Technical Article

Op Amp Slew Rate and Rise Time Explained

5 days ago by Robert Keim

To avoid distortion and slow transitions in an operational amplifier's output signal, it's important to understand slew rate. In this article, we examine its causes and effects.

We often begin an op amp design with an idealized model. Though this facilitates analysis, it also means our model lacks a variety of potentially important details about the op amp’s performance limitations. We previously covered one of these limitations, signal swing, in a two-part article series.

In this article, we’ll discuss a different non-ideality: *slew rate*, which is defined as the maximum rate of voltage change that an op amp’s output circuitry can produce. If the slope of a theoretical output waveform exceeds the slew rate, the real output waveform will deviate from the shape of the input waveform, as Figure 1 shows.

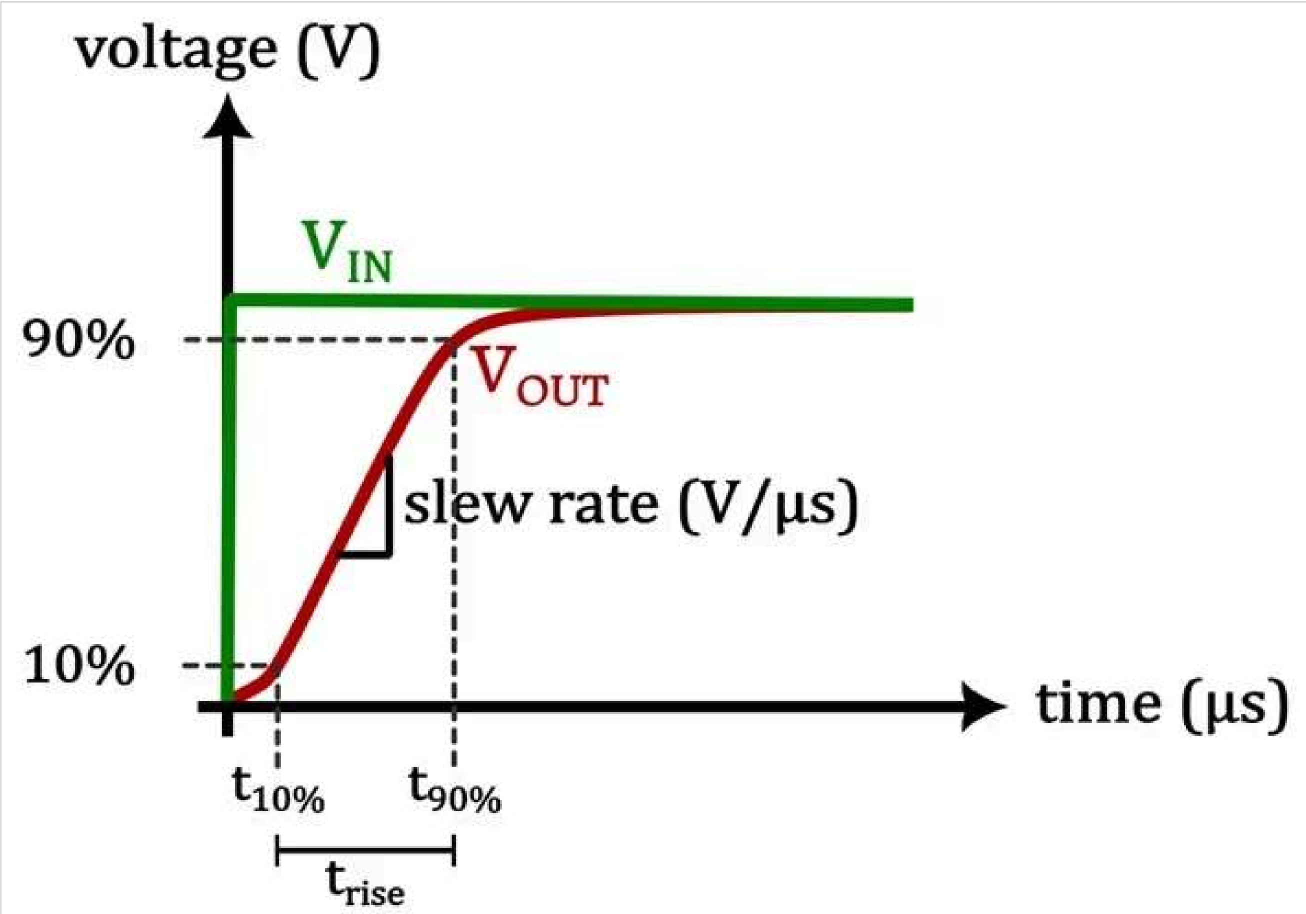

Figure 1. The slew rate limitation of an op amp's output, with rise time indicated by t_{rise}***. Image used courtesy of Robert Keim***

Slew rate is typically reported in volts per microsecond (V/µs). If we multiply slew rate by a period of time, the result tells us how much the output voltage will increase during this time period. More commonly, however, we use an op amp's specified slew rate to estimate *rise time*—or, in the opposite direction, *fall time*.

We can define the rise time—t_{rise} in the figure above—as the time required for a signal to increase from 10% to 90% of its new value. The slew rate for falling signals is similar, the only difference being that we now measure the change from 90% down to 10%. Note that the rest of this article will only discuss slew rate limitations for rising output signals.

To estimate rise time, we divide 80% of the expected output change by the slew rate. This method of measuring rise time reduces the effect of gradual changes that occur at the beginning or end of the rising edge. We can better understand this by looking at an example.

Rise Time: An Example

Let's say we need an op amp to amplify an incoming sensor signal that will transition rapidly from 0 V to 500 mV when a certain physical event occurs. We'll assume the following:

- We've configured an op amp as a non-inverting amplifier with a gain of 10, such that the expected output is a rapid transition from 0 V to 5 V.
- We're using the classic 741 op amp, which has a slew rate of about 0.5 V/µs.

In this case, the 10% to 90% condition corresponds to an increase from 0.5 V to 4.5 V, giving us a voltage increase of 4 V. The rise time is calculated as:

$$t_{rise} = \frac{4\text{ V}}{0.5\ \frac{\text{V}}{\mu\text{s}}} = 8\ \mu\text{s}$$

Next, we’ll use the LTspice schematic in Figure 2 to confirm the rise time via simulation.

