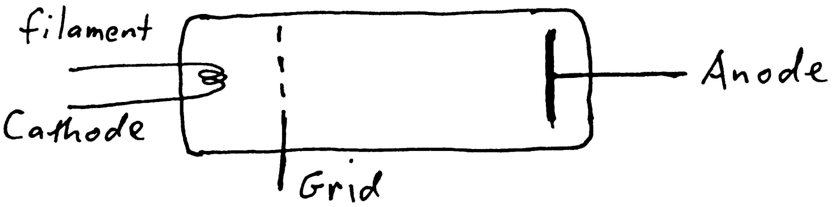
Phys. 334 **Day 4 Lecture Notes**

Gain, Feedback, and Operational Amplifiers:

The devices we have seen in the first 3 weeks, resistors, capacitors, inductors, and diodes are all two terminal passive devices, each providing a different relationship between the voltage applied across the device to the current that flows through the device. We now want to turn to active devices, that is, devices that can amplify voltage or current.

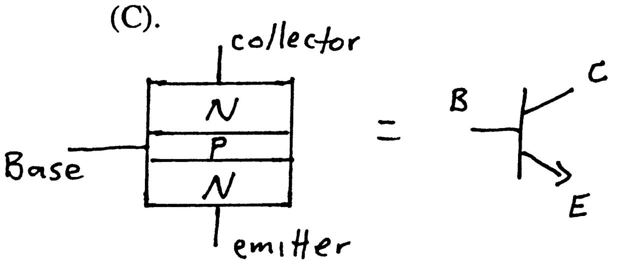
Before semiconductors, the standard amplifier was a vacuum tube triode, shown below. It is like the vacuum tube diode (Week 3 notes) but has an additional connection, called the 'grid' which is an open screen placed between the cathode and anode.

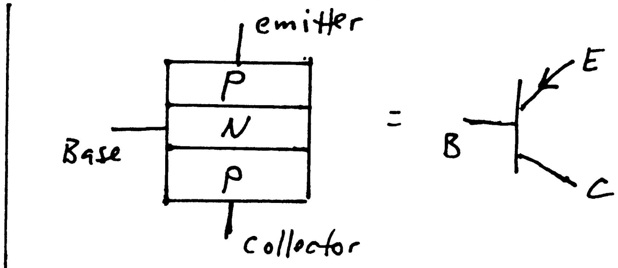


When current is flowing between anode and cathode, if the voltage on the grid is changed, ΔV_{grid}, this will repel or attract more electrons and will cause the anode current to change: $\Delta I_{anode} \propto \Delta V_{grid}$. Now if the anode current is passed through a resistor, then the voltage drop across the resistor, $\Delta V_{out} = \Delta I_{anode}R$, and you can have $\Delta V_{out} > \Delta V_{grid}$, ie voltage gain (amplification).

Transistors:

With semiconductors, the building block for amplification is the transistor: just a layer of P-type semiconductor sandwiched between two layers of N-type semiconductor (NPN transistor) or the opposite (PNP transistor). Let's have a brief look at these 'bipolar' transistors. Connections are made to each layer and are called the 'emitter' (E), base (B), and collector (C).





Because each N-P interface makes a diode (current flows from P to N), the transistor is constructed like back to back diodes, but is not used as such. Instead, it operates as follows for NPN transistors:

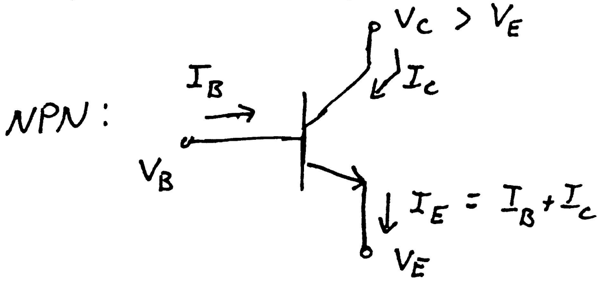
1.) We require that $V_C > V_E$.

