The Operational Amplifier
Sept. 1, 1999

1 Purpose

- To understand the basic concepts and characteristics of an ideal operational amplifier.

- To compare the characteristics of a high performance low cost IC op amp with those of the ideal.

- To investigate the properties of the IC op amp in several circuits which demonstrate its great versatility and range of operation.

- Note that this is a two-week lab. You should be able to complete through part 4 or part 5 during the first week.

2 Discussion

Modern integrated circuit operational amplifiers (op amps) have characteristics so closely approaching the ideal op amp that they are components of almost all signal processing and instrumentation equipment. The properties of a commonly used 741 op amp are compared to the ideal values listed in the table below:

Parameter	Ideal Value	$\mu A741$ Value	1990 best avail. value (not all in same device)
Input current	$I_{in} = 0$	~ 80 nA	0.1 pA
Voltage gain	$A_v = \infty$	$200,000$	2×10^6
Bandwidth	BW$= \infty$	1 MHz at $A_v = 1$	500 MHz
Balance	$V_o = 0$ for $V_i = 0$	$V_o = 0$ at $V_i = 1 - 2$ mV	$5\ \mu V$
Temperature dependence	none	$(dV/dT)_{offset}$ typically $15\ \mu V/^\circ C$	$(dV/dT)_{offset}\ 0.1\ \mu V/C$

Op amps can be obtained commercially for \$0.50 to \$3.00 each. This and their versatility are the reasons for their great popularity. As you perform the suggested investigations, be alert to observe and note those cases in which the real op amp fails to match the ideal properties. Try to find the relevant properties in the "spec sheets", and take note of the "typical applications" section – this is a prime spot for getting circuit ideas or finding out how new devices might be used.

Almost all applications of op amps involve negative feedback as indicated in the diagram below:
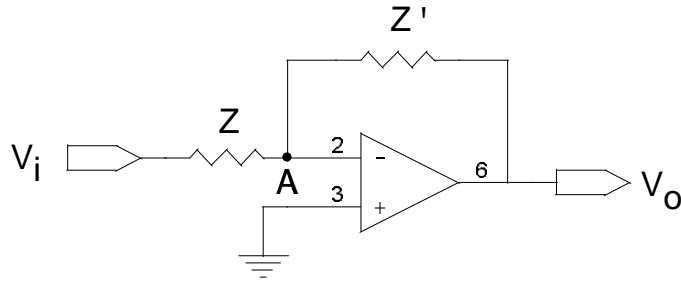
Assume that point A is a virtual ground (*i.e.* $V_- = V_+$), and that $I_i = 0$, and prove the general result that

$$A_{vf} = \frac{V_o}{V_i} = -\frac{Z'}{Z}$$

.

3 Procedure

- For each circuit you will test, first draw a schematic diagram in your lab notebook, that includes IC pin numbers for the integrated circuit (obtainable from the specification sheets). As you can see from the circuits in this handout, it is customary <u>not</u> to show the power supply connections or bypassing, so simply add a diagram at the beginning to show these connections, which can be left in place for the remainder of the single Op-Amp experiments.

- Near the supply pins (± 15 V), connect filter capacitors (0.01 μF) to ground.

- Where appropriate in the exercises listed below, compare the measured gain A and frequency response to the values listed on the specification sheets.