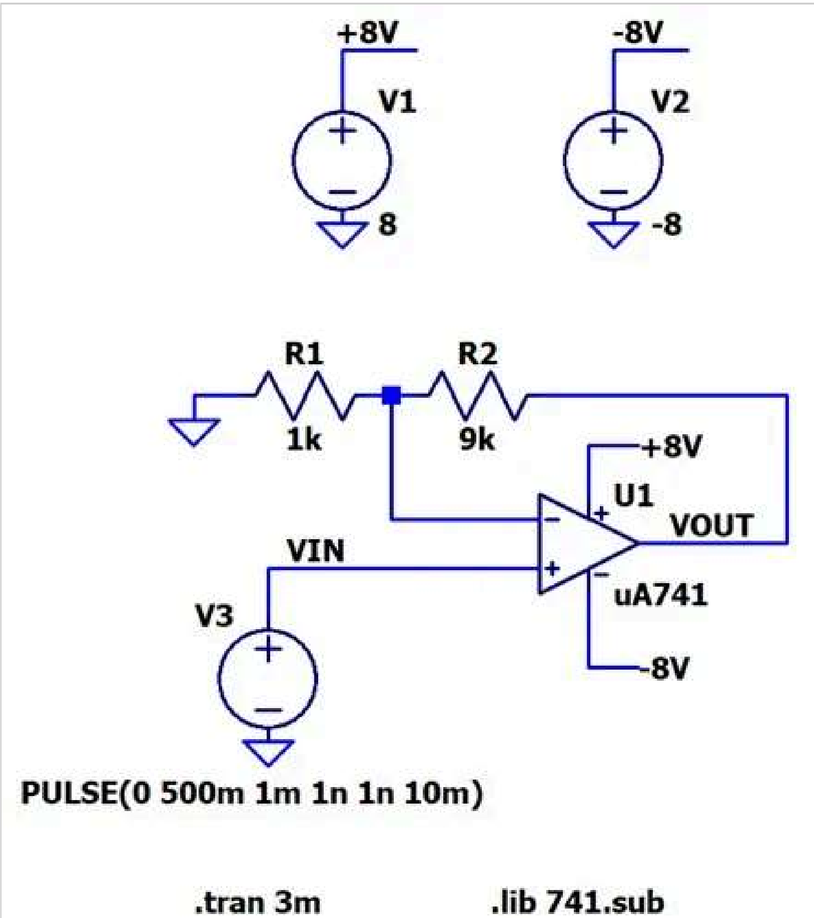

Figure 2. An LTspice circuit for testing the slew rate of the 741 op amp. Image used courtesy of Robert Keim

Figure 3 shows the simulation results. As you can see, the op amp’s output signal doesn’t rise as sharply as the input signal.

