Chapter 6N

Class 6: Op-Amps I

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6N.1 Why?

What problem do today’s circuits address? The very general task of improving performance, through the application of negative feedback, of a great many of the circuits we have met to this point.

6N.2 Preliminary: Negative Feedback as a general notion

This is the deepest, most powerful notion in this course. It is so useful that the phrase, at least, has passed into ordinary usage—and there it has been blurred. Let’s start with some examples of such general use—one genuine cartoon (in the sense that it was not cooked up to illustrate our point), and three cartoons that we did cook up. Ask yourself whether you see feedback at work in the sense relevant to electronics, and if you see feedback, is its sense positive or negative?

![Figure 1: Feedback: same sense as in electronics? Copyright 1985 Mark Stivers, first published in Suttertown News](image1)

Below is an example of feedback misunderstood. Outside electronics, the word “negative” has negative connotations: so, “negative feedback” sounds nasty, “positive feedback” sounds benign. A news story in the New York Times concerning an economic slowdown began thus:

![Figure 2: “Negative feedback” misunderstood](image2)
What this reporter describes is, of course, *positive* feedback. But since the news is bad—“panic”—he can’t resist his inclination to call it *negative*.

Sometimes a signal that usually would amount to negative feedback turns out to be positive (we will return to this topic, one that causes circuit instability, in a later lab). Is the observer applying positive or negative feedback to the two fellows on the left, in fig. 3? To decide, we need to judge whether his signal tends to increase or decrease the behavior that he senses.

![Figure 3: Freaks? Will he hurt their feelings?](image1)

The case below comes closer to fitting the electronic sense of *negative feedback*. In op-amp terms (not Hollywood’s), who’s playing what role?

![Figure 4: “Negative feedback:” a case pretty much like op-amp feedback](image2)

We drew the scene of fig. 4 in an earlier version of this book (a scene we hoped oldtimers might recognize from the film, “On the Waterfront”). You may imagine how excited we were to bump into the same thing happening at a construction site, on our way to work:
The crane operator could not quite see the place to which he was trying to lower the load of re-bars. An observer who could see, guided him. It worked.

6N.3 Feedback in electronics

In conversation, people usually talk (as that reporter did, in § 6N.2 on page 2) as if “positive feedback” is nice, “negative feedback” is disagreeable. In electronics the truth is usually just the opposite. Generally speaking, negative feedback in electronics is wonderful stuff; positive feedback is nasty. Nevertheless the phrase means in electronics fundamentally what it should be used to mean in everyday speech.

Harold Black was the first to formalize the effects of negative feedback in electronic circuits. Here is the language of his patent:2 explaining his idea:

Applicant has discovered how to use larger amounts of “negative feedback than were contemplated by prior art workers with a new and important kind of improvement in tube operation. One improvement is in lowered distortion arising in the amplifier. Another improvement is greater consistency of operation, in particular a more nearly constant gain despite variable factors such as ordinarily would influence the gain. Various other operating characteristics of the circuit are likewise rendered more nearly constant. Applicant has discovered that these improvements are attained in proportion to the sacrifice that is made in amplifier gain, and that by constructing a circuit with excess gain and reducing the gain by negative feedback, any desired degree of constancy or stability of operating characteristics can be realized, the limiting factor being in the amount of gain that can be attained, rather than any limitation in the method of improvement provided by the Invention.

He summarized his idea, in an article that he published many years afterward:

...by building an amplifier whose gain is made deliberately, say 40 decibels higher than necessary (10,000-fold excess on energy basis) and then feeding the output back to the input in such a way as to throw away the excess gain, it has been found possible to effect extraordinary improvement in constancy of amplification and freedom from nonlinearity.3

One proof of the originality of Black’s idea was the fact that the British Patent Office rejected his application, seeing Black as a dull fellow who had not understood that an amplifier should amplify, so that “throwing away...gain” showed the inventor’s confusion. Black had the last laugh.

