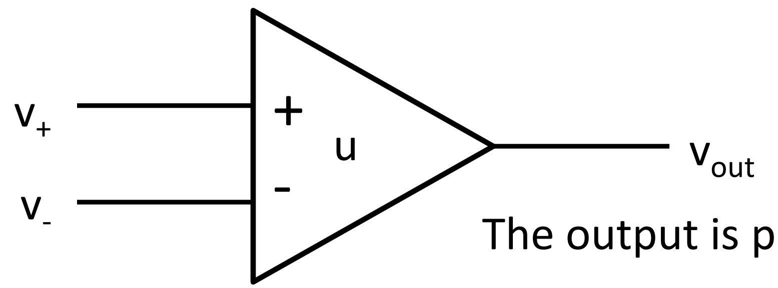
Operational Amplifiers

Op-amps are a particular type of Integrated Circuit with a very high gain (10^3-10^6).

(Ideally ∞)



$v_{out} = u(v_+ - v_-)$

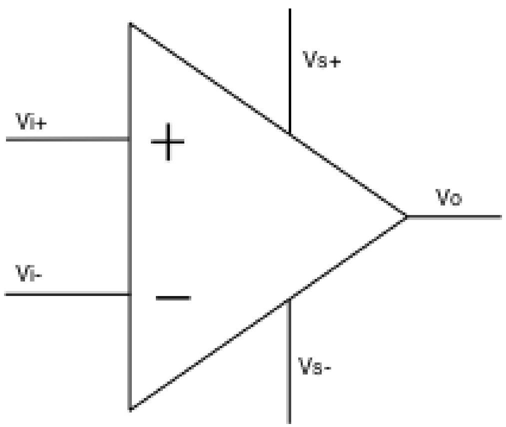
The output is proportional to the + & - inputs.

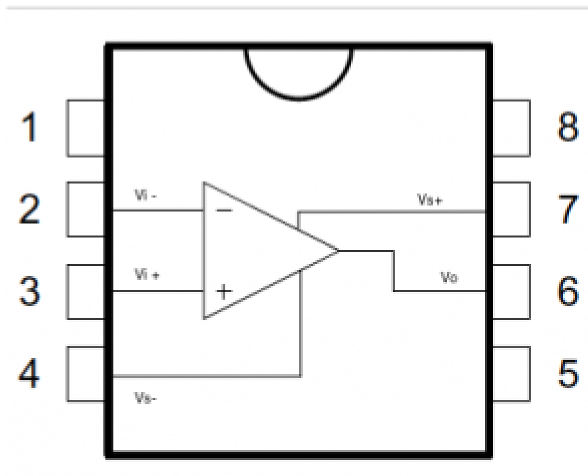
Notice: I have not shown the grounds nor the power supply connections.

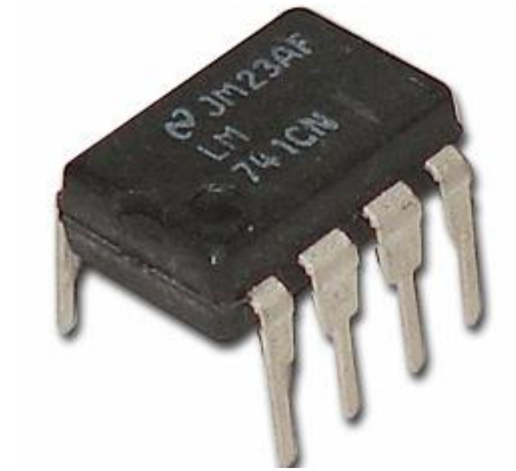
Ground & power supply connections are always present & are implicit. They very often are NOT drawn on the schematic in order to reduce the clutter.

Operational Amplifiers

Op Amps!

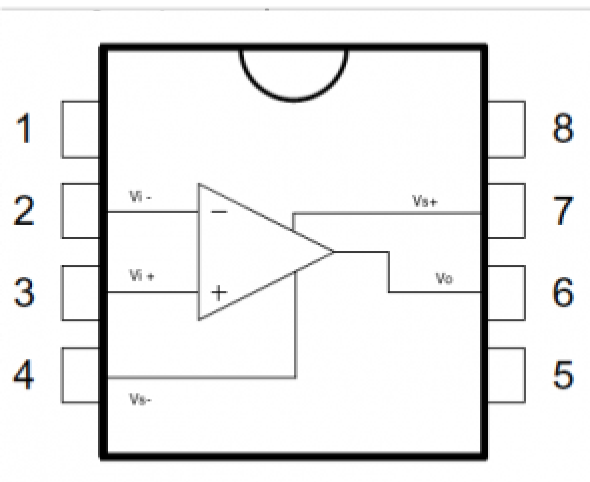


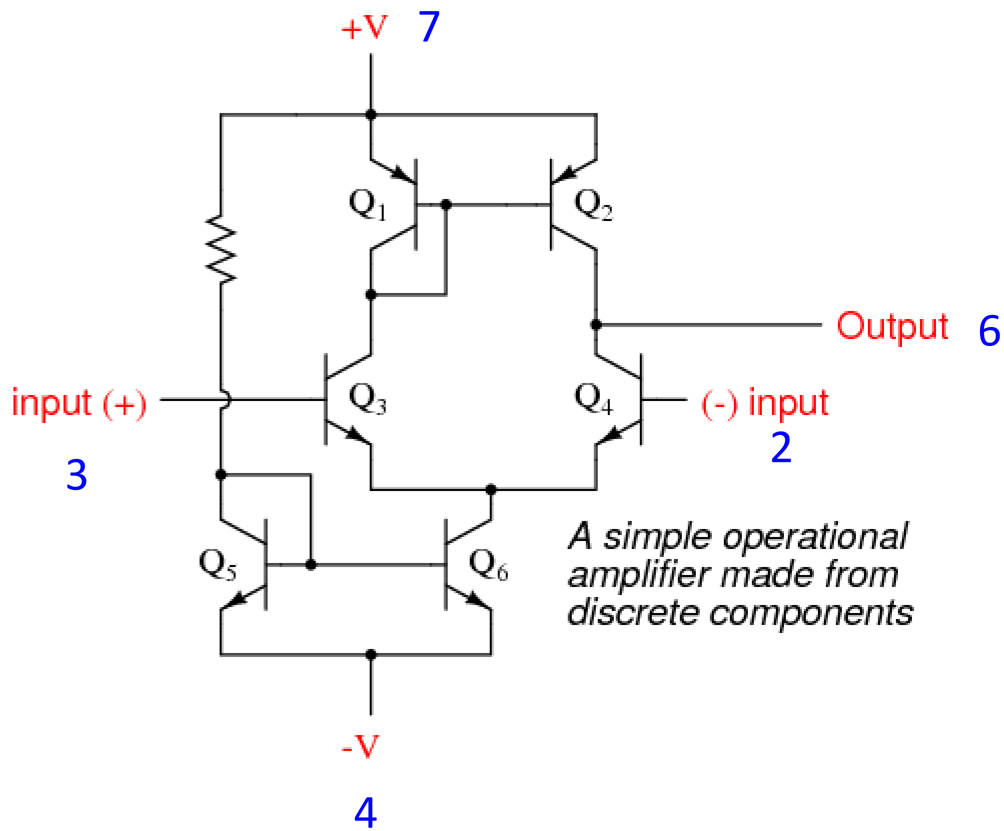




Op-amps may vary in a lot of parameters (frequency range, power, etc.) but packages try to adhere to standards set by the Industry.

