ECE 209: *Circuits and Electronics Laboratory*

Operational Amplifier Basics: It's Not Black Magic; It's Negative Feedback*

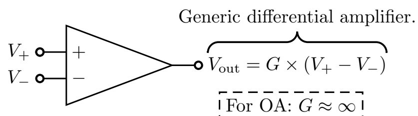


Figure 1: Operational amplifier (OA) alone.

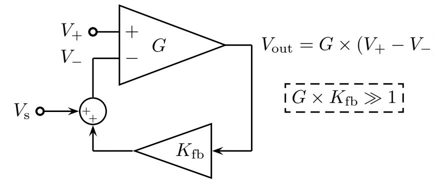


Figure 2: OA with negative feedback.

At the most basic level, an *operational amplifier* (OA) is a special kind of *differential amplifier* like the one shown in Figure 1; the output is a scaled version of the difference between its two inputs. The special feature of an operational amplifier is that its *gain* is extremely large. In fact, it is so large that an operational amplifier is *useless* as a typical differential amplifier. As Horowitz and Hill[1] say, you should "think of an op-amp as fodder for feedback."

An operational amplifier will almost always be used in a *negative-feedback* configuration like the one shown in Figure 2. A voltage divider is commonly used to implement the feedback, but any connection that provides this kind of connection between the OA output and the V_- input will suffice[2]. In this configuration,

$$\begin{aligned} V_- &= V_{\text{out}} K_{\text{fb}} + V_{\text{s}} \\ &= (V_+ - V_-)\, G K_{\text{fb}} + V_{\text{s}} \\ &= V_+ G K_{\text{fb}} - V_- G K_{\text{fb}} + V_{\text{s}}, \end{aligned}$$

and so

$$V_- \left(1 + G K_{\text{fb}}\right) = V_+ G K_{\text{fb}} + V_{\text{s}}$$

and

$$V_- = \frac{V_+ G K_{\text{fb}}}{1 + G K_{\text{fb}}} + \frac{V_{\text{s}}}{1 + G K_{\text{fb}}}.$$

However, because $G K_{\text{fb}}$ is very large, V_{s} has negligible impact on V_-, and V_- tends to follow V_+. That is,

$$\boxed{V_- \approx V_+ \qquad \text{because } G K_{\text{fb}} \text{ is very large.}} \tag{1}$$

In other words, the operational amplifier *monitors* the difference between V_- and V_+. If V_- strays from V_+ by even a small amount, the operational amplifier compensates appropriately to close the gap between them.

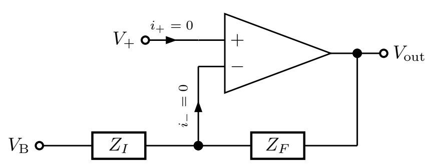
Because the operational amplifier ensures that V_- is identical to V_+, it also ensures that

$$\boxed{V_{\text{out}} \approx \frac{V_+ - V_{\text{s}}}{K_{\text{fb}}}.} \tag{2}$$

So with clever choice of V_{s} (e.g., 0 V or a known signal) and feedback gain K_{fb} (e.g., some sub-unity gain from a voltage divider), the operational amplifier will ensure some useful relationship among V_{out}, V_+, and V_s regardless of what else is connected to V_{out}. So an operational amplifier provides a *low-impedance output* that has the ability to *track* some other high-impedance output; we can avoid *loading* parts of our circuits by *buffering* them with an OA. Also, as in Figure 3, we can *amplify* or *filter* signals using Equation (2).

$$K_{\text{fb}} = \frac{Z_I}{Z_I + Z_F}$$

$$V_s = V_B \times \frac{Z_F}{Z_I + Z_F} = V_B \times (1 - K_{\text{fb}})$$



$$\begin{aligned} V_{\text{out}} &= \frac{V_+ - V_s}{K_{\text{fb}}} = \frac{V_+ - V_B \frac{Z_F}{Z_I + Z_F}}{\frac{Z_I}{Z_I + Z_F}} \\ &= V_+ \frac{Z_I + Z_F}{Z_I} - V_B \frac{Z_F}{Z_I} \\ &= \boxed{V_+ \left(1 + \frac{Z_F}{Z_I}\right) - V_B \frac{Z_F}{Z_I}} \end{aligned}$$

Figure 3: Typical ideal OA circuit. Uses voltage divider for feedback.

*Document from http://www.tedpavlic.com/teaching/osu/ece209/. Source code at http://hg.tedpavlic.com/ece209/.
[1] *The Art of Electronics* (2nd edition) by Paul Horowitz and Winfield Hill. Cambridge University Press, 1989. Page 176.
[2] In fact, even many nonlinear gains (e.g., K_{fb} gains that vary with the output level) will suffice.