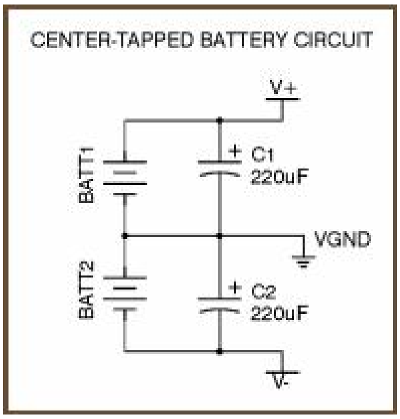
Virtual Ground Circuits

A common problem in analog electronics is having a requirement for a dual-voltage supply (e.g. ±5 V) but only having a single supply available, such as a battery. There are many ways to “split” a single supply so that it behaves like a dual supply. This article describes several such circuits and the tradeoffs involved.

This article is written with solid-state headphone audio circuits in mind. Generalizing this to other situations is an exercise left to the reader.

Two Batteries

The simplest way to solve the problem of needing a dual supply when using batteries is to simply use two batteries in this configuration:



The problem with this is that if one battery drains faster than the other such that one gets down to about 1 V or lower before the other gets low, the DC offset at the output will begin to rise. (I’ve tested this with several different op-amps. It’s possible some designs won’t have this problem.)

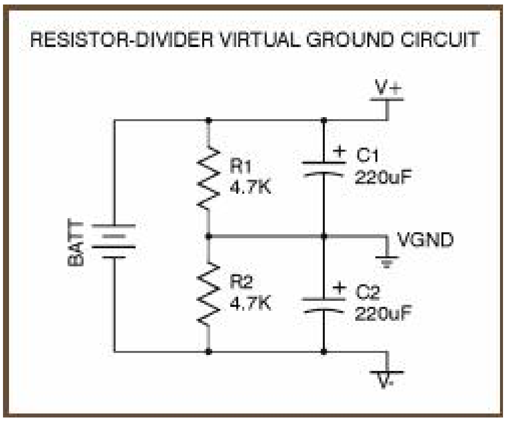
Batteries can drain unevenly for a number of reasons. Perhaps you put your batteries in a drawer after buying them and pull them out randomly and draw an old one and a new one. Perhaps you’re using rechargeables, and one or more cells is dying. Perhaps you’re just unlucky today.

To be fair, before this happens you will get a warning: the amp will start sounding bad for other reasons. It will probably audibly clip the music well before this danger point due to insufficient supply voltage, and it may also be current-starved due to battery exhaustion. So, the most likely way this problem will occur is if you leave a battery-powered headphone amp on for an extended period without music, or without listening to the music that is playing. Ever fall asleep while listening to headphones?

If you don't turn the amp off before you get to this danger point, the resulting high DC offset is likely to damage your headphones. So, we try various virtual ground schemes to let us use a single battery and still have a dual supply.

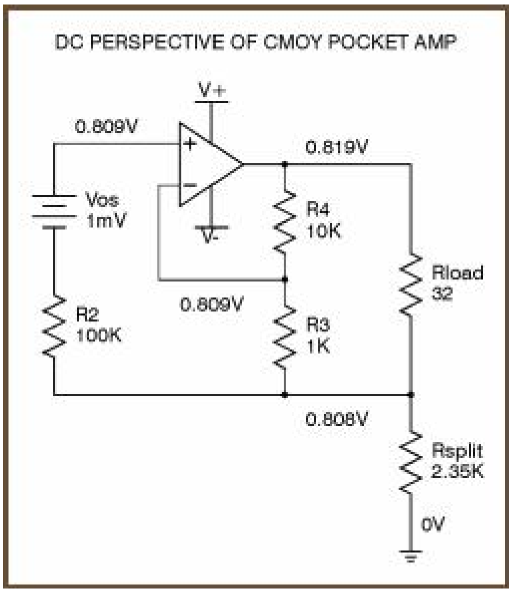
Resistor Divider

The CMoy pocket amplifier power supply is a resistor divider type virtual ground supply:



The two 4.7 kΩ resistors create a "virtual ground." Let's say there's 12 V across this circuit. The resistors are an 0.5× resistive divider: there is 6 V at the midpoint of the divider. The "distance" between the midpoint of the divider and the negative side of the power supply is -6 V and the distance to the positive side of the power supply is +6 V. *Voilá*, two equal but opposite voltages from a single power supply!

