Real op amps (non-ideal aspects)

Real op amps are not perfect.

These things are not a problem with a real op amp:

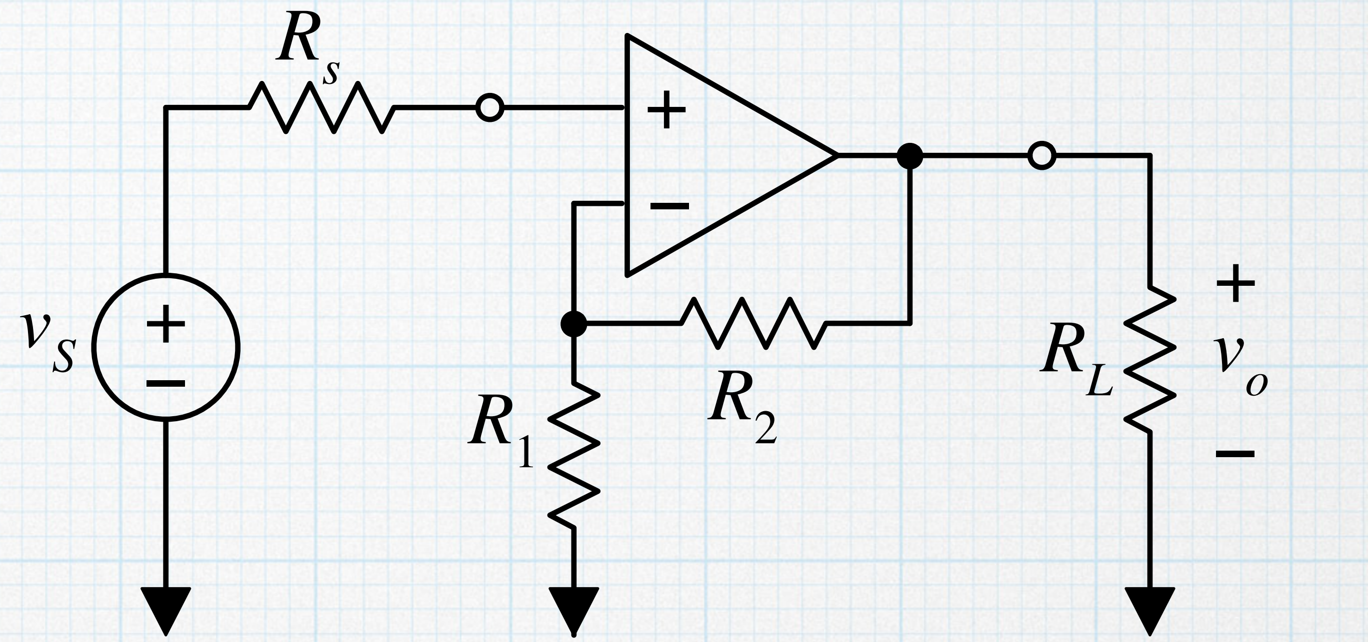
- finite open-loop gain, A
- finite input resistance, R_i
- non-zero output resistance, R_o

These do present limitations in op-amp performance

- power supplies and output voltage limits
- output current limits
- slew rate limits
- DC offsets
- gain-bandwidth limits

A bit of review:

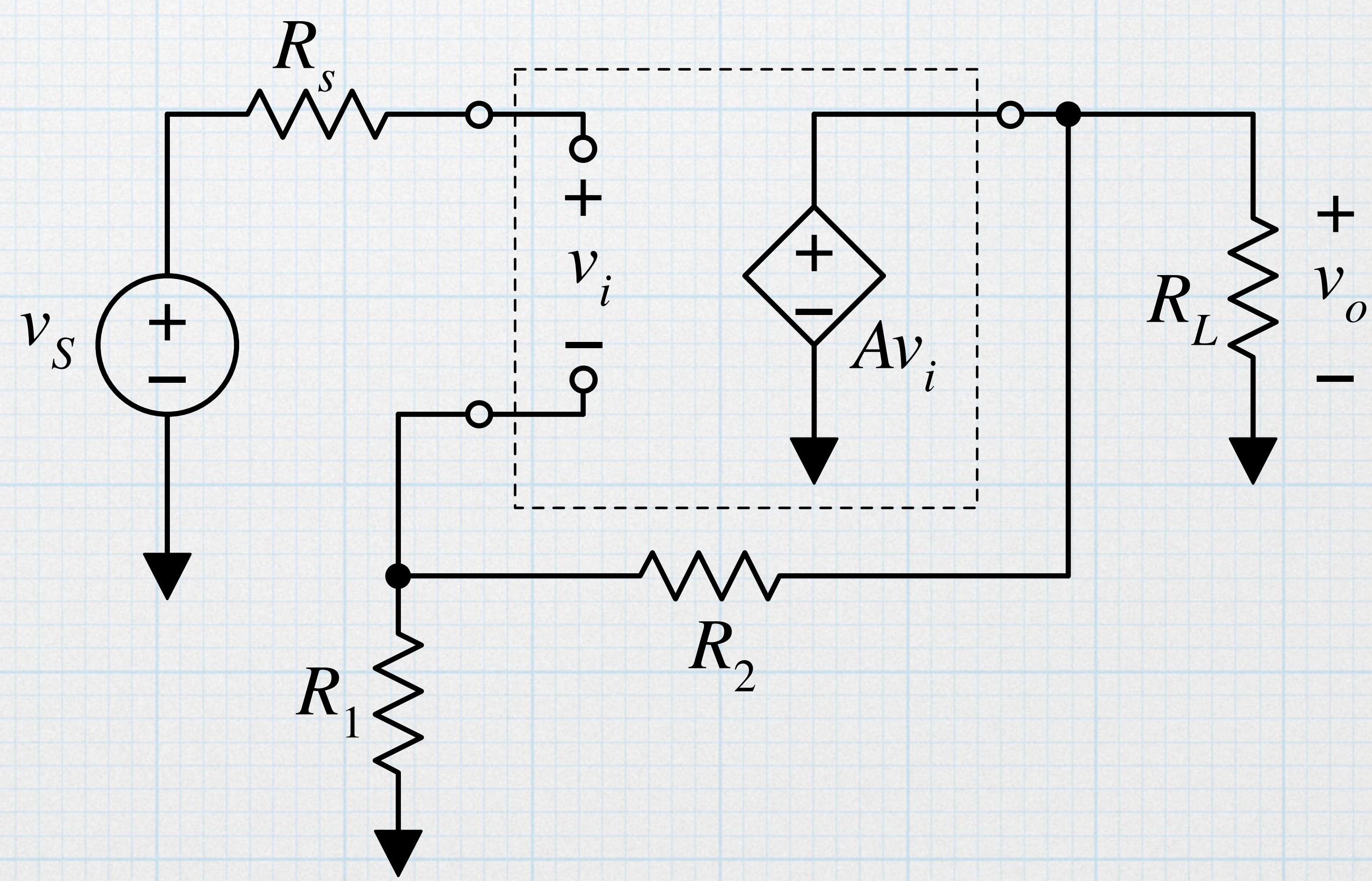
Non-inverting circuit with an ideal amp.



$R_2 = 10\ \text{k}\Omega, R_1 = 1\ \text{k}\Omega.$

$$\frac{v_o}{v_s} = 1 + \frac{R_2}{R_1} = 11$$

Now, keep the ideal resistances, but make the open-loop gain finite.