1. Connect the op amp as an **ordinary amplifier** as shown below.

    - Find the "output voltage swing" and the "slew rate" specifications on the data sheet and determine what they mean.
    - Can you measure them?
    - Check the magnitude and phase of the gain.
    - Measure the bandwidth and the input impedance at the V_{in} terminals. (The insertion of the R_{test} resistor is useful in determining the input impedance.)
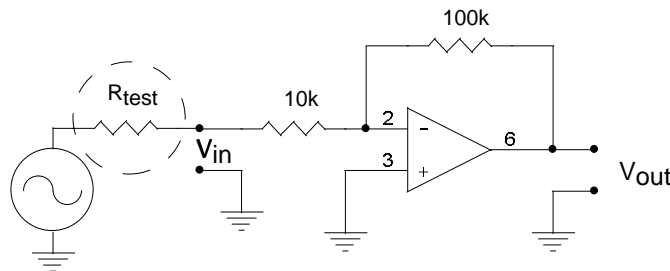
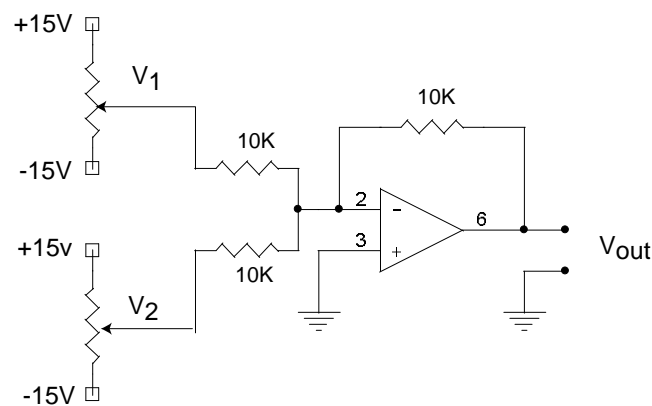2. Connect the op amp as a **non-inverting amplifier**.

- Confirm the magnitude and phase of the gain.
- What is the input impedance in this configuration?
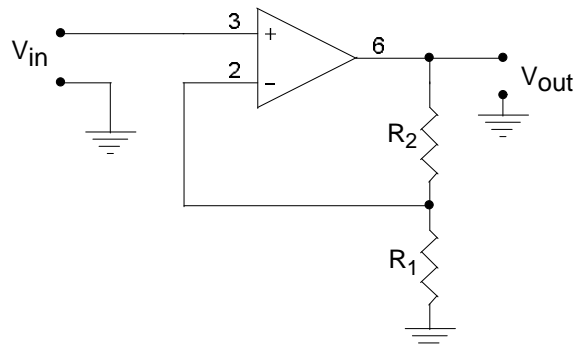
3. Construct an **adder**. Verify, using three or four pairs of input values, that:

$$V_o = - (v_1 + v_2)$$

It is most convenient to use the square blue 10k potentiometers with pins on the back side as adjustable voltage sources for v_1 and v_2.

4. As shown below, connect the op amp as an **integrator**. Use positive pulses 1 msec wide at a frequency of 40 Hz as the input.

- Observe the input and output using the ALT or CHOP mode scope inputs on DC. Because of the 100k resistor, this is not a true integrator, but is referred to as a **leaky integrator**.
- What is the effect of the resistor?
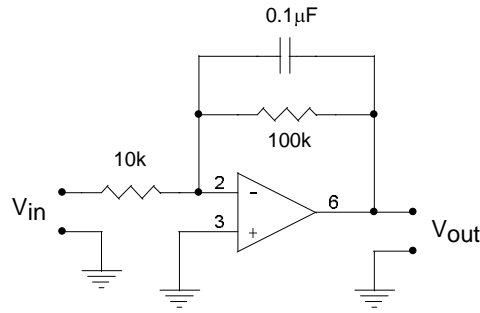
5. Now modify the integrator to be a **charge sensitive amplifier**. This is the electronic analog of a ballistic galvanometer.