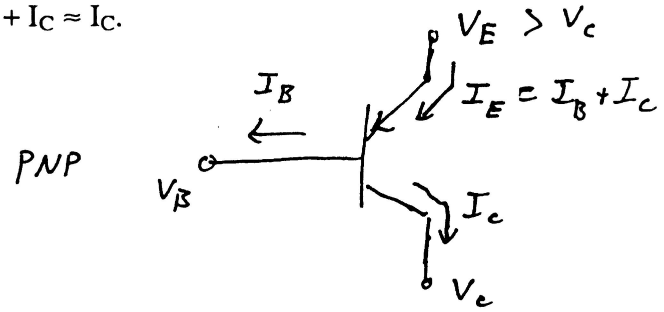
2.) We ensure that $V_B - V_E = 0.6$ Volts, so that the base-emitter diode is turned on.
Note, these two conditions guarantee that $V_B - V_C < 0.6$ V, so that the emitter-collector diode is always off.

It turns out that when current, I_B, flows through the base to emitter, it cancels the internal electric field within the P-layer and allows current, I_C, to flow from the collector to emitter.

3.) When conditions 1 and 2 are met, $I_C = \beta I_B$, where β is the current gain factor and is typically between 50 and 200, ie the transistor provides current amplification.

4.) The current flowing out of the emitter $I_E = I_B + I_C \approx I_C$.





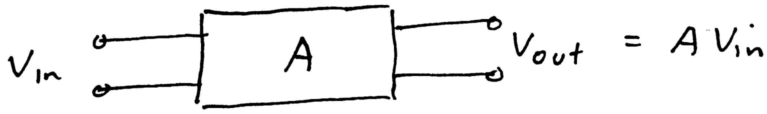
We can use transistors for voltage amplification as well by turning the current into a voltage with a resistor. For PNP transistors, you use the same rules but reverse the signs of all of the voltages and currents.

The key to using transistors in a circuit is to guarantee that conditions 1 and 2 are met, that is, to 'bias' transistor so that it is in its operating region. Chapters 2 and 3 in your text cover these topics in detail and you are encouraged to read these chapters. On the other hand, clever people have developed many clever and efficient transistor circuits and have packaged these circuits into easy to use modules. Operational amplifiers are high-gain, easy to use transistor circuits that are packaged as a unit. Most electronics today is designed around op-amps as the building block rather than individual transistors. For this reason, we will next look at op-amp circuits, and only talk about individual transistors when we need them.

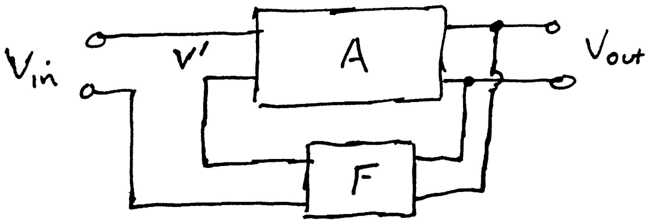
Feedback:

When using devices with high gain (large amplification), feedback is almost always present, either intentionally or unintentionally. Feedback describes when the output (or outcome of some action) is used to modify the input (or control of that action). For example, driving a car, riding a bicycle, or getting grades on homework. In electronics, feedback refers using some of an output voltage or current to modify the input voltage or current that produces that output.

As a simple model for feedback, consider an ideal amplifier with voltage gain A: $V_{out} = AV_{in}$



And now consider adding a circuit that adds a fraction, F, of V_{out} back to V_{in}.



$$V' = V_{in} + F V_{out}$$

$$V_{out} = A V'$$

Then, $V_{out} = A(V_{in} + FV_{out})$, or $V_{out}(1 - AF) = AV_{in}$, or $V_{out}/V_{in} = A/(1 - AF) = 1/(1/A - F)$.