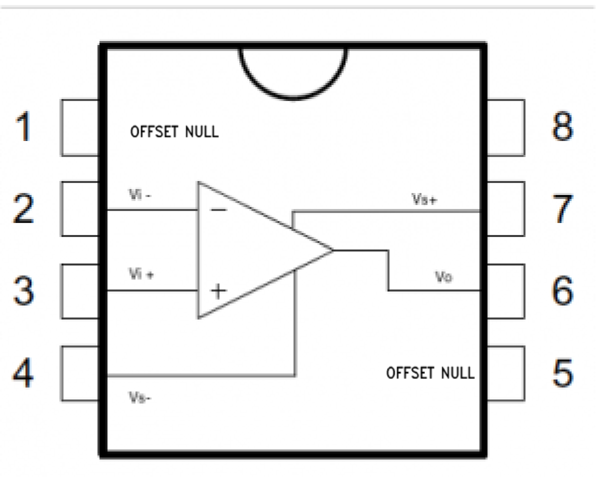
Operational Amplifiers

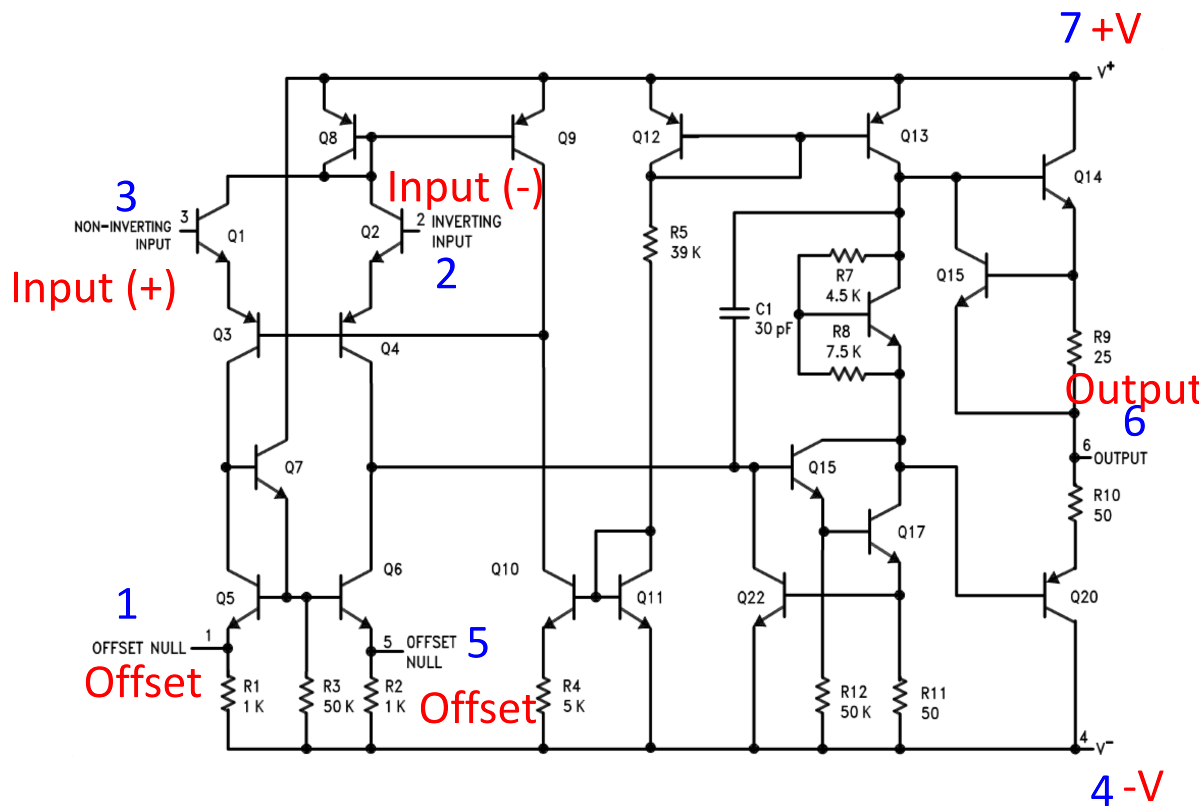




Operational Amplifiers

One of the oldest (& common) op-amps, a LM741





Operational Amplifiers

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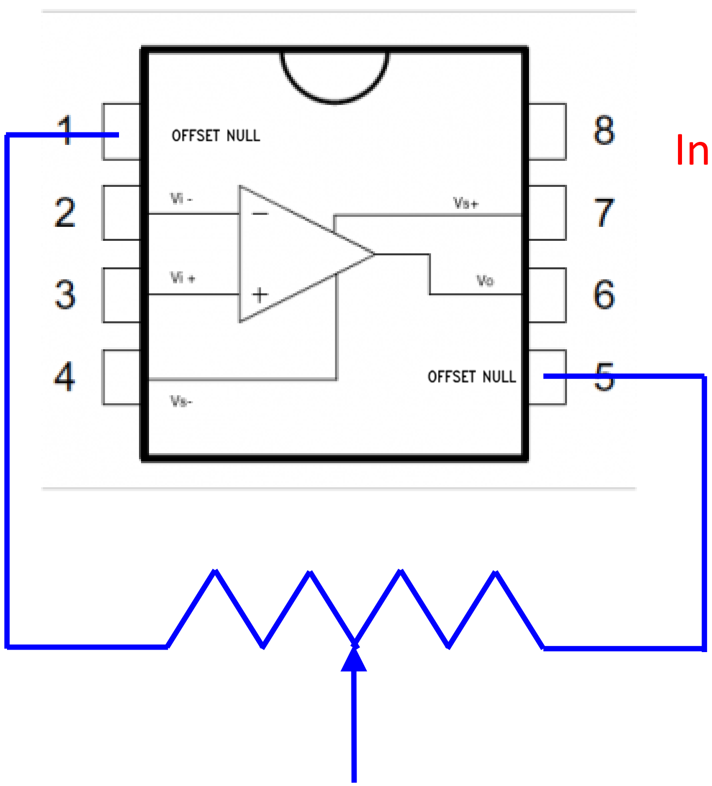
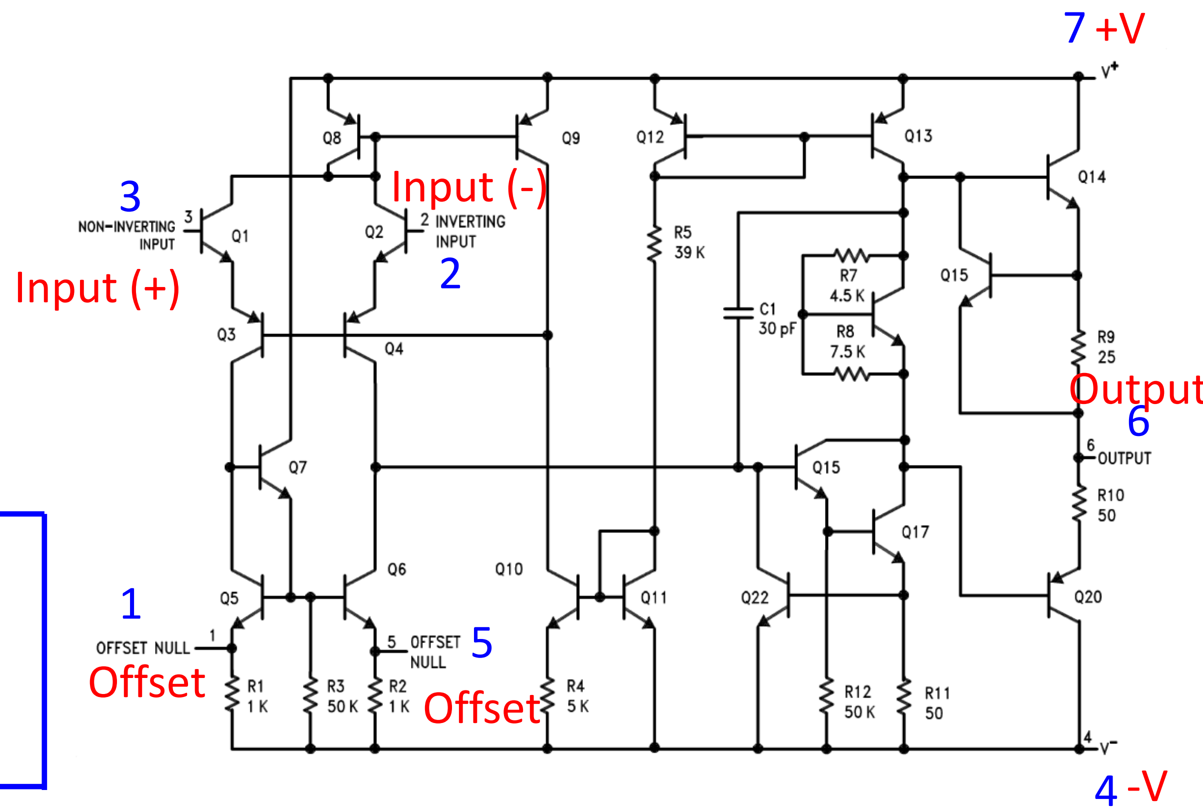
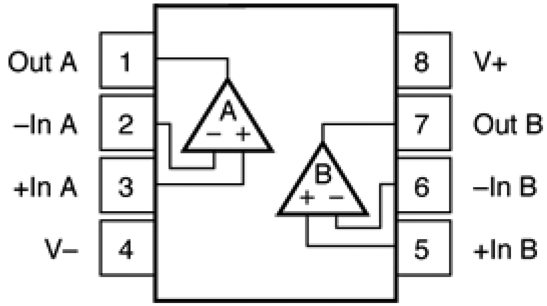


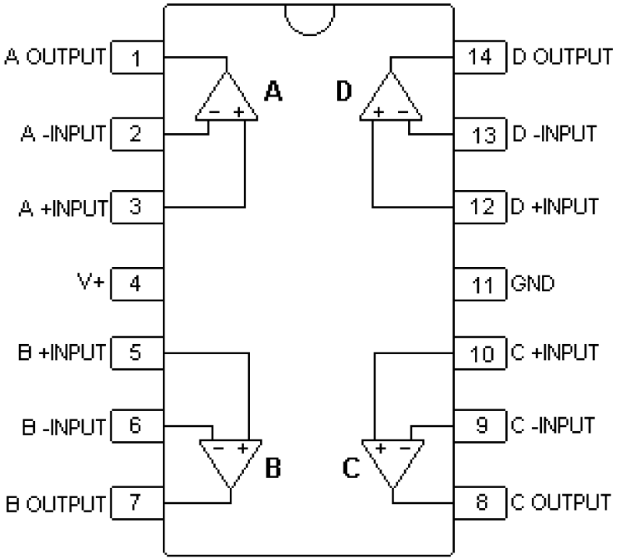


Operational Amplifiers

Op Amps!