- Charge a 0.1 μ F capacitor on the $+15$ V supply.
- Connect it to the inverting input.
- Derive the equation:

$$V_\circ = -\frac{1}{C_f} \int i_{in} dt = -\frac{Q_{in}}{C_f}$$

- Experimentally confirm it with your measurement.
- Try another value of input capacitance and note whether the peak value of V_{out} tracks the input charge.
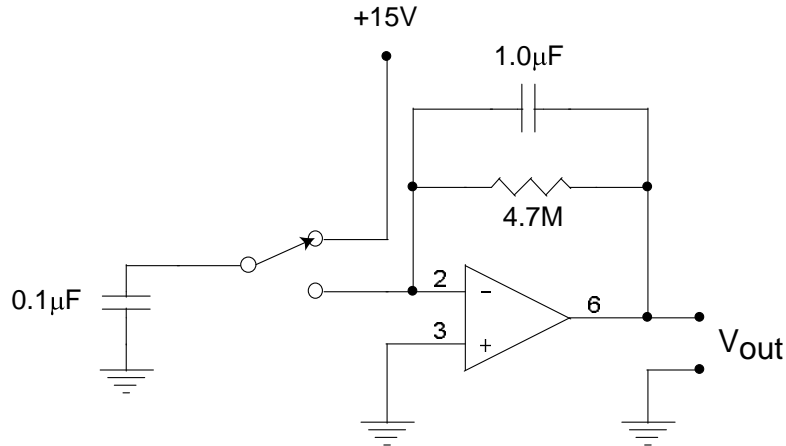

6. Construct a **logarithmic amplifier** as shown below.

- Vary V_{in} and plot $V_o = A + B \ln V_i$ using a semi-log scale. Five or six values are sufficient – be sure they cover a wide range in V_0. (You can use the Log functions on your calculator and the ruled paper in your notebook for the plot.)
- Does it make any sense to use an AC input voltage for this measurement?
- What are your values of A and B?

1N914

10k

500k

V_{in}

2
−
3
+
6

V_{out}
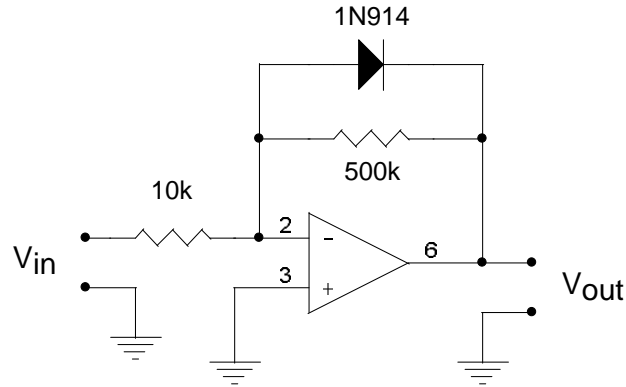
7. Note that, while an Op-Amp has differential inputs, the gain stabilized amplifier circuits in parts 1 and 2 above do not.

- To gain the advantages of a differential input with an accurate gain and good common mode rejection, construct the **Instrumentation Amplifier** as shown below.
- Understand out how it works.
- Try a few combinations of v_{in}^{+} and v_{in}^{-} to find the differential and common mode gains.

100k

V_{+} 10k

V_{-} 10k

2
−
3
+
6

V_{out}

100k
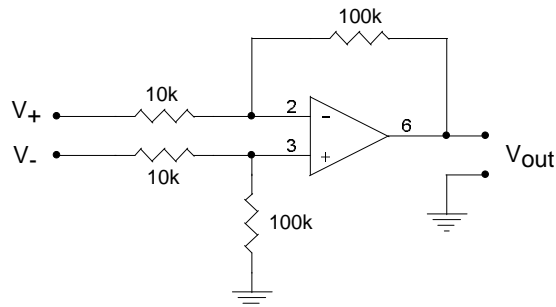
(This particular circuit has several drawbacks. Check Horowitz & Hill for a nifty "3 Op-Amp Instrumentation Amplifier" that has:

- a CMRR over 100,000
- an essentially infinite input impedance on both inputs
- gain that is adjustable over a wide range by changing one resistor.)

8. The final circuit will be used in the next lab, so build it on the circuit board that is marked with your name and save it. This is a high gain circuit and some care in the layout is needed; the instructor should have an example to show you before you start.

