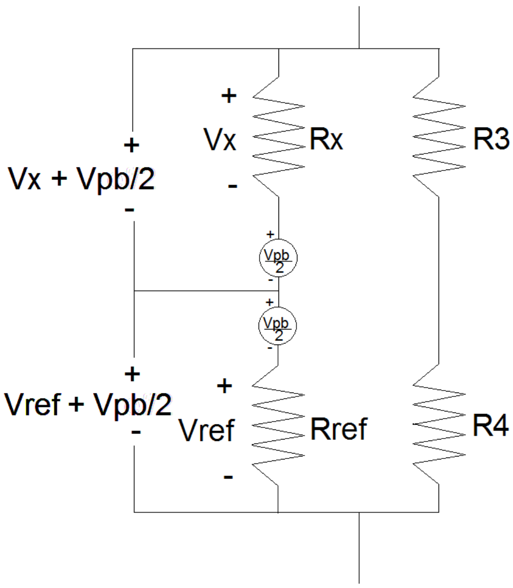
Starting at the top, I have the battery voltage which is marked V_{cc1}. It is around 2 volts when my test current is 1 amp. Those 1.5V batteries drop a lot of voltage with this kind of load.

Locate R_x and you will see four probes connected to it. Two of these probes carry the high current while the other two sense the resulting voltage and carry almost no current. This arrangement is called a Kelvin connection[3]. It enables you to tolerate large and unknown voltage drops in the current carrying path while having no voltage drop in the sensing path.

[3] http://en.wikipedia.org/wiki/Four-terminal_sensing



My goal is to compare the voltage across R_x with the voltage across my R_{ref}. The problem is that I have an unknown voltage drop in the "high current probe #2" between them. I don't know what this voltage drop is but I sure can divide it in half with R3 and R4. Doing this gives half of this unknown voltage to my R_x voltage drop and the other half to my R_{ref} voltage drop.

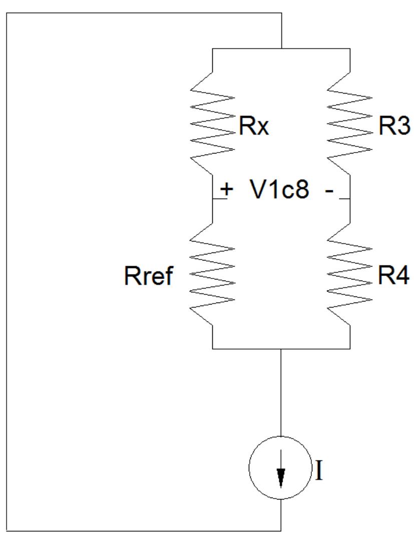


Going back to the high level schematic, I have added in my high current probe #2 voltage drop, V_{pb}. Thanks to R3 and R4, this unknown voltage has been equally shared by V_x and V_{ref}. Balance is detected when

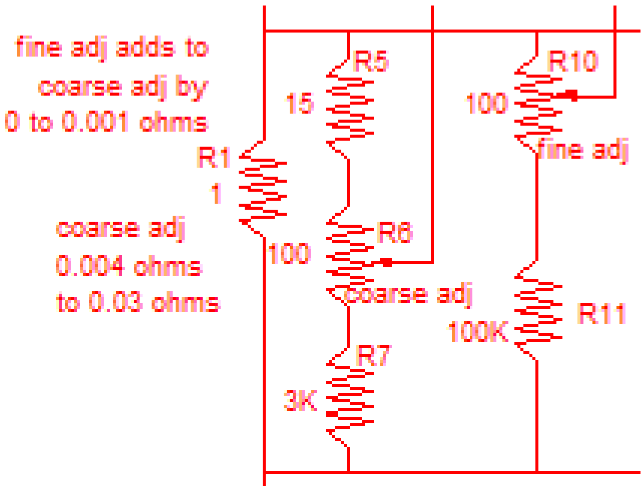
$$V_x + \frac{Vpb}{2} = V_{ref} + \frac{Vpb}{2} \qquad (2)$$

Which boils back down to my original equation of having balance at $V_x = V_{ref}$.

Since I measure V_{pb} using my "measurement probe #2", I pick up both the voltage drop in the high current probe #2 wire and its connection to R_x.



In a regular Wheatstone bridge I adjust R_{ref} to be equal to R_x. But R_x is in the milliohms and I don't have a potentiometer in that range. Not to worry, what I really want is the voltage across R_{ref}. I don't care about the value of R_{ref}, just the voltage.



So instead of having an Rref of, say 10 milliohms, I have R1 equal to 1 ohm. Then I use a voltage divider to cut this voltage down to the level I would get if my test current passed through a 10 milliohm resistor.

First look at R10 and R11. The voltage at the wiper of R10 equals

$$V_{w10} = \frac{R10L}{R10+R11} \times R_1 \times I \quad (3)$$

Where R_{10L} is the resistance from wiper to the top terminal. Say R10 is set 1/3 the way from the top so R_{10L} = 33.3 ohms. Then

$$V_{w26} = \frac{33.3}{100+100K} \times 1\ ohm \times I = 0.333 \text{ milliohms} \times I$$

So I simulate a 1 milliohm pot with a 100 ohm pot and a voltage divider. R_{10} is my fine adjust and lets me vary the effective R_{ref} by up to 1 milliohm.

