Feedback Concept

- Amplifier with no feedback

- Amplifier with feedback (some of the output is applied to the input)

Positive feedback:
- Feedback causes the input to be enhanced
- Example:

  - A waveform travels around the loop (including sound wave in air) becoming bigger each time
  - Result: Whistling noise, i.e., oscillation at the frequency where gain is highest.
negative feedback

- feedback causes the input to be diminished
- results in less overall gain, but
  - better frequency response
  - better linearity
  - avoids oscillation

In general, negative feedback is desirable for amplifier circuits. Positive feedback is used for oscillators.
Op-Amps

"Operational Amplifiers"

It’s a differential amplifier, on a chip

"chip" = "IC" = "Integrated Circuit"

Schematic symbol

Pin diagram

Some pins on chip are not used
It's okay to draw the symbol upside down

Major things to know about op-amps

- It's a differential amplifier
- High input impedance (inputs draw little current)
- Low output impedance
  - Output can source current, although not as much as a power transistor

Open-loop behavior

If you do not provide external feedback, an op-amp's output will simply swing to one of the power-supply "rails":

- If \( V_+ > V_- \), \( V_{out} \rightarrow +V_{CC} \)
- If \( V_+ < V_- \), \( V_{out} \rightarrow -V_{EE} \)

This is like a comparator (see later in this chapter).
Three Op-Amp Rules (ideal op-amp)

6) Check for feedback loop

- If you provide an external feedback network with negative feedback, then rule (6) below will apply.
- Otherwise, the open-loop behavior mentioned above occurs.

1) \( V_{os} = 0 \)

- The difference between the two input voltages \( V_{os} \equiv V_+ - V_- \) will be zero.
- This is achieved through the negative feedback mechanism - the op-amp's output voltage will swing to whatever output \( V_+ \) is required to achieve \( V_+ = V_- \) on the inputs.

2) \( I_{bias} = 0 \)

The two inputs draw no current.

Exception to rule (1):
The output voltage cannot exceed the power supply voltages. Clipping of the output waveform will occur.
Inverting Amplifier

To analyze, we will follow our usual strategy:
1. Identify components & nodal
2. Write equations for these
3. Combine to eliminate variables
4. Solve for the desired parameter

What is the desired parameter?

For amplifiers, the gain is the most important parameter.

Other parameters of interest include:
- Input impedance
- Output
- Frequency response
- Power-supply requirements

Here we will solve for gain:

\[ A_V = \frac{V_{out}}{V_{in}} \]
Identify components & nodes:

- Opamp = 3 rules
- Resistors = Ohm's Law or Voltage Divider Rule
- Node A = Kirchhoff's Current Law

Rule 1. (a) neg. feedback is provided thru R2

Rule 2. \( V_+ = V_- \)

Here we see that \( V_+ = 0 \) because that input of the opamp is connected directly to ground.

Another name for \( V_- \) here is \( V_A \) because that input of the opamp is connected to node A.

\( \Rightarrow V_A = 0 \)

Rule 3. Opamp inputs draw no current.

Here we combine this with Kirchhoff's current law for node A to see that all the current flowing thru \( R_1 \) into node A must also flow out of node A thru \( R_2 \).

i.e. \( I_{R_1} = I_{R_2} \)
Ohm's Law:
\[ I_{R_1} = \frac{V_A - V_{in}}{R_1} \]
\[ I_{R_2} = \frac{V_{out} - V_A}{R_2} \]

examine the circuit diagram to see why this is the correct voltage drop across the resistor.

we've now exhausted our list of components & nodes that required equations.

next step is to combine the equations, eliminating variable to yield an expression for the desired quantity, \( \frac{V_{out}}{V_{in}} \).

\[ I_{R_1} = I_{R_2} \]
\[ \frac{V_A - V_{in}}{R_1} = \frac{V_{out} - V_A}{R_2} \]

use \( V_A = 0 \)

\[ -\frac{V_{in}}{R_1} = \frac{V_{out}}{R_2} \]

rewrite

\[ \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \]

Note: you should be able to duplicate this kind of analysis yourself.

multisym demo
Unity Gain Inverter

\[ \frac{V_{\text{out}}}{V_{\text{in}}} = -1 \]

discuss usefulness of this.