Op amp IC packages also come in dual & quads, again generally adhering to Industry Standards for pin-outs.



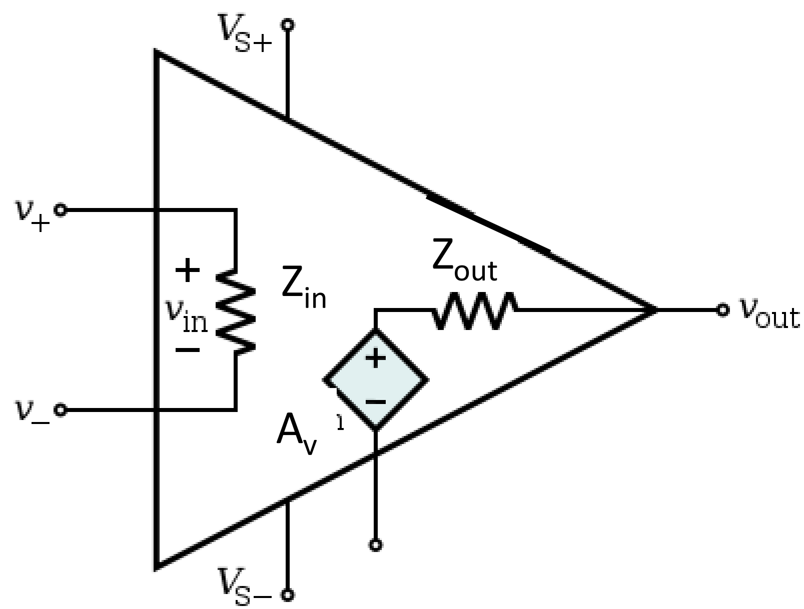


Operational Amplifiers

Op Amps! Op amp Characteristics.

1. Differential Inputs
2. Input Z_{in} large $\rightarrow \infty$
3. High open loop gain (A_v) ~ 10^3-10^6
4. Low Z_{out} < 100Ω

Different literature/datasheets use different symbols for the gain. A, G & u are most common.



You can buy an op-amp with a field effect transistor input (Z_{in} ~ 10^{14} Ω) for a couple of $.

Typical bipolar op-amps (LM741 is common) for about 10-cents in quantity.

Operational Amplifiers

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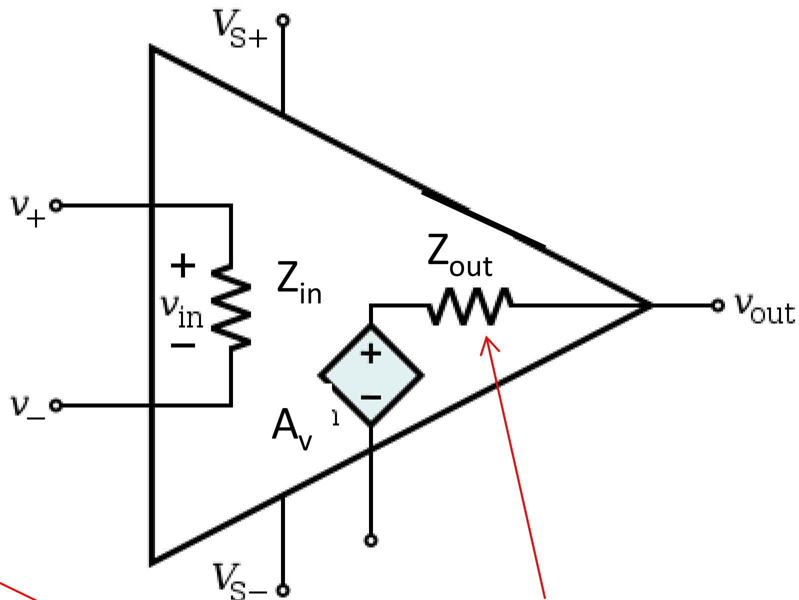

You can buy an op-amp with a field effect transistor input (Z_{in} ~ 10^{14} Ω) for a couple of $.

Typical bipolar op-amps (LM741 is common) for about 10-cents in quantity.

The output can be thought of as a voltage source, and like all voltage sources (batteries), ideally it has zero internal resistance.

Operational Amplifiers

Op Amps! Ideal Op amp Characteristics.

We will generally use “ideal” op-amp design rules:

1. $Z_{in} \rightarrow \infty$ means no current into inputs
2. $A_v \rightarrow \infty$ means $v_+ - v_- \rightarrow 0$ both inputs at the same potential
   (virtual short circuit – does not contradict #1)

Operational Amplifiers

Op Amps!   Ideal Op amp Characteristics.

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1. $Z_{in} \rightarrow \infty$ means no current into inputs
2. $A_v \rightarrow \infty$ means $v_+ - v_- \rightarrow 0$ both inputs at the same potential (virtual short – does not contradict #1)

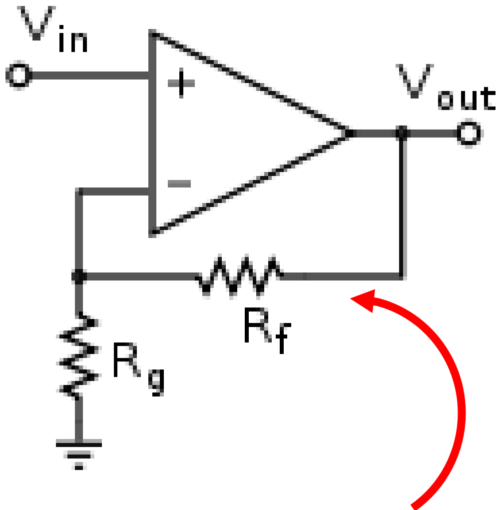
Why?

$$v_{out} = A_v \; (v_+ - v_-)$$

Finite = Infinite Must be zero

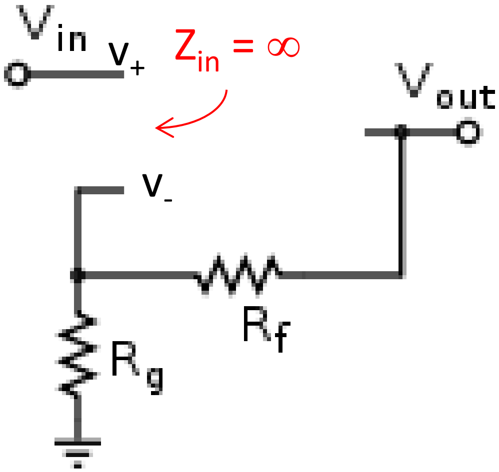
Operational Amplifiers

Op Amps! Non-inverting amp



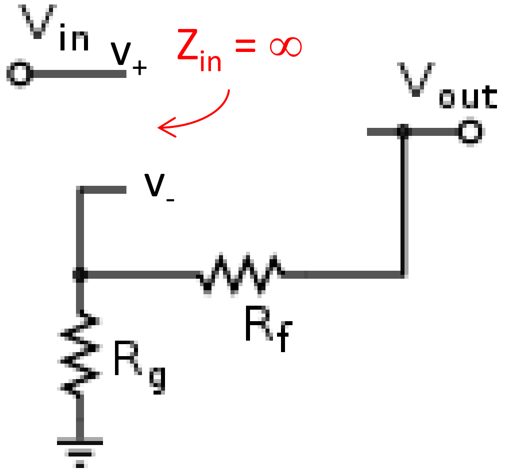
Negative feedback – we feed some of the output back into the negative input.