The coarse adjust works in a similar manner using R5, R6, and R7. Due to R5, I have a lower limit of

$$V_{w6} = \frac{R5}{R5+R6+R7} \times R_1\ ohm \times I \quad (4)$$

$$V_{w6} = \frac{15}{15+100+3K} \times 1\ ohm \times I$$

$$V_{w6} = 4.8\ milliohms \times I$$

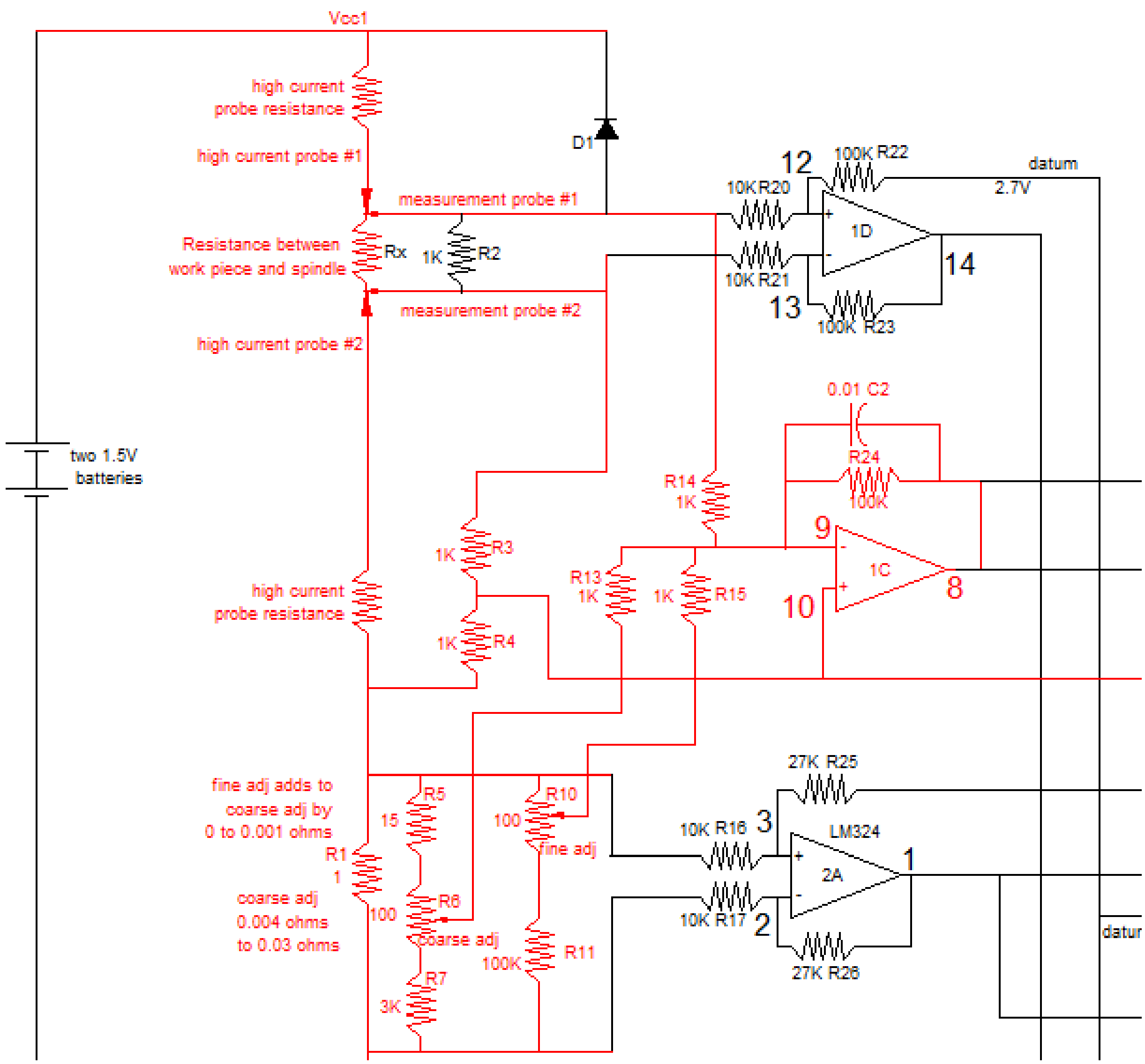
The upper limit is

$$V_{w6} = \frac{R5+R6}{R5+R6+R7} \times 1\ ohm \times I$$

$$V_{w6} = \frac{15+100}{15+100+3K} \times 1\ ohm \times I$$

$$V_{w6} = 36.9\ milliohms \times I$$

My advertised range is 9 to 25 milliohms so this gives me a little margin.



One nice thing about using an op amp to measure my effective R_{ref} is that I can simply add the fine adjust current to the coarse adjust current to get the full effect. So I can set my coarse adjust pot to 10 milliohms and use the fine adjust to move the effective R_{ref} between 10 milliohms and 11 milliohms.

Thanks to R3 and R4, I can ignore the voltage drop in high current probe #2. Taking pin 10 of op amp 1C as my ground, I can write

$$V_{1c8} = -R_{24}\left(\frac{V_{meas\,probe\,\#1}}{R_{14}} - \frac{V_{w6}}{R_{13}} - \frac{V_{w10}}{R_{15}}\right) \qquad (5)$$

But $V_{meas\ probe\ \#1}$ equals $R_x \times I$ and I know that the two wiper voltages are also functions of *I*. This can all be blown up into

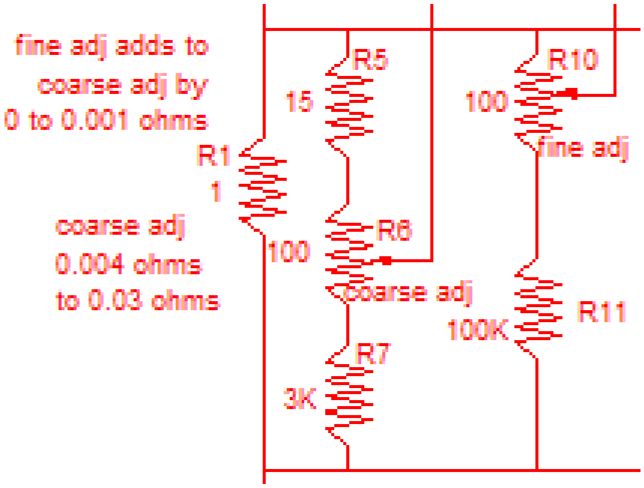
$$V_{1c8} = -R_{22}\left(\frac{R_x}{R_{11}} - \left\{\frac{R_5+R_{6L}}{R_{12}(R_5+R_6+R_7)} + \frac{R_{26L}}{R_{13}(R_{26}+R_{27})}\right\}\{R_1\}\right)(I) \quad (6)$$

