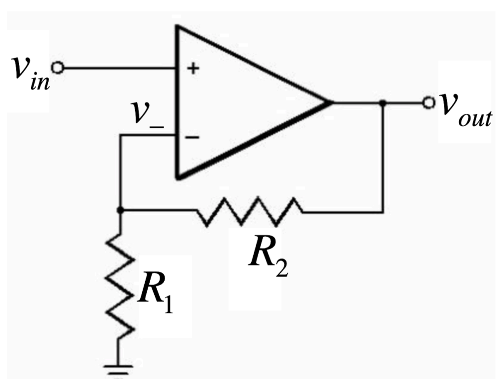
Phys2610 (2019)
Experiment 8: Introduction to operational amplifiers

Introduction

An operational amplifier is a dc-coupled amplifier with two inputs marked + and -, and one output. This amplifier will amplify the difference between the input signals with high gain (differential gain) but will amplify the average (common mode) signal with low gain. The ratio between the differential gain and the common mode gain is called the common mode rejection ratio (CMRR). The open loop differential gain (a_o) and the CMMR are typically high enough so that, in certain contexts, the amplifier may be considered to be a true difference amplifier with infinite gain. The assumption of infinite gain simplifies analysis in many cases.

Ideally the output should have zero dc output when both inputs are zero (or equal), but in fact there is an output error signal which is large and unstable because of the high gain, and typically there is a null adjustment to reduce this error, which itself will be dependent on the temperature and the particular power supply and is also unstable.

For stable operation with finite gain, operational amplifiers are normally operated with negative feedback, as in the non-inverting amplifier shown below, where a fraction of the output is fed back into the negative input.



If infinite gain and infinite input impedance are assumed, then the two inputs can be considered equal, so $v_{in} = v_- = \frac{v_{out}R_1}{R_1+R_2}$, and the gain is

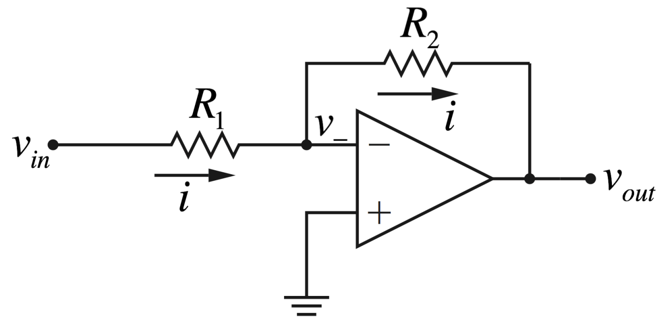
$$a = \frac{R_1+R_2}{R_1} \tag{1}$$

If finite gain is considered, but input current is still considered zero, then $v_- = \frac{v_{out}R_1}{R_1+R_2}$, and $v_{out} = (v_{in} - v_-)a_0$. Eliminating v_- gives

$$a = \frac{a_o(R_1+R_2)}{a_oR_1+(R_1+R_2)} \tag{2}$$

which reduces to the above expression for large open loop gain.

In the inverting amplifier shown below, the signal is connected to the negative input, and negative feedback is achieved by feeding part of the output back to the same input.



In this case, assuming infinite gain means the negative input is at virtual ground, so $v_{in} = iR_1$, and $v_{out} = -iR_2$, giving

$$a = \frac{-R_2}{R_1} \tag{3}$$

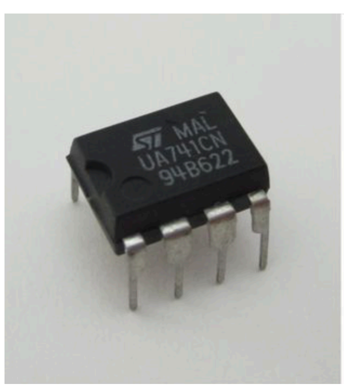
For finite gain, the current is $i = \frac{v_{in}-v_-}{R_1} = \frac{v_- - v_{oiut}}{R_{out}}$, and $v_{out} = a_o v_-$. Here, eliminating v_- gives