Apply Rule #1:



Operational Amplifiers

Op Amps! Non-inverting amp



Apply Rule #1:
Using the voltage divider equation:

$$v_- = \frac{R_g}{R_g+R_f} V_{out}$$

Apply Rule #2:

$v_+ = v_-$

Since $V_{in} = v_+$

$$V_{in} = \frac{R_g}{R_g+R_f} V_{out}$$

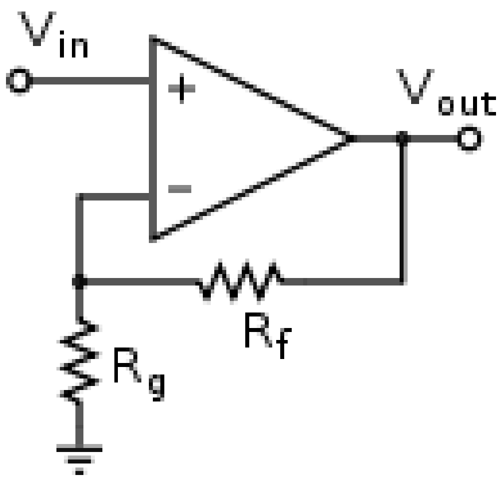
$$V_{out} = \left(1 + \frac{R_f}{R_g}\right) V_{in}$$

$$\text{Gain} = \left(1 + \frac{R_f}{R_g}\right)$$

"Closed loop" gain, because we used negative feedback to close a signal loop.

Operational Amplifiers

Op Amps! What if an op-amp is not ideal?



$V_{out} = A(v_+ - v_-) = A(v_{in} - v_-)$

Using the voltage divider equation:

$v_- = \frac{R_g}{R_g+R_f} V_{out}$ We'll assume this still holds

So $V_{out} = A(v_{in} - \frac{R_g}{R_g+R_f} V_{out})$

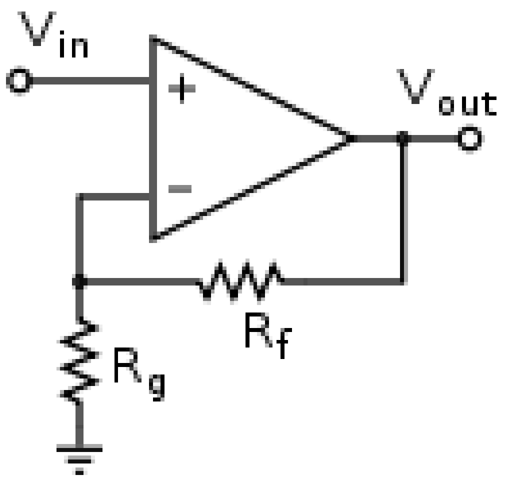
$V_{out}\,(1 - \frac{AR_g}{R_g+R_f}) = Av_{in}$

$V_{out} = (1 - \frac{AR_g}{R_g+R_f})\, v_{in} \equiv A_{eff}\, v_{in}$

So $A_{eff} = \frac{(R_f+R_g)A}{R_f+R_g+AR_g} = \left(\frac{(R_f+R_g)}{R_g}\right) = \left(1 + \frac{R_f}{R_g}\right)$ as $A \to \infty$

Operational Amplifiers

Op Amps!



What if an op-amp is not ideal?

So $A_{eff} = \frac{(R_f+R_g)A}{R_f+R_g+AR_g} = \frac{(R_f+R_g)}{\frac{1}{A}(R_f+R_g)+R_g}$

In real op-amps, even cheap ones, A ~ 10^6

So $A_{eff} \sim \frac{(R_f+R_g)}{\frac{1}{A}(R_f+R_g)+R_g}$

$A_{eff} \sim \frac{(R_f+R_g)}{\frac{1}{10^6}(R_f+R_g)+R_g}$

So to within something like 1 part in 10^6

$A_{eff} \sim \frac{(R_f+R_g)}{R_g}$

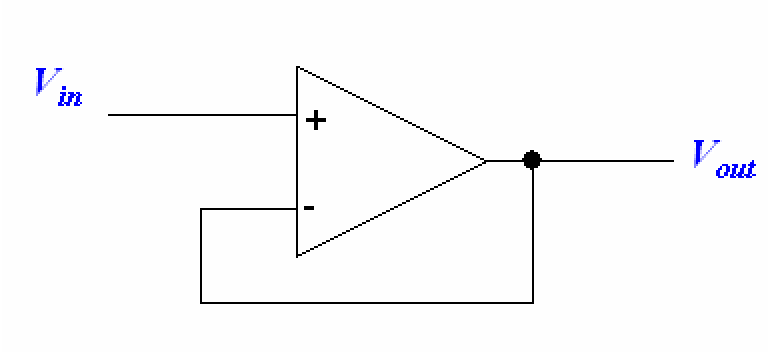
Operational Amplifiers

Op Amps!

Simplest Non-inverting amp

$$\text{Gain} = \left(1 + \frac{R_f}{R_g}\right)$$

Make $R_f = 0$ & $R_g = \infty$



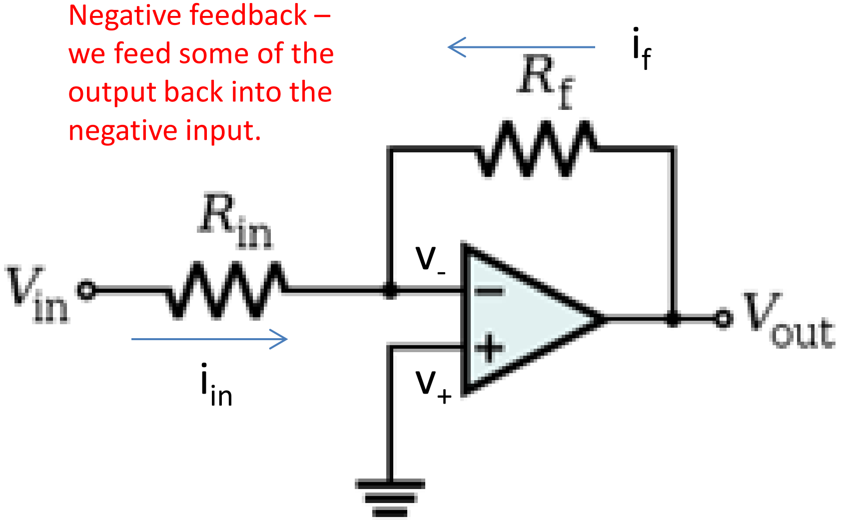
This is called a voltage follower or buffer amp. Used when you need to boost current but not voltage.

High Z_{in}, low Z_{out}

Operational Amplifiers

Inverting amp

Negative feedback – we feed some of the output back into the negative input.



Apply Rule #1: Input impedance ∞

So $i_{in} = - i_f$

Apply Rule #2:

$v_+ = 0$ since it's grounded, therefore

v_- also must be 0.

So, $i_{in} = \frac{V_{in}}{R_{in}}$ and $i_f = \frac{V_{out}}{R_f}$

From rule #1 above

$$\frac{V_{in}}{R_{in}} = - \frac{V_{out}}{R_f}$$

So $V_{out} = - \frac{R_f}{R_{in}} V_{in}$

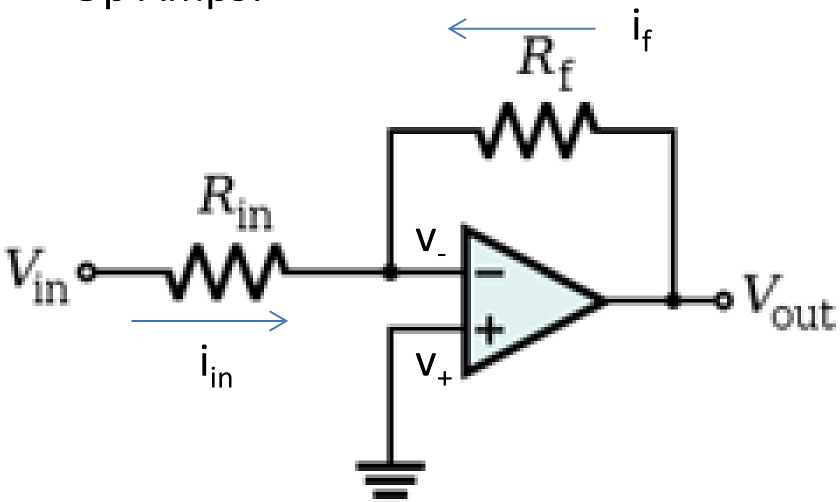
Gain = $\left(- \frac{R_f}{R_{in}}\right)$

"Closed loop" gain, because we used negative feedback to close a signal loop.

Operational Amplifiers

Inverting amp – Input Bias Current

Op Amps!



As a matter of practice, there will be a tiny current leaking (i_{leak})out of the inputs. This can be up to 100's of nanoamps depending on the op amp. This is called the input bias current.

v_- sees R_{in} connected to a low impedance voltage source V_{in}, and in parallel, sees R_f connected to the low impedance output. So v_- sees an impedance of $R_{in}||R_f$.