At balance, V_{1c8} goes to zero. This lets me simplify a little to

$$\frac{R_x}{R_{11}} = \left\{\frac{R_5+R_{6L}}{R_{12}(R_5+R_6+R_7)} + \frac{R_{26L}}{R_{13}(R_{26}+R_{27})}\right\}\{R_1\} \quad (7)$$

Now, $R_{11} = R_{12} = R_{13}$ so I can multiply both sides by this value and get

$$R_x = \left\{\frac{R_5+R_{6L}}{(R_5+R_6+R_7)} + \frac{R_{26L}}{(R_{26}+R_{27})}\right\}\{R_1\} \quad (8)$$



When I plug in values I get

$$R_x = \{\frac{15+R_{6L}}{(15+100+3K)} + \frac{R_{10L}}{100+100K}\}\{1\} \quad (9)$$

Where R_{6L} and R_{10L} can be set to any value between 0 and 100 ohms.

For example, if I reach balance at R_{6L} = 50 ohms and R_{10L} = 10 ohms, then I know that

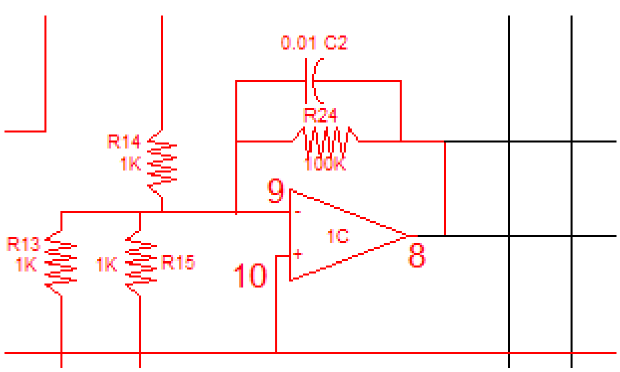
$$R_x = \{\frac{15+50}{(15+100+3K)} + \frac{10}{100+100K}\}\{1\}$$

$$R_x = \{\frac{65}{(3.115K)} + \frac{10}{100.1K}\}\{1\}$$

$$R_x = \{20.9 \text{ milliohms} + 0.1 \text{ milliohms}\}$$

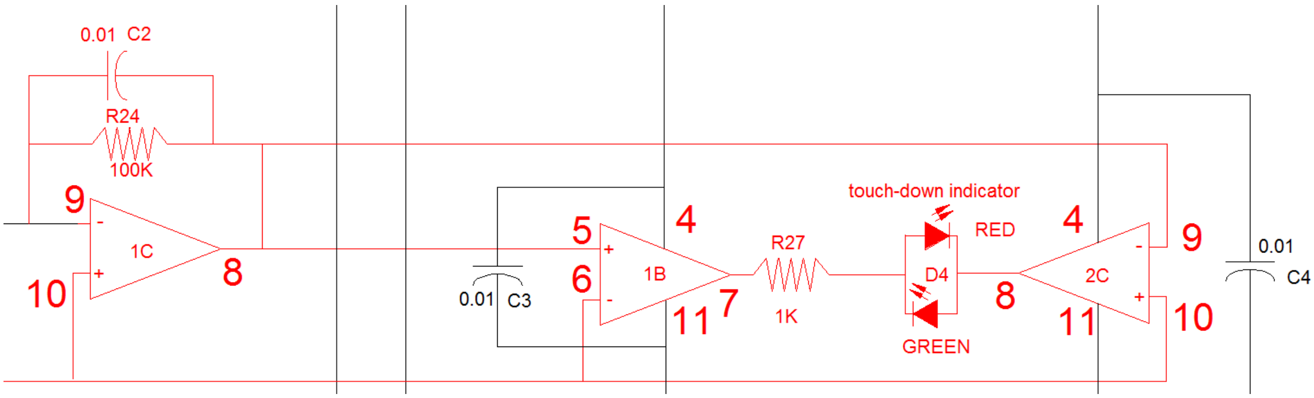
$$R_x = 21.0 \text{ milliohms.}$$

Thankfully, it is a lot easy to just twist the two knobs than run through the equations each time.



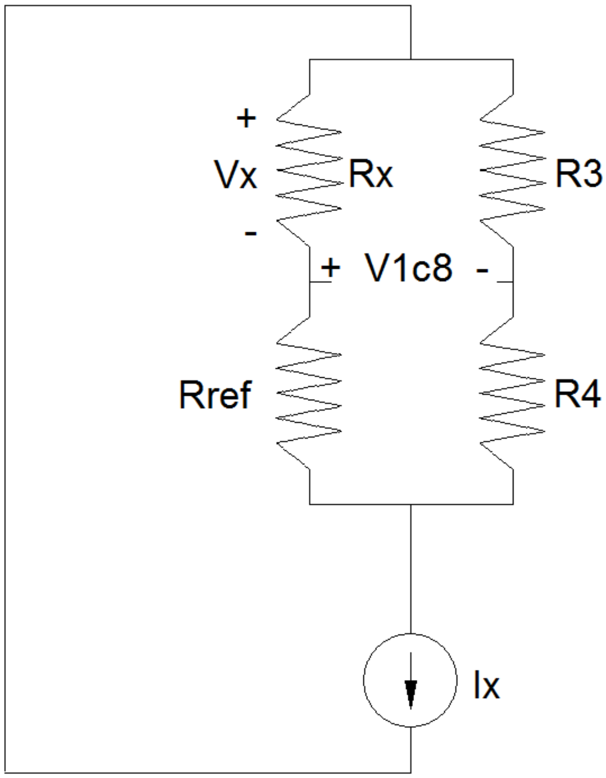
Capacitor C_2 causes the op amp to have less gain as the incoming signal increases in frequency. Since the only signal I care about is at DC, this cap is helping reduce any unwanted signals. C_2 with R_{24} create a corner frequency of 318 Hz.