Now, if $|A|$ is very large (and we'll see that it is often $\approx 10^5$), then we can neglect $1/A$ relative to the feedback fraction, F, and find to good approximation that:

$$V_{out}/V_{in} = -1/F$$

Without feedback, the amplifier has an 'open loop gain' = A, while with feedback, the 'closed loop gain' is $-1/F$.

Negative Feedback: If $AF < 0$ (ie A and F have opposite signs), the feedback is called negative feedback and the closed loop gain is always less than A (because $V_{out}/V_{in} = A/(1 + |AF|)$). For large $|AF|$ the closed loop gain = $-1/F$, independent of A as shown above.

Positive Feedback: if $AF > 0$ (called positive feedback), the closed loop gain is greater than A because our analysis above breaks down. The reason is that we assumed that $1/A << F$ or equivalently that $AF >> 1$. However, even if A is very large at DC or low frequencies, it will always get smaller at high enough frequencies (where stray capacitance acts like a short circuit). There will always be a frequency at which AF = 1 exactly. At that frequency, V_{out}/V_{in} becomes infinite and the amplifier oscillates (output with no input).

Positive feedback is used to make oscillators. It can also be a royal nuisance: sometimes the phase of negative feedback gets shifted by 180° by time delays in the amplifier or feedback circuit and turns into positive feedback, and the amplifier breaks into oscillation. One of the toughest jobs when using negative feedback is to provide 'compensation' to prevent positive feedback.

Except for a few specific applications (like building an oscillator, a comparator, or a Schmidt Trigger) positive feedback is avoided at all costs. Instead, negative feedback is used and has wonderful consequences for amplifier circuits. Some general features are listed below.

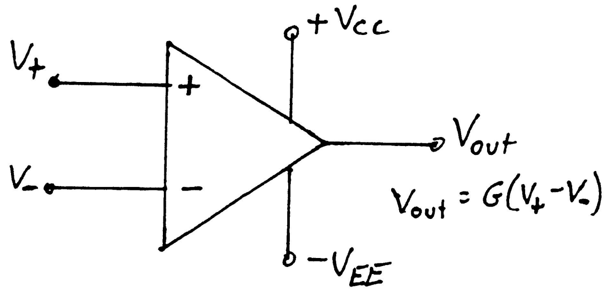
a.) The property that is sampled to produce the feedback is improved by the feedback.
b.) Feedback proportional to the output voltage produces a well-defined output voltage (ie a low output impedance).
c.) Feedback proportional to the output current produces a well defined output current (ie a good current source or high output impedance).
d.) Feedback added to the input voltage produces an output proportional to the input voltage (ie a high input impedance).
e.) Feedback added to the input current produces an output proportional to the input current (ie a low input impedance).

We will next see some of the ideas at work in operational amplifiers.

Operational Amplifiers:

An op-amp is a high gain differential amplifier. There are two inputs, labelled + and –. The + input is called the 'non-inverting input' and the – input is called the 'inverting input'.

There is a single output and typically 2 connections to external DC power supplies (V_{CC} is the positive DC power connection and $-V_{EE}$ the negative). Op-amps have the following properties:



1.) $V_{out} = G(V_+ - V_-)$: The voltage difference between the two inputs is amplified (hence the name 'differential amplifier').

2.) G = open loop voltage gain $\approx 10^4 - 10^6$ at DC and low frequencies (hence 'high gain').

3.) V_{CC} and V_{EE} are typically between 10 and 20 Volts and V_{out} cannot exceed these values.

Note, the + and – input symbols do not mean that only + and – voltages can be applied to these inputs. Instead, they tell you that what is amplified is $V_+ - V_-$.

The open loop gain, G, is so large even a tiny voltage difference between the inputs, say 1 mV will cause the output voltage to try to become 100 - 1000 Volts. (It can't, of course, the output would 'saturate' at a voltage of V_{CC} or $-V_{EE}$). We seldom need such a high gain. This high gain becomes most useful when we sacrifice some of it by using negative feedback. Remember, with negative feedback, the closed loop gain became $-1/F$, independent of A (which I'm now calling G), where F was the fraction of the output that was added back to the input.

