

STUDENT MANUAL FOR

THE



ART OF
ELECTRONICS



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CHAPTERS 4, 5, 6

FEEDBACK: Op amps, oscillators, power supplies: Overview

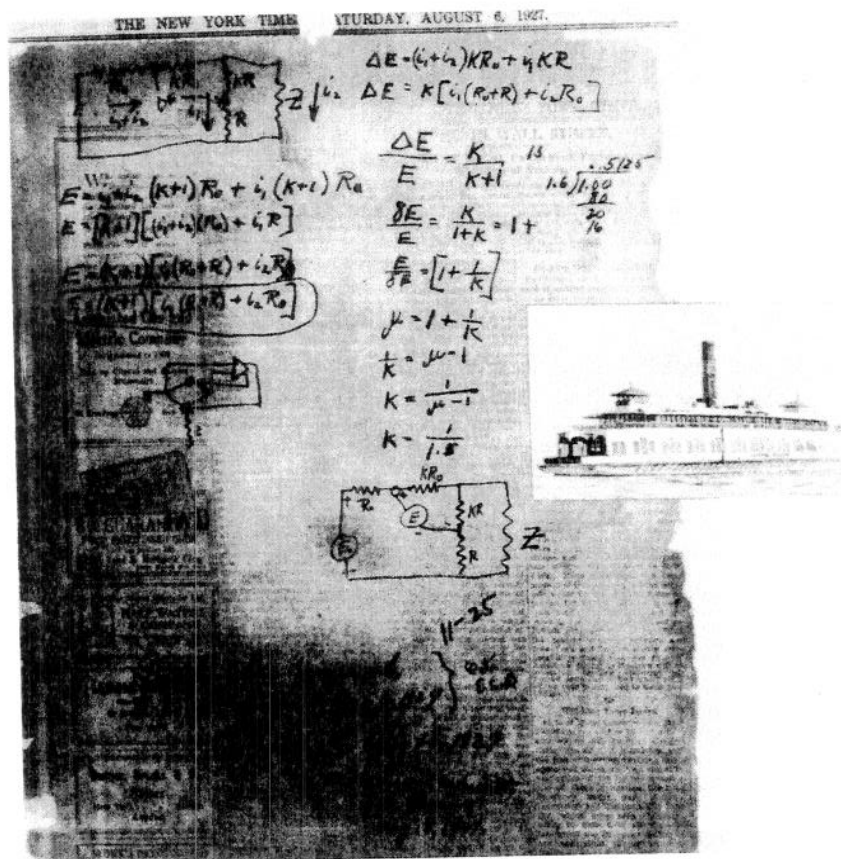


Figure OVR4.1: Harold Black's notes on the feedforward amplifier conceived as he rode the ferry from Staten Island to work, one summer morning in 1927. (Copyright 1977 IEEE. Reprinted, with permission, from Harold S. Black, "Inventing the Negative Feedback Amplifier," *IEEE Spectrum*, Dec. 1977)

We have been promising you the pleasures of feedback for some time. You probably know about the concept even if you haven't yet used it much in electronics. Now, at last, here it is.

Feedback is going to become more than just an item in your bag of tricks; it will be a central concept that you find yourself applying repeatedly, and in a variety of contexts, some far from operational amplifiers. Already, you have seen feedback in odd corners of transistor circuits; you will see it constantly in the next three chapters; then you will see it again in a digital setting, when you build an analog-to-digital converter in Lab 17, and then a phase-locked-loop in the same lab. It is a powerful idea.

Chapter four begins, as Chapter two did, with a simple, idealized view of the new devices—this time, ‘operational amplifiers:’ little high-gain differential amplifiers that make it easy to build good feedback circuits. As the chapter continues, we soon feel obliged once again to disillusion you—to tell you about the ways that op amps are imperfect. At the same time, we continue throughout these four labs to look at additional applications for feedback, and we never lose our affection for these circuits. They work magically well. The third op amp lab, Lab 10, introduces the novelty of *positive* feedback: feedback of the sort that makes a circuit unstable. Sometimes that is useful, and sometimes it is a nuisance; we look at cases of both sorts. Several of the circuits that use positive feedback are *oscillators*, a circuit type treated primarily in Chapter 5 (*Active Filters and Oscillators*).