Touch-down LED Driver



The output of op amp 1C with respect to V_{1C10} drives a pair of op amps used as comparators. When this voltage is positive, V_{1B7} swings up to near the positive power rail while V_{2C8} swings to near the negative power rail. This causes current to flow through the red LED. When this voltage is negative, the green LED lights. If this voltage is very close to zero and there is any AC noise, both LEDs will dimly light.

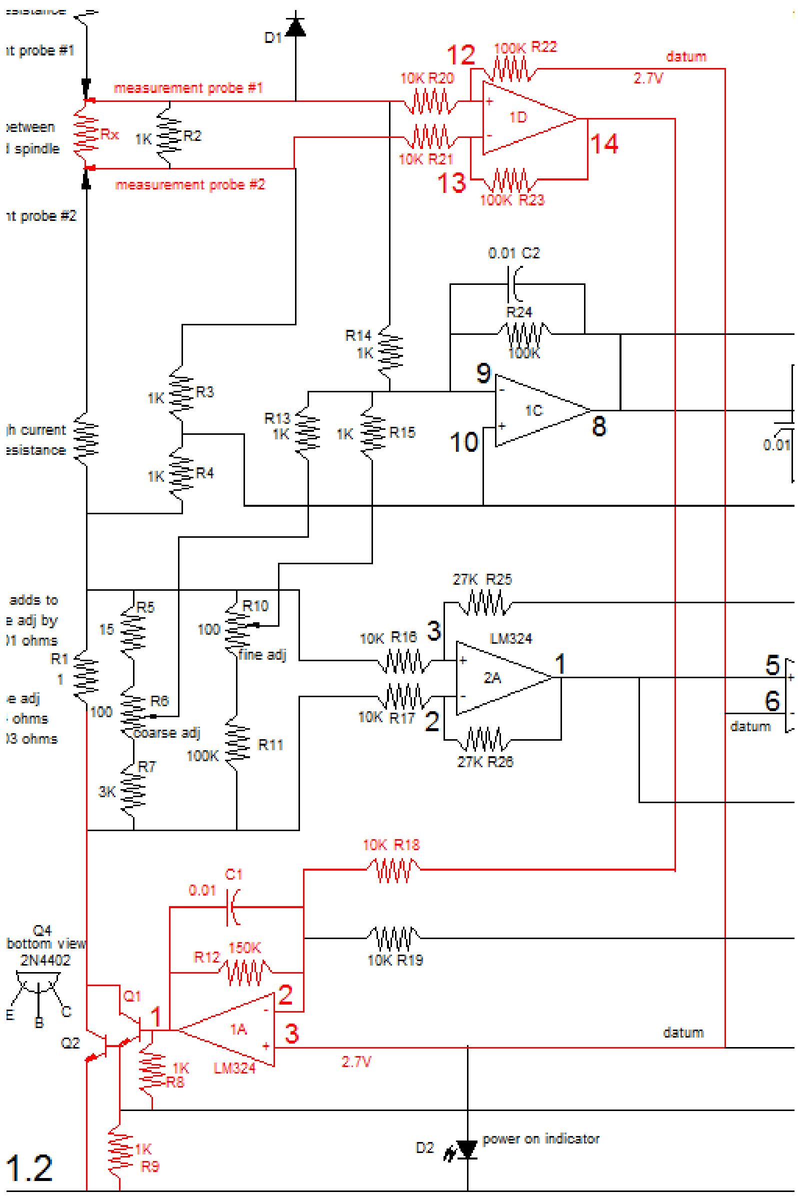
The Current Source



Recall that the current that flows through my Wheatstone bridge comes from a Voltage Controlled Current Source. It is defined by equation 1:

$$I_x = \frac{10\ mV}{R_x} \qquad (1)$$

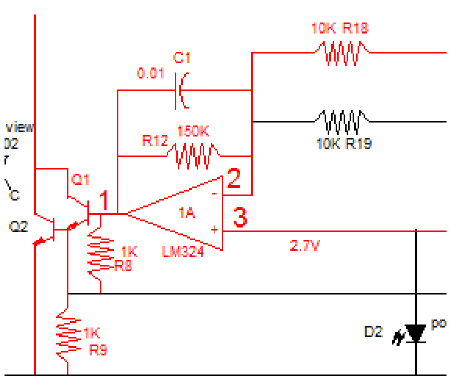
In other words, I_x is adjusted such that the voltage across R_x is always 10 mV. Well, not *really* always; only over a range of currents.



Op amp 1D directly measures the voltage across R_x and multiplies it by 10. But wait, wasn't my ground pin 10 at op amp 1D? Well, I lied a little. While true for op amp 1C, I use a different "ground" for op amp 1D. I will call it my "datum". All this means is that my voltage V_{1D14} is with respect to my datum. I did this to move my output voltage of op amp 1D away from the negative rail of the power supply. It also has another use which will become evident soon.

The output of 1D feeds into an inverting amplifier involving 1A, R18, and R12. It has a gain of 15. Its output feeds a small NPN which in turn feeds a power NPN.

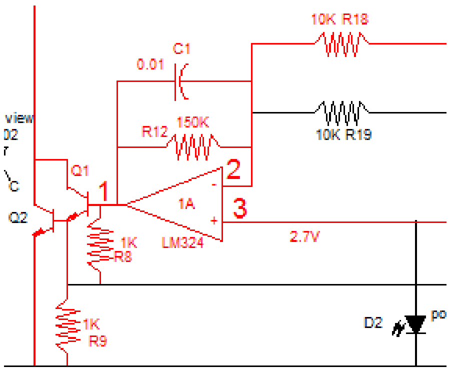
Now, bear with me as I really mess with your mind. I am about to use the convoluted logic of feedback to explain how this part of the circuit works.