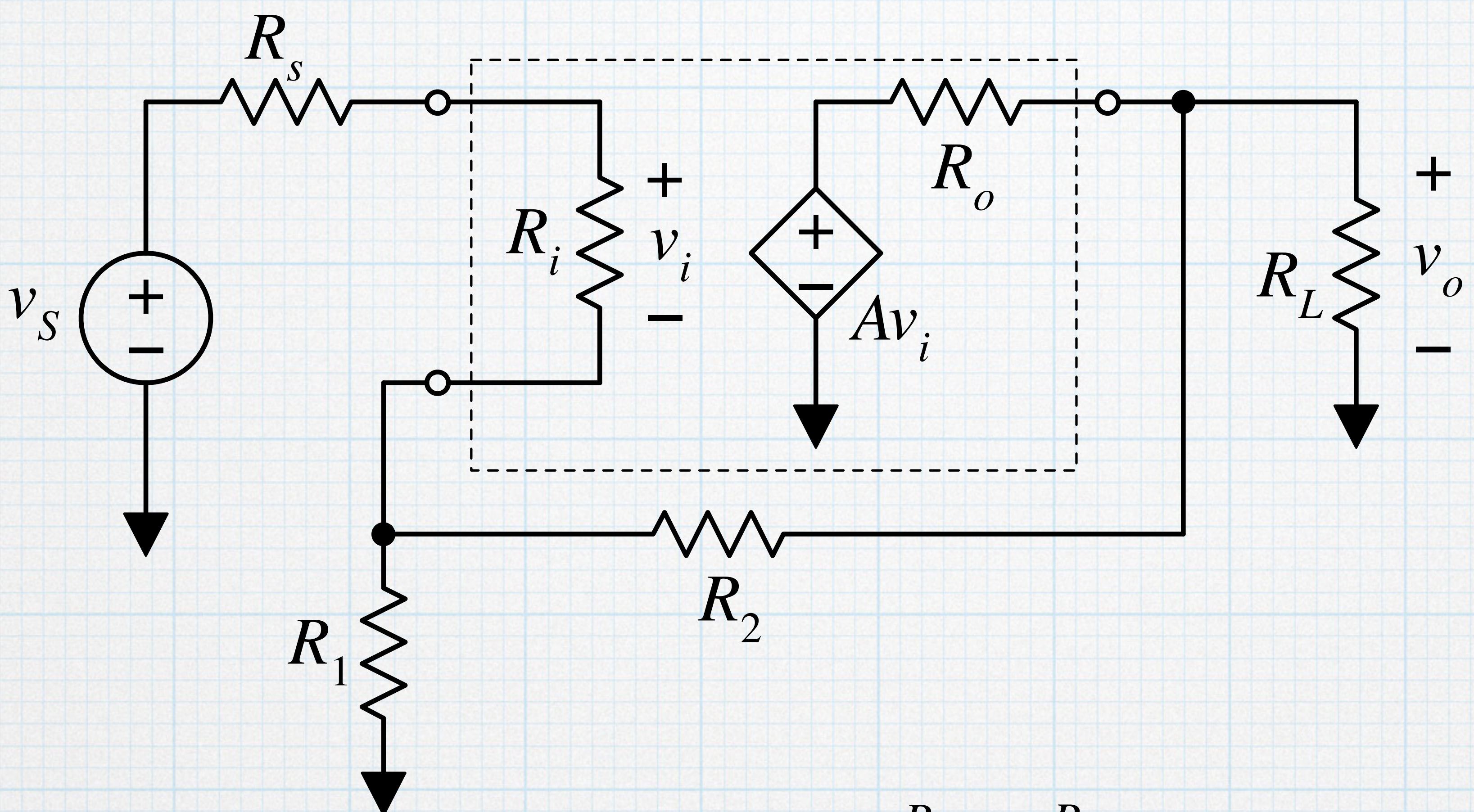


$$\frac{v_o}{v_s} = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{1}{A}\left[1 + \frac{R_2}{R_1}\right]}$$

If $A = 1000$, which is really bad for an op amp.

$$\frac{v_o}{v_s} = 10.88$$

Maybe Ri and Ro need to change to see the some real differences.



$$\frac{v_o}{v_s} = \frac{1 + \frac{R_2}{R_1} + \frac{R_o}{AR_i}}{1 + \frac{R_i + R_s}{AR_i}\left[1 + \frac{R_2}{R_1} + \frac{R_o}{R_1} + \frac{R_o}{R_L} + \frac{R_o R_2}{R_1 R_L} + \frac{R_2}{R_i + R_s}\left(1 + \frac{R_o}{R_L} + \frac{R_o}{R_2}\right)\right]}$$

$R_i = 100{,}000\ \Omega$, $R_o = 1000\ \Omega$, A = 10,000, $R_S = 10\ \mathrm{k}\Omega$, $R_L = 100\ \Omega$.

$v_o / v_s = 10.85$.

$R_o = 0$ $$\frac{v_o}{v_s} = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{R_i + R_s}{AR_i}\left[1 + \frac{R_2}{R_1} + + \frac{R_2}{R_i + R_s}\right]}$$

$$= 10.99$$

$R_i \rightarrow \infty$ $$\frac{v_o}{v_s} = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{1}{A}\left[1 + \frac{R_2}{R_1} + \frac{R_o}{R_1} + \frac{R_o}{R_L} + \frac{R_o R_2}{R_1 R_L}\right]}$$

$$= 10.87$$

$A \rightarrow \infty$ $$\frac{v_o}{v_s} = 1 + \frac{R_2}{R_1}$$

$$= 11$$

Far and way, the most important thing is that the open-loop gain of the amp be large ($>10^4$). If it is, then the feedback works works nearly perfectly and none of the other stuff really matters.

	A_o
LM324	10^5
LMC660	$2x10^6$
TL082	$2x10^5$
NE5532	10^5
OP27	$1.8x10^6$
AD843	$3x10^4$
LT1028	$7x10^6$

Power supplies and voltage limits

- We know that op-amps need power supplies in order to function. (Well, most of us know that.) The op-amp is really just a power converter, taking DC power from the supplies and converting it to signal power sent to output.
- Ultimately, the power available to deliver to the load will depend on power capabilities of the supplies, and the efficiency of the output current stages of the op amp. Since the current is flowing through the op amp, any voltage drops within the op amp represent power being lost in the form of heat — with big currents, the op amp can heat up and be damaged. More on this shortly.
- Power supplies also impose a limit on the maximum and minimum voltage that can appear at the output. It's very simple — the output cannot be more positive or more negative that the power supply voltages. Where would extra voltage come from?

- In fact, for many op amps, the maximum and minimum voltages are slightly less than the power supply values. We acknowledge the possibility by using different notation for the power supplies and the actual voltage limits.

  V_{S+} → positive power supply voltage
  V_{S-} → negative power supply voltage
  V_{L+} → most positive voltage that can be produced at the output
  V_{L-} → most negative voltage that can be produced at the output

- Typically, there is a volt or two difference between V_{S+} and V_{L+} and between V_{S-} and V_{L-}.

