Operational Amplifier Basics: It’s Not Black Magic; It’s 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,

\[
V_- = V_{\text{out}} K_{fb} + V_s = (V_+ - V_-) G K_{fb} + V_s = V_+ G K_{fb} - V_- G K_{fb} + V_s,
\]

and so

\[
V_- (1 + G K_{fb}) = V_+ G K_{fb} + V_s
\]

and

\[
V_- = \frac{V_+ G K_{fb}}{1 + G K_{fb}} + \frac{V_s}{1 + G K_{fb}}.
\]

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

\[
V_- \approx V_+ \quad \text{because } G K_{fb} \text{ is very large.}
\] (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

\[
V_{\text{out}} \approx \frac{V_+ - V_-}{K_{fb}}.
\] (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 \(V_{\text{out}}, V_+,\) and \(V_s\) regardless of what else is connected to \(V_{\text{out}}\). 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).

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Footnotes:

2. In fact, even many nonlinear gains (e.g., \(K_{fb}\) gains that vary with the output level) will suffice.

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Figure 1: Operational amplifier (OA) alone.

Figure 2: OA with negative feedback.

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