- You can split the feedback loop, as shown, so that feedback comes directly from the op-amp's output at high frequencies, where instability lurks. And at lower frequencies the feedback accurately controls the signal seen by the load. This is not really a compromise, because those high frequencies are exactly where the thing would oscillate anyway if you were to allow feedback from the load.
- You can reduce the loop gain, for example by increasing the closed-loop gain, to regain stability.
- You can seek an op-amp that guarantees stability into the range of load capacitances you expect. Many op-amps provide good data in the form of plots of "Stability versus Capacitive Load." Figure 4.79 shows an example, taken from the datasheet for the LMC6482.
- You can add a unity-gain buffer, with its low native output impedance, either within or outside the feedback loop. If you add it inside the loop, you need to worry about phase shifts introduced by the buffer; it should have significantly higher f_T than the op-amp, and it's often a good idea to include a 50–100 Ω series resistor at the buffer's input (not shown). You may need to rolloff the op-amp's response with a small capacitor, as in Figure 4.87 on page 274.

4.6.3 "Single-supply" op-amps

As we just remarked, some op-amps are designed specifically to allow inputs and outputs to go to the negative rail. These are called "single-supply" (or "ground-sensing") op-amps, the idea being that their negative rail is actually tied to ground. The input range actually extends slightly below ground, typically to −0.3 V. In some cases the outputs can swing also to the positive rail ("rail-to-rail output"), and a subset of these permits input swings to (and slightly beyond) both rails ("rail-to-rail input"). Linear Technology has introduced an exotic new twist – op-amps that permit input swings well beyond the positive rail (they call them "Over-The-Top™" amplifiers).

These amplifiers can simplify single-supply circuits because you don't need a midsupply reference, rail splitter, etc. But you have to remember that the output cannot go *below* ground – so you can't build an audio amplifier like Figure 4.70, whose output would need to swing both sides of ground. Before looking at the characteristics of these op-amps in more detail, let's look at a design example.

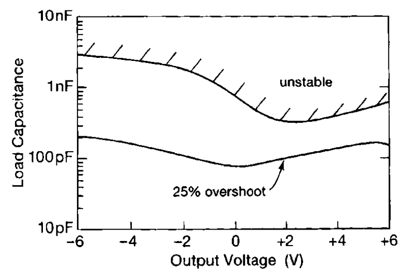

Figure 4.79. Stability versus capacitive load for a LMC6482 op-amp follower with R_{load}=2k and ±7.5 V supplies.

A. Example: single-supply photometer

Figure 4.80 shows a typical example of a circuit for which single-supply operation is convenient. We discussed a similar circuit earlier under the heading of current-to-voltage converters (and we will go further in Chapter 4x). Because a photocell circuit might well be used in a portable light-measuring instrument, and because the output is known to be positive only, this is a good candidate for a battery-operated single-supply circuit. R_1 sets the full-scale output at 5 volts for an input photocurrent of 0.5 μA. The small feedback capacitor is added to ensure stability, as we'll explain in §4.9.3. No offset voltage trim is needed in this circuit, since the worst-case untrimmed offset of 10 mV corresponds to a negligible 0.2% of full-scale meter indication. The TLC27L1 is an inexpensive micropower (10 μA supply current) CMOS op-amp with input and output swings to the negative rail. Its low input current (0.6 pA, typ, at room temperature[37]) makes it good for low-current applications like this. If you choose a bipolar op-amp for this kind of low signal-current circuit, better performance at

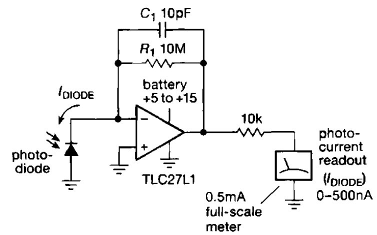

Figure 4.80. Single-supply photometer.

[37] Usually taken as 25°C on datasheets. This is a bit warmer than typical office or lab space (77°F, in the King's units), but you can rationalize that choice by saying that it allows for some heating inside the electronics enclosure.