The circuit consists of three identical stages, which should be arranged from left to right across the upper breadboard block, leaving about 1/3 of the block free on the left. Clip the component leads short and bend them with your pliers so that the component bodies lie flat against the breadboard – this minimizes stray capacitances. **Use a single bus on the socket for all the grounds – for example, the inner strip just below the op**

amps. It is a good idea to put 0.1 μF ceramic capacitors from the $\pm$ 15 V supply pins to the ground bus as close as possible to each op-amp. The instructor will show you a sample layout before you start.
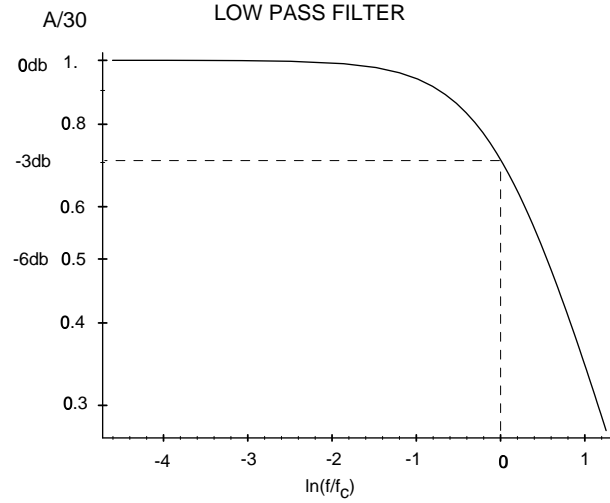
The circuit for a single tuned amplifier stage is:
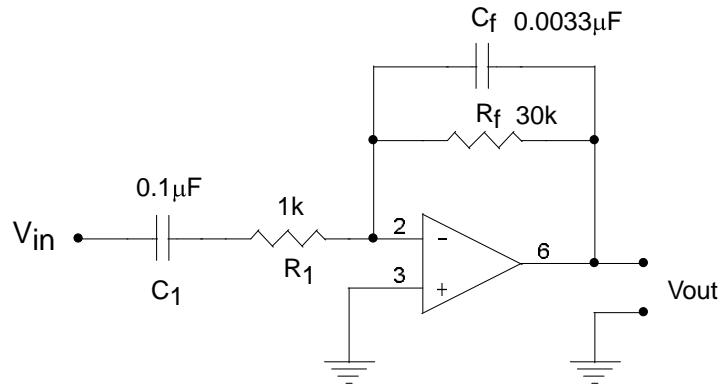
Ignoring the capacitors for a moment, this is just an inverting amplifier with a gain of $R_F/R_1 = 30$. The addition of C_1 introduces a high-pass corner at $f_1 = 1/2\pi R_1 C_1$ that reduces the gain at **low** frequencies, ie $f \ll f_1$:
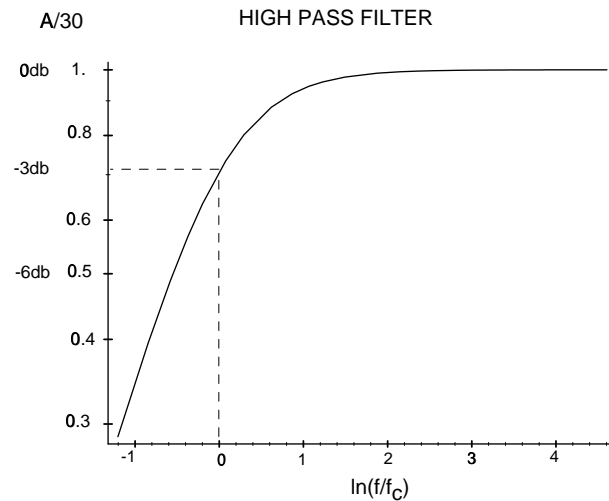
The addition of C_f reduces the gain at **high** frequencies, i.e. $f_2 = 1/2\pi R_f C_f$