Lest we oversell Black’s invention, let’s acknowledge that Black did not invent or discover feedback. Our bodies are replete with homeostatic systems, like the one that holds our body temperature close to 99°F, whether we are shivering in the snow or sweating on a beach (with shivering and sweating part of the stabilizing mechanism). And Newcomen used a speed “governour” on his mine-pumping steam pumps: the spin rate raised or lowered the weights, closing down or opening the steam valve appropriately, so as to hold the speed nearly constant despite variations in load.4

Figure 6: Watt-Boulton speed governor adjusted steam pressure to hold rotation rate constant, despite load variation (1788)

Open-loop vs feedback circuits

Nearly all our circuits, so far, have operated open-loop—with some exceptions noted below. You may have gotten used to designing amplifiers to run open-loop (we will cure you of that); you would not consider driving a car open loop (we hope), and you probably know that it is almost impossible even to speak intelligibly open-loop.

6N.3.0.1 Examples of Feedback without op-amps

We know that feedback is not new to you, not only because you may have a pretty good idea of the notion from ordinary usage, but also because you have seen feedback at work in parts of some transistor circuits:

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3IEEE Spectrum, Dec. 1977
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increase in collector current pushes $V_e$ up, squeezing down $V_{BE}$

DC feedback adjusts $V_{BE}$, while permitting signal to wiggle this point

Figure 7: Some examples of feedback in circuits we have built without op-amps

6N.3.0.2 Feedback with op-amps

op-amp circuits make the feedback evident, and use a lot of it, so that they perform better than our improvised feedback fragments. The name “Operational Amplifier” derives from the assumption, early in their use, that they would be used primarily to do a sort of analog computing.5

op-amps have enormous gain (that is, their open-loop gain is enormous: the chip itself, used without feedback, would show huge gain: $\approx 200,000$ at DC, for the LF411, the chip you will use in most of our labs). As Black proposed, op-amp circuits deliberately throw away most of that gain, in order to improve circuit performance.

6N.4 The Golden Rules

Just as we began our treatment of bipolar transistors with a simple model of device behavior, and that model remained sufficient to let us analyze and design many circuits, so in this chapter we start with a simple, idealized view of the op-amp, and usually we will continue to use this view even when we meet a more refined model.

The golden rules (below) are approximations, but good ones:

<table>
<thead>
<tr>
<th>op-amp “Golden Rules”</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The output tries to do whatever is necessary to make the voltage difference between the two inputs zero.</td>
</tr>
<tr>
<td>2. The inputs draw no current.</td>
</tr>
</tbody>
</table>

Three observations, before we start applying these rules:

- Rule 2: we’re confident that you understand that the “inputs” that draw no current are the signal inputs, labelled “+” and “−”, not the op-amp’s power supply terminals (16)
- Rule 1: the word “tries” is important. It remind us that it’s up to us, the circuit designers, to make sure that the op-amp can hold its two inputs at equal voltages. If we blunder—say, by overdriving a circuit—we can make it impossible for the op-amp to do what it “tries” to do.

5They seem to have been named in a paper of 1947, which envisioned their important uses as follows: “The term ‘operational amplifier’ is a generic term applied to amplifiers whose gain functions are such as to enable them to perform certain useful operations such as summation, integration, differentiation, or a combination of such operations.” John R. Ragazzini, Randall and Russell, “Analysis of Problems in Dynamics by Electronic Circuits,” *Proceedings of the IRE*, vol. 35, May 1947, pp. 444-452, quoted in op-amp Applications Handbook, Walt Jung editor emeritus (Analog Devices Series, 2006), p. 779.

6You may think this is obvious, but every now and then some students, impressed by all our praise of op-amps and their magic, fail to connect the op-amps power supply pins. The students wait expectantly for truly miraculous circuit performance—and are disappointed.
More generally: the GR apply only to op-amp circuits that use negative feedback.

These simple rules will let you analyze a heap of clever circuits.

Applications

6N.5 A Follower

Here’s about the simplest circuit one can make with an op-amp.

![Image](follower.png)

Figure 8: Follower

It may not seem very exciting—but it is the best follower you have seen. The Golden Rules let you estimate,…

- …$R_{IN}$ (try GR #2);
- …$V_{OFFSET}$ (try GR #1); and compare this to the DC-offset we are accustomed to in a bipolar transistor follower.
- …$R_{OUT}$?