- Unfortunately, the actual difference is usually not specified in the data sheet, making it necessary to measure the real limit. Or just assume the difference is a couple of volts on each side, and design accordingly.

- All op amps have a maximum allowable voltages for the supplies. Sometimes this given as the total difference between V_{S+} and V_{S-}, and sometimes it is given as +/– limits. Some amps also have a minimum supply voltage listed.

Rail-to-rail output / single-supply operation

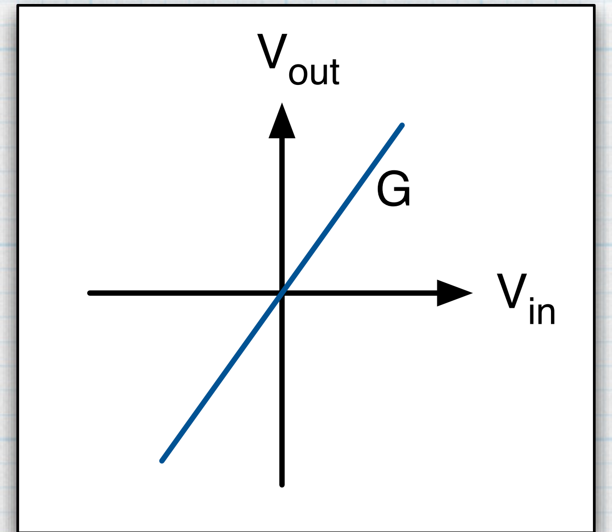
- Some op amps are designed to provide output voltages extending over the entire power supply range. These are known as rail-to-rail outputs. (The power supply voltages are often referred to as the "rails".) In that case,

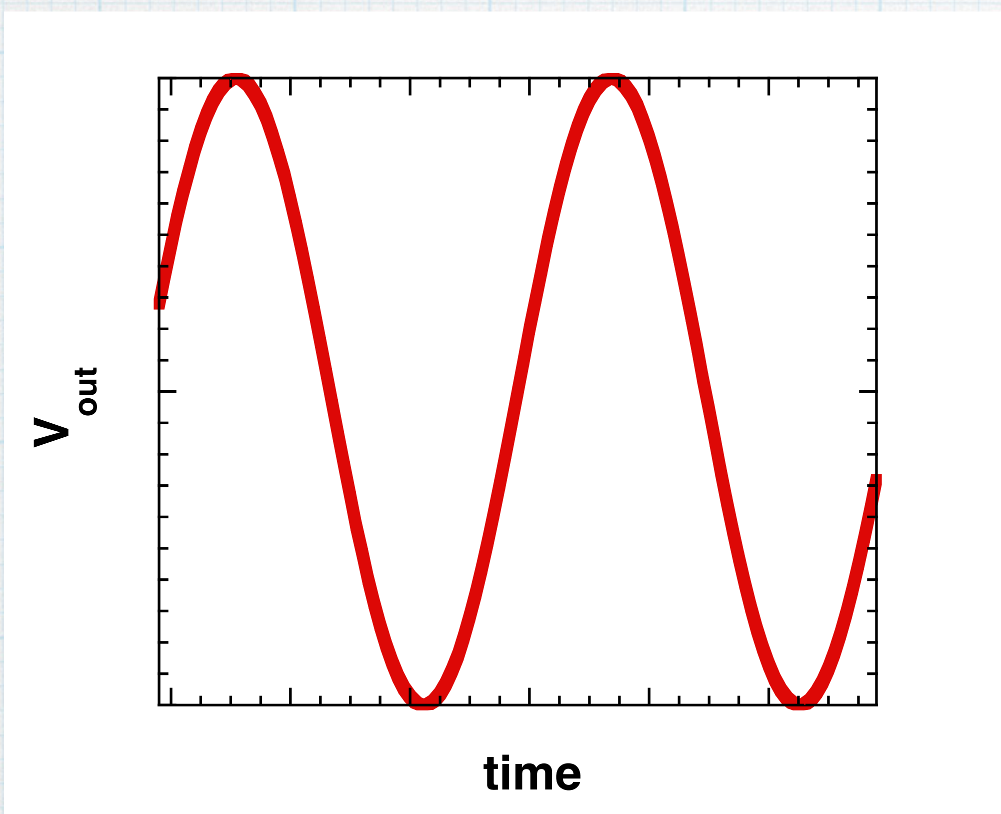
  $V_{L+} = V_{S+}$ and $V_{L-} = V_{S-}$.

- The rail-to-rail advantage is another 2 V or 3 V of available output swing before clipping occurs.
- The LMC600 is an example of an amp with rail-to-rail output.
- Also, some op-amps can work with a single power-supply. In that case, one side — usually the negative side — is connected to ground. Using a single supply can be advantageous in battery powered applications. However, since the output voltage cannot go past ground, the circuit must be designed accordinglyt. (We will discuss single-supply designs in a future lecture.) Not all op-amps will work with a single supply.