Unless told otherwise, we will now always use negative feedback with op-amps. Negative feedback for op-amps means adding some of the output back to the inverting input, V_-. With negative feedback, op-amps follow two Golden Rules:

I.) The output attempts to do whatever is necessary to make the voltage difference between the inputs equal to zero.

II.) The inputs draw no current.

Some silver rules:

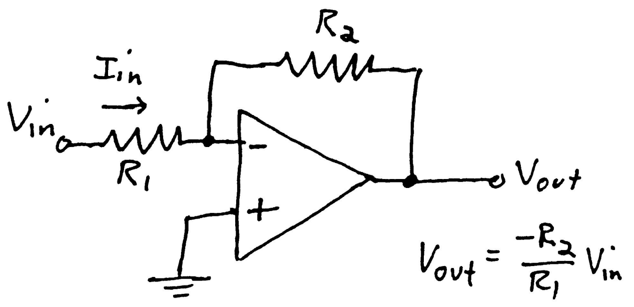
a.) The output range is limited. Some op-amps outputs can nearly reach the power supply voltages but most get to within about 2 Volts of the power supply voltages.

b.) The input range is limited. Don't allow $V_+ - V_-$ to exceed a few volts.

c.) Always have DC feedback as well as AC or the output will saturate (a very small DC current flows out of the inputs).

Op-Amp Circuits:

We will begin by using the Golden Rules to understand op-amp circuits.



Inverting Amplifier:

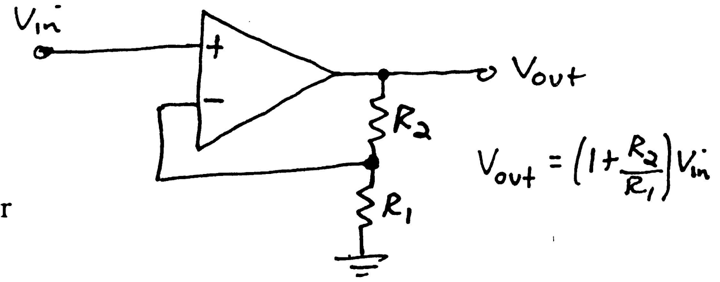
Rule I. $V_- = 0$ because $V_+ = 0$
(ie the output does what it must to make $V_- = V_+$)

Rule II. $I_{in} = V_{in}/R_1$
And this current also flows through R_2 because the input to the op-amp draws no current.

$$V_{out} = -I_{in} R_2 = -V_{in} R_2/R_1$$

Note, $Z_{in} = \Delta V_{in}/\Delta I_{in} = R_1$ and $Z_{out} = \Delta V_{out}/\Delta I_{out} \approx 0.1\ \Omega$ (typical Z_{out} of an op-amp).

This is a DC and AC inverting amplifier with a voltage gain of $V_{out}/V_{in} = -R_2/R_1$. It's major short-coming is its relatively low input impedance, Z_{in} (remember large Z_{in} and small Z_{out} are what we usually strive for). The small Z_{in} is a consequence of adding a current back to the input.



Non-Inverting Amplifier:

Rule I. $V_- = V_+ = V_{in}$

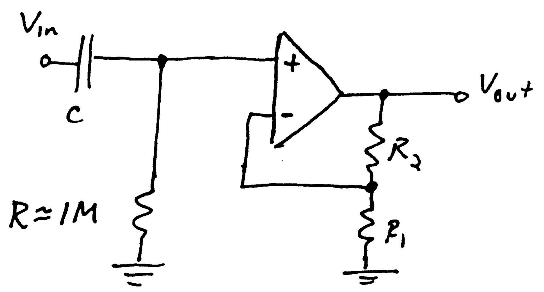
Rule II. Because no current flows into the inverting input, V_- is created by the voltage divider of V_{out}, R_2, and R_1: $V_- = V_{out} R_1/(R_1 + R_2)$.

$$V_{out} = (1 + R_2/R_1)\ V_{in}$$

Now, $Z_{in} \approx 10^8 - 10^{12}$ (typical input impedance of an op-amp) because we are adding a voltage to the input.

