PWM-controlled constant current sources and sinks

Stefan Nikolaj

While doing research for an advanced PT2399 guitar pedal build, I came to the issue of building constant current sinks and sources which can be controlled from a microcontroller, ideally through PWM or a DAC. In this article, I will explore the solutions I came up with and the calculations behind them.

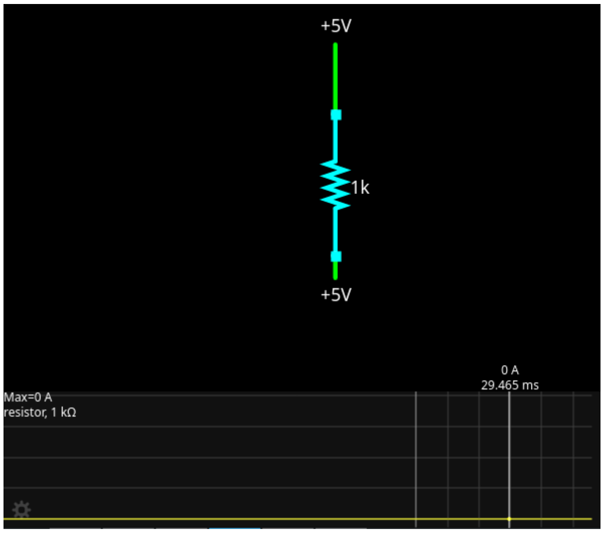
Simple current sink

The simplest current limiting element is the resistor, and creating constant current sources and sinks with a resistor is extremely simple. The only formula necessary, in this case, will be V=IR. To add electronic control with PWM, it is only necessary to vary the duty cycle. For example, with an input voltage Vin = 5V, a PWM that varies between 0 and 5V, going through a 1K resistor, there is a large possible variety of current settings possible, which can be calculated with the formula:

$$I_{avg} = D * \frac{V_{\text{in}}}{R}$$

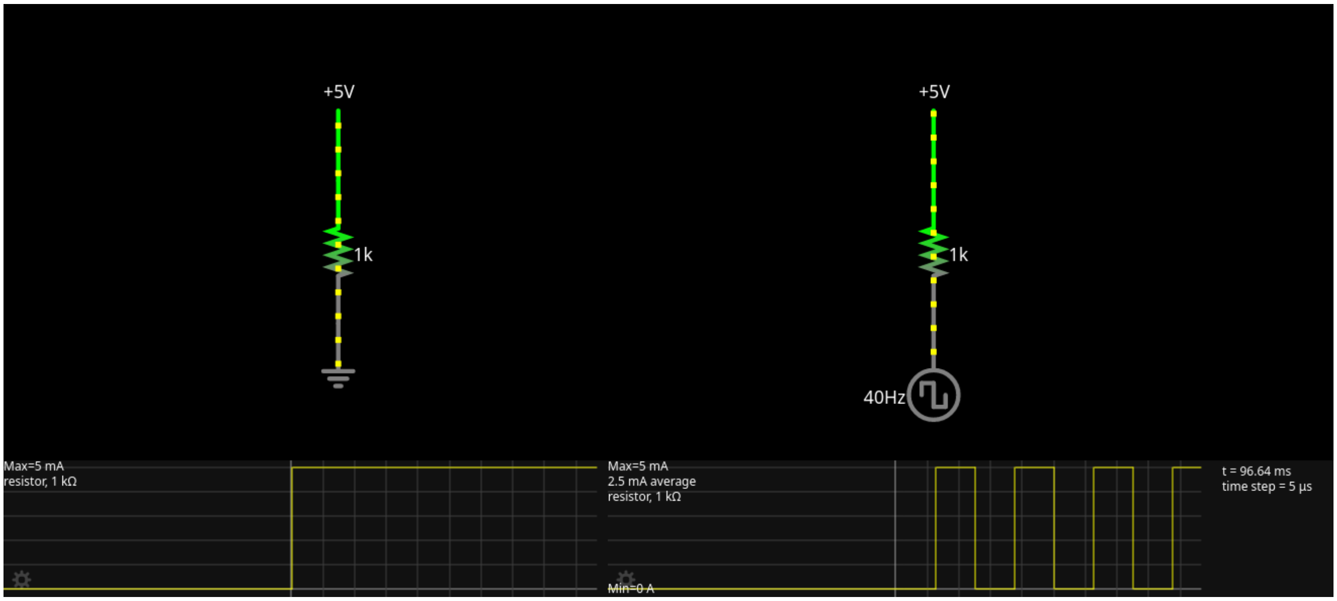
where D is the duty cycle as a decimal number between 0 and 1.