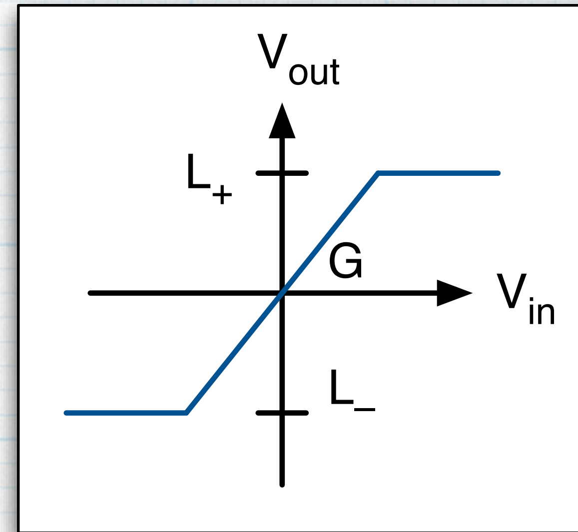
	A_o	$V_{S+} - V_{S-}$
LM324	10^5	3 V - 30 V
LMC660	2×10^6	5 V - 16 V
TL082	2×10^5	5 V - 36 V
NE5532	10^5	5 V - 30 V
OP27	1.8×10^6	44 V
AD843	3×10^4	44 V
LT1028	7×10^6	36 V

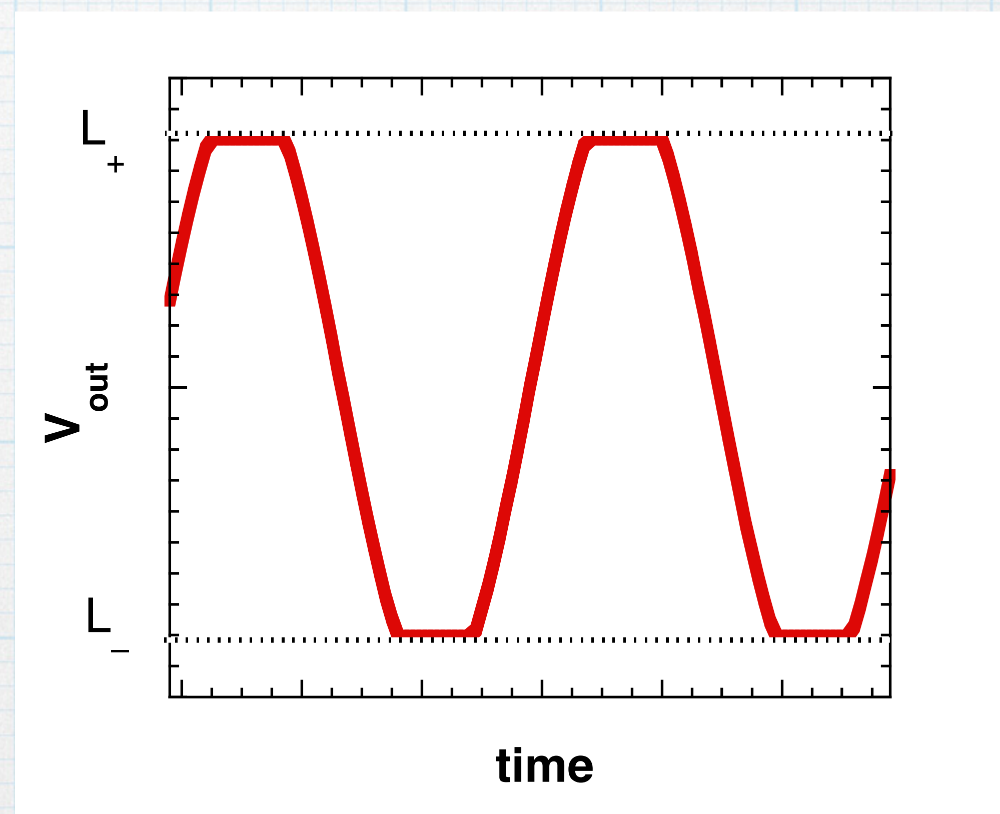
Ideal





Real





Output current limits

Most general-purpose op amps have relatively modest output current capabilities. Internally, there is a limiting sub-circuit that prevents the output current from becoming too big. If too much current flows, the output transistors can be overheated and destroyed. An extreme case occurs when the output is accidentally shorted to ground.

The current limit for most op amps is in the range of a few tens of milliamps. This means that the amp is not capable of directly delivering large power to a load.

For example, suppose you wanted to use an op amp to try to drive a larger bookshelf type speaker, having an 4-Ω coil (modeled as a load resistance of 4 Ω). To deliver 4 W of power to the speaker requires 4 V / 1 A, which is well beyond the current drive capability of most general-purpose amps.