Lab 11 concentrates on FET’s, this time used as switches; but this lab includes circuits that use feedback, and among them is the only *active filter* that you will meet in this course.

Lab 12 returns us to circuits that for the most part rely on negative feedback, but these are specialized circuits designed for the narrow but important purpose of providing stable power supplies. The Text devotes a chapter to these circuits (Chapter 6: *Voltage Regulators and Power Circuits*); we give them a lab, and hope that you will feel the continuity between this use of feedback and the more general cases that you met first in Chapter 4. With Lab 12 we conclude the analog half of the course, and with the very next lab you will find the rules of the game radically changed as you begin to build *digital* circuits. But we will save that story till later.

A piece of advice (unsolicited): How to get the greatest satisfaction out of the feedback circuits you are about to meet:

Here are two thoughts that may help you to enjoy these circuits:

- as you work with an op amp circuit, recall the equivalent circuit made without feedback, and the difficulties it presented: for example, the transistor follower, both bipolar and FET, or the transistor current sources. The op amp versions in general will work better, to an extent that should astonish you.

You have labored through two difficult chapters, 2 and 3, and have learned how to work around annoying characteristics of both sorts of transistor. Now you are entitled to enjoy the ease of working with op amps and feedback.

Here is a picture of you climbing—as you are about to do—out of the dark valleys through which you have toiled, up into that sunny region above the clouds where circuit performance comes close to the ideal:

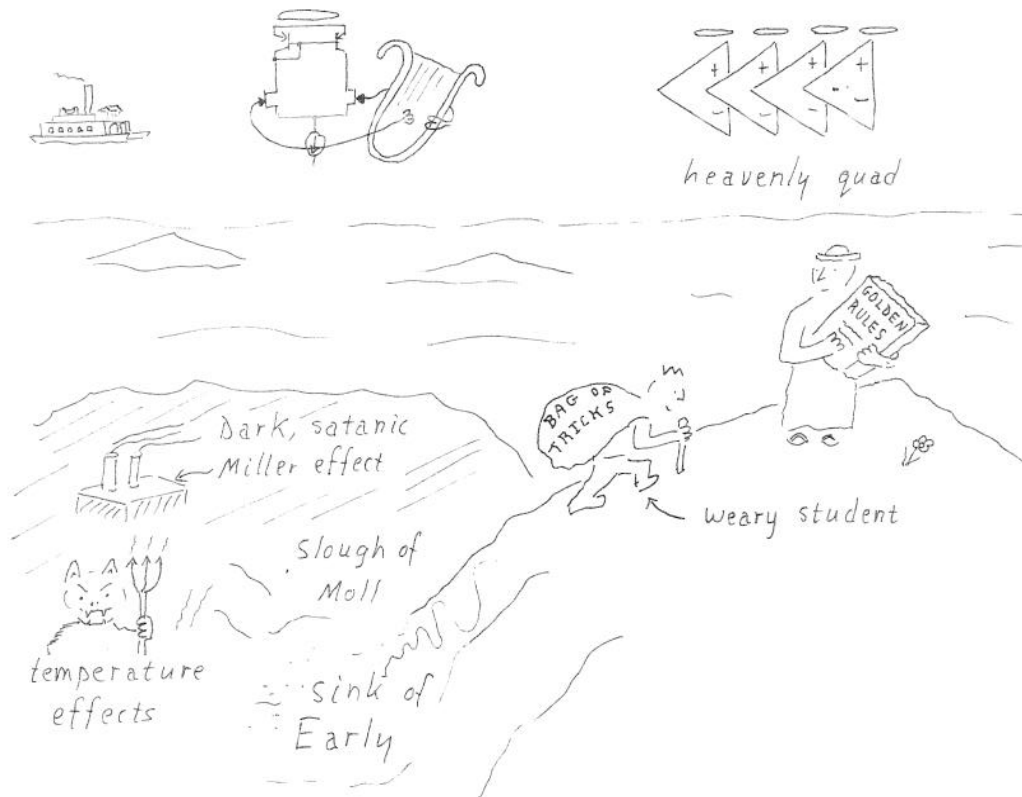


Figure OVR4.2: Righteous and deserving student, about to be rewarded for his travails with discrete transistors: he climbs into the sunny alpine meadows where feedback blooms

Pat yourself on the back, and have fun.