Unfortunately, this simple configuration is prone to becoming unbalanced. To see why, consider this schematic, a CMoy pocket amplifier driving headphones, drawn from the DC perspective:



The 1 mV battery (V_{OS}) simulates the op-amp's input offset voltage. This is a reasonable value for an OPA132, though it does vary between chips in practice.

This offset forces 1 mV across R3. Because op-amps always force their input voltages to be equal, this in turn forces 10 mV across R4. As you can see, this puts 11 mV of DC across the load. If the load is 32 Ω at DC (such as a pair of Grado SR-60s), 0.34 mA is forced through the load. This current can only come from the rail splitter, which looks like two parallel resistors to the load. Ohm's law tells us that since the current is 0.34 mA and the resistance is 2.35 kΩ (two 4.7 kΩ resistors in parallel), the voltage at the midpoint of the divider is forced ~0.8 V away from the ideal midpoint.

In this particular situation, then, a 9 V battery would split to about +3.7 V and -5.3 V instead of the ideal ±4.5 V. Different op-amps, headphones, and resistor values will give a different split. Therefore, it is best to simply realize that this offset will be significant with low-impedance loads, and it will increase as the load impedance goes down, rather than calculating offset and trying to counteract it somehow.

The Problem with Unequal Virtual Ground Splits

In a circuit like the CMoy pocket amplifier, an uneven virtual ground split doesn't hurt the sound all by itself. The input and output are both referenced to the same ground point, so the shift doesn't create an electrical compatibility problem. You're probably asking, then, why worry about it?

Most op-amps can't swing the output voltage from rail to rail; they have some minimum distance. The OPA132, for example, needs approximately 3 V of distance between the power rails and the output with relatively low-impedance loads like headphones.

Let's say we're using a 9 V battery, and under load our virtual ground circuit splits that unevenly to +4 V and -5 V. Let's also say our output signal's peaks are 1 V from ground. Add in the 3 V of headroom needed by the op-amp, and we're right at the clipping point on the V+ rail. Since our power supply is a battery, its voltage will drop over time, so we'll get very little run time before it starts clipping.

Ways to Fix the Problem

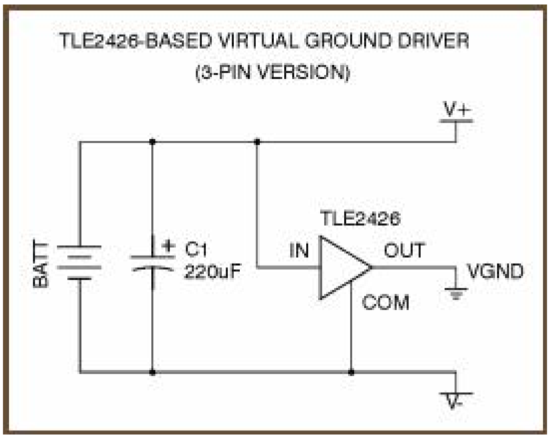
One quick and dirty way to fix this problem is to simply increase the power supply voltage. But, this requires a larger, more expensive power supply if you're using wall power, or more batteries.

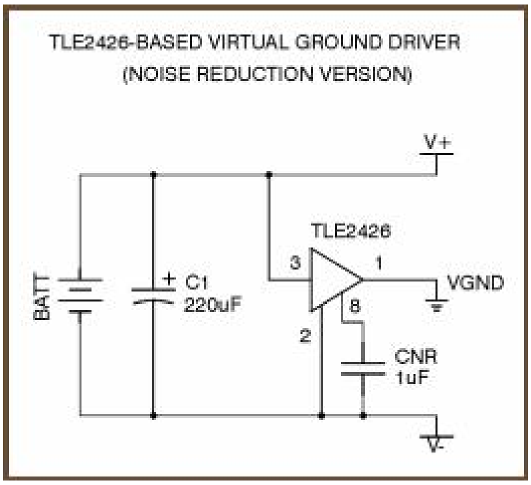
Another way to fix the problem is to lower the virtual ground resistors' values. The problem with this is that it increases the current the divider draws. This is a balancing act: if the the extra current drawn from the battery is high enough, it can wipe out the run-time increase you get from having a lower battery voltage where clipping starts.

Most of the subsequent circuits in this article use an entirely different solution: buffering the virtual ground. These techniques make the voltage divider appear to have a very low impedance while still drawing little current. This keeps the virtual ground point nicely centered between the rails under load. The extra parts can easily pay for themselves by allowing you to use a smaller power supply, or by increasing your battery's run time.