This formula holds because there are two conditions present in this system: when the PWM signal is high, and when the PWM is low. When it is high, the circuit is equivalent to this circuit:



Since the difference between potentials is $\Delta V = 5 - 5 = 0$, no current flows. When the PWM output goes low, $\Delta V=5-0=5 \rightarrow I=\frac{V}{R}=\frac{5}{1000}=0.005\,A=5\,mA$. Given a 50% duty state (D=0.5), $I_{avg}=0.5*\frac{5}{1000}=2.5\,mA$

The image below, taken from the Falstad circuit simulator, shows 5V going to ground through a 1K resistor, leading to a 5mA current, and 5V going to a PWM source, giving us the average current of 2.5mA.



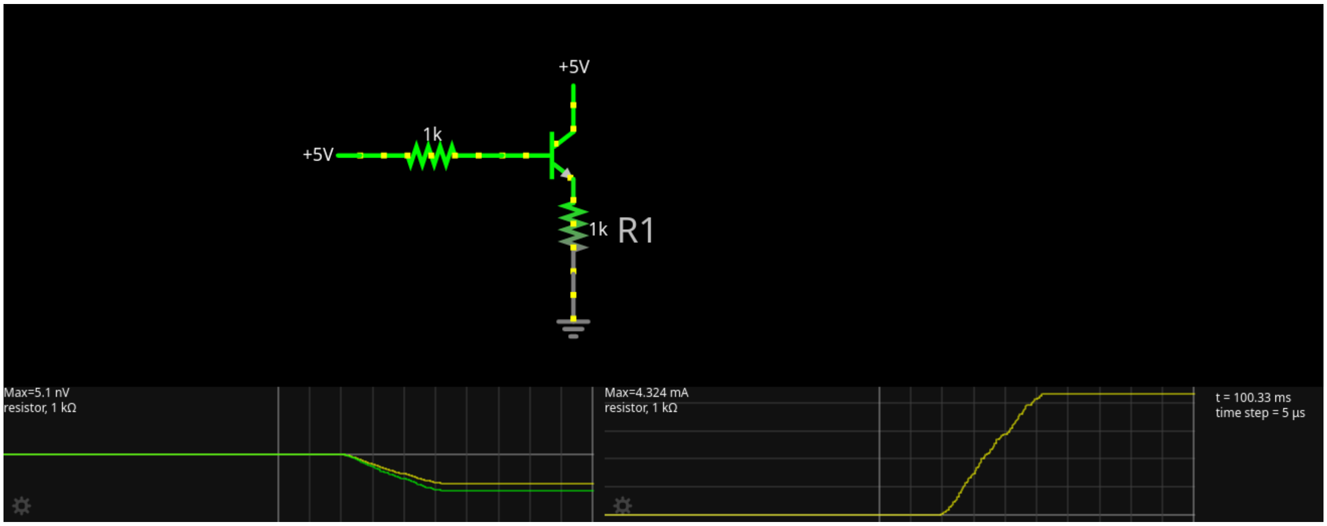
However, for some applications, this might not be enough, as the maximum possible current is limited by the resistor, and the PWM needs to be able to source or sink the current needed. In this case, the maximum current given the input voltage is 5mA. By the way, the current sourcing version of this circuit would just have the terminals reversed: PWM at the top, ground at the bottom.

One issue that prevents this circuit from being used in audio applications is the fact that the frequency is in the audible range and will make it completely useless for audio unless a very agressive filtering scheme or higher frequency PWM is used.

Better current sink

An issue with the last circuit was the fact that for higher currents this would be impractical (disregarding all discussions about accuracy), and the range of currents is quite small. To increase small currents and make them larger, the BJT comes to mind. The important equation relating to BJTs that will be used here is $I_B*\beta=I_{CE}$ where beta is the amplification factor of the BJT. This property may seem easy to use, however beta is highly variable between transistors and even temperature- and current-dependent. Thus, a good circuit should be independent of beta and only use the transistor as a current buffer.