That leakage current creates a voltage due to $R_{in}||R_f$, ~ $i_{leak}(R_{in}||R_f)$

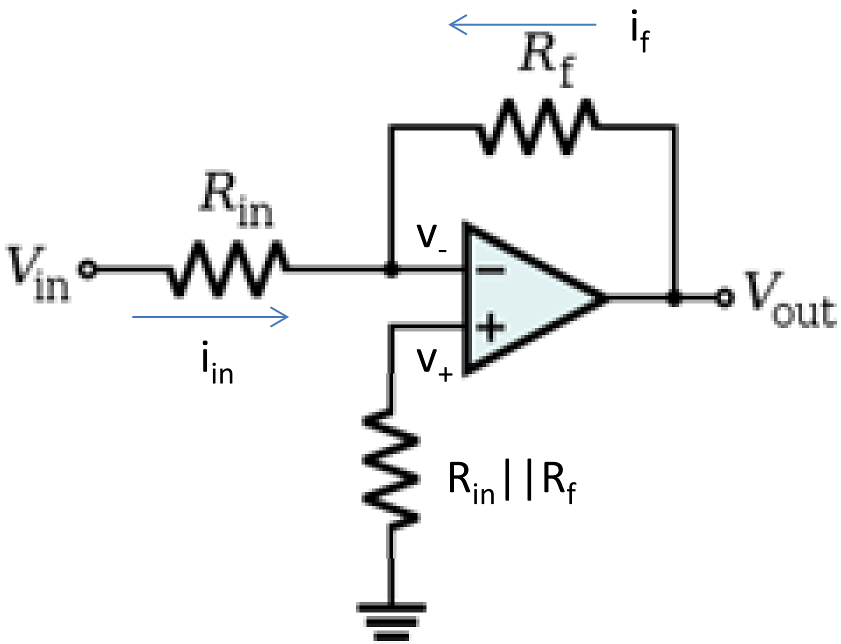
Operational Amplifiers

Inverting amp – Balancing Input Bias Current

Op Amps!

That leakage current creates a voltage due to $R_{in}||R_f$.

That voltage at v_- can be balanced at the + input by adding a resistor equal to $R_{in}||R_f$ to make the voltage from its leakage the same.

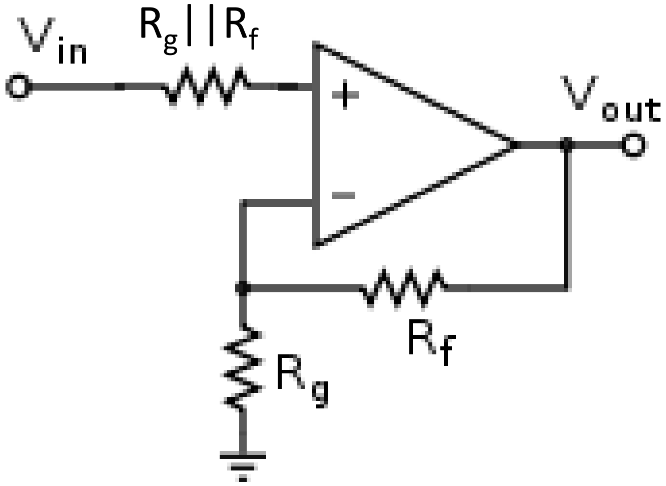


Operational Amplifiers

Op Amps!

Non-inverting amp – Balancing Input Bias Current

Same issue. Can be balanced by adding a resistor to the + input of value $R_g||R_f$.



Operational Amplifiers

Frequency Response

Op Amps!

Op-amps come in two flavors in terms of frequency response:

1. Uncompensated
2. Compensated

Uncompensated op-amps require external components in the feedback (R_f) to be stable. (i.e. R_f really has to be a Z_f that meets certain criteria.

Compensated op-amps ***do not*** require external components in the feedback (R_f) to be stable.

Operational Amplifiers

Frequency Response

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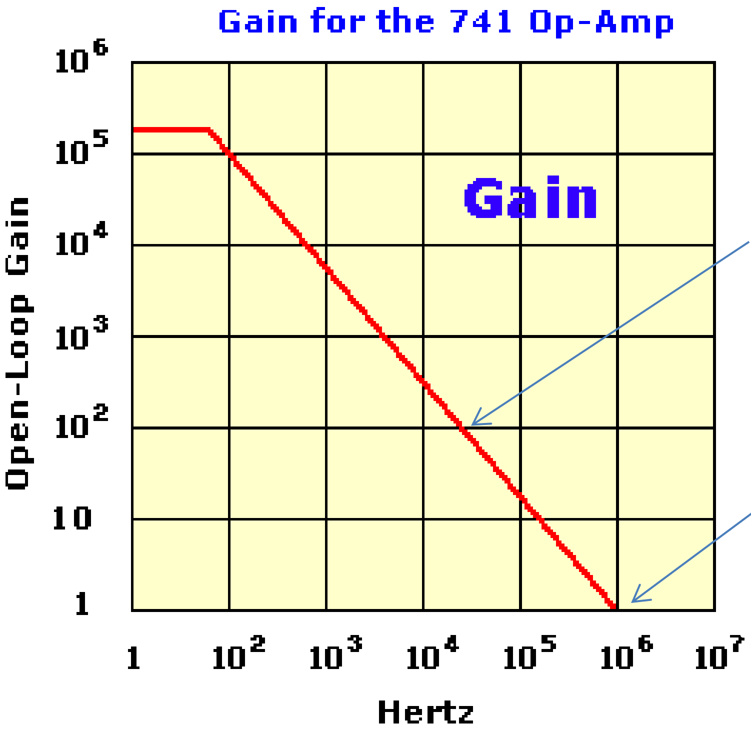
Compensated op-amps ***do not*** require external components in the feedback (R_f) to be stable.

Stable means “works like it should”. Unstable means it behaves like an oscillator, or the output just sits at V_{s+} or V_{s-}.

Operational Amplifiers

Frequency Response

Op Amps!



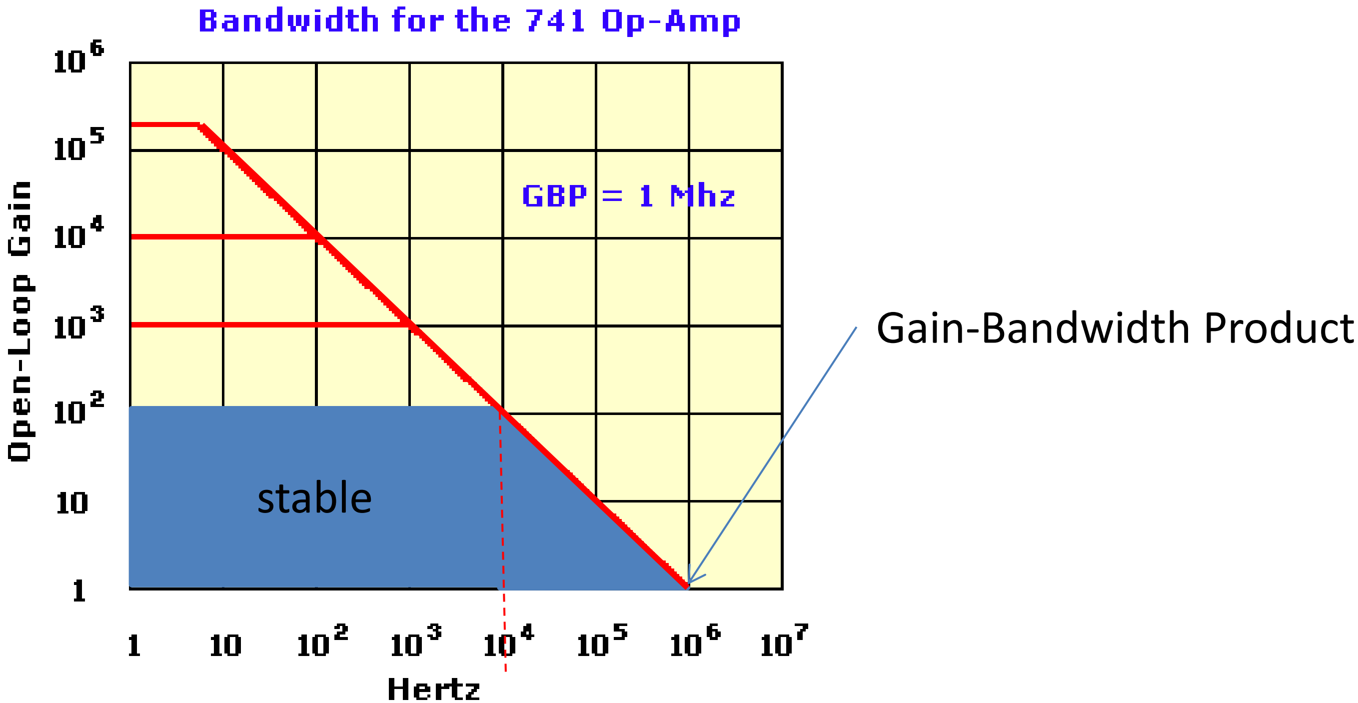
Slope 1/f

Gain-Bandwidth Product
(Freq that Gain=1)

Operational Amplifiers

Frequency Response

Op Amps!