A second thought:

- Recall that negative feedback in electronics was not always used; was not always obvious—as the Text points out in its opening to Chapter 4, and as Harold Black was able to persuade the patent office (Black comes as close as anyone to being the inventor of electronic feedback).

The faded and scribbled-on newspaper that is shown at the start of these notes is meant to remind you of this second point—meant to help us feel some of the surprise and pleasure that the inventor must have felt as he jotted sketches and a few equations on his morning newspaper while riding the Staten Island Ferry to work one summer morning in 1927. A facsimile of this newspaper, recording the second of Black's basic inventions in the field, appeared in an article Black wrote years later to describe the way he came to conceive his invention. Next time you invent something of comparable value, don't forget to jot notes on a newspaper, preferably in a picturesque setting—and then keep the paper till you get a chance to write your memoirs.

Class 8: Op Amps I: Idealized View

Topics:

- *old.*
 - earlier examples of feedback
- *new:*
 - negative feedback: a notion of wonderful generality
 - feedback without op amps: examples you have seen
 - feedback with op amps
 - ◆ the Golden Rules
 - ◆ Applications: Two amplifiers
 - ◆ Preconditions: when do the Golden Rules apply?
 - ◆ More Applications: improved versions of earlier circuits
 - current source
 - summing circuit
 - follower
 - current-to-voltage converter
 - ◆ A generalization: strange things can sit within the feedback loop:
 - sometimes we want the op amp to hide the strange thing;
 - sometimes we want the op amp to generate (strange-thing)⁻¹

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 the sense positive or negative?



Figure N8.1: Feedback: same sense as in electronics? Copyright 1985 Mark Stivers, first published in *Suttertown News*

The two cases below are meant to raise the question, "To which op amp terminal is the feedback being applied?" (If you have not yet looked at the Text, that question will not yet make sense to you. We assume you know what an op amp is, at this point.)



Figure N8.2: "Negative Feedback": poor usage: which terminal is getting the feedback?

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?

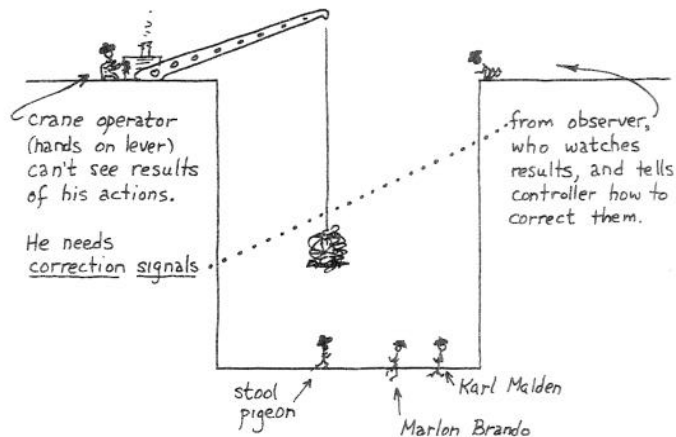


Figure N8.3: "Negative feedback:" a case pretty much like op amp feedback

In conversation, people usually talk as if "positive feedback" is nice, "negative feedback" is nasty. In electronics the truth is usually just the opposite.

Feedback in electronics

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, the first to apply negative feedback to electronic circuits, described his idea this way:

Text sec. 4.26, p. 233

...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.¹

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*.