The voltage at the output of 1A equals

$$10 \times (-15) \times V_x = -150V_x$$

with respect to the datum. With respect to my negative power rail, it would be lower by the voltage across D_2. So I can say that the voltage at the output of 1A equals V_{D2} $-150V_{x.}$ with respect to the negative power rail.



But since current is flowing through R_x in order to generate V_x, I know that Q_1 and Q_2 are on. Therefore, the voltage at pin 1 of op amp 1A must equal V_{be1} + V_{be2}.

I have calculated the voltage at pin 1 of op amp 1A in two different ways but there can be only one voltage. So I will simply set them equal and see what happens:

$$V_{be1} + V_{be2} = V_{D2} - 150V_x \quad (10)$$

A reasonable voltage for V_{be} is 0.7V and for my LED it is around 2.7V. This gives me

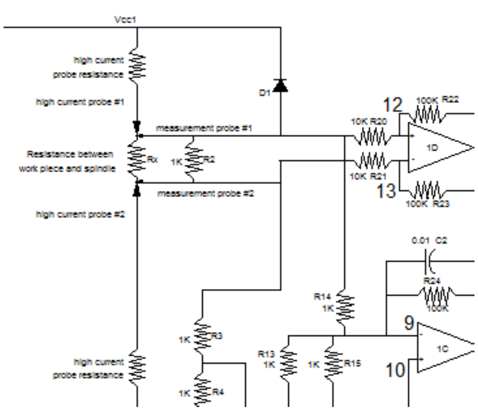
$$0.7 + 0.7 = 2.7 - 150V_x$$

Solving for V_x I get

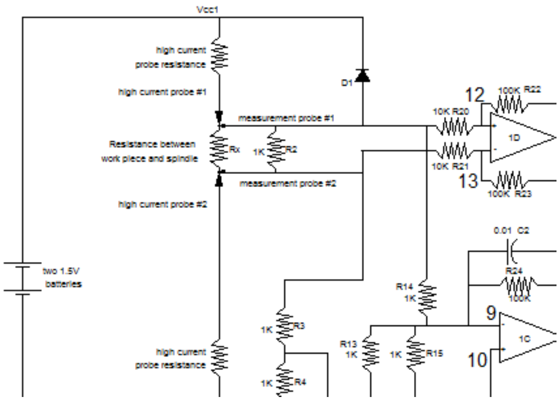
$$V_x = \frac{2.7-0.7-0.7}{150} = 8.7 \text{ mV}$$

You have caught me in a tradeoff. I really wanted 10 mV but what I want more is to limit the number of different resistor values in my circuit. So I ended up with a regulated voltage a little bit smaller than my target. On the other hand, V_{be} and V_{D2} are not precision either so I would be kidding myself if I finely tuned the circuit to give me exactly 10 mV. It is better to be a little bit under to insure I can tolerate a R_x of 10 milliohms.

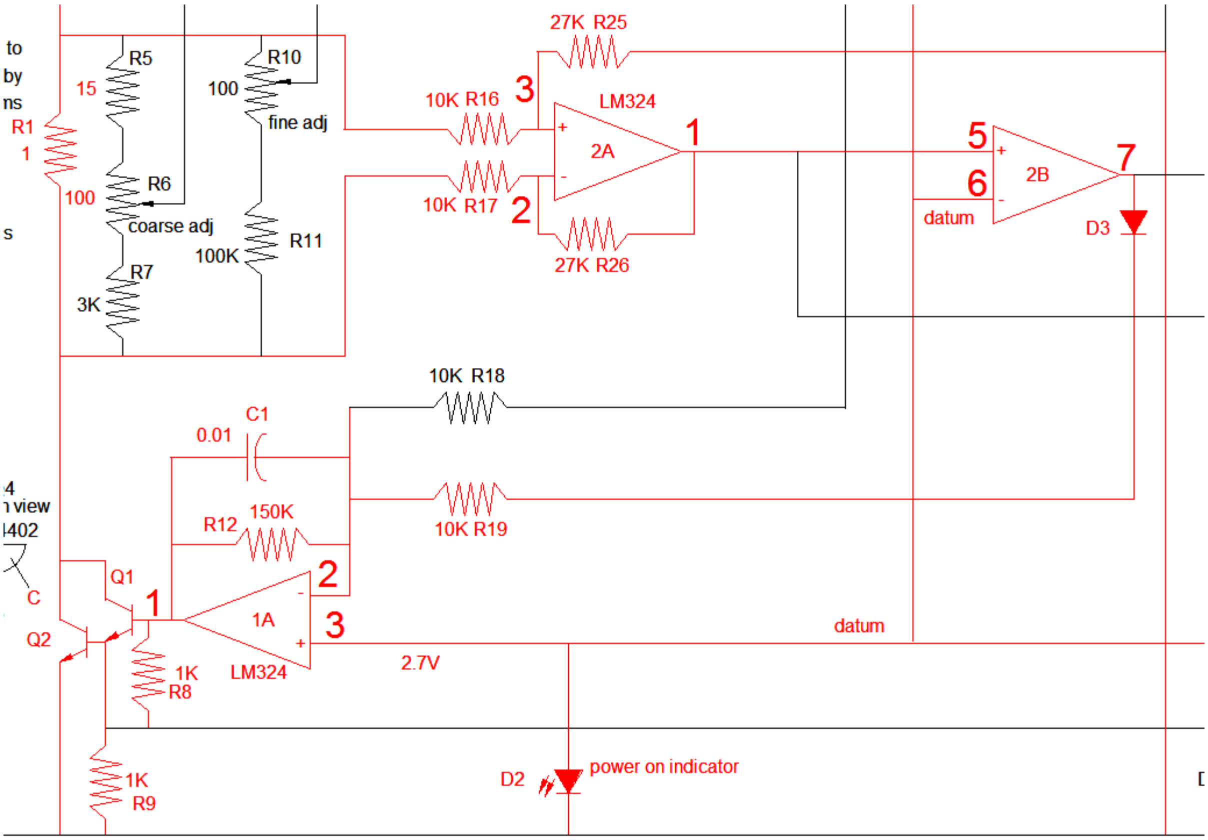
So what this circular argument has demonstrated is that Q_1 and Q_2 will adjust such that the voltage across R_x is around 8.7 mV over a wide range of R_x values.