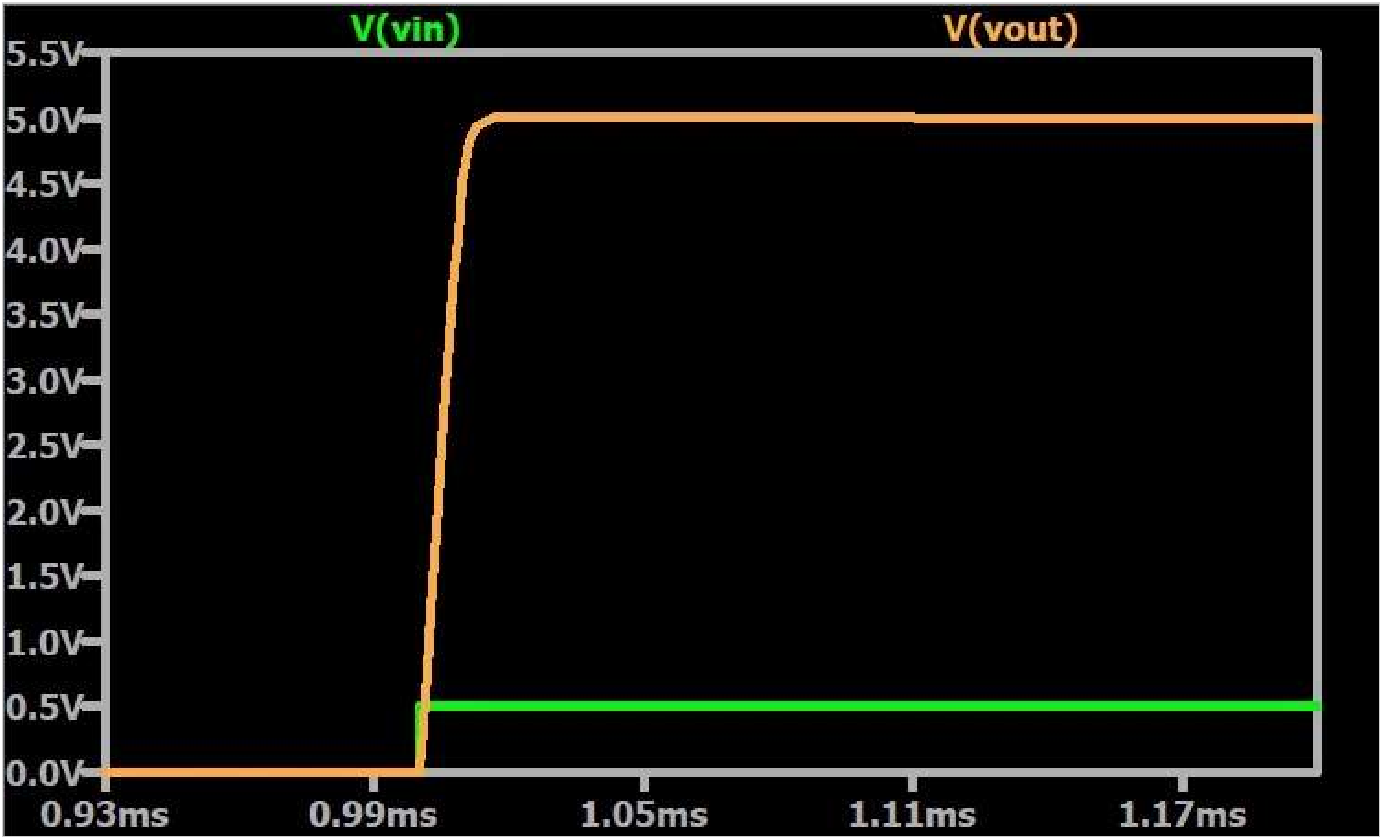

Figure 3. Simulated step-function input and slew-rate-limited output. Image used courtesy of Robert Keim

We can measure the rise time and the slew rate by zooming in and using the cursor functionality (Figure 4).