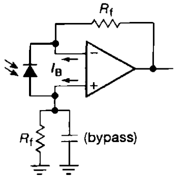

Figure 4.81. Photodiode amplifier with simple bias current cancellation.

low light levels results if the photodiode is connected as in the circuit shown in Figure 4.81.

It's worth noting that the "current budget" of this circuit is dominated by the output current that drives the meter, which can go as high as 500 μA. It's easy to overlook a point like that, blithely assuming that the battery need provide only the op-amp's 10 μA quiescent current. At 10 μA a standard 9 V battery lasts 40,000 hours (5 years), whereas with continuous operation at 500 μA it would last a month.

B. Single-supply op-amp innards

It's helpful to look at the circuitry of a typical single-supply op-amp, both to understand how these types achieve operation to one or both rails, and also to appreciate some of the subtleties and pitfalls of designing them into your circuits. Figure 4.82 is a simplified schematic of the very popular TLC270 series of CMOS single-supply op-amps. The input stage is a *p*-channel MOSFET differential amplifier with current-mirror active load. The use of enhancement-mode *p*-channel input transistors lets the inputs go to the negative rail (and a bit beyond, until the omnipresent input protection diodes begin to conduct), but prevents input operation to the positive rail (because there would be no forward gate-source voltage).

Unlike the classic conventional op-amp with its push–pull follower output stage (Figure 4.43), this output stage is unsymmetrical: an *n*-channel follower Q_6 for the pullup and another *n*-channel common-source amplifier Q_7 for the pull-down. That's done because a follower at Q_7 (which would have to be *p*-channel) could not pull all the way down, given that its lowest gate drive voltage is ground. This unsymmetrical output requires the common-source driver Q_5 for Q_6's gate, with matching threshold voltages for Q_5 and Q_7 to set the output-stage quiescent current. The feedback capacitor C_{comp} is for frequency compensation (see §4.9.2). This output stage can saturate at ground, with an impedance of Q_7's R_{ON}; but it can't reach V_+, because Q_6 is an *n*-channel MOSFET follower.

Exercise 4.20. What sets the source voltage of Q_1 and Q_2 when the inputs are approximately at ground? And what determines the high end of the input range? Why is the latter always below V_+?

Exercise 4.21. What sets the maximum positive voltage to which Q_6 can pull the output, assuming the op-amp is lightly loaded?

This same output-stage structure – follower pullup with amplifier pull-down – can be built with bipolar transistors; an example is the popular LT1013/LT1014 single-supply dual–quad op-amps, improved variants of the classic LM358/LM324 op-amps. A note of caution: don't make the mistake of assuming that you can make *any* op-amp's output work down to the negative rail simply by providing an external current sink. In most cases the circuitry driving the output stage does not permit that. Look for explicit permission in the datasheet!

One way to achieve rail-to-rail outputs – i.e., operation to *both* supply rails – is to replace the *n*-channel follower pullup Q_6 in Figure 4.82 with a *p*-channel common-source amplifier; then each transistor can saturate to its respective rail. This requires some driver circuitry changes, of course. An analogous circuit can be built with bipolar transistors – common emitter *pnp* pullup and *npn* pull-down. Contemporary examples include the CMOS TLC2270, LMC6000, and MAX406 series, and the bipolar LM6132, LT1881, and MAX4120 series. As we'll see in Chapter 4x, there are other ways to make single-supply and rail-to-rail outputs. These amplifiers differ in important ways, and you must watch out for misleading statements about output swing to the negative rail (ground).

These output stages are pretty straightforward, and not surprising. But they don't generalize to the *input* stage. How, indeed, can you possibly achieve rail-to-rail input capability? To complete the picture without going into any

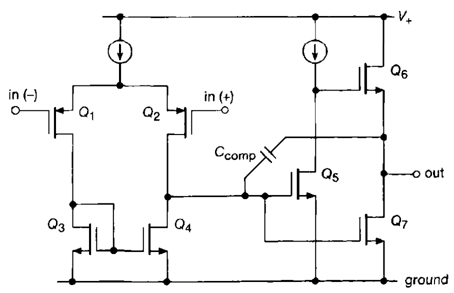

Figure 4.82. Simplified schematic of the TLC271-series single-supply op-amp.