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:

Lab 5:
5-2, 5-3, 5-5

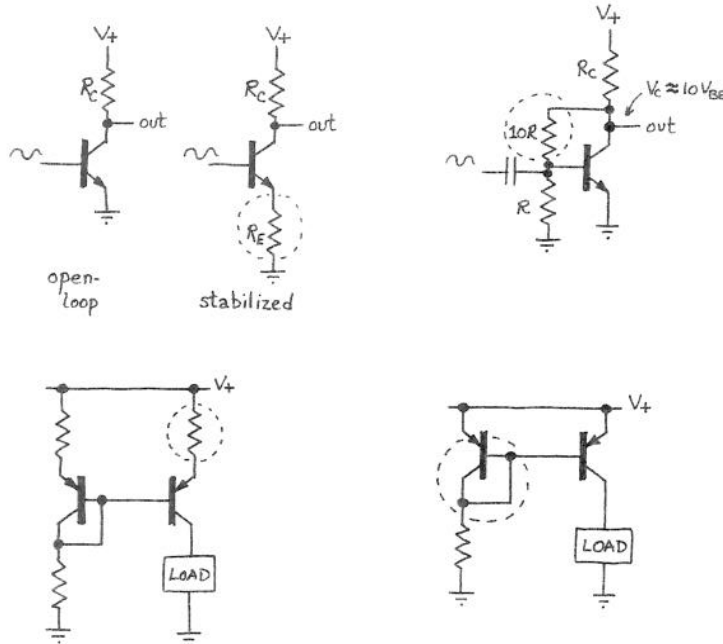


Figure N8.4: Some examples of feedback in circuits we have built without op amps

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. 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 suggests, op amp circuits throw away most of that gain, in order to improve circuit performance.

The Golden Rules

Just as we began Chapter 2 with a simple model of transistor 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 :

Text sec. 4.03, p. 177

Op amp "Golden Rules"

1. The output attempts to do whatever is necessary to make the voltage difference between the two inputs zero.
2. The inputs draw no current.

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

Applications

Two Amplifiers

Text sec. 4.04, 4.05:
p. 178

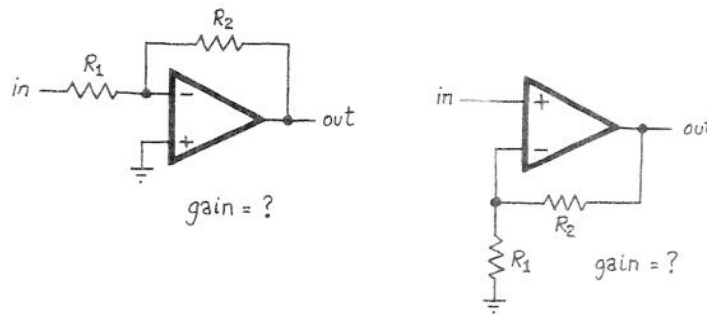


Figure N8.5: Inverting and non-inverting amplifiers

What are the special virtues of each?

- What is R_{in} for inverting amp? (Golden Rule 1 should settle that.)
- Approximately what is R_{in} for the non-inverting amp? (Golden Rule 2 should settle that.)
- The inverting amp's inverting terminal (the one marked "-") often is called "virtual ground." Do you see why? (Why ground? Why "virtual"?) This point, often called by the suggestive name "summing junction," turns out to be useful in several important circuits.

When do the Golden Rules apply?

Text sec. 4.08

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

- note a **preliminary assumption**: these rules are useful only for circuits that include—
 1. Feedback; and
 2. Feedback of the right flavor: *negative* feedback
- And note the careful wording of the first rule: “the output *attempts*...” This rule is like a guarantee written by a cautious (and prudent) lawyer. It warns a careful reader that the person designing op amp circuits retains an obligation to use his head: apparently there are circuits in which the op amp will be unable to deliver the desired result: it will *attempt* and fail. Let’s look at some such cases, to be warned early on.

