A Constant-current Source

Frequently, such as when you want to measure temperature with a silicon diode, it is desirable to have a source of a reproducible, constant current. Many laboratory power supplies can be used as constant current sources. The difficulties you may encounter are reproducibility or a requirement for very small currents.

You may remember a circuit from the notes for the op-amp lab in Physics 140 that will produce a constant current. This circuit, which is reproduced with modifications in Figure 1, results in both a quite reproducible current and can reliably provide currents in the $\mu$A range.

![A simple constant current source using an op-amp. C3 is a 0.01 $\mu$F capacitor on the output to reduce high-frequency noise. C4 is a 0.1 $\mu$F capacitor from the base of the 2N3906 to ground, also to reduce high-frequency noise. C1, the bypass capacitor on the power supply line, is usually necessary for stable operation. C1 is typically 0.1 $\mu$F. The op-amp can be any general purpose op-amp such as the 741 or the TL3472. The two vertical lines, labeled “Vcc+” and “Vcc−” extending from the center of the op-amp symbol indicate the power supply connections. The upper one is for the positive supply and the lower one for the negative supply. Because all the voltages on the op-amp are positive it is possible to run this circuit with a unipolar power supply. If you connect Vcc− to $-15$ V, it is necessary also to provide a bypass capacitor to ground on that line.](image-url)
This circuit is fairly simple to understand. The voltage divider made from R1 and R2 provide a reference voltage, $V_{\text{ref}}$, at the non-inverting input of the op-amp. With negative feedback, as provided by this circuit, the op-amp will now do everything in its power to keep the inverting input at the same voltage ($V_{\text{ref}}$) as the non-inverting input. It will do this by varying the current through R3. The current is modified by changing the voltage on the base of the 2N3906 transistor. It will be able to maintain this current as long as the voltage on the upper terminal of the output (or the collector of the 2N3906) stays at least 0.3 V (or so) below $V_{\text{ref}}$. Alternatively, if the voltage across the output device (e.g., the temperature measurement diode) is $V_{\text{output}}$ then the circuit will function properly if

$$V_{\text{ref}} > V_{\text{output}} + 0.3 \text{ V}.$$  

The output current (the current provided at the output terminals) is then set by

$$i_{\text{out}} \cdot R3 = \frac{15 \text{ V} - V_{\text{ref}}}{R3},$$

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NOTE: If you are using the TL3472 op-amp in this circuit $V_{\text{ref}}$ must be less than 13.2 V for a 15 V supply voltage.

The bypass capacitor, C1, is connected between the power supply line (Vcc+) and ground. This capacitor is absolutely necessary for loads that draw significant currents, especially if those currents change rapidly. For low output currents, the supply may work properly without a bypass capacitor, but it is usually good practice to always include bypass capacitors placed as near the power supply pins on integrated circuits as possible.

$V_{\text{ref}}$ and the voltage on the base of the 2N3906 transistor are always positive with respect to ground. It is possible to run this circuit with a single $+15 \text{ V}$ supply connected to Vcc+. Vcc- would be connected to ground.

If you operate this circuit with a bipolar power supply (i.e., $+15 \text{ V}$ attached to Vcc+ and $-15 \text{ V}$ attached to Vcc-), you will also have to include a bypass capacitor between Vcc- and ground.

### 1.0 Optional voltage monitor

Figure 1 includes an optional item labeled “Voltage Monitor”. For many applications, this would not be included. For our temperature measurements, it is included to...
provide a connection for monitoring the voltage across the diode to determine the
temperature of the diode. Including this output for the temperature measurement
diode will allow you to have a single set of clip leads attached to the diode. Having
multiple clips on each lead of the diode will usually result in some frustration with
clips coming off the leads.

2.0 Current and power limits

The carbon composition resistors that we use in Physics 240 are rated at $1/4 \text{ W}$ but it
is usually best to run them at about half that power if you are going to have the circuit
on for long periods (if you run them at full power, they will get quite toasty, and if
you exceed the rated power, they will probably turn black and may start to smell
or emit smoke). Running at lower power may extend the lifetime of the components
and will also help with stability since the resistance of most components is usually
temperature dependent.

For small currents ($\approx 100 \mu\text{A}$) you usually don’t have to worry about the power in
R3, but you should check the power in R1 and R2. For larger currents, you need to
check R1, R2, and R3 to be sure that you are not exceeding the power limits on those resistors.