For example, if this op-amp is set as a voltage follower (closed loop gain =1) works out to 1 MHz.

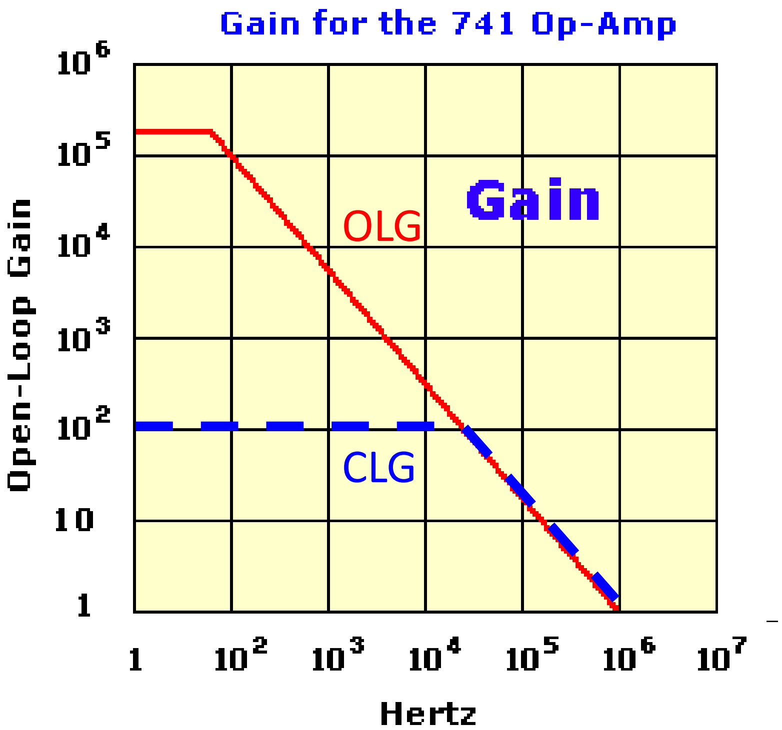
If used as a x100 amp (closed loop gain =100), only works correctly to 10kHz.

For stability, need CLG < OLG

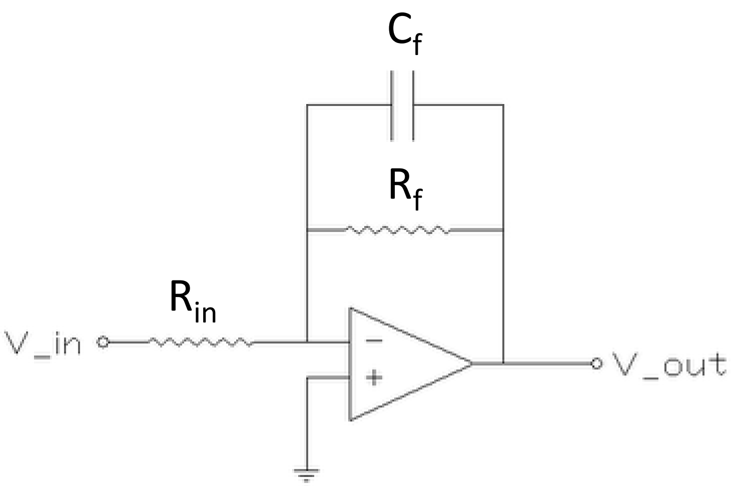
Operational Amplifiers

Conservative Design

Op Amps!



So how do you make sure your amp always stays where it will be stable ? (Since you don't necessarily know what someone's going to put into it.)



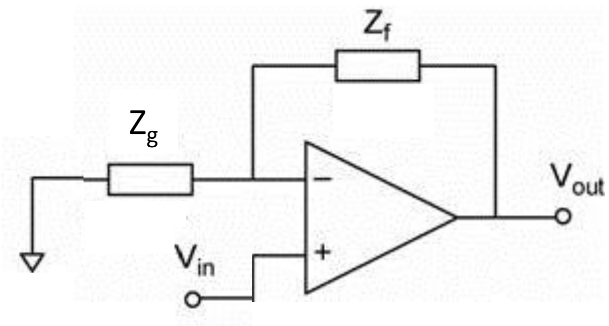
Add a capacitor in parallel with R_f, so that the roll-off frequency will be $1/R_fC_f$.

Operational Amplifiers

Gains in general

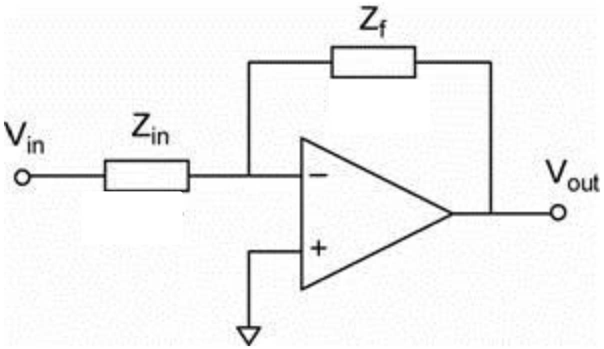
Op Amps!

Non-Inverting



Gain(ω) = $\left(1 + \frac{|Z_f(\omega)|}{|Z_g(\omega)|}\right)$

Inverting



Gain(ω) = $-\frac{|Z_f(\omega)|}{|Z_{in}(\omega)|}$

Operational Amplifiers

Other Op Amp parameters

Op Amps!

<u>Slew Rate</u> - Delineated in Volts/time. E.g. 10V/μsec

Slew rate is, in a way, telling you how the gain depends on amplitude. In other words, even if the signal frequency is within the amp designs CLG bandwidth, if to amplify your signal correctly requires the amp to exceed it's slew rate, it won't and your output won't be correct.

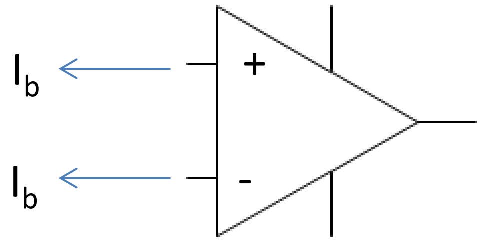
Operational Amplifiers

Other Op Amp parameters

Op Amps!

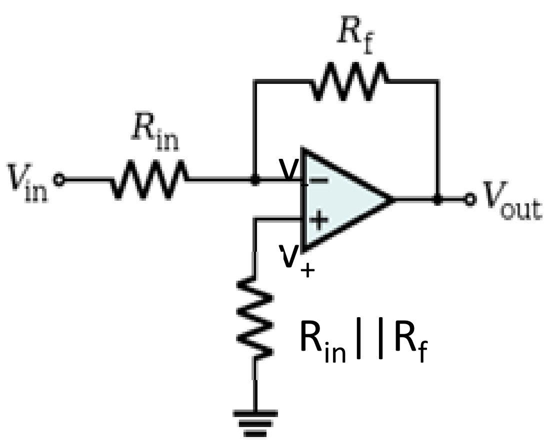
Input bias current (we mentioned this earlier)

Bias currents can be ~100nA each



If input R's not the same, can cause $v_+ - v_- \neq 0$, which will get amplified just like any other signal.

Make if so the R_{TH} of circuits connected to the + & - inputs is symmetric.



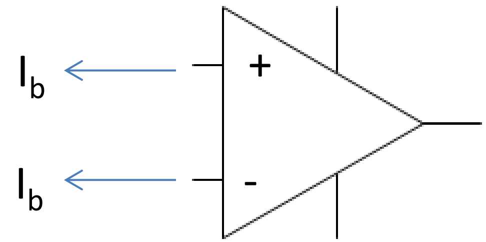
Operational Amplifiers

Other Op Amp parameters

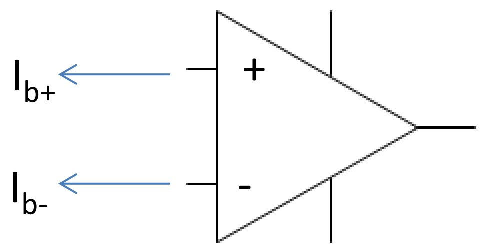
Op Amps!

Offset Current

Remember the input offset currents?