Try your understanding of the golden rules and their restrictions, by asking yourself whether the golden rules apply to the following circuits:

p. 182, item “2”

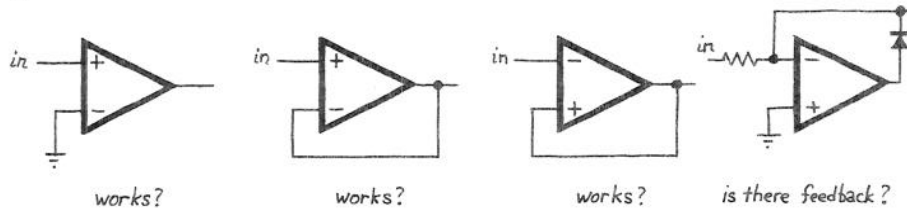


Figure N8.6: Do the Golden Rules apply to these circuits?

And will the output’s “attempt...” to hold the voltages at its two inputs equal succeed, in these cases?

p. 182, item “1”

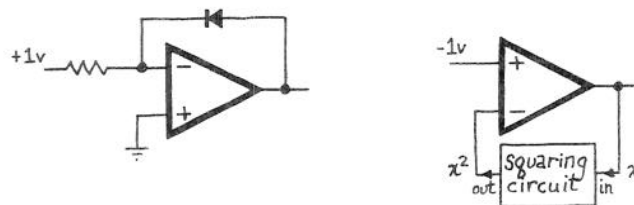


Figure N8.7: Will the output’s “attempt...” succeed here?

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*.

Current Source

Text sec. 4.07, fig. 4.11;
Lab 8-5

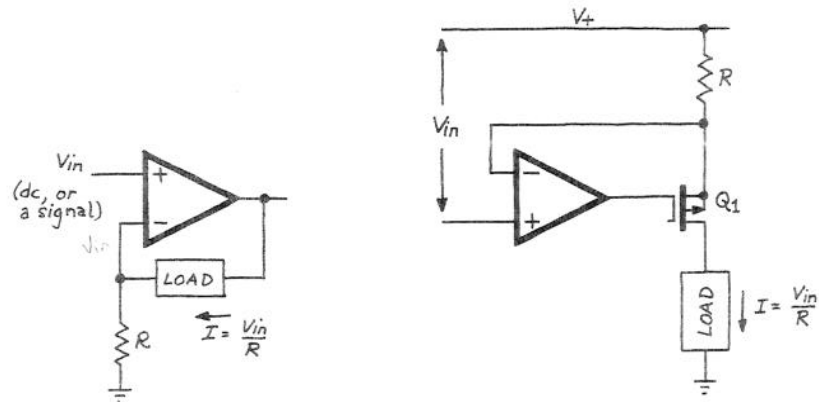


Figure N8.8: Op amp current sources

The right-hand 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 both the slope of the I_D vs. V_{DS} curve in the "saturation" region (a slope that reveals that the FET is not a perfect current source) and the more radical departure from current-source performance in the "linear" region—a region one must stay out of when using a naked FET. Are you beginning 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.

Summing Circuit

Text sec. 4.09,
p. 185 fig. 4.19;
Lab 8-7

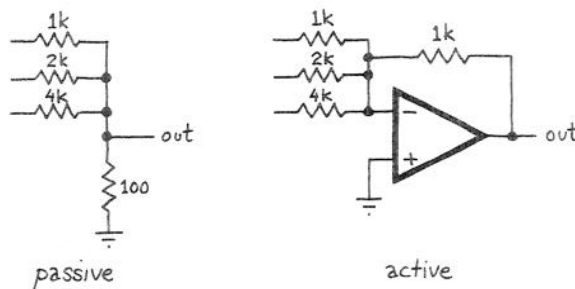


Figure N8.9: Summing Circuits

In the lab you will build a variation on this circuit: a potentiometer lets you vary the *DC offset* of the op amp output.

