The question at the end of last class was how to design with feedback. We’ll see a few examples, but let’s look at the essentials. The non-inverting input can collect any number of signals and these will be added to the output. The inverting input can also collect any number of signals and these will be subtracted at the output. The importance of any one signal is determined by the current of that signal into either input (recall that the input has a constant impedance and so the current controls the internal voltage. The feedback network sets the overall gain.
Of course the feedback sets a frequency constant gain if it consists of a frequency independent component (a resistor). If the feedback loop is frequency dependent then the gain will vary with frequency. In the above example the resistor sets the gain for most frequencies, but the LC circuit is a short on resonance \(2\pi/LC\) and thus this frequency component is suppressed. Note when the feedback current is increased the gain is reduced.
Feedback determines the gain #2

Feedback is R except at the resonance frequency, where it is made higher. This selectively amplifies the resonance frequency.

∴ Can add/subtract amplify and do this selectively of input and Selectively of frequency.

Here we accomplish just the opposite, the resonance circuit suppresses the resonance frequency (passes all others) and so the feedback current is suppressed at the resonance frequency and thus the gain is highest there.
The summing amplifier is a slightly more complicated version of the inverting amplifier, but now there are two voltage sources contributing to the input. Again we simply require that the sum of the currents into the inverting input are zero, and go through the algebra to show that this does indeed act to sum the inputs. Notice that the relative resistors determine how each voltage contributes and the ratio of the feedback resistor to the input resistors gives the gain.
Here we wish to look at the difference of two inputs (exactly what an op amp is supposed to do), but with a lower gain than would be seen if we drove the op amp directly. To analyze this we use both rules (1) that the current into the inverting input is zero, and (2) that the voltages are equal. Notice that in this case when we calculate the currents we cannot assume that the voltage at the op amp is zero (nothing is pulled to ground in this case). So in the calculation of the current at the inverting input we introduce the inverting voltage as a free parameter. Of course this will latter be set the the voltage at the non-inverting input which is known.
An integrator shows what can be accomplished with a frequency dependent feedback. In this case the feedback path you should pay attention to is the capacitor (the 10 meg resistor is included to provide a feedback path for DC signals and thus provide stability for the op amp - forget it for now). One way to think about this is to picture the capacitor as charging and providing a voltage offset between the output and the input. The rate of charging depends on the RC time constant. Again the circuit is analyzed by setting the currents equal and then integrating to find the output voltage. As R or C is increased the rate of charging decreases.
Assume that the waveform is more complex and we want to integrate for a fixed period of time and then reset the integrator and start over.

1. What do you need to do to the circuit to reset the integrator.
2. Using a JFET, how would you do this?

Just a problem to think about and to help you remember that JFETs are useful devices as well. In fact for this application a MOSFET or JFET is much better than a BJT.
The differentiator has the capacitor in the input with a feedback resistor. Again we look at matching currents going into the inverting input and see that the output voltage is the derivative of the input voltage. Again the time constant is just the RC time constant. The 100 pF capacitor provides high frequency stability (avoids the circuit oscillating).
Positive feedback drives the op amp into saturation faster than it would normally. Notice that part of the output is fed to the non-inverting input.
Positive Feedback
Positive feedback drives the op amp even harder into saturation. But it also introduces a hysteresis.

Look at the values of $V_{in}$ required for $V_+ = 0$

$V_{in} = \pm V_{cc} \frac{R_1}{R_2}$

Here we have another example of hysteresis. I’ll explain this on the board and hand out another page with notes. The concept of hysteresis is seen in the switching properties. When the output is saturated at $+V_{cc}$ the input voltage must be dragged down to $- \frac{R_1}{R_2} V_{cc}$ to switch, but when the output is $-V_{cc}$ the input switches at $+ \frac{R_1}{R_2} V_{cc}$. So in between these two switching points we don’t know (from just looking at $V_{in}$) if the output is positive or negative - it depends on the history. The slide is poorly done, so look at the notes I hand out until I fix this.
Positive Feedback

Note: there is essentially no current into $V_+$. 

$\therefore$ Current through the resistors is 

$$\frac{\pm V_{CC} - V_{in}}{R_1 + R_2}$$

and the voltage drop across $R_2$ is 

$$\frac{R_1}{R_1 + R_2} (\pm V_{CC} - V_{in})$$

$\therefore$ the voltage at $V_+$ is 

$$V_+ = \pm V_{CC} - (\pm V_{CC} - V_{in}) \frac{R_2}{R_1 + R_2}$$

We want to find $V_{in}$ when $V_+ = 0$ (then $V_- = V_+$) 

$$V_{in} = \frac{R_1 + R_2}{R_2} \mp V_{CC} \pm V_{CC} = \left(\frac{R_1}{R_2}\right) V_{CC}$$
A simplified schematic of the transistor model of the 741. It is not easy to walk through this, but with the sections identified you should be able to get an idea.
Op amp specs.