Follower

Analyze: list components & nodes: op-amp, nothing else
list equations:
- neg feedback
- \( V_+ = V_- \)

^ Here, \( V_- = V_{\text{out}} \)
^ Here, \( V_+ = V_{\text{in}} \)

Because these inputs are connected directly to the circuit input & output

(2) next page
(2) op-amp inputs draw no current

Here, the only significance of this is that the circuit’s input impedance will be the same as the op-amp’s (since they are directly connected)

\[ V_{in} \rightarrow \infty \]

which is a good thing.

From rule 1:

\[ V_{out} = V_{in} \]

"follower"

Discuss comparison to emitter follower

Discuss use: has high Z in,

low Z out

use it as a "buffer"

A circuit that provides a desired output voltage, but cannot drive much current

\[ X1 \text{ buffer} \]

load
Non-inverting Amp

![Circuit Diagram]

Analyze:

1. Identify components & nodes:
   - Op amp ⇒ 3 rules
   - 2 resistors ⇒ Ohm's Law or Voltage Divider rule
   - Node A ⇒ Kirchhoff's Current Law (easier, here)

2. Write equations:
   - Rule 1
     - Negative feedback thru $R_2$
     - $V_+ = V_-$
     - Here, $V_- = V_A$
     - Here, $V_+ = V_{in}$
     - $\Rightarrow V_{in} = V_A$
   - Rule 2
     - Op amp inputs draw no current
     - Combine with Kirchhoff's Current Law
     - All current thru $R_2$, must also flow thru $R_1$
we could use Ohm's Law for the two resistors, although doing so here would ultimately just re-derive the voltage divider rule, so we'll just use the one directly. Redraw the $R_1 - R_2$ network like this:

\[
\begin{align*}
V_{\text{out}} & \quad \downarrow \quad \frac{R_2}{V_A} \\
R_2 & \quad \downarrow \quad V_A \\
R_1 & \quad \downarrow \quad \text{sink}
\end{align*}
\]

where we have exploited the fact that no current flows from node A to the op-amp's input.

use voltage divider rule:

\[
V_A = V_{\text{out}} \frac{R_1}{R_1 + R_2}
\]

combine with Rule 1 result $V_A = V_{\text{in}}$ to:

\[
V_{\text{in}} = V_{\text{out}} \frac{R_1}{R_1 + R_2}
\]

\[
\left[ \frac{V_{\text{out}}}{V_{\text{in}}} \right] = 1 + \frac{R_2}{R_1}
\]

gain is pos & non-inverting
discuss how gain < 1 is not achievable here
Bad Op-Amp Circuits

1. Will this work as a buffer?
   A. No. Although op-amp rule #1 would indicate that $V_{out} = V_{in}$ as desired for a buffer, this circuit has a fatal flaw because feedback is positive, violating rule #1.

2. Will this work as a buffer?
   A. Yes, but the circuit has a non-fatal design error. The 1k resistor serves no purpose. A resistor is useful only if current passes through it, but because of op-amp rule #2 no current will flow through this one, so that no voltage drop will appear across it. You might as well replace it with a wire.
Q. Will this circuit work as a voltage adder?