Followers

Text sec. 4.06;
sec. 4.09, p. 186

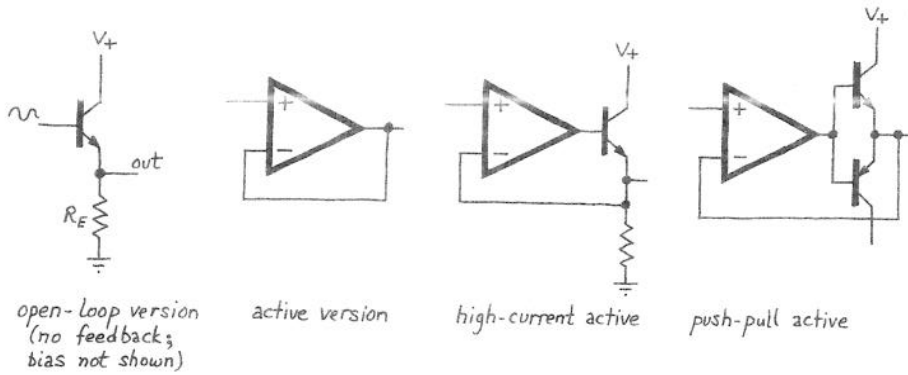


Figure N8.10: Op amp followers

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?

Current-to-voltage converter

Text sec. 4.09,
p. 184

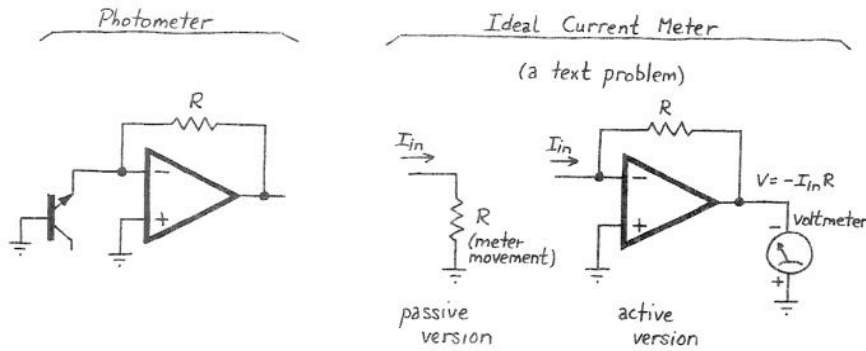


Figure N8.11: Two applications for I-to-V converter: photometer; "ideal" current meter

(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?)

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.

Here's the cheerful scheme:

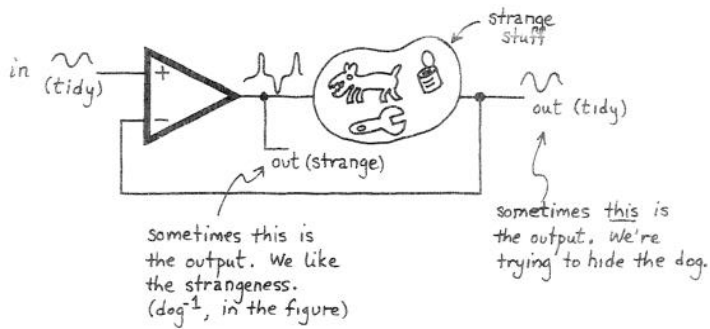


Figure N8.12: Op Amps can tidy up after strange stuff within the loop

In the push-pull follower, we treat the “tidied-up” signal as the output; the strange tricks the op amp output needs to perform to produce a tidy output do not interest us. In other circuits, however, the “strange signal” evoked by the “strange stuff” in the feedback loop may be precisely what *does* interest us. Here are two examples:

Compare Text sec. 4.14, p. 212, fig. 4.35

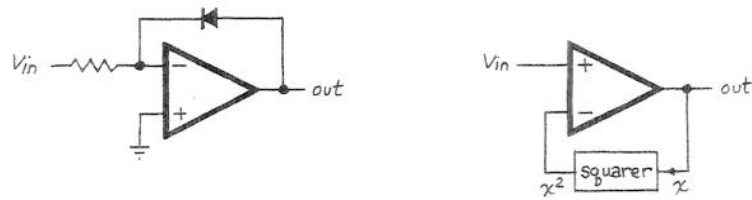


Figure N8.13: Two cases where we plant strange stuff in loop, to get “strange” and interesting op amp output

In both of these cases, far from trying to hide “the dog” (of Fig. N8.12, above), we are proud of him; so proud that we want to gaze at his image, which appears at the op amp output (the image is always dog^{-1} : inverse-dog).