6N.5.1 The effect of feedback on the follower’s $R_{OUT}$

$R_{OUT}$ raises a much subtler question. The GR don’t answer it, but you can work your way through an argument that will show that $R_{OUT}$ is very low. The novel point, here, is that it is low not because the IC itself has low $R_{OUT}$; this value, rarely specified, is moderately low—perhaps around 100Ω. What’s new is that feedback accounts for the very low $R_{OUT}$ of this circuit—and of nearly all other op-amp circuits.7

Let’s redraw the op-amp to resemble a Thevenin model: perfect voltage source in series with a series resistance that we might call “$r_{out}$.” Our drawing will include the op-amp’s high open-loop gain, $A$. Then we can try the thought experiment of tugging the output by a $\Delta V$, and seeing how the output responds:

![Image](feedback.png)

Figure 9: Feedback lowers op-amp circuit’s $R_{OUT}$

7The one exception to this rule is an op-amp current source, whose output should be high (the ideal current source, as you know, would show $R_{OUT}$ infinite).
If you try to change $V_{OUT}$, the circuit hears about it, through the feedback wiring. It is *outraged*. Its high-gain amplifier squirts a large current at you, fighting your attempt to push the output away from where the op-amp wants it to stand. We’ll leave the argument at this qualitative level, for now. We’ll settle for calling the output impedance “very low.” Later (mostly on Day 9), we will be able to quantify the effects of feedback so as to arrive at a value for $R_{OUT}$.

**Two Amplifiers**

### 6N.6 Non-Inverting Amplifier

This circuit is a bit more exciting than the follower: it gives us voltage gain.\(^8\)

![Non-inverting amp](image)

**Figure 10: Non-inverting amp: Golden Rules allow inferring its behavior**

Evidently, to satisfy the Golden Rules (GR) the op-amp has to take its output to 11V, if we apply 1V to the input. Generalizing, you may be able to persuade yourself that the gain is the inverse of the fraction fed back. \(1/11\) is fed back, so gain is 11. The gain usually is recited more simply as

$$G = 1 + R_2/R_1.$$

Students are inclined to forget this pesky “1 +.” We hope you won’t forget it. Sometimes, of course, it is sensible to “forget it” in the sense that you neglect it: when the $R_2/R_1$ fraction is very large. But throw out the “+1” only once you have determined that its contribution is negligible.

#### 6N.6.1 A Skeptic’s Challenge to the Golden Rules

Suppose that a skeptical student wants to take advantage of his awareness that the op-amp is a differential amplifier (and a circuit familiar from the second transistor lab); such a student might present a plausible challenge to the GR’s. This skeptic doesn’t fall for the notion that the op-amp is a weird little triangle that relies on pure magic.

This person might object that our Golden Rules’ analysis must be wrong, because the analysis is not consistent with our understanding of the differential amp that is the core of any op-amp. Our GR’s predict $V_{OUT} = 11$. But if GR #2 says that the op-amp has driven the input voltages to equality, then—Aha! We have caught a self-contradiction in the analysis! Equal voltages at the input of a diff amp cannot produce 11V out; the GR must be wrong!

But, no; you’re too sophisticated to fall for this argument. The resolution of the seeming-contradiction is only to acknowledge that the Golden Rules are approximate. The op-amp does not drive the inputs to equality, but to near-equality. How close? Just close enough so that your differential-amplifier view can

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\(^8\)Incidentally, it was this sort of circuit that interested Black. He was concerned to make “repeater” amplifiers for the telephone company, in order to transmit voice signals over long distances. It was this need to send a signal through a great many stages—hundreds, in order to cross the country—that made the phone company more concerned than anyone else with the problem of distortion in amplifiers. Distortion that is minor in one or two stages can be disastrous when superadded hundreds of times.