This circuit is a DC and AC non-inverting amplifier with voltage gain = $1 + R_2/R_1$.

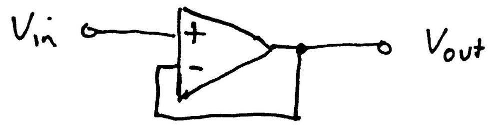
If we wanted an AC amplifier only, you could use a capacitor on the input to block the DC input voltage, but you would need to remember to add a resistor to ground as well (to provide a path for the small input current of silver rule c.)



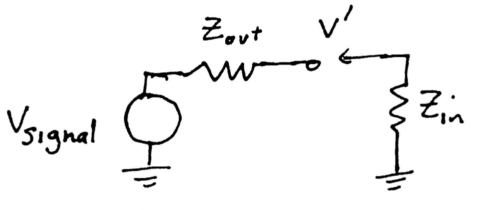
Follower/Buffer:

$$V_{out} = V_- = V_+ = V_{in}$$

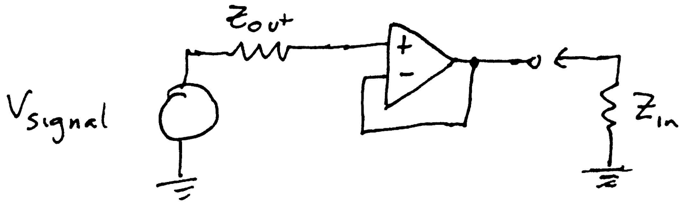
$Z_{in} \approx 10^{12}\ \Omega$ and $Z_{out} \approx 0.1\ \Omega$ It seems that this circuit does nothing, $V_{out} = V_{in}$, but in fact it is a very useful and common circuit. It is the answer to our problem of how to connect a circuit or signal with a high output impedance to another circuit with a small input impedance.



If $Z_{out} > Z_{in}$, then connecting the circuits forms a voltage divider that reduces the signal voltage: $V' = V_{signal} Z_{in}/(Z_{out} + Z_{in}) << V_{signal}$.

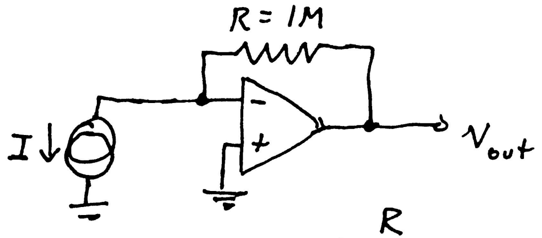


To solve the problem, put an op-amp follower between the two circuits. Now Z_{out} 'sees' the high input impedance of the op-amp while Z_{in} 'sees' the low output impedance of the op-amp.

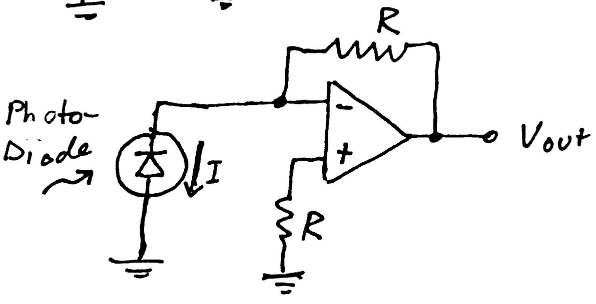


Current to Voltage Converter:

$V_{out} = I \times 10^6$ (V_{out} = 1 Volt/μA)



Your source of current might be a photo-diode or photo-transistor (which convert light to current). One problem is the small current that flows out of the op-amp V_- input now has to flow through the 1 M resistor (the current source has an even higher impedance), making the DC value of $V_{out} \neq 0$. But the current that flows out of the V_+ input is nearly equal to that of the V_- input (called the input 'bias current'). To re-zero V_{out}, all you need to do is add a 1 M resistor to V_+ as well. Now, $V_+ = V_-$ when $V_{out} \approx 0$.