Really is more like



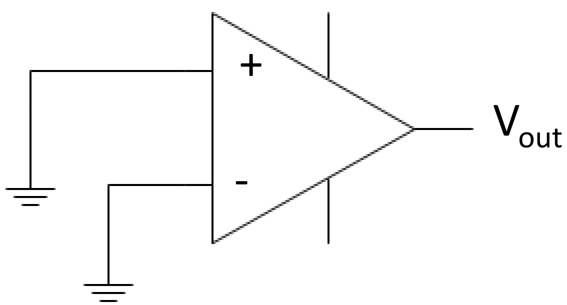
They are not really the same, $|I_{b+} - I_{b-}| \sim 10\%$ of $\overline{I_b}$

Operational Amplifiers

Other Op Amp parameters

Op Amps!

Offset Voltage

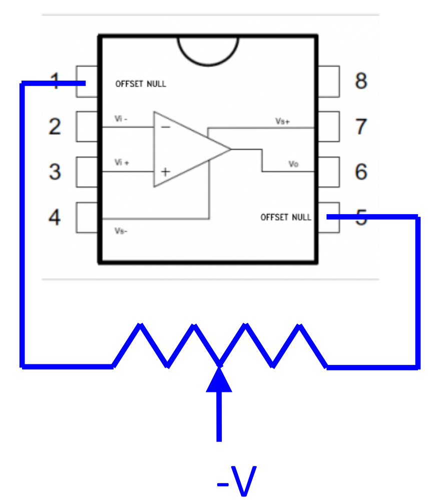


With both inputs grounded, V_{out} should be 0.

No such luck!

V_{offset} ~ 1-5 millivolts DC

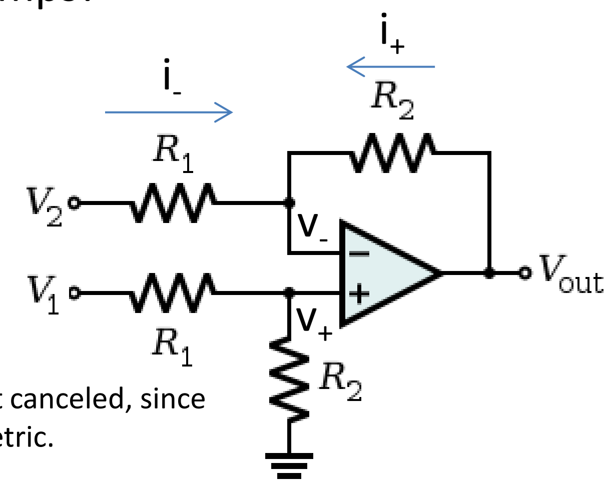
One of the reasons a lot of op-amps have offset null pins, as we showed earlier.



Operational Amplifiers

Differential Amp (input signal is not grounded)

Op Amps!



Input bias current canceled, since input look symmetric.

$v_+ = \frac{R_2}{R_1+R_2} V_1$ (voltage divider)

From Rule 1: $i_- = \frac{V_2 - v_-}{R_1} = - i_+ = - \frac{V_{out} - v_-}{R_2}$

From Rule 2: $v_- = v_+$

$$\frac{V_2 - v_-}{R_1} = \frac{v_- - V_{out}}{R_2}$$

$$\frac{R_2}{R_1}(V_2 - v_-) = v_- - V_{out}$$

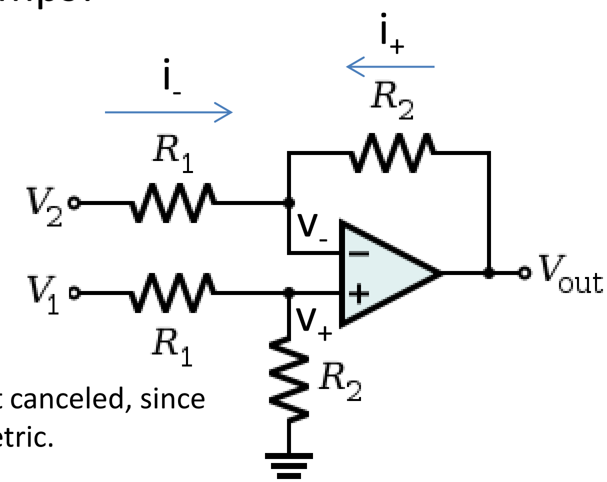
$$V_{out} = \frac{R_2}{R_1} v_- - \frac{R_2}{R_1} V_2 + v_-$$

$$V_{out} = \frac{R_1 + R_2}{R_1} v_- - \frac{R_2}{R_1} V_2$$

Operational Amplifiers

Differential Amp

Op Amps!



Input bias current canceled, since input look symmetric.

Remember, $v_+ = \frac{R_2}{R_1+R_2}V_1$

$i_- = (v_- - V_2)/R_1$

$i_+ = (V_{out} - v_-)/R_2$

$i_- = i_+$ & $v_- = v_+$

So $V_{out} = \frac{R_1 + R_2}{R_1} v_- - \frac{R_2}{R_1} V_2$

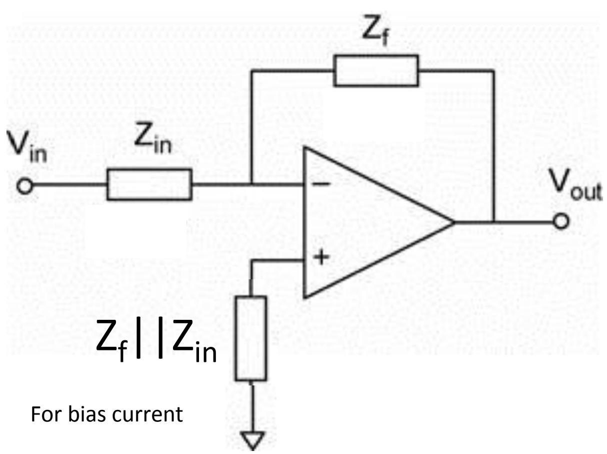
Becomes $V_{out} = \frac{R_1 + R_2}{R_1} v_+ - \frac{R_2}{R_1} V_2$

$V_{out} = \frac{R_1 + R_2}{R_1} \frac{R_2}{R_1+R_2} V_1 - \frac{R_2}{R_1} V_2$

$$V_{out} = \frac{R_2}{R_1}(V_1 - V_2)$$

Operational Amplifiers

Op Amps!

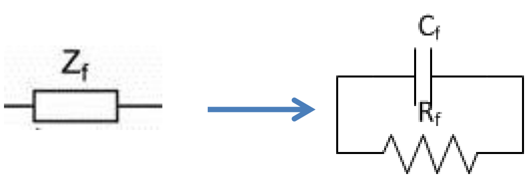


Example: AC op amp

$$A_{eff} = -\frac{|Z_f(\omega)|}{|Z_{in}(\omega)|}$$

Roll on frequency – we will use Z_{in} as a high pass filter.

Hi-freq roll off – we will use Z_f for this by making Z_f a high pass filter ($A_{eff} \to 0$)



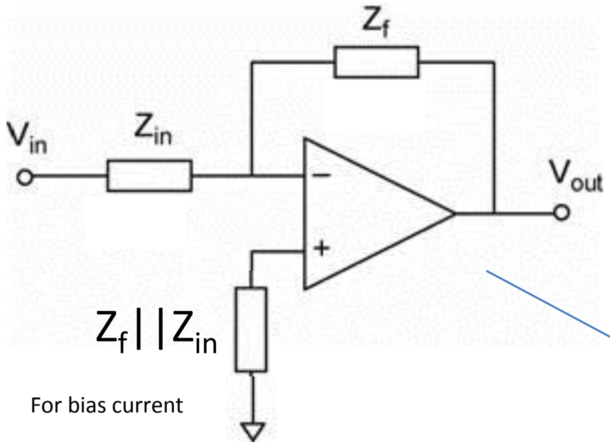
$$|Z_f| = \left[\frac{1}{R_f{}^2} + (\omega C_f)^2\right]^{-1/2}$$

Low freq: $Z_f \sim R_f$
High Freq $Z_f \sim 0$

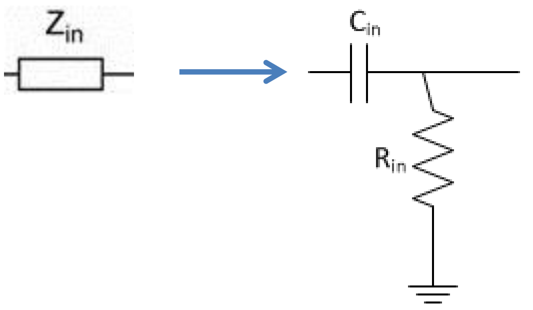
Roll off at frequency $\frac{1}{R_f C_f}$

Operational Amplifiers

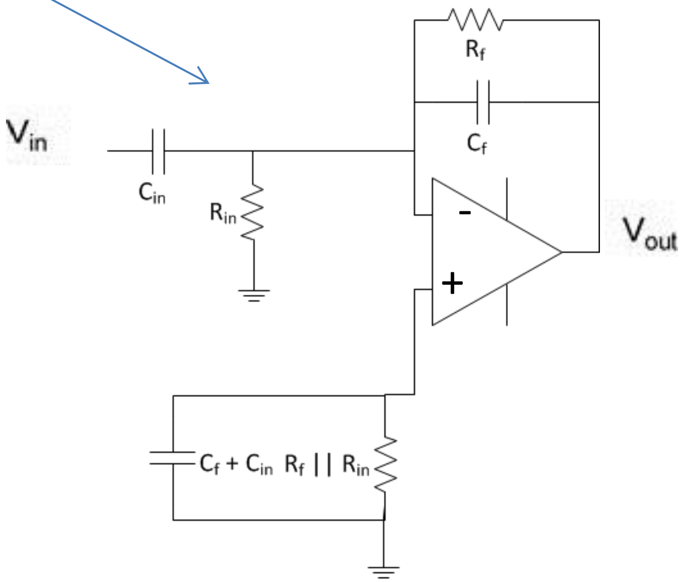
Op Amps!