There are a few loose ends here. R_2 and D_1 can be found near R_x. They do nothing under normal circuit operation. When the measurement probes are removed from R_x, their voltages would be undefined and that can lead to strange behavior or even damage to the op amps. So instead I have R_2 which ties the measurement probes together. The 1K value has a minimal effect on the value of R_x seen by the rest of the circuit.



The input transistors in these op amps are PNPs so current flows out of them. D_1 provides a path for this current into the two 1.5V batteries. I used a diode here rather than a resistor because I do not want any current to flow from these batteries into the rest of the circuit when the probes are removed.



The current through R_x must not get above 1 amp. This function is accomplished by directly measuring the voltage across R_1. This voltage equals our test current times R_1. So at 1 amp, op amp 2A sees 1V. It amplifies this voltage by 2.7 to generate the voltage V_{2A1} which is with respect to my negative power rail. Op amp 2B is used as a comparator. It compares V_{2A1} to the voltage across D_2 which is about 2.7V. I get a state change in 2B when

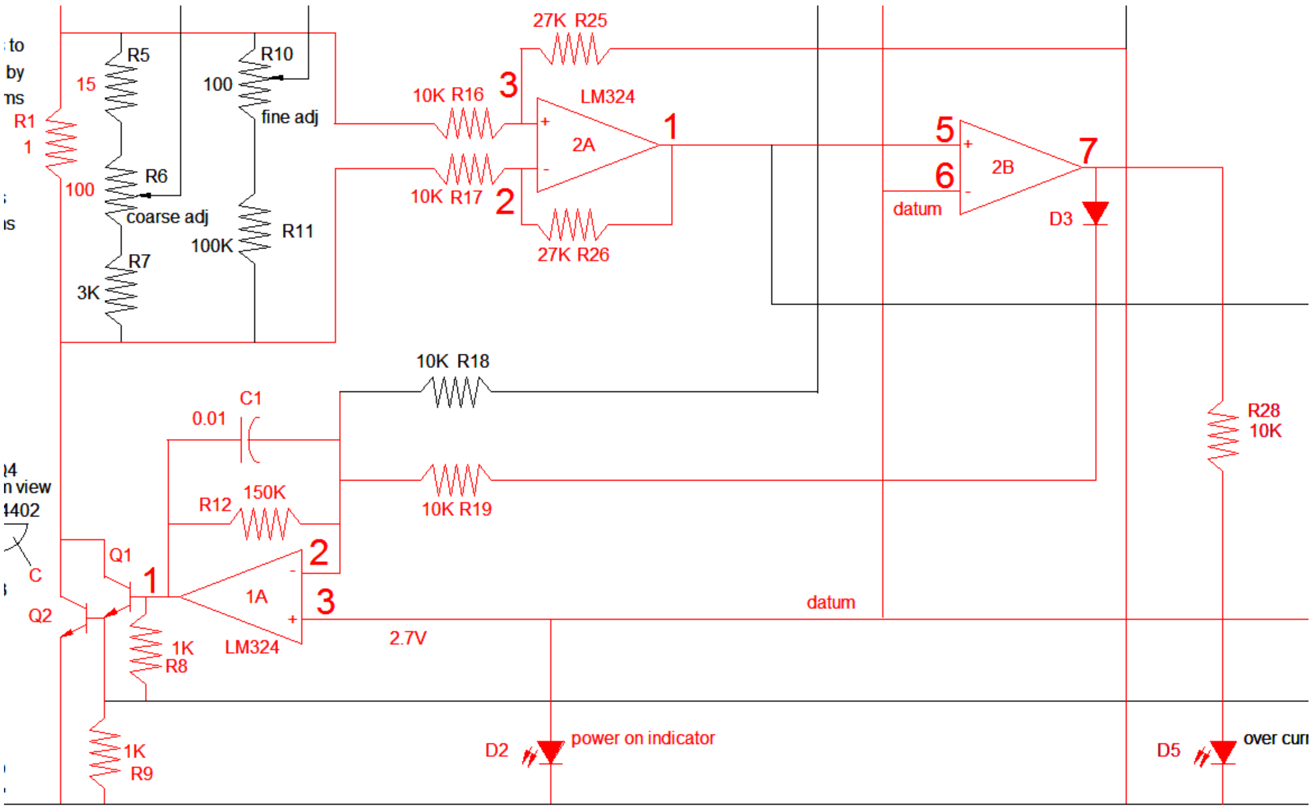
$$V_{D2} = 2.7 \times R_1 \times I_x \quad (11)$$

Where V_{D2} equals about 2.7V, R_1 equals 1 ohm, and $I_x = I_{c1} + I_{c2}$.

I therefore have

2.7 = 2.7 ohms × I_x so I_x = 1 amp, my current limit.

At this current level, the output of 2B swings from near the negative power rail up to near the positive power rail.