A. No - design has a fatal design error: two outputs are connected directly together at node B.
Active Filters using Op-Amps

First, recall inverting amp using resistors:

\[ V_{\text{out}} = -\frac{R_2}{R_1} V_{\text{in}} \]

Generalize this, using impedances:

\[ V_{\text{out}} = -\frac{Z_2}{Z_1} V_{\text{in}} \]

Next, recall passive low-pass filter

\[ \frac{V_{\text{out}}}{V_{\text{in}}} \]

(response curve)

\[ (RC)^{-1} \rightarrow \omega \]
two attempts to design an active low-pass filter

(1)

\[ v_{out} = -\frac{1}{2\pi} \frac{V_i}{V_{in}} \]
\[ = -\frac{1}{j\omega R \text{Re}} V_{in} \]

Response curve:

\[ \text{|Vout/Vin|} \approx \frac{1}{\omega^1} \]

not good: gain \(\approx 00\) instead of \(\text{gain} \to \text{const} \) at low frequency

(2) improve design by adding resistor to feedback loop

\[ R_2 \]
\[ R_1 \]
\[ \text{in} \quad 0 \quad \text{out} \]

which looks like

\[ Z_L = \frac{Z_L}{Z_L + Z_L} \]

\[ Z_i = k_1 \]
\[ z_2 = \frac{Z_{r_2} Z_c}{Z_{r_2} + Z_c} \]

\[ = \frac{\frac{R_{r_2}}{j\omega C}}{R_{r_2} + \frac{1}{j\omega C}} \]

\[ = \frac{R_{r_2}}{j R_{r_2} \omega C + 1} \]

\[ V_{out} = -\frac{Z_c}{Z_{r_2}} V_{in} \]

\[ \frac{V_{out}}{V_{in}} = -\frac{R_{r_2}}{R_{r_1}} \left( \frac{1}{j\omega R_{r_2} C + 1} \right) \]

\[ \left| \frac{V_{out}}{V_{in}} \right| \rightarrow \begin{cases} \frac{R_{r_2}}{R_{r_1}} \text{ as } \omega \rightarrow 0 \quad \text{(a constant, that's \textit{what we want})} \\ \frac{1}{\omega} \text{ as } \omega \rightarrow \infty \end{cases} \]
Putting stuff in the feedback loop of an op-amp

Next, we will examine three circuits involving a diode junction where we will make an undesirable feature of the junction (diode drop & the temperature sensitivity of the diode drop) vanish. We’ll do this by putting the diode junction in the feedback loop of an op-amp.

The three circuits we’ll examine that do this:
- current source
- power booster
- ac to dc rectifier

**Op-Amp Current Source**

First, recall three earlier ways of making a current source:

1. Big resistor in series with voltage source

   \[ V_{in} \overline{R_{big}} \boxdownarrow I \]

   a simple resistor converts voltage source at input into current output

   Pros: simple

   Cons: poor compliance - (Iout will diminish a lot if connected to a high Z load)
(2) BJT & resistor combined w/ voltage source.

Here, $I_C$ is the regulated output current

$$I_C = \frac{(V_B - 0.6\,\text{Volts})}{R_E}$$

from Ohm's Law for $R_E$

Pros: 1. Improved Compliance
       2. Adjustable output current by adjusting input voltage applied to $V_B$

Cons: 1. Current depends on B-E diode drop which depends on temp
       2. more complex than the simple "big resistor" current source
(3) SFET current diode, combined with voltage source

n-SFET or p-SFET

Here, \( I_{\text{oss}} \) is the regulated output current

Pros: simplicity, only one component, just like the simple "big resistor" current source

Cons: very poor temperature dependence (\( I_{\text{oss}} \) varies 0.4% per °C)
next, two op-amp current source designs:

(1) simple op-amp current source

\[ V_n \rightarrow + \]
\[ - \rightarrow \text{load} \]
\[ R \rightarrow \]

To analyze, identify components & nodes & rules

op-amp rule (a) neg feedback w'ok

(1) \( V_{in} = V_n \)

(2) no current flows into
- input of op-amp

node A \( \rightarrow \) kirchhoff current law
combine w/ rule (2) result
\( \Rightarrow \) all current I thru load
must flow thru resistor

resistor \( \rightarrow \) ohm's law
\[ \text{current thru resistor} = \frac{V_n - 0}{R} \]
combine w/ rule (1) result
\( \Rightarrow \text{current thru resistor} = \frac{V_n}{R} \)**

combine ** & *** above \( \Rightarrow \)
\[ I = \frac{V_n}{R} \text{ is current thru load} \]
Pros: no B-E diode drop