For R1 and R2, the process is quite simple. In the worst case, each of these resistors
will have the full power supply voltage across them (15 V). Since $P = \frac{V^2}{R}$, $R \geq 8 \frac{V^2}{2} = 1.8 \text{k}\Omega$ is a safe limit for both R1 and R2. If you want to be more specific, the
limits are $R1 \geq 8 (V - V_{\text{ref}})^2$ and $R2 \geq 8 V_{\text{ref}}^2$. Since there is considerable flexibility in choosing the values of R1 and R2 it is not hard to be sure that these restrictions are met.

The value of R3 is determined by the combination of $V_{\text{ref}}$ and $i_{\text{out}}$. Once this value is
determined, the power is given by $P = \frac{i_{\text{out}}^2}{R3}$. If the power for your chosen resistor is
greater than about $1/8 \text{ W}$, it will be necessary to put two or more resistors in
parallel such that you get the proper value for R3 but spread the power across several resistors.

For example, if you wanted a current of $20 \text{ mA}$ and $R3 = 600 \Omega$, the resistor would
have to dissipate $0.24 \text{ W}$. In order to bring the power in each resistor to an acceptable
level, you could use two $1.2 \text{k}\Omega$ resistors in parallel. Each resistor would then dissipate
$0.12 \text{ W}$ since each would only be conducting half the total current.

Also, the absolute maximum collector current for the 2N3906 transistor is $100 \text{ mA}$. If you exceed this current your transistor will have a very short lifetime (possibly measured in $\mu\text{s}$ if the current is large enough).
3.0 Filter capacitors

Two of the capacitors in this circuit serve as low-pass filters to reduce high-frequency noise in the output current.

The first, C3, is a 0.01 µF capacitor in parallel with the current output. This capacitor is added to reduce the level of high-frequency noise at the current output. The value of this capacitor would normally be chosen to match the resistance of the load on the current source combined with the fastest variation you would expect to see in the load. You need the time scale of the fastest expected output variation, \( \tau \), to be \( \tau \geq RC \) where \( R \) is the effective output resistance of the supply and \( C \) is the parallel capacitance. To be safe, you should choose the values such that \( \tau \) is several times greater than \( RC \). For example, at around 400 K a 1N4148 diode has an effective resistance of about 20 kΩ and R3 typically has a value near 100 kΩ. This gives an effective output impedance as viewed from the voltage monitor, of about 17 kΩ. With \( C = 0.01 \mu F \) this gives \( \tau \geq 170 \mu s \). It is very rare for thermal processes to respond that quickly so we should be safe. A choice of \( C = 0.1 \mu F \) would give \( \tau \geq 1.7 \) ms which would still be quite safe.

Noise signals with frequencies higher than the cutoff frequencies will be filtered out (attenuated) by this low-pass filter. The nominal cutoff frequency is given by \( f_0 \approx 1/(2\pi RC) \). For \( C = 0.01 \mu F \) and \( R = 17 \) kΩ this gives \( f_0 \approx 900 \) Hz.

The second, C4, is a 0.1 µF capacitor from the base of the 2N3906 to ground. Again, this is intended to reduce the amount of high-frequency noise by serving as a low-pass filter for the control signal applied to the base of the transistor. It is desirable to select a capacitor that is appropriate for the fastest variation you would expect to see in the load current. The time constant will tend to be dominated by the output resistance of the op-amp you are using. For the 741 op-amp, this is approximately 75 Ω with a cutoff frequency of about 20 kHz. For the TL3472 the output resistance is about 30 Ω, giving a cutoff frequency of about 50 kHz. The cutoff is actually somewhat below these values, but an accurate determination is difficult.

Note that op-amps don’t work well with large capacitive loads connected directly to the output. Trying to lower the cutoff frequency of the low-pass filter composed of capacitor C4 and the output resistance of the op-amp too far will result in a sufficiently large value of C4 to make the op-amp unstable.

From previous experience with this circuit, it is critical that you include C3 and C4.

4.0 Getting your circuit to work

If your constant current source doesn’t work after you finish assembling it, you probably want to consult the electronics section of The Art of Debugging.
Art of Debugging in Learning Suite). Two common problems with the constant current sources are solder bridges between pins and cold solder joints. By methodically going through your circuit you should be able to find the errors.

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