It’s a curious historical fact that the telephone company, which we may be inclined to view as a stodgy old utility, repeatedly stood at the forefront of innovation: not only Black’s invention, but also bipolar transistors, field-effect transistors and fiber-optic signal transmission were developed largely at “the phone company,” if one includes within this company the famous Bell Laboratories.
work. In order to drive $V_{\text{OUT}}$ to 11, the difference between the inputs—$V_{\text{diff}}$, in fig. 10 on the preceding page—must be not zero but $V_{\text{OUT}}/(\text{op-amp's open-loop gain})$. For a '411 op-amp at DC, that indicates $V_{\text{diff}} \approx \frac{11V}{200,000\,\Omega \times 0.2M} = 50\mu V$. Not zero, but pretty close.

Doing that calculation can help one to appreciate why it is useful to have all that excess gain to throw away (as Black put it): the Golden Rule approximations come closer to the truth as open-loop gain rises. $A_{\text{OPEN-LOOP}} = 1$ million, for example (a value available on many 'premium' op-amps) would reduce $V_{\text{diff}}$, in the example above, to just $5\mu V$.

6N.6.2 Some Characteristics of the Non-inverting Amp

A couple of other characteristics are worth noting—perhaps they seem obvious to you:

- $R_{\text{IN}}$ is enormous, as for the follower;
- $R_{\text{OUT}}$ is tiny, as for the follower

Incidentally, you might note that the follower can be described as a special case of the non-inverting amplifier. What is its peculiar $R_1$ value?

6N.7 Inverting Amplifier

The circuit below also amplifies well. It differs from the non-inverting amplifier in one respect that is obvious—it inverts the signal!—and in some respects that are not so obvious.

![Inverting amplifier](image)

GR #1 tells us that the inverting terminal voltage should be zero. From this observation, we can get at the circuit’s properties:

6N.7.0.1 Gain

Let’s look at the particular case: 1V causes 1mA to flow toward the inverting terminal. Where does this current go? Not into the op-amp (that is forbidden by GR #2). So, it must go around the corner, through the 10k feedback resistor. Doing that, it drops 10V. So, $V_{\text{OUT}} = -10V$.

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9We’ll see later, when we look at the effects of feedback quantitatively, that the amplifier trades away a very little of its impedance virtues in exchange for gain. Still, this is a minor correction to the claim that amplifier and follower share good input and output impedances. The dependence of circuit impedances upon $B$, the fraction of output that is fed back, is treated in AoE §2.5.3.2 and §2.5.3.3.

10For the follower, $R_1$ is infinite; so, gain goes to one.
Generalizing this result, you’ll be pleased to see no nasty “1+...” in the gain expression: just \( G = -\frac{R_2}{R_1} \). The *minus* sign means—as in the common-emitter amp—only that the circuit inverts: that output and input are 180° out of phase.

If you’re not too proud to use a primitive way of looking at the circuit—a way that’s based on its appearance, along with the fixed *virtual ground* at the inverting terminal—try thinking of the circuit as a child’s see-saw. It pivots on virtual ground. If the two arms are of equal length, it is balanced with equal voltages: its gain is –1. If one arm is 10 times longer, as in fig. 11 on the preceding page, the long arm swings 10 times as far as the short arm. And so on.

6N.7.0.2 Impedances, In and Out

Now, let’s consider the input impedance of the inverting amps of fig. 11 on the previous page. From the observation that the inverting input is fixed at 0V also flow some of the circuit’s peculiarities:

- \( R_{IN} \): Let’s see if we can get you to fall for either of two *wrong answers*:
  - Wrong answer #1: “\( R_{IN} \) is huge, because input goes to an op-amp terminal, and GR #2 says the inputs draw no current.”
  - Wrong answer #2: “Oh, no—what I forgot is that it’s the output of the circuit that is at low impedance (we saw that back in § 10 on page 8, above). So \( R_{IN} = R_1 + R_2 \)”.

What’s wrong with these answers? To give you a chance to see through our falsehoods on your own, we’ll hide our explanations in a footnote.\(^1\)

- The inverting amp’s inverting terminal (the one marked “-”) often is called “virtual ground.” Why “virtual”?\(^1\) This point, often called by the suggestive name, “summing junction,” turns out to be useful in several important circuits, and helps to characterize the circuit.