Cons: inconvenient that neither side of load can be connected directly to GND or power-supply voltage — for many applications, this would not be useful

I thru load can't be very big because op-amps can output only milliamps of current

2) Op-Amp with BJT Current Source

This circuit is like the earlier BJT current source, except that the B-E diode drop problems are eliminated by putting the BJT's B-E diode junction in the feedback loop of an op-amp.
to analyze: identify components & nodes & rules

Op Amp Rule (0)  ok - neg feedback thru transistor

(1) \( V_h = V_{in} \)

(2) no current into input of op-amp

Node A \( \rightarrow \) Kirchhoff’s current law
combine w/ rule (2) result

\[ \Rightarrow I_E = \text{current thru } R_E \]

Ohm’s Law \( \rightarrow \) current thru \( R_E = (V_{cc} - V_h)/R_E \)
combine w/ rule (1) result & node A result \( \rightarrow \)

\[ I_E = \frac{V_{cc} - V_h}{R_E} \]

Transistor \( \rightarrow \) \( I_c \times I_E \)
combine with \( \times \) \( \rightarrow \)

\[ I_c = \frac{V_{cc} - V_h}{R_E} \]

\[ \text{is current thru load} \]

Pros: I thru load:

- doesn’t depend on B-E diode drop; temp dependance of B-E diode drop has no effect
- can be big, multiple amps, becuase transistor supplies current

Cons: Complexity
Power Booster

Another example of placing a B-E diode junction in the feedback loop of an op-amp.

Power Booster = Voltage Amplifier capable also of sourcing/sinking large currents, as would be required by a low Z load like a loudspeaker.

Problem:
- Emitter Follower can drive Amps of current but has no voltage gain. It also has an unwanted B-E diode drop.
- Op-Amp can provide voltage gain, but can source/sink only milliAmps of current.

Solution:
Combine Emitter Follower & Non-inverting op-amp amplifier, placing the BJT's B-E junction in the op-amp feedback loop.
Active Rectifier

Another example of placing a B-E diode junction in the feedback loop of an op-amp.

Problem with passive rectifier: no diode drop

\[ \text{signal diode} \]

\[ \text{1N4014} \]

\[ \text{in} \rightarrow \text{N} \rightarrow \text{out} \]

![Graph showing voltage waveforms](image)

- The actual waveform is lacking the portion of the input waveform between zero and 0.5 Volt.
- Even worse, if \(|V_n| < 0.5 \text{ Volt}\), the passive rectifier will have zero output!

Solution

- Place a diode in the feedback loop of a non-inverting op-amp circuit.

![Circuit diagram](image)

- The resistor "ties an input to ground"
aside: using a resistor to tie an input to ground

this is a use of resistors we haven't
seen before

problem: if a circuit's input
is sometimes unconnected,
it's output, will be
unpredictable

solution: tie input to ground w/ resistor:

circuit input will be
established at zero volts
if no input otherwise
has no input

now back to the active rectifier

to analyze: identify components 
& nodes 
& roles

diode: two cases:
  - if forward biased
    by more than 0.5 Volts:
    - diode conducts
    - voltage drop across diode
      of 0.5 Volt
  - otherwise - no conduction
op-amp:

Rule (0) - If diode conducts, satisfied external feedback thru diode

- If diode does not conduct, not satisfied

op-amp has no feedback, so Rule (0) will not apply, & op-amp output will swing to rails +Vcc or -Vee depending on which op-amp + or - input is more positive.

Rule (1) - If diode conducts,

\[ V_+ = V_- \]

Note: \( V_- \) is connected directly to \( V_{out} \) =>

\[ V_- = V_{out} \]

\( V_+ \) is connected directly to \( V_+ \) =>

\[ V_+ = V_\pm \]

=> \( V_{out} = V_\pm \)

- If diode does not conduct, rule (1) does not apply. See above.