- CMRR - common mode rejection ratio. Op amps also amplify the average of $V_+ + V_-$. CMRR measures the attenuation of this.
- Voltage gain ($A_v$) - typically $10^4$ to $10^6$ (80 to 120 dB).
- Slew rate - the maximum rate of change of the output voltage with time.
- Unity gain frequency ($f_T$) = frequency at which the gain drops to 1.
- Output current - maximum current the op amp can provide.

Characteristics to think about when choosing an op amp. There are many to choose from with designs optimized for:
1. Linearity
2. Switching speed
3. High frequency applications
4. Low common mode signals
5. Power ranges
### Typical Op amp specs.

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<th>supply voltage min (V)</th>
<th>supply voltage max (V)</th>
<th>current mA</th>
<th>voltage offset mV</th>
<th>slew rate V/µs</th>
<th>fT MHz</th>
<th>CMRR dB</th>
<th>gain dB</th>
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</table>

A few common examples of op amps. The lab uses the 741.
Offset compensation

Input offset voltage adjustment.

Short the inputs together and adjust the potentiometer to zero the output.

There are additional pins on the 741 to adjust and offset null. This can be used to correct for current mismatches into the inputs, so if the source loads are not the same you can remove the op amp bias in this fashion.
Offset compensation
Input offset current adjustment.

The input bias current into (-) introduces an output voltage offset. The compensating resistance balances this. Not necessary with FET (pA) op amps, but important for bipolar (nA) devices.

This is a better method of correcting the offset bias. Since FET devices have very low input currents this is rarely necessary, but with BJT devices the offsets are easily seen.
It is the slew rate that determines the power bandwidth of an op amp, so by reducing the gain of an amplifier you can increase the frequency response.

\[ f_{\text{max}} = \frac{\text{slew rate}}{2\pi \text{peak output voltage}} \]

So for a slew rate of 5 V/\(\mu\)s and a peak output voltage of 10 V the maximum frequency of an undistorted sine wave is 80 kHz.

The slew rate reports the dynamical properties of the op amp (how fast the output can vary). Since this is best reported in volts/time, it does not directly provide a limit on the frequency. However, in combination with the size of the output signal it does provide a limit.
Go to the manufacturer’s web site to obtain a datasheet of their product. Please follow these steps:

2. View the conditions of use for the web site by following the link on the home page called Site Terms and Conditions of Use, or by following this link: http://www.national.com/webteam/site_terms_of_use.html
3. Return to the home page.
4. In the search box, enter the product number (LM741) for a specific Operational Amplifier in the Search box and click “go”.
5. You will be presented with several options (view online, download PDF, email for example). Select how you would like to receive this datasheet.
Here an op amp is used as a voltage regulator. The basic circuit we saw before with the zener directly driving the BJT. With the op amp we see there is a feedback path (so we can use the feedback rules). The voltages into the two inputs must be the same, so the inverting input has the zener voltage across it. Since the input impedance into the op amp is very high, then the current through R1 is the same as that through R2 and the output voltage is held at that shown in the figure.
Here is a slightly more complex version of the same circuit. Identify the feedback path and say why Rs is important.
Output Drivers

Here the load is either on or off. Thus it is useful to employ a single sided supply. Choose the resistor to provide the correct current for the device.

An op amp acting like a switch.
Output Drivers

Where more power is needed, the op amp can drive a transistor (or FET). The base diode prevents reverse base-emitter breakdown.
Op amp are also useful for interfacing to digital electronics, the 10 k resistor acts as a pull-up resistor.
Multiple comparators

The reference voltage of the comparators increases as you move up the list. The variable resistor sets the range. The LEDs light as the corresponding comparator turns on.
A pair of transistors can provide a greater current source than the typical op amp. Note the feedback loop includes the transistor pair.
We already looked at the non-inverting amplifier and found it has a gain of:

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{R_{\text{load}} + R_{\text{gnd}}}{R_{\text{gnd}}}
\]

The current is therefore:

\[
I_{\text{out}} = \frac{V_{\text{out}}}{R_{\text{load}} + R_{\text{gnd}}} = \frac{V_{\text{in}}}{R_{\text{gnd}}}
\]

So, by adjusting $V_{\text{in}}$ one may set the current through the load.
We explored the inverting amplifier for a voltage source. The situation is quite similar for a current source.

\[
I_{in} = -\frac{V_{out}}{R_F} \\
V_{out} = -I_{in}R_F
\]

The feedback resistor adjusts the proportionality between the input current and output voltage.
The CMOS IC 4066 is a set of digitally controlled bi-lateral switches. Thus with 4 bits one can select a variety of feedback resistors. The effective feedback resistance is the parallel combination of all those selected.

One convenient set of resistor values is in the ratio of 1: 2: 4: 8 to select (1-15).
Turning on the MOSFET allows the capacitor to charge (with a time constant $1/RC$). When the FET is open the capacitor holds its charge (except for leakage into the non-inverting input), and this voltage is reported at the output. Use a MOSFET op amp to have a low leakage current.
The diode permits the capacitor to sample the highest value of the input voltage. Thus the output is the maximum input voltage since the last reset.

Notice that the feedback loop of the buffer includes the diode, this removes the 0.6V drop that would otherwise be observed.