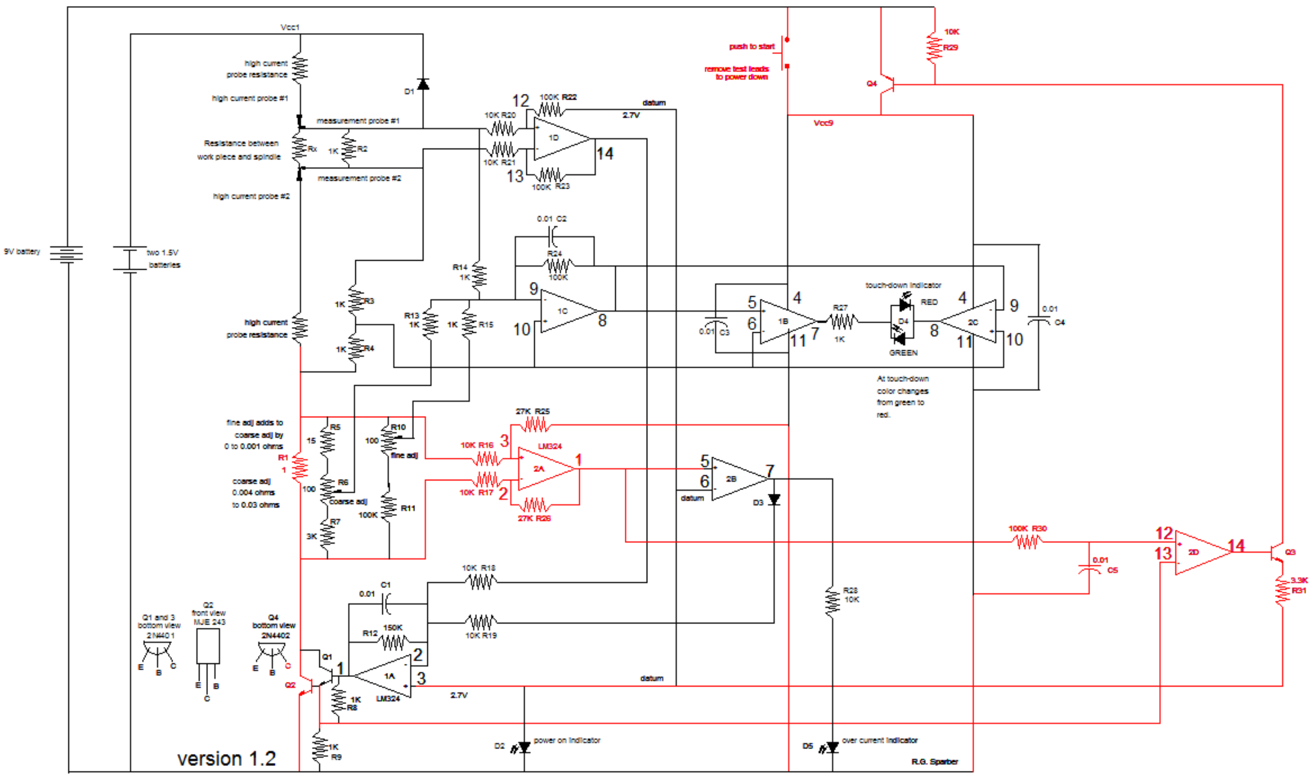


This turns on diode D_3 and applies about 7V to R_{19}. This large flow of current into amplifier 1A cause V_{1A1} to slam down to near the negative power rail. Q1 and Q2 quickly turn off so no current flows through R_1.

But wait, didn't I start by saying that 1 amp was flowing through R_1? Yup. So I have a contradiction *until* I consider the factor of time.

We start with 1 amp flowing. This causes 2B to change state which slams 1A's output down. That starts to turns off the transistors and the current through R_1 falls. But then 2A sees that the voltage is now smaller so 2B changes state again and diode D_3 turns off. In other words, when we reach the current limit, the current limiter oscillates between a current of 1 amp and a value less than 1 amp. Capacitor C_1 slows down the cycle but provides some noise immunity.

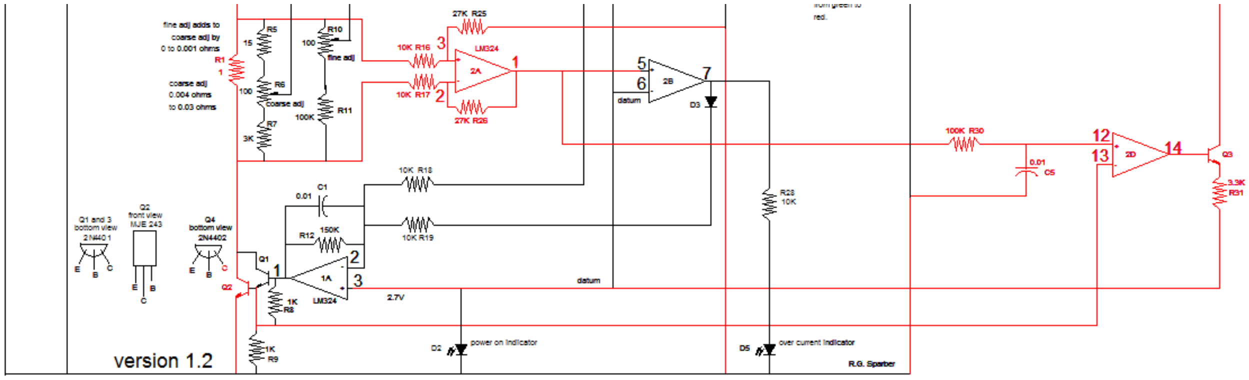
Sitting off to the side is R_{28} and D_5. Each time 2B's output slams up to near the positive rail, D_5 lights up to tell us that we have reached the maximum current.



When the test current falls below about 0.25 amps, the circuit powers down. In this way, when you remove the test probes, you can't leave the power on to drain the batteries.

The shutdown circuit uses the same voltage as the current limiter. The output of op amp 2A with respect to the negative rail is applied to a filter using R_{30} and C_5. This filter prevents short disruptions of current from killing power. It has a time constant of $R_{28} \times C_5 = 100K \times 0.01\ uF = 1\ ms$. That is a corner frequency of 318 Hz.

Op amp 2D is used as a comparator. The positive input equals $2.7 \times R_1 \times I_x$ if the signal is DC. The negative input equals V_{be2} which is around 0.7V.



State change in 2D occurs when

$$2.7 \text{ x } R_1 \text{ x } I_x = V_{be2} \quad (12)$$

Solving for I_x to get

$$I_x = \frac{V_{be2}}{2.7 \times R_1} \quad (13)$$

$$= \frac{0.7}{2.7\ ohms}$$

$$I_x = 0.259 \text{ amps}$$

As long as I_x is above this value, the output of 2D remains near the positive power rail.