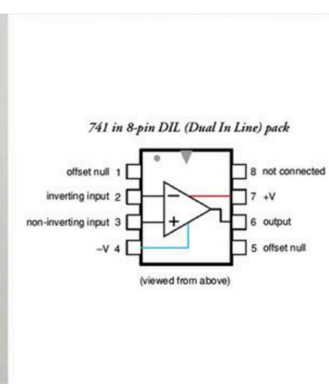
$$a = \frac{-a_o R_2}{R_1+R_2+a_o R_1} \tag{4}$$

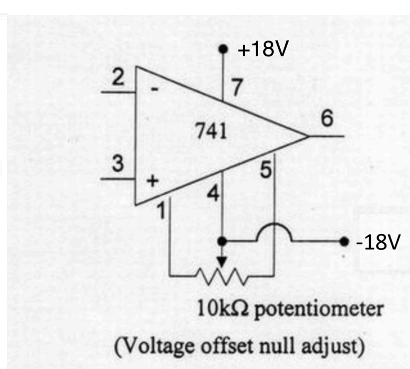
which again reduces to the above expression for large open loop gain.

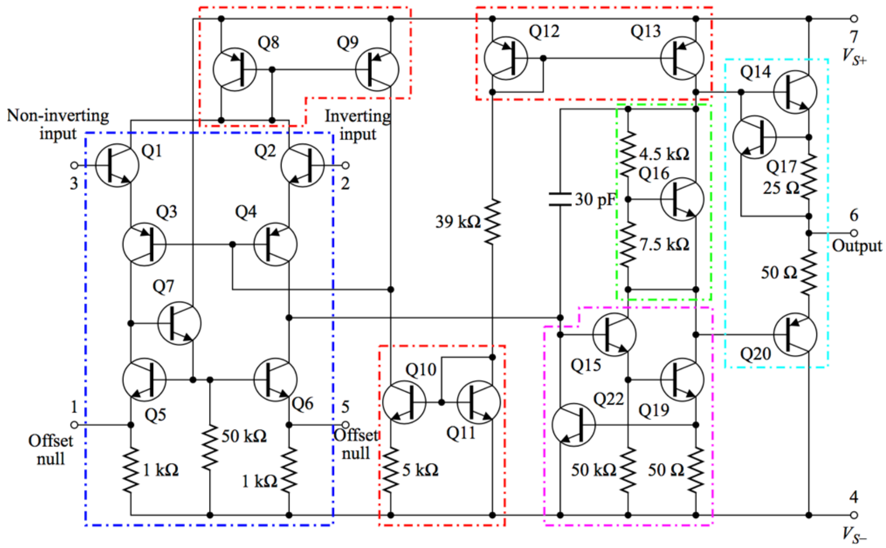
Experimental

A 741-type op-amp is shown below, along with the pinout and the schematic diagram for the power and null adjustment. The grey arrow head at the top of the pinout diagram corresponds to the small notch in the device. A schematic diagram of the complete integrated circuit is shown on the next page. The open loop gain of the 741 is more than 10^5 at very low frequency, but decreases at 20 dB per decade above 6 Hz.