Example: AC op amp

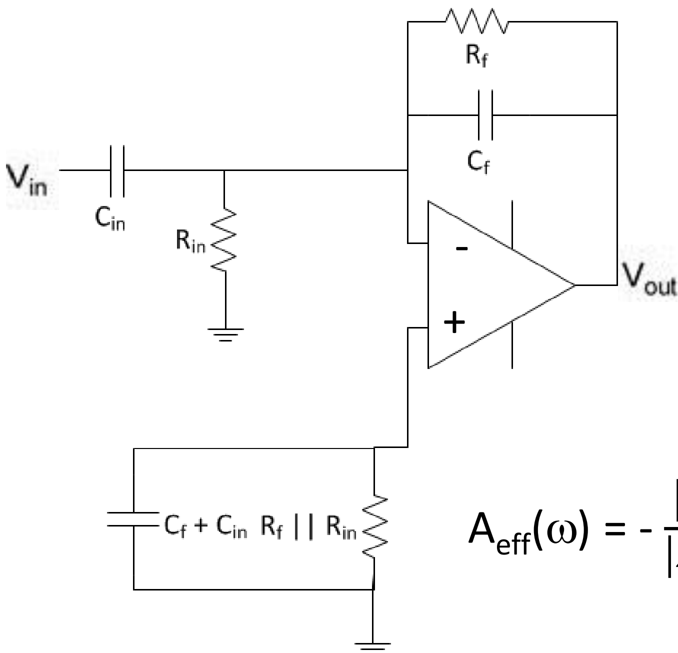


$$\omega_{on} = \frac{1}{R_{in}C_{in}}$$



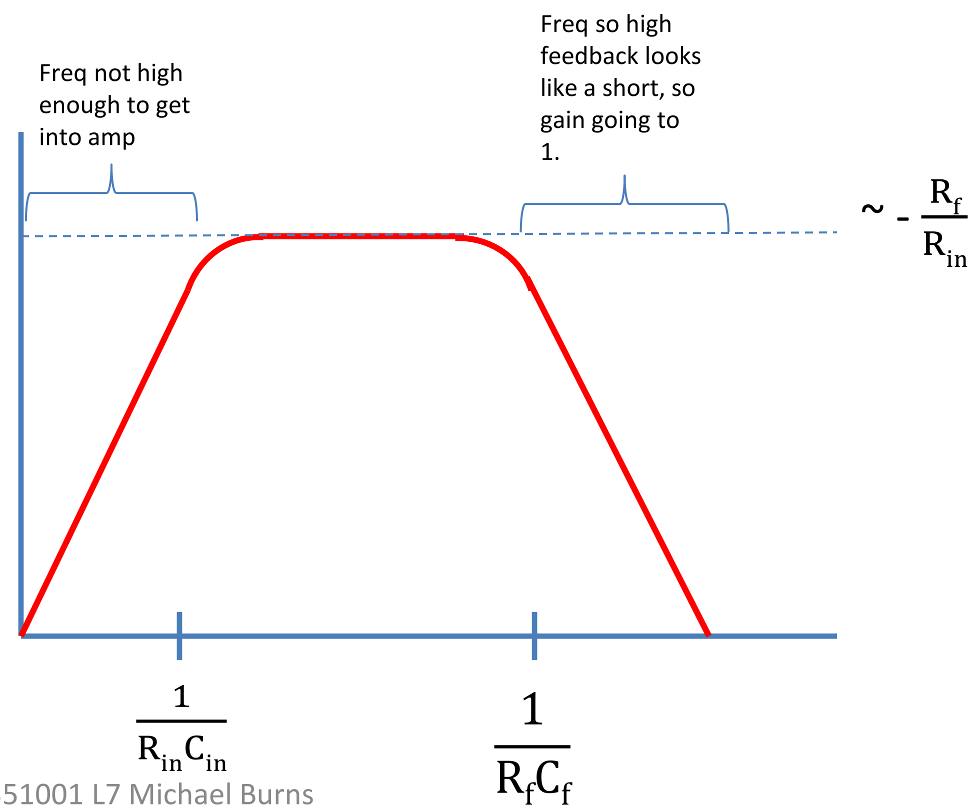
Operational Amplifiers

Op Amps!

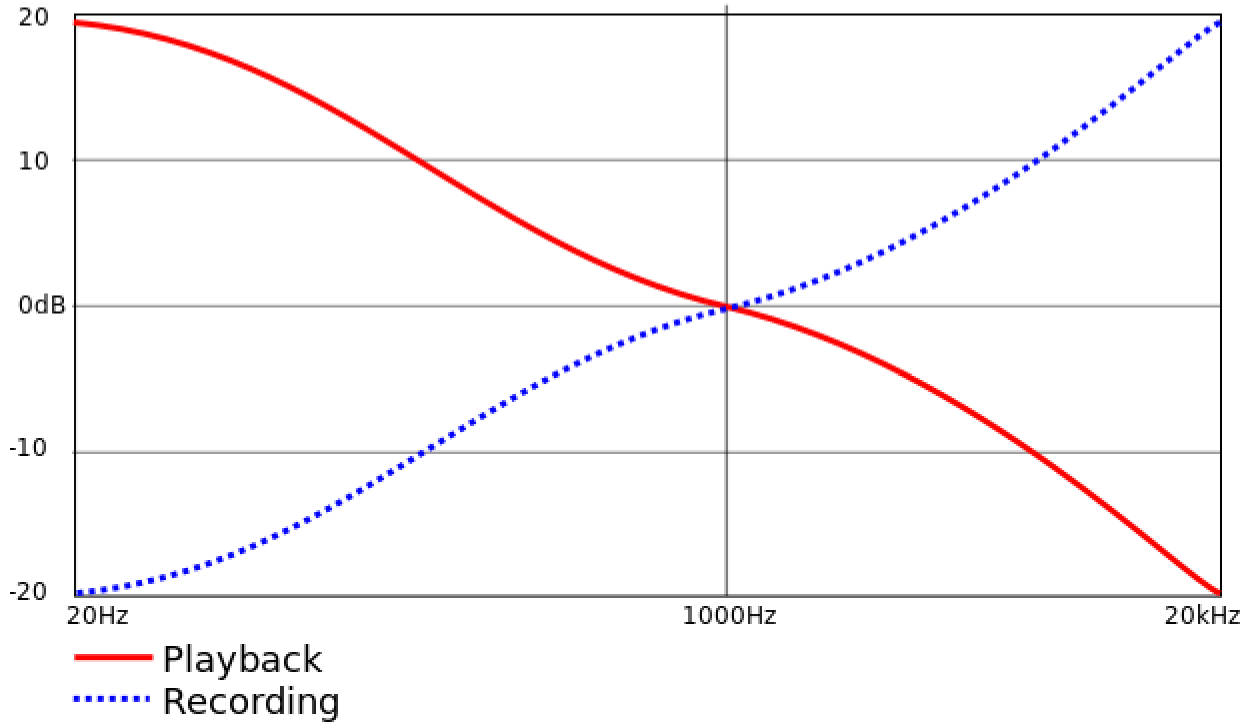


Example: AC op amp

$$A_{eff}(\omega) = -\frac{|Z_f(\omega)|}{|Z_{in}(\omega)|}$$



Operational Amplifiers



(RED) The RIAA equalization curve for playback of vinyl records. (BLUE) The recording curve performs the inverse function, reducing low frequencies and boosting high frequencies. This is to make up for the frequency limitations of the recording medium & it's playback (channels in vinyl mechanically moving a needle). In other words, these non-flat frequency curves for recording & playback are to compensate for this sound recording & playback methods inability to record all frequencies equally well. Ideally, the result is these two curves multiplied together resulting in flat frequency response.