There are high-current op amps (consider the LM383), but the usual approach to use a low-power amp followed by a transistor circuit designed to drive higher current. More on this later.

	A_o	$V_{S+} - V_{S-}$	I_o (max)
LM324	10^5	3 V - 30 V	20 mA
LMC660	2×10^6	5 V - 16 V	18 mA
TL082	2×10^5	5 V - 36 V	—
NE5532	10^5	5 V - 30 V	38 mA
OP27	1.8×10^6	44 V	30 mA
AD843	3×10^4	44 V	50 mA
LT1028	7×10^6	36 V	30 mA

Gain-bandwidth

We have a separate set of notes on the bandwidth limitation of op amps. Finite GBW is one of the most important properties of "real" op amps, and deserves its own section

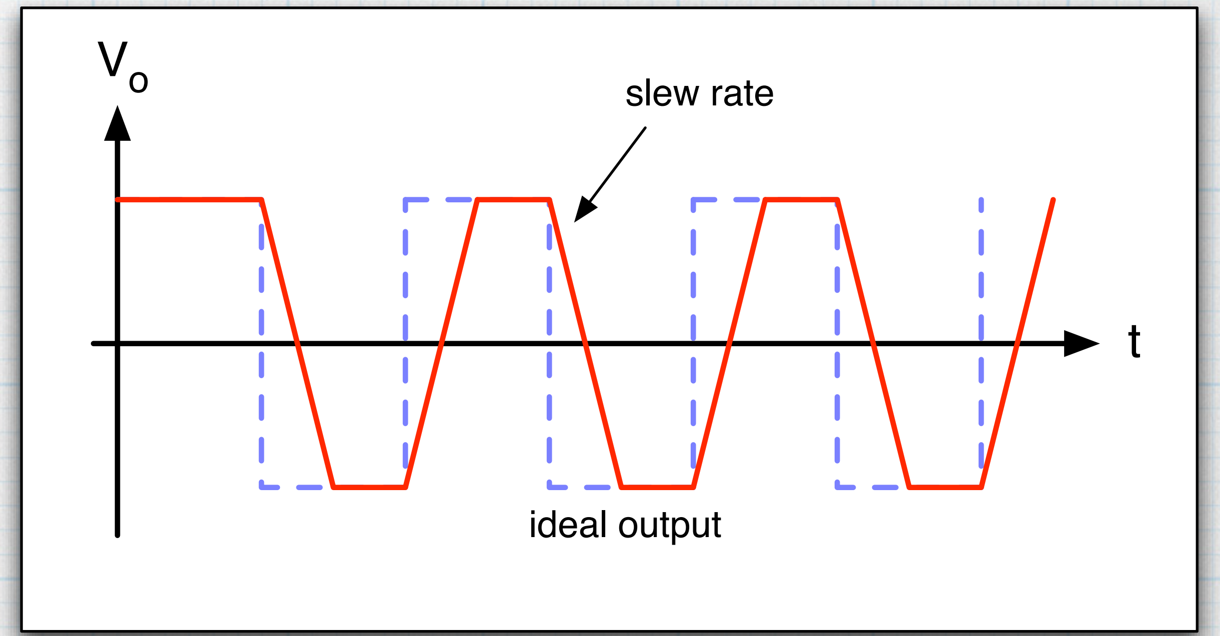
Slew rate

Another limitation is the "slew rate" of the op amp, meaning that there is a limit on how fast he output voltage can change. This is a hard limit and can be another source of distortion.

$$SR = \left.\frac{dv_o}{dt}\right|_{max}$$

Whenever the output tries to change faster than this, the output rate-of-change will be limited to the slew rate.

Slew-rate limits can be most easily seen when an op amp circuit is amplifying a square wave – the output won't keep up.