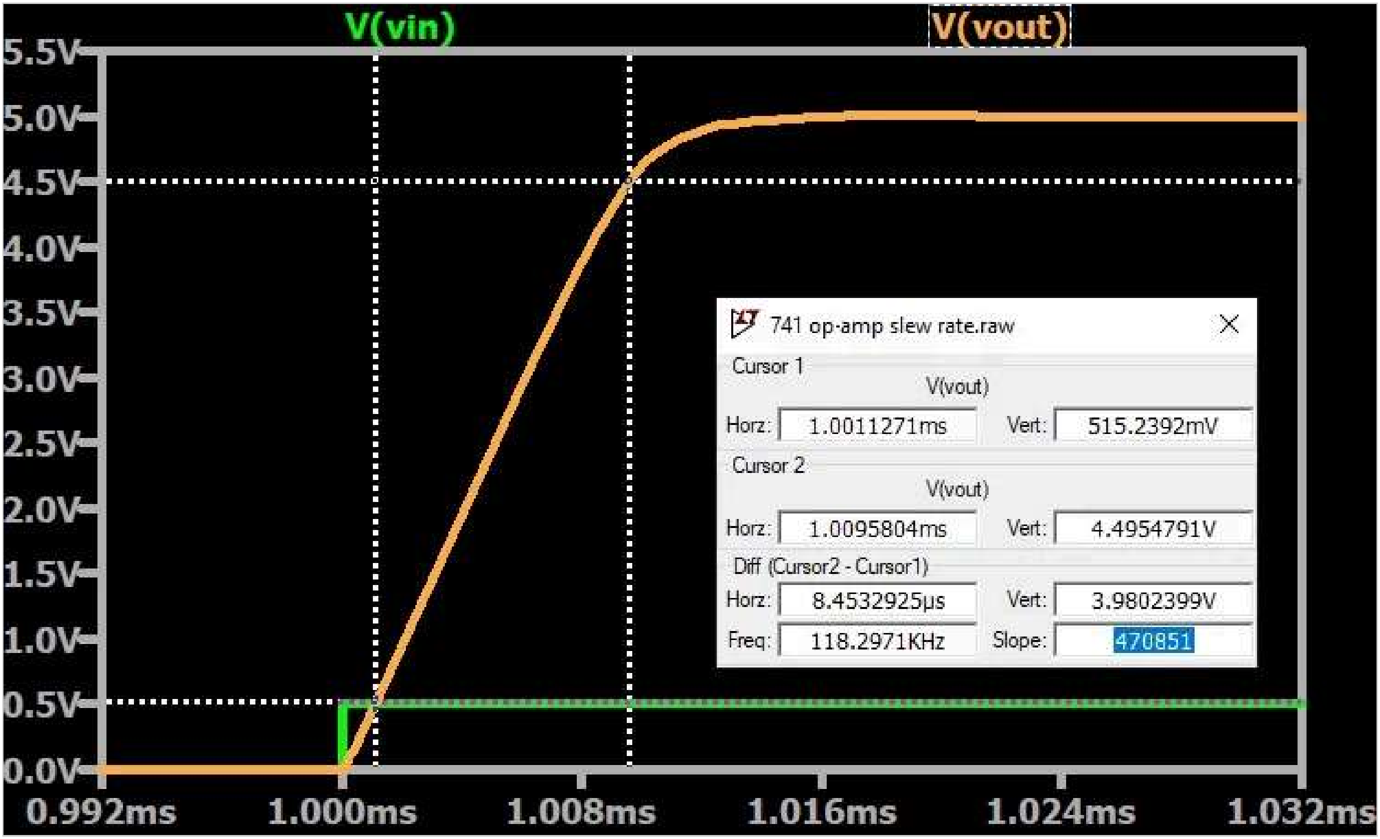

Figure 4. LTspice's cursor functionality allows us to measure the slope of the output ramp. Image used courtesy of Robert Keim

The output signal from V_{OUT} = 0.5 V to V_{OUT} = 4.5 V appears to be quite linear. The rise time is ~8.5 µs, which is close to our theoretical value. The slope during this portion of the waveform is reported as 470,851 V/s, which is about 0.47 V/µs. This indicates that the SPICE model used in the simulation successfully reproduces the expected 741 slew rate of approximately 0.5 V/µs.

The Effect of Slew Rate on Sinusoidal Signals

We've now seen how an op amp's slew rate can increase the output waveform's rise time, causing a rapid input step transition to become a linear-ramp output transition. Slew-rate limitations don't only affect step functions, however. They impact any output signal that needs to change faster than the op amp can support—high-frequency sinusoidal signals, for example.

With a sinusoidal signal, we mainly think in terms of distortion resulting from nonlinearity. If the actual output signal can't rise as quickly as the higher-slope portions of the expected output signal, the op amp won't maintain a linear relationship between input and output.

Figure 5 shows an extreme example of slew-rate-induced distortion. The output's rising and falling edges are slew-rate limited. As a result, the signal is now a triangular wave instead of a sinusoid.