Rule (2) no current flows into - input of op-amp
Kirchhoff's Current Law:

for this circuit, we won't actually need the results of Rule (2) or Kirchhoff's current law.

resistor:

ties op-amp input to ground, so that ... will be at zero volts if no diode does not conduct.

combine these results:

two cases

If $V_n > 0$, diode conducts *

$V_{out} = V_n$

If $V_n < 0$, diode does not conduct

$V_{out} \rightarrow -V_{ee}$

* Internal to circuit, $V_e = V_n + 0.5$ Volt

diode drop

is op-amp's output voltage, which is ... provided in order to satisfy Rule (1)
active rectifier result:

\[ V_{out} = \begin{cases} 
V_n & \text{if } V_n > 0 \\
0 & \text{if } V_n < 0 
\end{cases} \]

Note the advantage of this circuit, as compared to passive rectifiers, that the diode drop does not affect the output voltage!
active rectifier (continued)

Let's look at what the op-amp's output (internal to circuit) does:

\[ V_{in} \]
\[ V_{out} \]
\[ V_{ce} \text{ (output of op-amp)} \]

0.5V

\[ \frac{1}{T} \]

op-amp output goes into negative saturation when there is no ext feedback & the - input of op-amp is more positive than the + input
Real-life limitations of op-amps

Until now, we have assumed ideal behavior of op-amps.

However, op-amps do not perfectly obey rules 1 & 2.

Does it matter?

For some circuit applications yes, others no. You must understand these limitations when you design a circuit, and ask yourself whether they will affect your design.

Let's look at the various limitations:

1. Finite Slew Rate dV/dt
2. Input Bias Current Iᵦ
3. Input Offset Voltage Vₒᵦ

There are others, also, but these are the most important.

1. Finite Slew Rate

Voltage at an op-amp's output can change no faster than the op-amp's "slew rate"
Finite slew rate (cont.)

<table>
<thead>
<tr>
<th>op-amp</th>
<th>slew rate</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>741</td>
<td>0.5 V/μs</td>
<td></td>
</tr>
<tr>
<td>411</td>
<td>15.0 V/μs</td>
<td></td>
</tr>
<tr>
<td>&quot;damn fast&quot;</td>
<td>6000 V/μs</td>
<td>expensive</td>
</tr>
</tbody>
</table>

Q. When does slew rate matter?

1. When voltage changes are large & sudden (as in active rectifier)
2. Or when frequencies are high (above audio frequency)

For Active Rectifier:

- Actual circuit output (red) will differ from ideal (black)
- Ideal waveform (no slew rate)
- Actual waveform (finite slew rate)
2. Input Bias Current $I_B$

Rule (2) isn't perfectly satisfied:
inputs to op-amp actually draw non-zero current $I_B$

<table>
<thead>
<tr>
<th>op-amp</th>
<th>$I_B$</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>741</td>
<td>100,000 pA (BJT input)</td>
<td></td>
</tr>
<tr>
<td>411</td>
<td>50 pA (FET input)</td>
<td></td>
</tr>
</tbody>
</table>

much better

Q. When does Input Bias Current matter?

A. When small currents flow through feedback network, the unwanted $I_B$ can be significant. This can easily happen if you use Mega-Ohm resistors instead of Kilo-Ohm...
Input Bias Current (cont.)

example: non-inverting amplifier

The unwanted current $I_B$ from node A into op-amp input must flow thru $R_1$ and/or $R_2$, and this will cause an unwanted voltage drop across $R_1$ & $R_2$ due to Ohm's law. If output voltage of circuit will not obey the expected $\frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1}$, the discrepancy will be most severe if:

- desired voltages (your signal) are small (µV or mV)
- resistors $R_1$ & $R_2$ are big (MΩ)

so that desired currents at node $\Theta$ are small (2 nano-Amp)
3. Input Offset Voltage $V_{os}$

Rule 0: isn't perfectly satisfied:

instead of ideal $V_+ = V_-$ at inputs
of op-amp,

what happens is $V_+ = V_- + V_{os}$

input offset voltage (due to manufacturing
variations)