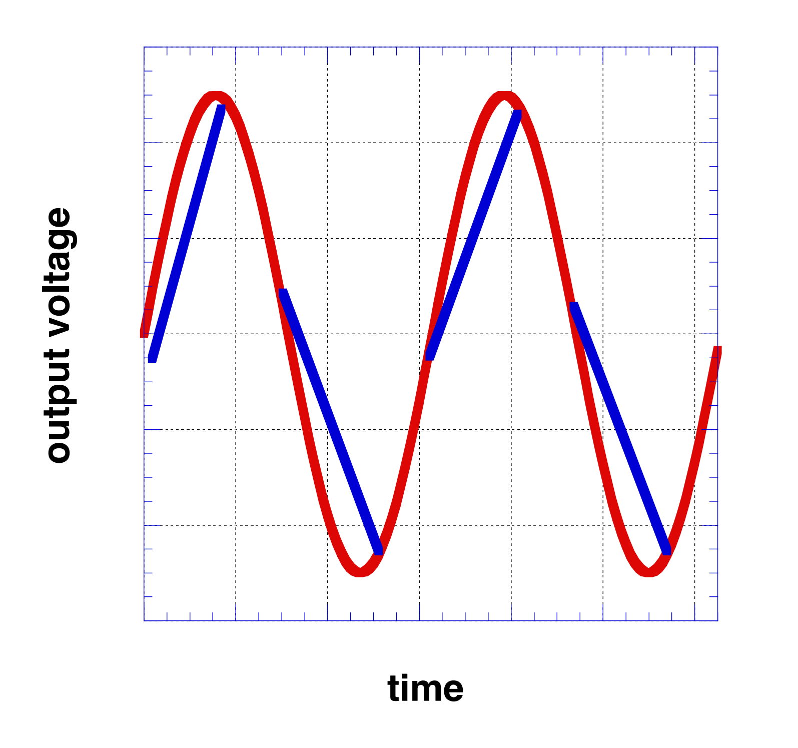
Although slew rate limits are most evident with square-wave transitions, they can affect any waveform. Consider a sinusoid at the output: $v_o(t) = V_m \cos(\omega t)$.

The time rate of change for the cosine is $\dfrac{dv_o}{dt} = -\omega V_m \sin(\omega t)$

If the magnitude of the derivative ever becomes bigger than the slew rate, the output will become distorted. To avoid this problem, we would have to observe the following requirement:

$$\left.\frac{dv_o}{dt}\right|_{max} = \omega V_m < \text{SR}$$

Meaning that you may need to limit either the frequency or the amplitude of the output to avoid distortion.



Even though the slew rate imposes a frequency limit for sinusoidal signals, it is fundamentally different than the gain-bandwidth. Slew rate limits will distort the signal. The bandwidth limitation will give an undistorted signal, but with a possibly reduced amplitude.

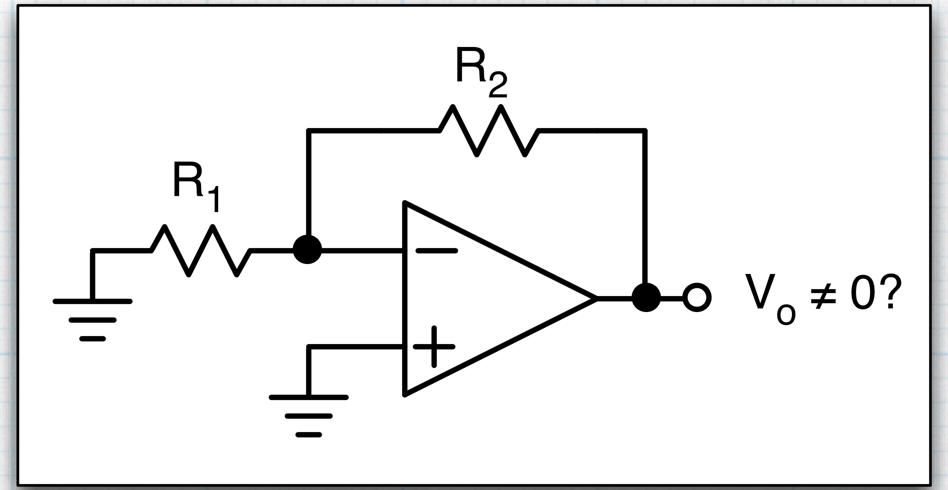
Example: An op amp has listed slew rate of 1 V/μs. In trying to amplify a sine wave with output amplitude of 3 V, what is the highest frequency that can be used without distortion?

$$f < \frac{\mathrm{SR}}{2\pi V_m} = \frac{1\ \mathrm{V}/\mu\mathrm{s}}{2\pi\,(3\ \mathrm{V})} = 53\ \mathrm{kHz}$$

	A_o	$V_{S+} - V_{S-}$	I_o (max)	SR
LM324	10^5	3 V - 30 V	20 mA	0.5 V/μs
LMC660	2×10^6	5 V - 16 V	18 mA	1.1 V/μs
TL082	2×10^5	5 V - 36 V	—	13 V/μs
NE5532	10^5	5 V - 30 V	38 mA	9 V/μs
OP27	1.8×10^6	44 V	30 mA	2.8 V/μs
AD843	3×10^4	44 V	50 mA	250 V/μs
LT1028	7×10^6	36 V	30 mA	11 V/μs

Offset voltage and bias current

The circuit at right is an inverting amp with no input voltage. (Or is it a non-inverting amp with no input?) Whichever, we expect the output voltage to exactly zero for an ideal op amp.