Simple Buffered Virtual Ground Circuits

The most elegant buffered virtual ground circuit is Texas Instruments' TLE2426. This part is called a "rail splitter:" it splits a single supply in two, so you have two "voltage rails" plus ground. It's basically a glorified voltage divider, so it replaces the resistors in the simple resistor-divider power supply: you apply a voltage between its IN and COM pins, and it puts out ½ that on the OUT pin. Unlike a simple resistor divider, though, it has some buffering circuitry inside so it doesn't become unbalanced. (Oh, there may be a tenth of a volt of error or so, but that's a small matter.) Here's the modified power circuit:

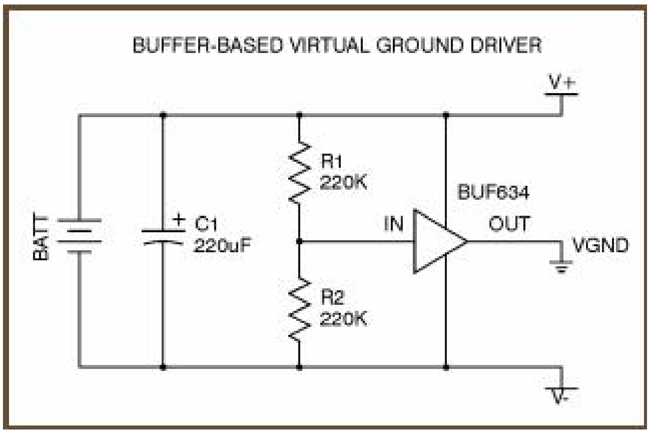




The first schematic shows the simple 3-pin package, and the second shows the circuit for the 8-pin versions which have a noise reduction pin. The latter has slightly better performance.

Notice that there is just one capacitor across the battery instead of a cap between each rail and virtual ground as in the resistor divider supply. In the resistor divider circuit, two capacitors are absolutely necessary to the success of the circuit. Below, I will talk about the advantages of using two caps like this in an active virtual ground circuit, as well as the disadvantages. For now, assume that it's better to have just one before the active "rail splitter."

The main problem with the TLE2426 is that it can only handle 20-40 mA of current, depending on conditions. If your load draws more than that, a TLE2426-based power supply will become unbalanced. For higher-load situations, you can try a buffer-based power supply instead:

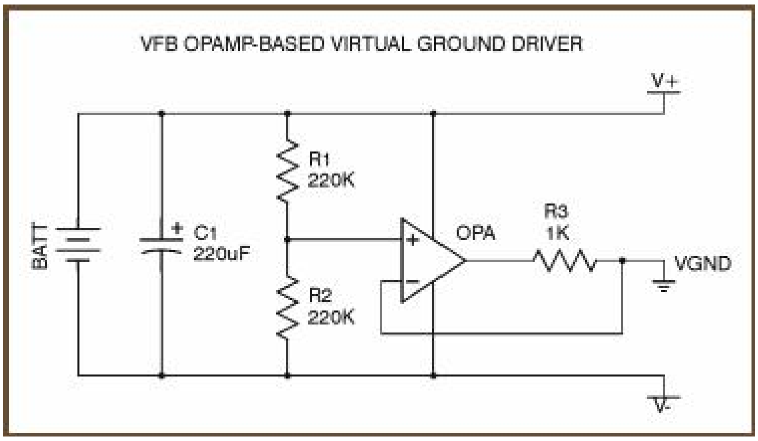


This is similar to the circuit inside a TLE2426. By making a rail splitter out of parts, we can get higher output current. Notice that the resistor values are much higher than in the simple CMoy power supply. By adding the buffer, we don't need low divider resistors to keep offset under control. Because the resistor values are so high, the quiescent current of the circuit is dominated by the quiescent current of the buffer alone; the divider contributes negligible current draw.

The high resistor values work as long as the power draw on this circuit is evenly balanced, as it is in a simple headphone amp. If you have an unbalanced draw, the divider is likely to become unbalanced. In that case, you can replace the divider with a TLE2426. Another virtue of the TLE2426 over resistors is that it takes less space, and you don't need to do resistor matching to get high accuracy. That's how we did the virtual ground in the META42 amp.

I've used Burr-Brown's BUF634 here. It can handle up to 150 mA in the DIP-8 package, and in the larger metal-based packages it can source up to 250 mA, with appropriate heat sinking. There are many other open-loop buffers on the market that will give similar performance in this circuit. The disadvantages relative to the lone TLE2426 are that it's more complicated, it costs more, it has higher output impedance, and it has a higher quiescent current draw (~1.5 mA vs. ~0.3 mA).