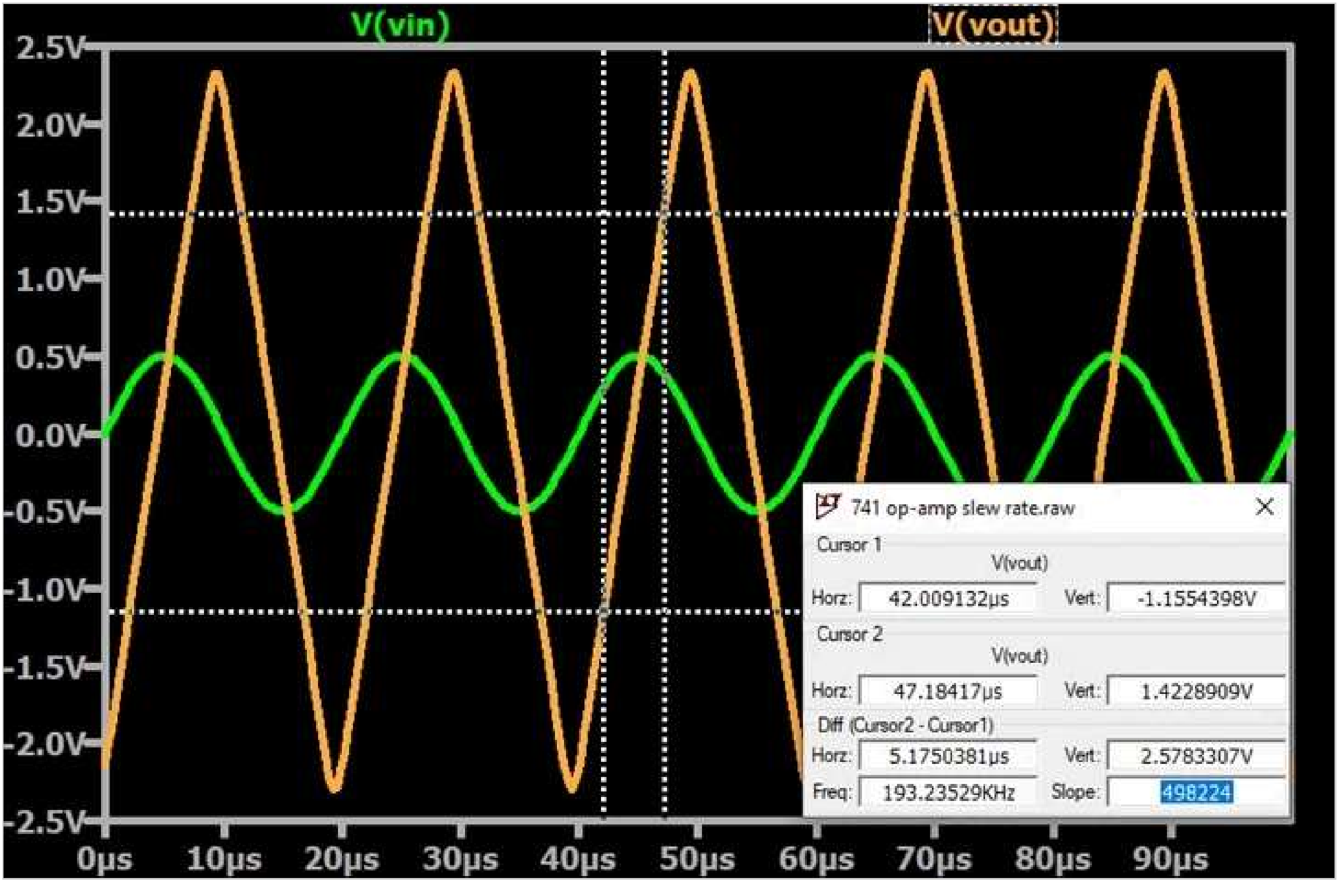

Figure 5. The simulated 741 op amp experiences slew-rate limitation during the higher-slope portions of the sinusoid. Image used courtesy of Robert Keim

What Causes Slew-Rate Limitation?

Delays and bandwidth restrictions in electrical circuits are fundamentally caused by capacitance. Currents flow within circuits and generate voltages as they pass through impedances. Voltages don't appear instantly, however—the currents must first charge or discharge parasitic and intentional capacitances. Larger capacitances require more charging current and cause longer delays.

Op amps have internal capacitances that must be charged and discharged, and these limit the rate at which the output voltage can change. In many cases, these internal capacitances include a relatively large compensation capacitor.

For example, Figure 6 shows an internal schematic of the LM124 op amp from Texas Instruments. Its compensation capacitor (C_C) reduces the rate at which voltage can change in the amplifier's second stage.