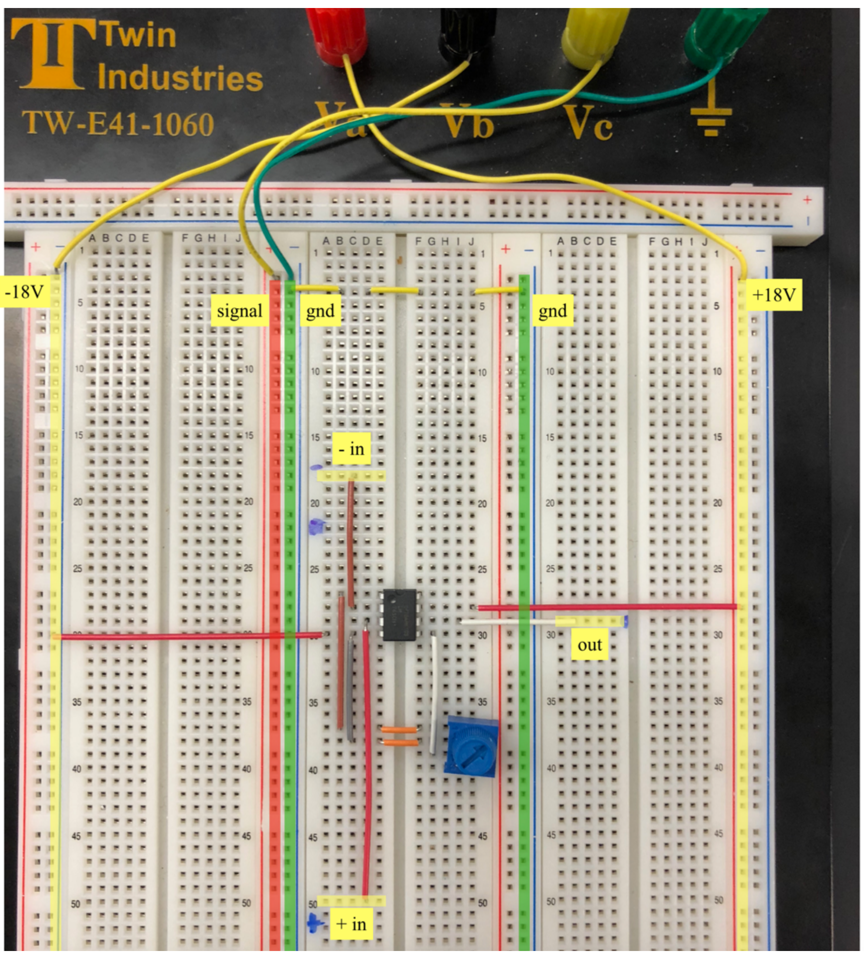






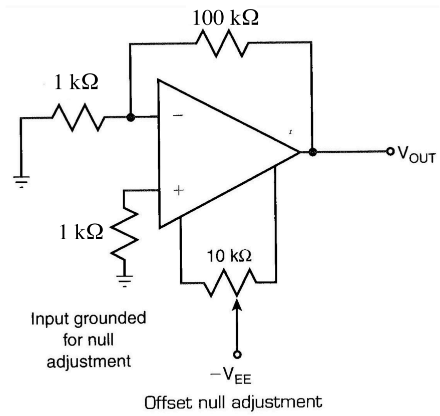


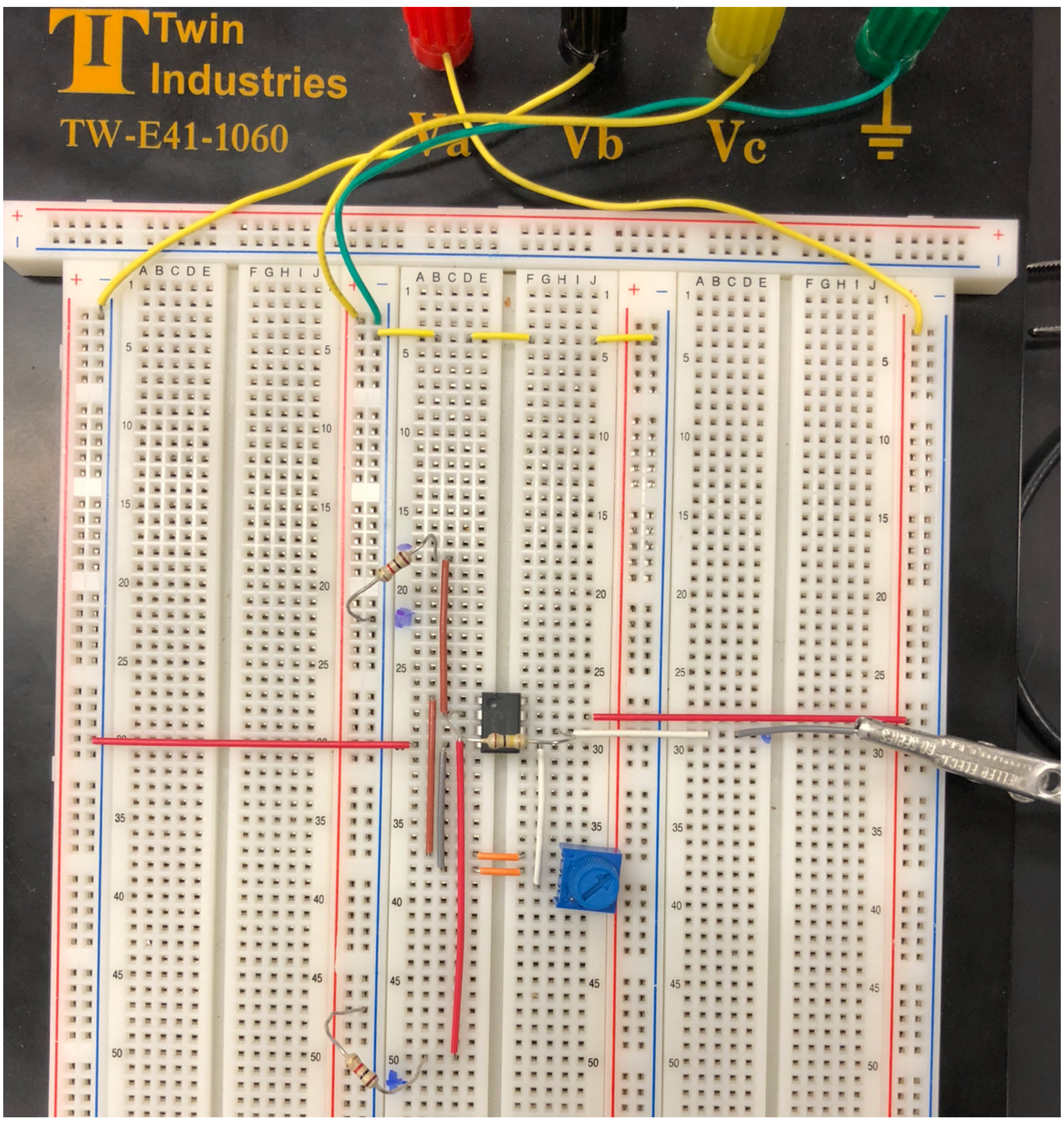
Using a breadboard and two power supplies, provide the +/- 18 V and a 10 kΩ trim pot according to the schematic on the previous page. An example setup is shown in the photograph below. This allows the circuits described below to be constructed with simple insertions of components.



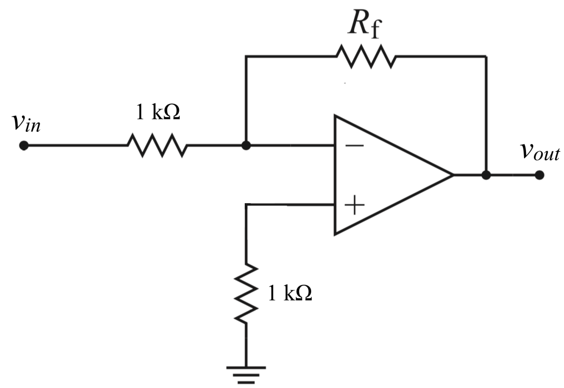
Take the + voltage from the red connector on one power supply and then connect black and green connectors on that supply together. Take the – voltage from the black connector on the other power supply, and then connect the red and green connectors on that supply together.

1. **Null adjustment**. Connect both + and – inputs to ground via 1-kΩ resistors and measure the voltage at the op-amp output. Try to adjust the null balance to zero this voltage. Because of the very high gain for dc, this will be difficult. Now connect a 100 kΩ resistor between the output and the inverting input and try again. The negative feedback will reduce the gain, allowing the offset voltage to be brought close to zero.