If you can't get a TLE2426 and you don't want to mail order one, this is a closer substitute than the above circuit:

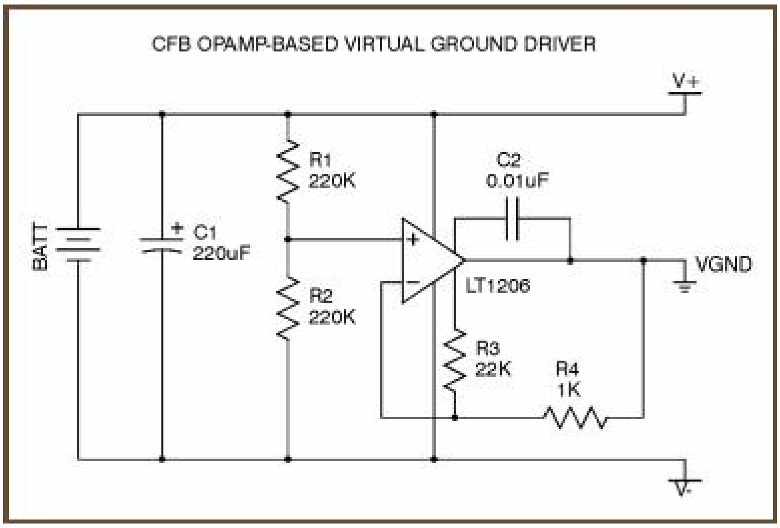


You can use a cheap generic op-amp — such as the ubiquitous µA741 — here. It's acting like a buffer, just as in the previous circuit. The major difference is that it has lower output current than the buffer, but unlike an open-loop buffer it has feedback so it has low output impedance. Low output impedance has many salutary effects on the circuit; in a heapdhone amp, the biggest is lower crosstalk.

The 1 kΩ resistor in the feedback loop is arguably optional. Its purpose is to keep the op-amp stable in the face of heavy capacitive loads, such as bypass capacitors in the circuit being powered.

If you use a cheap generic op-amp, this circuit's performance is no better than for a TLE2426 and it takes more board space, so you should only do that when you can't get a TLE2426. But, if you use a better op-amp, you can get better performance than a TLE2426. The main spec to look for here is high output current. More-or-less drop-in replacements with higher than average output current are the LMH6642 and the AD817.

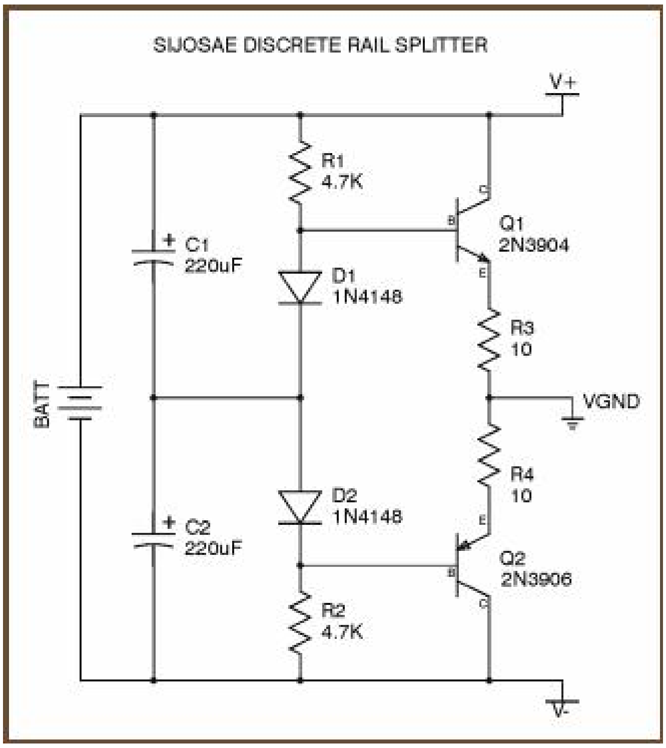
The highest output current op-amps tend to be current feedback types. These require a bit more care in application than the common voltage feedback type. Consider this circuit, which can put out 250 mA:



C2 is the compensation capacitor, and R3 is there to reduce supply current a bit as explained in the datasheet in the section on the shutdown feature.