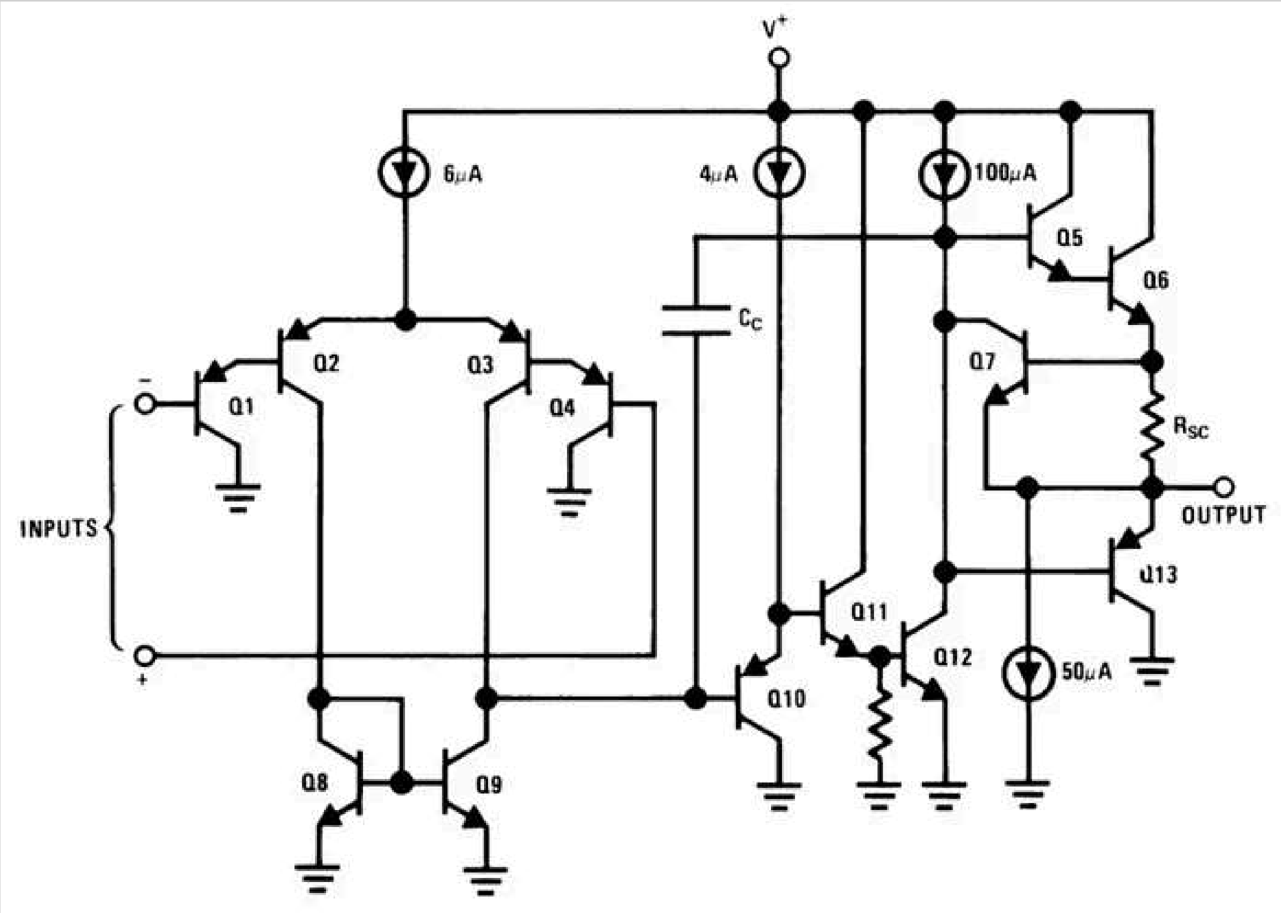

***Figure 6.** Internal schematic for the LM124 op amp. Its compensation capacitor is labeled as* C_C*. Image used courtesy of [Texas Instruments](#)*

An internal compensation capacitor makes an op amp more stable but reduces the slew rate. Instead of a compensation capacitor, non-compensated op amps are limited by smaller parasitic capacitances. They therefore offer a higher slew rate.

Choosing an Op Amp Based on Slew Rate

Modern op amps have far surpassed the 741's slew-rate capabilities, and designers now have many op amp options to choose from. The LT1817, for example, has a slew rate of 1500 V/µs. If that's not enough, you could consider a current-feedback amplifier (CFA) such as the AD8009, which goes up to 5500 V/µs.

The CFA architecture is fundamentally different from the VFA (voltage-feedback amplifier) architecture used in most op amps. If your application needs a high slew rate to avoid excessive rise times, a CFA may be the better choice. For those wanting to explore this topic further, Dr. Sergio Franco's article series on CFAs is a good resource. I also recommend his article "How to Increase Slew Rate in Op Amps" if you want to learn more about the electrical and mathematical details of op amp slew rate.