To achieve this, a simple emitter resistor is necessary as shown in this simulation:



The emitter resistor will limit both the current from the base and from the collector. This means that the base current will become (mostly) independent of beta, and will instead depend on the size of the resistor. In this case, the only relevant formula becomes

$$I_{CE}=\frac{V-V_{BE}}{R_1}$$

Where V is the voltage at the base (can be from a DAC or PWM + filter), Vbe is the base-emitter voltage drop and R1 is the emitter resistor. The base resistor can be any size, as long as it is not too small or too big. A general rule of thumb is to set beta to 10 and then calculate safe resistor sizes. This circuit will work with Darlington transistors, for which the base-emitter voltage Vbe is ~1.4V, while for regular BJTs it will be ~0.7V.

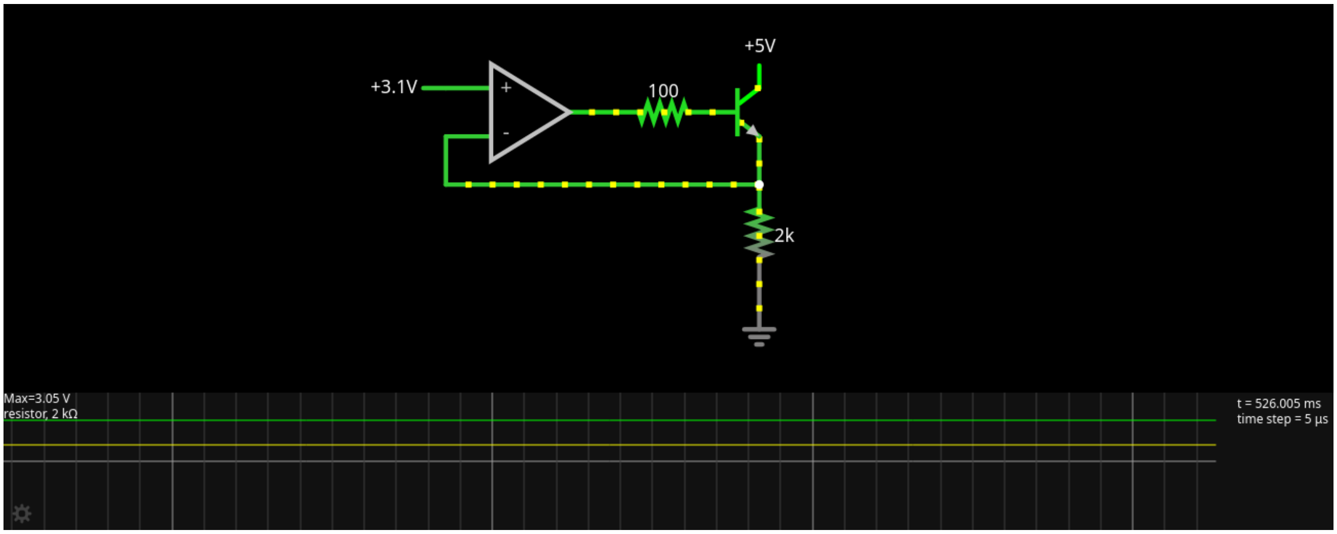
The issue with this circuit is that Vbe is quite variable as well, so even though we fixed the current handling issues, we've introduced the issue of variable base-emitter voltage, and we also complicated our current handling with the base-emitter voltage drop.

By the way, to make it a constant current source, just make the transistor PNP and connect the collector to ground.

More better current sink

To fix this issue, we somehow need a circuit to compensate for the base-emitter voltage drop automatically, by introducing some sort of feedback... Oh yeah, opamps.

First, let's start by creating a voltage-feedback linear voltage regulator. You might be familiar with this circuit, as this is how most of the popular linear regulators work (the 78XX series).