In today's lab you will be so bold as to put the *oscilloscope* itself inside one feedback loop, with entertaining results:

Lab 8-6

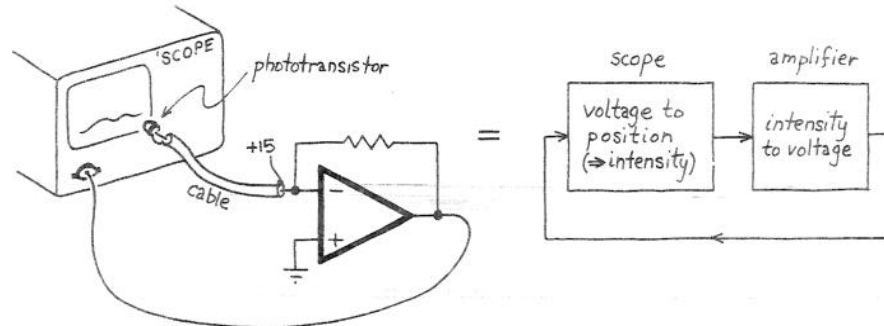
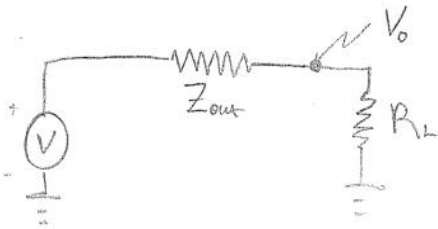


Figure N8.14: Scope brought within feedback loop: adjusts location of CRT beam

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 the Text's Chapter 4, see the books of application notes published by National Semiconductor, among others, or the application notes that follow many op amp data sheets, including the LF411's (see Text appendix K for the '411's data sheet).

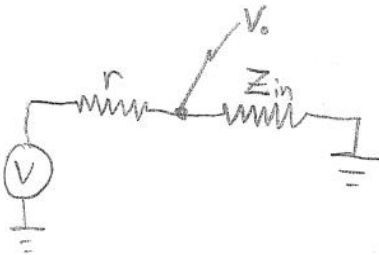
Measuring Z_{out}



$$V_o = \frac{R_L}{Z_{out} + R_L} V$$

$$\Rightarrow Z_{out} = R_L \left(\frac{V}{V_o} - 1 \right)$$

Measuring Z_{in}



$$V_o = \frac{Z_{in}}{Z_{in} + r} V$$

$$\Rightarrow Z_{in} = \frac{V_o}{V - V_o} \cdot r$$

Ch. 4: Worked Examples: Op Amps Idealized

Two worked examples:

1. an inverting amplifier
2. a summing circuit

1. • (-100) Amp

Problem: Inverting Amplifier

Design an inverting amplifier with a gain of -100 , to be driven by a source whose output impedance is high and uncertain: 100k to $1\text{M}\Omega$.

The inverting amp is easy enough, apart from the impedance issues:

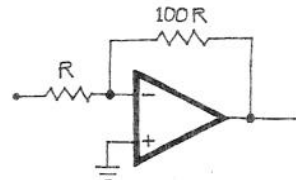


Figure X8.1: Inverting amplifier—but postponing the questions that call for some thought: part values

Will *any* pair of resistor values do, in the ratio $100:1$? Does the high and uncertain source impedance matter, here?

A plausible—but wrong—first response might be, ‘I don’t have to worry about source impedance, because op amps have giant input impedances: that follows from the second golden rule, which says the inputs draw no current.’