<table>
<thead>
<tr>
<th>Op-Amp</th>
<th>$V_{os}$</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>741</td>
<td>2 mV typ.</td>
<td>6 mV max</td>
</tr>
<tr>
<td>411</td>
<td>0.8 mV typ</td>
<td>costs $1</td>
</tr>
<tr>
<td></td>
<td>2.0 mV max</td>
<td></td>
</tr>
<tr>
<td>LTC-1150</td>
<td>0.005 mV max</td>
<td>&quot;precision op-amp&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>costs $7</td>
</tr>
</tbody>
</table>

two choices if you need a very low $V_{os}$:

* buy an expensive precision op-amp
* add "trim-pot" between pins 1 & 5
Input Offset Voltage (continued)

Q. When does $V_{os}$ matter?

A. When your signal is small ($\mu V$ or $mV$)

Example: Inverting amplifier

The effect of $V_{os} \neq 0$ is like having a fixed voltage drop from a battery between the op-amp's - in and + inputs.

Ideal ($V_{os}=0$)

- $V_{in}$
- $I$ $\rightarrow$ $1k$ & $\rightarrow$ zero volts
- $I$ $\downarrow$ $\rightarrow$ $10k$

$V_{out} = 0 - (I)(10k\Omega)$

$\Rightarrow V_{out} = \frac{-10k\Omega}{1k\Omega}V_{in}$

Actual ($V_{os} \neq 0$)

- $V_{in}$
- $I$ $\rightarrow$ $1k$
- $4 \rightarrow V_{os}$
- $I$ $\downarrow$ $\rightarrow$ $10k$

$V_{out} = V_{os} - (I)(10k\Omega)$

$\Rightarrow V_{out} = \frac{-10k\Omega}{1k\Omega}V_{in} + 2V_{os}$
Input Offset Voltage (continued)

example, continued
so, the circuit output voltage will have a constant DC bias of $2V_{os}$ which is undesired

since $V_{os} \approx 1mV$, this is not a big problem if your expected output voltage is big (~1V)

but it is a problem if your expected output voltage is a few mV or smaller - then you must buy a precision op-amp or trim the cheaper op-amp with a trim-pot.
Comparators

- A chip that compares two analog input voltages to determine which is more positive.

- Used in:
  - Analog circuits, typically as a trigger
  - Analog-to-digital conversion
Comparator

Recall Op-Amp behavior:

A. What happens if you do not provide external feedback.

A. The op-amp is then just a high-gain differential amplifier. Its output will:

\[ V_{at} \rightarrow \begin{cases} +V_{cc} & \text{if } V_+ > V_- \\ -V_{ee} & \text{if } V_+ < V_- \end{cases} \]

**Comparator** is like an op-amp but it is intended to be used without a feedback network. It will behave as described above.

- Useful to determine which of two signals is larger.

- LM311 is a popular comparator.

\[ \text{It has one peculiarity you must know about: if you use one, it has an "open-collector output."} \]
Example: Provide an output signal that indicates whether an input voltage is positive or negative, i.e., \( V_n > 0 \) or \( V_n < 0 \).
you can choose another voltage as the "threshold" or reference voltage for a comparator.

[Diagram of a comparator circuit with +15V and -15V inputs, a threshold level at +3.0V, and output levels depicted over time.]
A complication for comparators: Noisy input signals

Schmitt Trigger Input

- Feature built into some comparators & logic chips to reduce glitches

The trick: Use two different thresholds for input:
  - Upgoing threshold: +5.0V
  - Downgoing: +4.76V
Schmitt trigger, input for comparator, continued

- $+5.0 V$ upgoing threshold
- $+4.76 V$ downgoing threshold

Small amplitude noise does not cause a change in output voltage.
aside: about open-collector outputs

the manufacturer did not "finish" the circuit inside the chip. you must finish it by adding external parts, typically like this:

pnp transistor inside the chip