If you need even more than 250 mA, the LT1206's big brother, the LT1210, works in a very similar circuit. Other manufacturers make similar high-current CFB chips that can work here, but read their datasheets before making circuits for them: CFB op-amps generally won't drop into an existing circuit without changes.

Another option is to make a buffer from generic discrete components. This simple design comes from miniaturization guru Sijosae:



The transistors can be most any complementary pair of small-signal transistors. Suitable alternatives are the PN2222A and PN2907A.

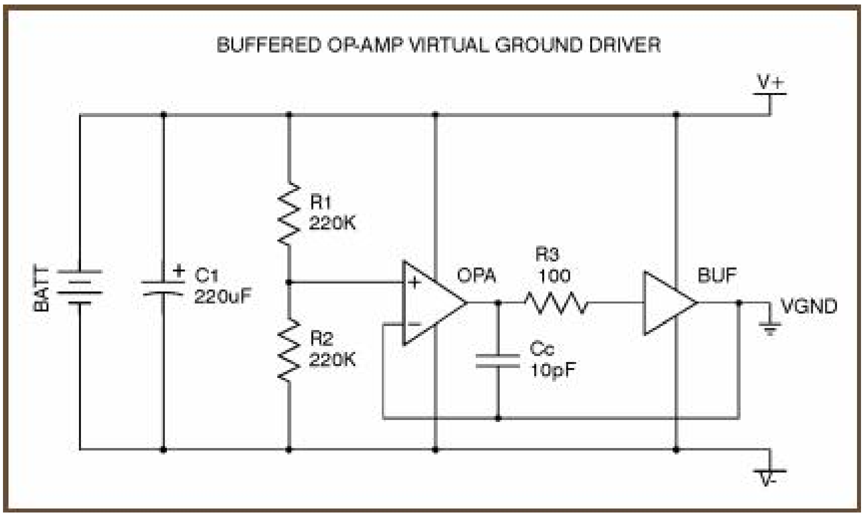
The diodes are generic small-signal types. An acceptable alternative is the 1N914.

This circuit has better performance than a simple resistive divider virtual ground, and the parts cost is lower than for any other circuit mentioned here. It is, however, the least accurate of the buffered virtual ground circuits.

Getting More Complicated

The above buffered virtual ground circuits have one of two major problems. The TLE2426 and VFB op-amp based circuits have fairly low output current abilities. The other circuits have higher output current, but most lack feedback so their output impedance is relatively high; this can result in problems like increased crosstalk in a headphone amplifier. For simple circuits, the CFB circuit above is the best balance of high output current, low output impedance, and simplicity.

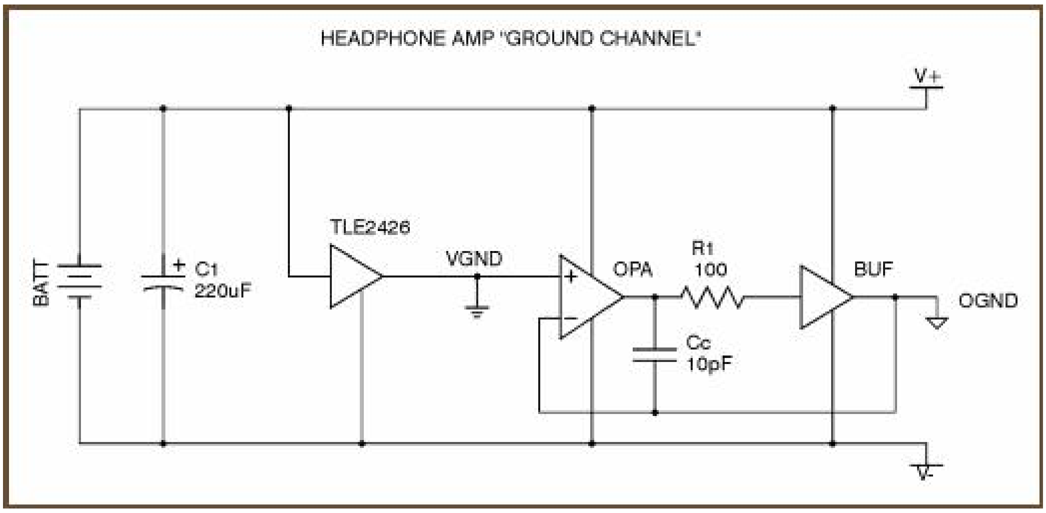
If you can sacrifice simplicity, you can still use VFB op-amps by combining them with a buffer, like so:



By wrapping a buffer in an op-amp's feedback loop, you get the higher current ability of the buffer plus the high accuracy afforded by feedback.