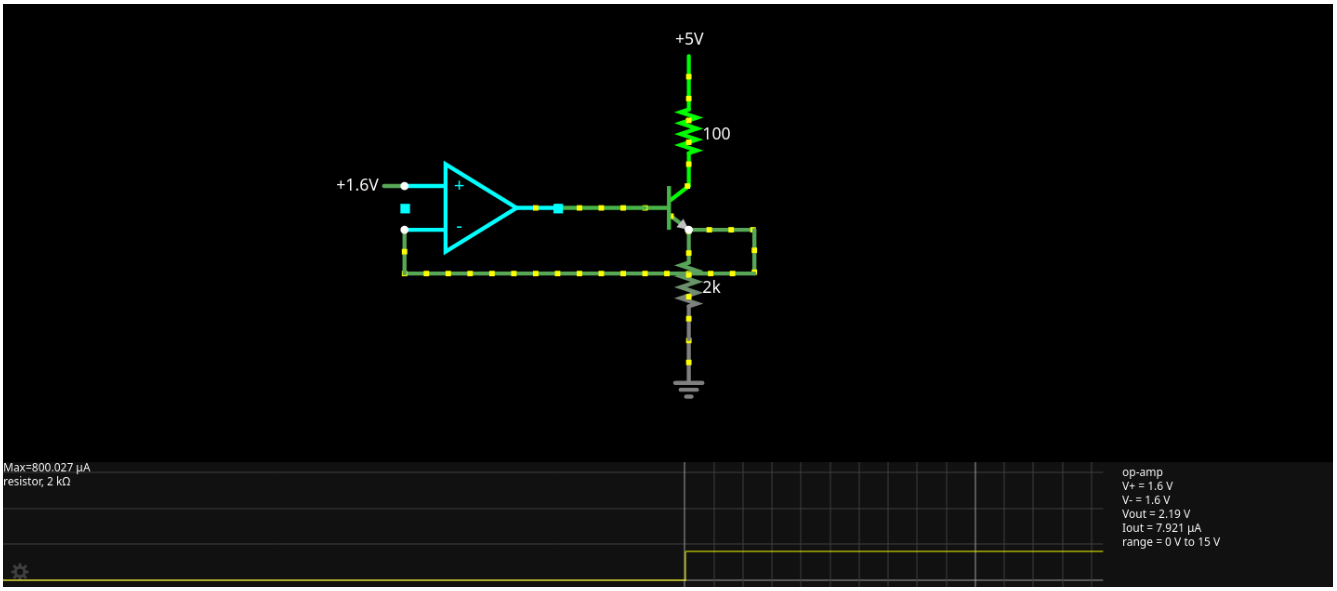
In this circuit, regardless of the input voltage, resistor beta and load resistor, the emitter voltage will be equal to the voltage at the + terminal of the opamp - that's just what an opamp does. In this case, the feedback is the voltage at the emitter. To make a constant current sink from this we just need to rethink the way we look at the circuit. In the example above, the opamp will always set the voltage at the emitter to 3.1V, regardless of the input. However, the current will depend on the voltage divided by the resistance, which in this case is:

$$I=\frac{V}{R}=\frac{3.1}{2000}=1.55\,mA$$

However, all currents coming out must come in, so the current through the transistor will also be 1.55mA. If we increase the voltage to 4V, the equation will give us 2mA flowing through, and the total current going through the circuit will be 2mA. This means that the circuit acts as a current sink when observed seen from the power supply's point of view. If we add a resistor between the emitter and the power supply, as long as that resistor isn't large enough so that the power supply can't regulate properly, a constant current will pass through it. We have created a constant current sink with the formula:

$$I_{sink}=\frac{V_+}{R_1}$$

It's important to note that in this circuit, since the opamp will account for the transistor's base-emitter voltage drop, the output of the opamp will equal the emitter voltage + ~0.7V. This makes microcontroller interfacing really easy, as many external variables are taken care of, and even better, the opamp has a very high input impedance, meaning that DACs and passively filtered PWM signals can be directly connected. On the other hand, one downside is that the supply voltage should be higher than the maximum input voltage, plus around a volt or two depending on how close your opamp can go to the positive supply rail.



```
Max=800.027 µA
resistor, 2 kΩ
```

```
op-amp
V+ = 1.6 V
V- = 1.6 V
Vout = 2.19 V
Iout = 7.921 µA
range = 0 V to 15 V
```

In this case, the no matter what we place in the location of the 100 ohm resistor (within reason), it will pass 800μA of current. If the resistor at 2K (R1) is changed to 1K, it will pass 1.6mA. The opamp will be lightly loaded (~Ice / β), and the load on the input signal will be around a few megaohms.

Conclusion

All of these circuits are good ways to sink (or source) current in their own way, with varying complexity given the features that they have. In many cases, a resistor is just what you need, while in others, a transistor will do just fine. Guitar pedal circuits usually use the one-transistor approach and they have worked perfectly fine for over half a century now. Who can afford opamps anyway.