6N.7.1 What Virtual Ground Implies

6N.7.1.1 \( R_{in} \)

First, recognizing “virtual ground”—the point locked by feedback at zero volts—makes the circuit’s \( R_{in} \) very simple: it is just \( R_1 \). So, compared to the non-inverting amp, the inverting amp’s input resistance is only mediocre.

“Mediocre?” you may protest. “I can make it as large as I like, just by specifying \( R_1 \). I’ll make mine 10M or 100M, if I’m in the mood.” Well, no. Your defiant answer makes sense on this first day with op-amps, when we are pretending that they are ideal. But as soon as we come down to earth (splashdown is scheduled for next time), we’re obliged to admit that things begin to go awry when the \( R \) values become very large. So, if we treat about 10M as a practical limit on \( R \) values, we must concede that the inverting amp cannot match the non-inverting amp’s \( R_{in} \).

What happens to the circuit’s \( R_{in} \) if you omit \( R_1 \) entirely, replacing it with a wire? The resulting \( R_{in} \approx 0 \), alarming though it looks, is exactly what pleases one class of signal sources: it pleases a *current source*. In the first op-amp lab you will exploit this characteristic when you convert photodiode current to a voltage.

\(^1\)The first wrong answer confounds two distinct questions: *circuit- and op-amp-* input impedances. These are not the same, here. It’s true that a GR says the inverting input will not pass current; but no rule says that the circuit should not take current, through \( R_1 \), a current that can pass around the op-amp, through \( R_2 \) to the op-amp output terminal. That is, of course, how the input current does flow.

\(^{1\alpha}\)“Virtual” because it doesn’t behave like ordinary (real) ground: current flowing to virtual ground bounces; it doesn’t disappear, but runs off somewhere else (around the op-amp, using the op-amp’s feedback path), where it can be measured.
6N.7.1.2 Summing Circuit

The fact that virtual ground is fixed allows one to inject several *currents* into that point without causing any interaction among the signals; so, the several signals sum cleanly. The left-hand circuit, below, shows a *passive* summing circuit. It is inferior, because the contribution of any one input slightly alters the effect of any other input.

![Passive and Active Summing Circuits](image)

*Figure 12: Summing Circuits*

In the lab you will build a variation on this circuit: a potentiometer lets you vary the *DC offset* of the op-amp output. The circuits shown in fig. 12 form a *binary-weighted* sum.\(^{13}\) In principle, this is one way to build a digital-to-analog converter (DAC), though this method is used only rarely.

**One more Summing Circuit** Does a summing circuit have to use the *inverting* configuration? No, but the non-inverting form is not so simple, and is difficult to extend beyond two inputs. Does the circuit in fig. 13 form the sum of \(V_A\) and \(V_B\)?

![Summing Circuit](image)

*Figure 13: Summing Circuit?*

This is *almost* a summing circuit. The output is the *average*, rather than sum. An op-amp circuit could easily convert it to a sum (what gain is required?\(^{14}\)). But unlike the inverting summer, this one doesn’t easily extend to three, four and more inputs. So, the usual summing circuit uses the inverting configuration.

6N.7.1.3 Integrator, Differentiator, and others

Virtual ground allows one to make a nearly-ideal integrator, as we’ll see next time. The key is, again, that the point where \(R\) meets \(C\), a point that must be kept *close to ground* in the passive version, sits anchored *at ground*\(^{15}\) in the op-amp version:

\(^{13}\)“Binary-weighted” means that one can think of the three inputs as digits of a binary value, with each given double the weight of its “less significant” neighbor (you may find this notion easier to recall if you recall the weights of Homer Simpson and his less significant neighbor, Ned Flanders). So, the output voltage in the right-hand circuit of fig. 12 is \(V_{\text{out}} = -(4C + 2B + A)\).

\(^{14}\)That’s right: two.

\(^{15}\)Well, OK: *very close* to ground; we’ll see, next time, that some departure from the ideal is inevitable.
The same sort of improvement is available for the op-amp differentiator, though there it is less impressive, compromised by a subtlety that we are happy to postpone: concern for circuit stability. We will meet differentiator and integrator in lab, next time.

6N.8 When do the Golden Rules apply?