You don’t fall for that answer, though, because you can see that the golden rule describes how the op amp behaves, whereas what concerns us here is how the op amp *circuit* behaves. In this case, its input impedance is *not* the same as that of the op amp: the circuit input impedance is much lower. It is just R_1 :

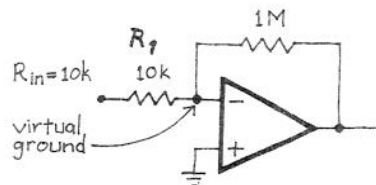


Figure X8.2: R_{in} of inverting amp: as low as R_1

And here’s a plausible—but wrong—solution: just make R_1 much bigger than R_{source} : make it, say, $10\text{M}\Omega$. That’s a good thought, but it implies that the feedback resistor should be 1000M — $1\text{G}\Omega$, and that is excessive, for reasons we will make sense of only when we admit that op amps are not quite as good as their idealized model.

Easy solution to the impedance problem: a follower

A follower solves the problem neatly:

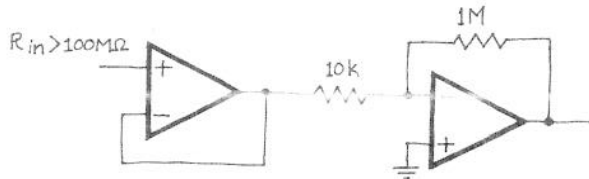


Figure X8.3: Follower buffers the input of the inverting amp

Now we can choose modest resistor values for the inverting amp, like those shown above. At first you may feel uncomfortable tacking in extra op amps to solve circuit problems. We hope you will soon get over this discomfort. A slogan worth remembering will recur in this chapter: *op amps are cheap*. They come 2 and even 4 to a package. One more op amp is no big deal, and often is the best way to refine a circuit.

2. 'Arithmetic'

Problem: Summing Circuit

Design a circuit that forms the following sum of the input voltages A , B , and C .

$$V_{\text{out}} = A + 2B - 3C$$

Again let's make the source impedances high and uncertain: 100k to 1M Ω , just to drum home our earlier point.

And here's a solution. It is so similar to the preceding problem that it does not call for much explanation. Let's do the problem with just comments in "balloons":

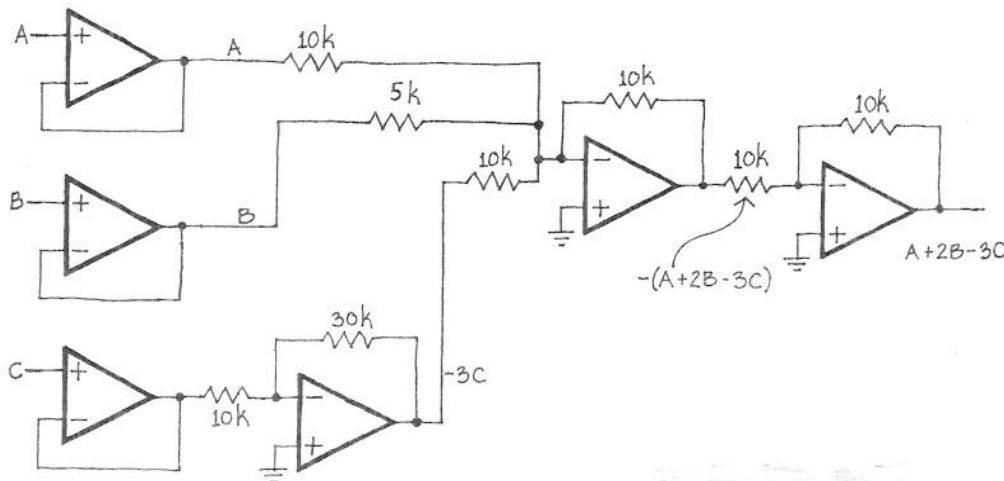


Figure X8.4: Summing circuit II

The function of this circuit— $V_{\text{out}} = A + 2B - 3C$ —recalls why op amps were given that name: they can do mathematical operations—and other, fancier ones such as multiplication and division as well, with the help of log amps.