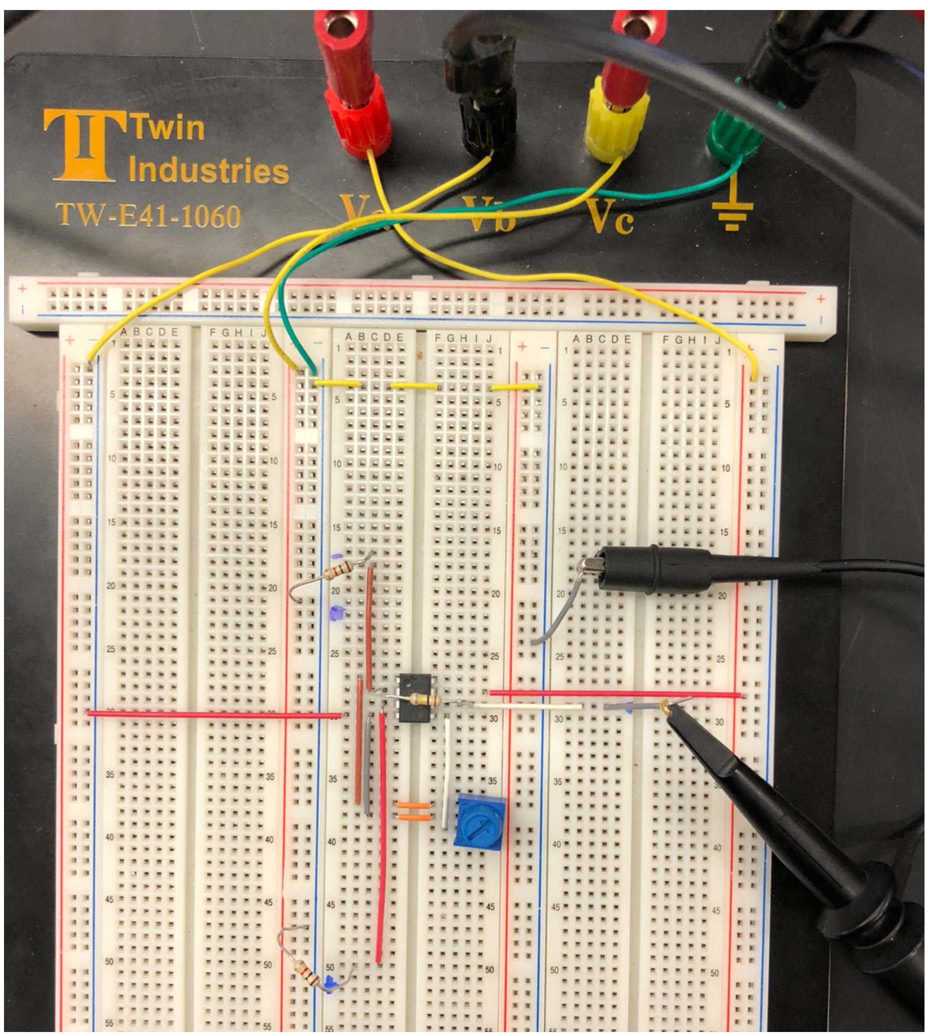


2. **Inverting amplifier**. Connect a signal generator to the inverting input and an oscilloscope to the output and input for gain measurements. Leave the 1-kΩ resistor to ground on the + input to compensate for non-zero bias currents (as described in the text).

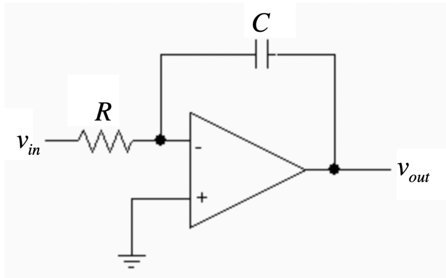


Using 100 kΩ for the feedback resistor, measure the gain at a low frequency around 10 Hz and compare to equation (3). Determine the frequency at which the gain drops by 3 dB, and then use equation (4) to determine the open loop gain a_o at this frequency. Assuming $a_o = 2 \times 10^5$ at low frequency, how many dB lower is it at the higher frequency?