Now that we have applied the Golden Rules a couple of times, we are ready to understand that the Rules sometimes do not apply.

6N.8.1 Try some cases: do the rules apply at all?

The question may seem to you silly: a) pretty clearly is not a golden-rule circuit; it’s just a high-gain amplifier—either a mistake or an anticipation of the circuit we will meet as a “comparator” in the third op-amp lab. It uses no feedback. b) works, c) does not, and the reason is that c) uses the wrong flavor of feedback: positive.

So, generalizing a bit from these cases, one can see that the Golden Rules do not automatically apply to all op-amp circuits. Instead, they apply to op-amp circuits that...

- use feedback, and
- ...use feedback that is negative.

6N.8.2 ...Subtler cases: Golden Rules apply for some inputs

Will the output’s “attempt...” to hold the voltages at its two inputs equal succeed, in these two cases?
No. But for the other polarity of input the answer would be “Yes.” We will return to such conditional-feedback circuits, next time.

### 6N.8.3 More Applications: Improved Versions of Earlier Circuits

Nearly all the op-amp circuits that you meet will do what some earlier (open-loop) circuit did—but they will do it better. This is true of all the op-amp circuits you will see today in the lab. Let’s consider a few of these: current source, summing circuit, follower, and current-to-voltage converter.

#### 6N.8.3.1 Current Source

The left-hand circuit is straightforward—but not usually satisfactory. For one thing, the load hangs in limbo, neither end tied to either ground or a power supply. For another, the entire load current must come from the op-amp itself—so, it is limited to about ±25mA, for an ordinary op-amp.

The right-hand circuit is better—though the signal “$V_{in}$” is defined unconventionally, and inconveniently: as a voltage relative not to ground, as usual, but relative to the positive supply. Despite this peculiarity, the circuit gives you a chance to marvel at the op amp’s ability to make a device that’s brought within the feedback loop behave as if it were perfect. Here, the op-amp will hide $V_{BE}$ variations, with temperature and current, and also the slope of the $I_C$ vs. $V_{CE}$ curve (a slope that reveals that the transistor is not a perfect current source; this imperfection is described by “Early Effect,” a topic discussed in Supplementary Note S52).

Do you begin to see how the op-amp can do this magic? It takes some time to get used to these wonders. At first it seems too good to be true.
6N.8.3.2 Followers

![Figure 18: op-amp followers](image)

How are the op-amp versions better than the bare-transistor version? The obvious difference is that all the op-amp circuits hide the annoying 0.6V diode drop. A subtler difference—not obvious, by any means, is the much better output impedance of the op-amp circuits. How about input impedance?\(^{16}\)

6N.8.3.3 Current-to-voltage converter

![Figure 19: Two applications for I-to-V converter: photometer; “ideal” current meter](image)

(A Puzzle: if you and I can design an “ideal” current meter so easily, why do our lab multimeters not work that way? Are we that much smarter than everyone else?)\(^{17}\)

6N.9 Strange Things Can be put Into Feedback Loop

The push-pull follower within the feedback loop begins to illustrate how neatly the op-amp can take care of and hide the eccentricities of circuit elements—like bipolar followers, or diodes.

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\(^{16}\)Yes, the op-amp circuits win, hands down. Recall Golden Rule #1.

\(^{17}\)Here’s a thought or two on that question: as in the first current source drawn above (fig. 17 on the preceding page), nearly the entire input current passes through the op-amp, so maximum current is modest, and the batteries powering the circuit will not last long.
6N.9.1 In general…

Here’s the cheerful scheme:

![Fig 20: op-amps can tidy up after strange stuff within the loop](image)

The figure above shows two distinct cases that fit all the op-amp circuits we will meet.

6N.9.1.1 Hiding the “dog”…

Sometimes, instead of treating the op-amp output as circuit output—and thus showing the inverse of the signal fed back—we use the op-amp to “hide the dog.” The push-pull is such a case. The weirdness of the transfer function of the bare push-pull is not interesting or useful; it is a defect that we are happy to hide. Active rectifiers do a similar trick so as to hide diode drops.