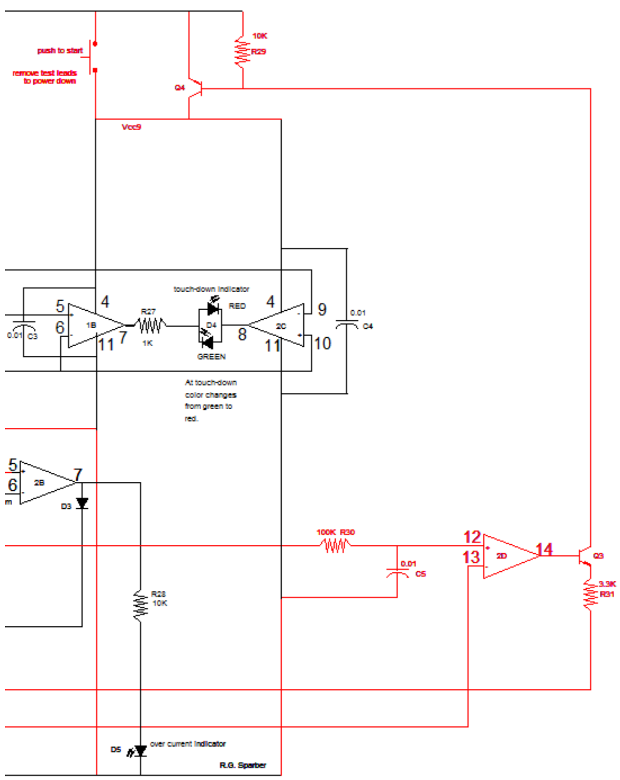
When the current source is in overload, the R_{28} C_5 filter removes most of the AC component. What is left is high enough not to shut down the circuit.

V_{2D14} feeds the base of Q3 which is part of a current source:

$$I_{c3} = \frac{V_{2D14} - V_{be3} - V_{D2}}{R_{31}} \quad (14)$$

V_{2D14} is near the positive power rail and is around 7V. V_{be3} is around 0.7V and V_{D2} is around 2.7V. None of these voltages are critical.

$$I_{c3} = \frac{7 - 0.7 - 2.7}{3.3K} = 1.1 \text{ mA}$$



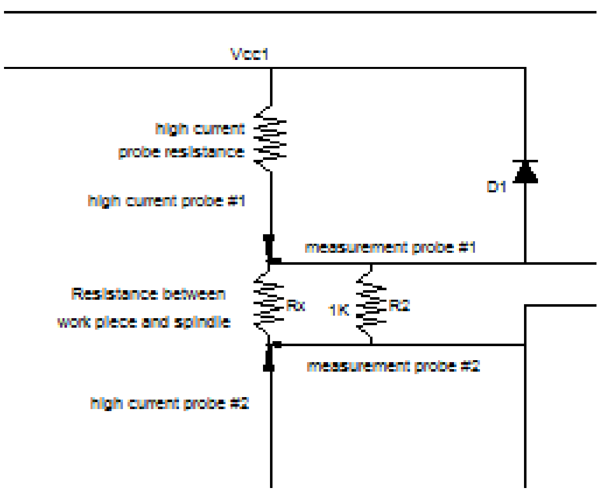
This current is drawn from the parallel combination of R_{29} and the base of Q_4. Since V_{be4} is around 0.7V, this leaves

$$1.1 \text{ mA} - \frac{0.7V}{10K} = 1 \text{ mA}$$

to saturate Q_4. Assuming a minimum beta for Q_4 of 20, this is more than enough to insure all needed current can pass to the rest of the circuit. I measured a load of less than 10 mA.

In order to start up the circuit, the "push to start" button is pressed. It shorts out Q_4 and, assuming the test leads are connected, brings up the circuit. If the test leads are not connected, then power will not remain on when the button is released.

Mechanical Considerations



The circuit will only work correctly when all four probes are connected to the unknown. I plan to use magnetic clips[4] to attach these probes. The high current probe #1 and measurement probe #1 will be run in the same length of common lamp cord. Each conductor will terminate in its own magnetic clip. I will then run a bead of heat glue between the clips to hold them together without providing a path for current. In a similar fashion, high current probe #2 will be paired with measurement probe #2.

The 1.5V batteries might be AA or maybe D size. It depends on how often the circuit is used. I own AA batteries with a power rating of over 2.5 ampere-hours so they should have a decent lifetime if each use of the circuit is limited to less than a minute.

Parts Considerations

D_1 and D_3 are common small signal diodes. I used Super Bright white LEDs for D_2 and D_5 because I had them. D_4 can be a single, red/green LED or it can be formed from two LEDs. All resistors are 1/4W except R1 which can dissipate up to 1 watt. I happen to have a 5W resistor so that is what I used there. A heat sink may be needed for Q_2. Given a V_{cc1} of around 2V and a test current of 1 amp, V_{ce2} is around 1V. So it could dissipate up to a watt.

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[4] See http://rick.sparber.org/electronics/mwc.pdf

Normal Operation

The circuit is intended to look for a small drop in resistance. When this drop is detected, the touch-down LED changes from green to red.

Testing procedure:

1. connect the test probes across the unknown resistance
2. push the start button
3. the power-on LED should light
4. set the fine adjust to the center of its travel
5. adjust the coarse adjust until the touch-down LED is barely green (that is, a slight turn of the coarse adjust makes it red)
6. adjust the fine adjust until the touch-down LED is green but very close to changing to red
7. switch to the lower value of unknown resistance without disrupting the test current
8. the touch-down indicator should change from green to red; if not, use the fine adjust to make it just turn red and verify that it is green when you return to the higher resistance.

Fault conditions:

A. power won't stay on - unknown resistance is greater than about 30 milliohms
B. over current LED on - unknown resistance is less than about 8 milliohms
C. moving from higher to lower resistance does not cause a state change in the touch-down LED (assuming circuit is not in over current and the coarse and fine adjust were done right) - change is less than 0.1 milliohms.

I welcome your comments and questions.

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