A/30   LOW PASS FILTER

With **both** capacitors, the gain is just the **product** of these two curves. Since $f_1 = f_2 \equiv f_\circ$, the result is :

A/30   COMBINED HIGH/LOW PASS
$f_L = f_H = f_C$
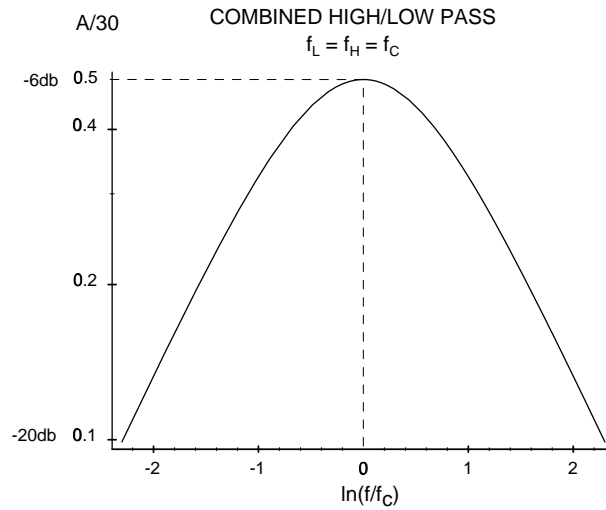
Therefore, the maximum gain of the stage is $1/2(R_1/R_F) = 15$ at $f_\circ$, and drops off $\propto f$ for $f \ll f_\circ$ and as $1/f$ for $f \gg f_\circ$ – both 6 *db per octave*. What is $f_\circ$ for the given component values?

To make a high gain amplifier with a fairly narrow bandwidth, we cascade **three** (3) identical stages. The gain is then:

$$A_v = (30)^3 \left(\frac{f/f_\circ}{1 + (f/f_\circ)^2} \right)^3$$

The peak gain is now $A_v = 30^3/8 = 3375$ at $f = f_\circ$ and drops off as $1/f^3$ for $f \gg f_\circ$, and as f^3 for $f \ll f_\circ$.

$A/(30)^3$ 3 STAGE CASCADE FILTER
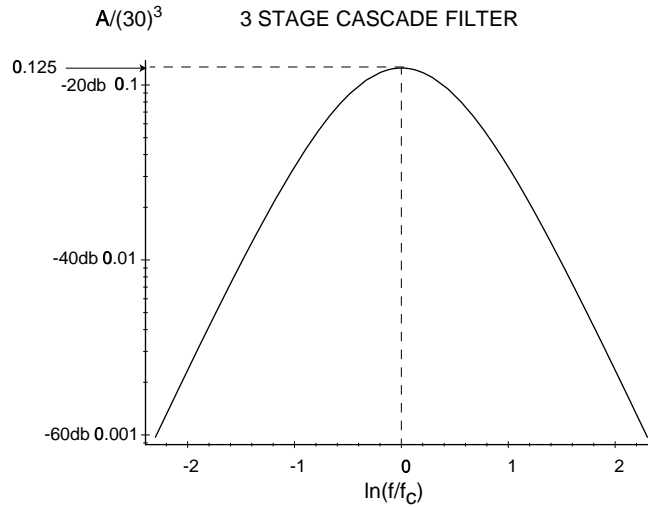
- Construct the three stage amplifier;

- measure the frequency at which the gain is maximum; and

- record the gain at this frequency.

- How does the frequency of peak gain compare to your calculated $f_\circ$? (For the input signal, use the $100\times$ attenuator on the wave-form generator output). Measure the input and output voltage with a scope, not the DVM.
  You can use the DVM if *you are careful to take the noise into account. How do you do this?*

- Plot the frequency response ($\log A_v$ *vs.* $\log \omega$ from ~ 50 Hz to 50 kHz with about 3 points per decade. (This implies about a factor of 2 between points to be about evenly spaced on the logarithmic scale.)

- Record the value at 60 Hz.