Change the feedback resistor to 10 kΩ and re-measure the low frequency gain and the 3 dB frequency.



3. **Integrating circuit.** An electronic integrator can be constructed using capacitive feedback in an inverting amplifier:

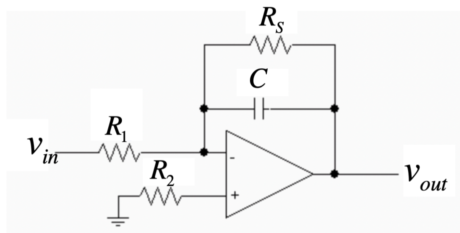


The output of this circuit is given by

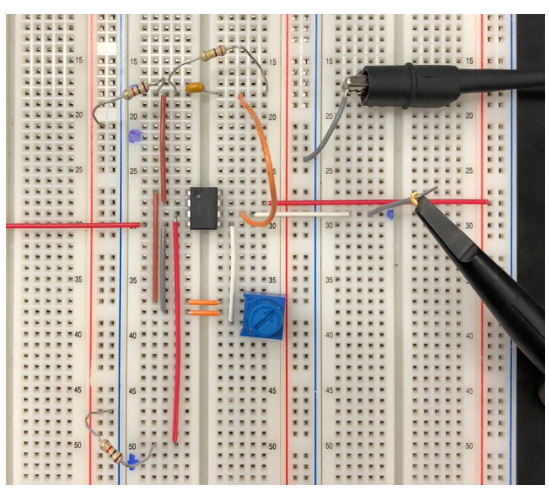
$$v_{out} = \frac{-1}{RC}\int v_{in} dt$$

provided $|v_{out}| \ll a_o|v_{in}|$. The corresponding equation for the simple RC circuit is the same, except for the sign, but is valid only when $|v_{out}| \ll |v_{in}|$.

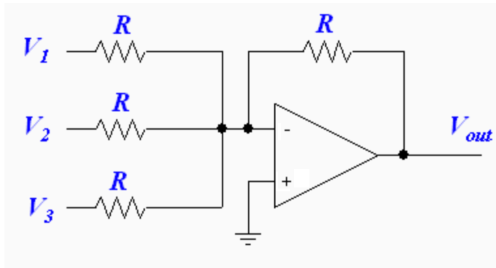
Because of drift in the op amps, the capacitor gradually acquires a dc charge. This can be minimized by adjusting the offset but is difficult to eliminate. When the charge saturates at 16 V, the output will be distorted. This can be prevented by connecting a resistor across the capacitor which is large enough so ac operation is not appreciably affected, but small enough to prevent dc charging. And as above, a resistor on the + input compensates for bias currents. A useful practical integrator is shown below:



Construct the above circuit using $R_1 = R_2 = 1$ kΩ, $R_S = 100$ kΩ, and $C = 0.47$ µF. Since the feedback impedance is frequency dependent, the gain will be proportional to the inverse of the frequency. Measure the phase shift for a sinusoidal input at 1 kHz. Is it consistent with the equation? Capture the output for a square wave input and for a ramp input. Does the output represent the integral of the input? Using a square wave input, reduce the frequency until the output is no longer an accurate integral of the input. What is the gain at this frequency?



4. **Summing circuit.** Construct the summing circuit below with 2 inputs using 1 kΩ resistors. The second input will require an alligator clip. Leave a 1 kΩ resistor from the positive input to ground (not shown).



Verify the circuit's operation by connecting two identical sinusoidal inputs at 2 V and 1 kHz. The output will depend on the phase, which will be random, and will probably drift slowly, taking several minutes to drift by one period or so.

Change one of the inputs by 0.1 Hz and measure the beat frequency. Recall

$$\sin(\omega_1 t) + \sin(\omega_2 t) = 2\sin\left(\frac{\omega_1 + \omega_2}{2} t\right) \cos\left(\frac{\omega_1 - \omega_2}{2} t\right)$$

Is the beat frequency correctly predicted by this equation?

Try summing different waveforms. Does the output make sense?