The value of the resistor between the buffer and op-amp may need to vary in your circuit. If you're getting peaking at high frequency or even instability, you need to raise its value, to perhaps 1 kΩ. Similarly, the compensation capactior C_C might need to be increased if you're having instability problems; it probably shouldn't go much higher than 100pF.

You can replace the resistor divider with a TLE2426 to get some of the benefits described above. Then it's just one small step from there to the ground channel concept used by the PIMETA and PPA amplifiers:



The ground channel concept works best when you have many small ground currents and one big one. In a headphone amp, the circuit has several resistors and such going to ground, but virtually all of the dynamic current to ground is the return current from the headphones. The buffered op-amp handles the big currents (OGND), and the TLE2426 sets the input of the big driver and handles all the small currents (VGND).

For audio, I prefer to use the same op-amp and buffer in the virtual ground as I do in the audio driver circuits. For instance, if the audio channels use an AD8610 op-amp and a HA3-5002 buffer, I will usually use those parts for the virtual ground driver as well. This gives the most symmetric performance since the virtual ground driver and the headphone driver circuits effectively sit across the load from each other.

Capacitors on the Output of a Virtual Ground Driver

Above I said that when moving to an active rail splitter, you want to seriously consider putting the rail capacitors in front of the splitter. The purpose of putting caps across the resistive ground divider shown at the start of this article is because this passive splitter cannot deliver very much current, so we need the caps to do that. The resistors are only maintaining the DC level of virtual ground here. An ideal virtual ground circuit would have infinite current delivery, so there should be no advantage to putting caps on its ouptut. In fact, it can be detrimental.

An active virtual ground circuit has some “bandwidth:” that is, it will be effective over some range of frequencies. If you put capacitors across its output, that lowers its bandwidth: as frequency goes up, the capacitors are “in charge” to a greater and greater extent. If the caps are large enough, the virtual ground circuit’s bandwidth is completely swamped. It could end up being good for no more than maintaining the DC level of virtual ground.

Output caps can be a good thing if the rail splitter has a fairly low output current limit. That’s the situation in the MINT amp, for example. The TLE2426 has an output current limit of between 20 to 40 mA, depending on operating conditions. When it goes into current limiting, its output goes to the negative rail, which would make for a massive shift in the virtual ground point, so we cannot allow this to happen. A heavy headphone load could indeed exceed 20 mA, so putting caps on the ouptut of the TLE2426 saves the design. Although the TLE2426 has no effect at audio frequency, it still has benefits compared to a resistive voltage divider. First, its output impedance is much lower, so the virtual ground shift described above doesn’t happen. Second, it requires less operating current than the CMoy’s resistive divider.

Another potential problem with big caps on the output of a virtual ground splitter has to do with stability. Some circuits will become very stable in this situation: no bandwidth and no gain, hence no oscillation. Most circuits aren’t made to cope with capacitive loads, however. They become *less* stable when driving a capacitive load. Study the datasheets for the ICs you will be using.

Unless they specifically tout the fact that they can drive large capacitive loads, beware of using them in virtual ground circuits. Don't forget to consider the system bypass caps, if they go from each rail to virtual ground: there are many chips out there that will become unstable with less than a nanofarad of capacitance on their output, and the bypass capacitors will count against this. Ultimately, you will have to build real circuits and test them before you know whether a given chip can cope with the capacitive load in your setup.

There's one more problem with putting caps on the output of the virtual ground circuit: it wastes capacitance. In a very real sense, two caps across the output of a virtual ground circuit are in series, so the total capacitance is cut in half. Also, you require one capacitor in front of the rail splitter, but two after it. This means putting the rail capacitance in front of the splitter is actually four times as efficient: you can have twice the effective capacitance in half the board area, or four times the capacitance in the same board area.

References and Acknowledgements

The DC-perspective CMoy pocket amplifier schematic above and the original explanation of it is due to PRR of Headwize, in this post.

Many other interesting virtual ground ideas and discussions are in the thread containing PRR's post.

Sijosae posted his discrete rail splitter idea in this thread.

Section 4.1.5 in Jerald Graeme's *Optimizing Op Amp Performance* was useful in designing the VFB op-amp based splitter. This section concerns running op-amps into capacitive loads, which will often happen with a virtual ground driver.

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