To see the op-amp dutifully generating, at the input to the push-pull, whatever strange waveform is needed in order to hide the push-pull is quite dazzling, the first time one sees it. See if you find it so. Here are some scope images showing the process.

Crossover distortion in two forms… We rigged a demonstration of the op-amp’s cleverness by switching the feedback path between two points: the “silly” point, the op-amp output, produces a clean sinusoid in the wrong place, while delivering nasty crossover distortion at the circuit output. The “smart” feedback point, the circuit’s output, delivers a clean sinusoid where we want it.

![Fig 21: Details of circuit set up to show op-amp cleaning up crossover distortion](image)

First, here is cross-over distortion, shown in two forms. The left-hand image shows what it looks like when the load is resistive. This might be called “classic” crossover distortion. The image on the right shows what the distortion looks like when the load is not a resistor but an 8-ohm speaker, whose inductance produces stranger shapes.
...op-amp to the Rescue: crossover fixed

Could the op-amp be clever enough to undo the strange distortion introduced by the push-pull—and rendered even stranger (asymmetric, too) by the speaker as load? Surely not!

Well, yes: the op-amp is that clever (at moderate frequencies): it generates just what’s needed \( (\text{dog}^{-1}) \) to produce a clean output.

6N.9.1.2 ...Admiring the “dog”

In other cases, as the comments in fig. 20 on the previous page say, we want—and treat as circuit output—the op-amp output. In such cases, the “strange stuff” in the feedback loop is something we have planted in order to tease the op-amp into generating the inverse of that strange stuff (“inverse dog”\textsuperscript{18}).

The “strange stuff” need not be strange, of course; if we insert a voltage divider that feeds back \( \frac{1}{10} \) of \( V_{\text{out}} \), then \( V_{\text{out}} \) will show us \( 10 \times V_{\text{in}} \).

But here are two more exotic cases: two examples where the “strange signal” \( (\text{dog}^{-1}) \) evoked by the “strange stuff” in the feedback is what does interest us. The left-hand example in fig. 24, with the diode in the feedback loop, may look at first like a rectifier. But consider what it does for an always-negative input voltage.

\textsuperscript{18}We would like to have included a visual representation, in the figure above, of \textit{inverse dog}—but we lost our nerve. What does \textit{inverse dog} look like? Is it a dog with his paws in the air? Is it a cat? Is it god? You can see why we abstained.
Far from trying to hide “the dog” (of Fig. 20 on page 15, above), we are proud of him; so proud that we want to gaze at his image, \( \text{dog}^{-1} \).

In the left-hand circuit of Fig. 24 on the facing page that image is proportional to the \( \log \) of \( V_{\text{in}} \), for \( V_{\text{in}} \) negative; in the right-hand circuit, \( V_{\text{out}} \) is the square-root of \( V_{\text{in}} \), for \( V_{\text{in}} \) positive. Both circuits fail for inputs of the wrong sign, as we meant to suggest when we first showed these two circuits, in Fig. 16 on page 12.

In today’s lab you will be so bold as to put the...

### 6N.9.2 oscilloscope itself inside one feedback loop...

This is an odd idea, but one that produces entertaining results:

You’ll see lots of nifty circuits in this chapter. Soon you may find yourself inventing nifty circuits. op-amps give you wonderful powers. In case you find yourself wanting still more when you have concluded the orgy of cleverness that appears in the Circuit Ideas at the end of AoE’s Chapter 4, see the books of application notes published by National Semiconductor, among others (now absorbed into Texas Instruments: see http://www.ti.com/general/docs/lit/getliterature.tsp?genericPartNumber=lf411-n&fileType=pdf), or the application notes that follow many op-amp data sheets, including the LF411’s (see http://www.ti.com/general/docs/lit/getliterature.tsp?genericPartNumber=lf411-n&fileType=pdf for the ’411’s data sheet).

### 6N.10 AoE Reading

- Chapter 2: Once again, introduction to negative feedback: §2.5 (this was assigned for Lab 5, but remains a relevant introduction)
- Chapter 4: §4.0 – §4.2
- Bad circuits, Chapter 4: B, D, F, G, I, K, L, M (none of these requires any deep understanding of op-amps)
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