Summing Amplifier:

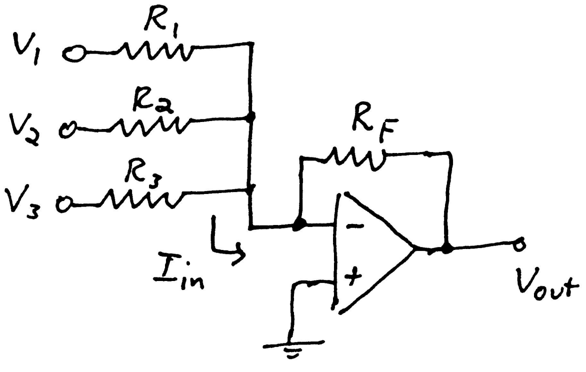
$V_- = V_+ = 0$

and $I_{in} = V_1/R_1 + V_2/R_2 + V_3/R_3$

and $V_{out} = -I_{in} R_F = -R_F(V_1/R_1 + V_2/R_2 + V_3/R_3)$

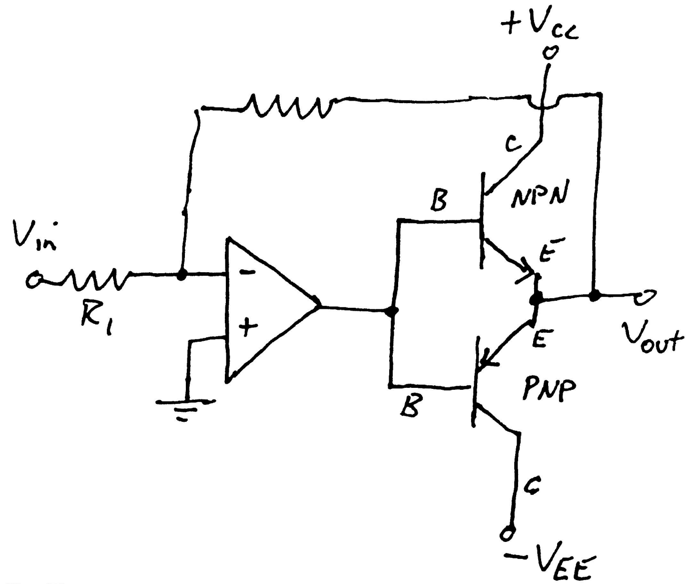
Let $R_1 = R_2 = R_3 = R_F$

Then $V_{out} = -(V_1 + V_2 + V_3)$



Or, You could take $R_3 = 2R_2 = 4R_1 = 4R_F$ and then $V_{out} = -(4V_3 + 2V_2 + V_1)$ = binary equivalent of the input voltages: this forms the basis of digital to analog conversion.

Power Booster:



Op-amps can typically provide only ≈ 20 mA of current from their output. If you need more current, you can add transistors to the output (remember, transistors provide current gain). A common way to boost the output current is with the 'push-pull' configuration shown to the right. (Remember, when the base emitter diode of the transistor is on, the current flowing out/ into the emitter is ≈ 100 x the current flowing in/out of the base emitter diode.)

Like before, $I_{in} = V_{in}/R_1$ and $V_{out} = -I_{in} R_2 = -V_{in} R_2/R_1$

but now, the transistor provides 99% of the output current. The op-amp makes its output equal to $V_{out} + 0.6$ Volts to turn on the NPN transistor when $V_{out} > 0$ (the PNP transistor is then off) and when $V_{out} < 0$, the op-amp makes its output equal to $V_{out} - 0.6$ Volts to turn on the PNP transistor (turning the NPN transistor off). The output stage of most audio amplifiers are push-pull transistors to provide the current needed to blast your speakers.