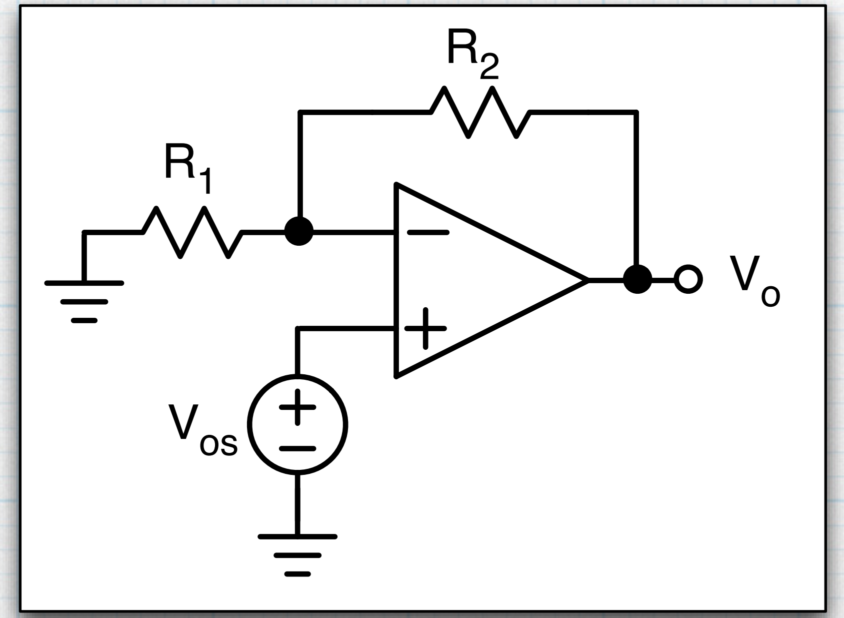


However, if we do this in lab, we would find a non-zero DC voltage at the output. This is the result of two more imperfections: DC offset voltages and bias currents. DC offset voltages result from imperfect matching of transistors at the input of the op amp. These are manufacturing imperfections and show up in all op amps. Bias currents are small DC currents needed for proper operation of the transistors at the inputs of some op amps. The current level varies widely for different op amps. It is rarely bigger than a few microamps (as for the 741 and 324) and can be nearly neglible for some amps (picoamp range for the 660).

The end effects of offset voltages and bias currents are the same: unexpected DC output voltages. For simplicity, we'll start by considering the two separately.

DC offset voltages

We're not yet able to understand the origin of offset voltages. However, the effect is easy to model: Simply add a DC voltage to the non-inverting input of an otherwise ideal op amp.



It looks like a non-inverting amp.

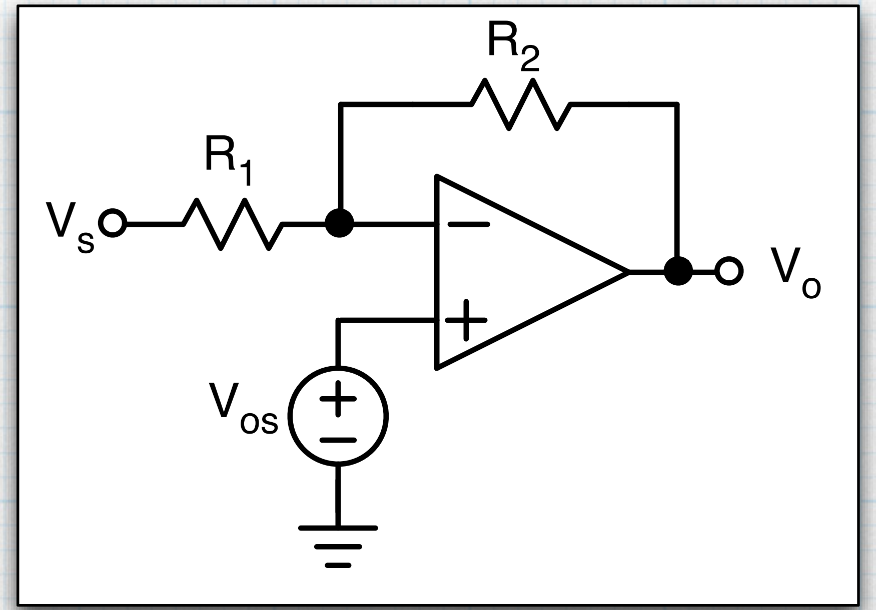
$$v_{oDC} = \left(1 + \frac{R_2}{R_1}\right) V_{OS}$$

Since the error is associated with the input of the op amp, it will be multiplied by the gain of the circuit. Obviously, offset problems are worse for amps with high gain.

Example

An inverting amp is made using R_2/R_1 = 500. The input signal is V_S = (10mV)sinωt. The offset voltage for the op amp is 5 mV. What is the expected output voltage?

This could be analyzed using a several different methods. Here's one approach.



$$\frac{v_i - v_-}{R_1} = \frac{v_- - v_o}{R_2}$$

$$v_- = V_{OS}$$

$$v_o = -\frac{R_2}{R_1} v_i + \left(1 + \frac{R_2}{R_1}\right) V_{OS}$$

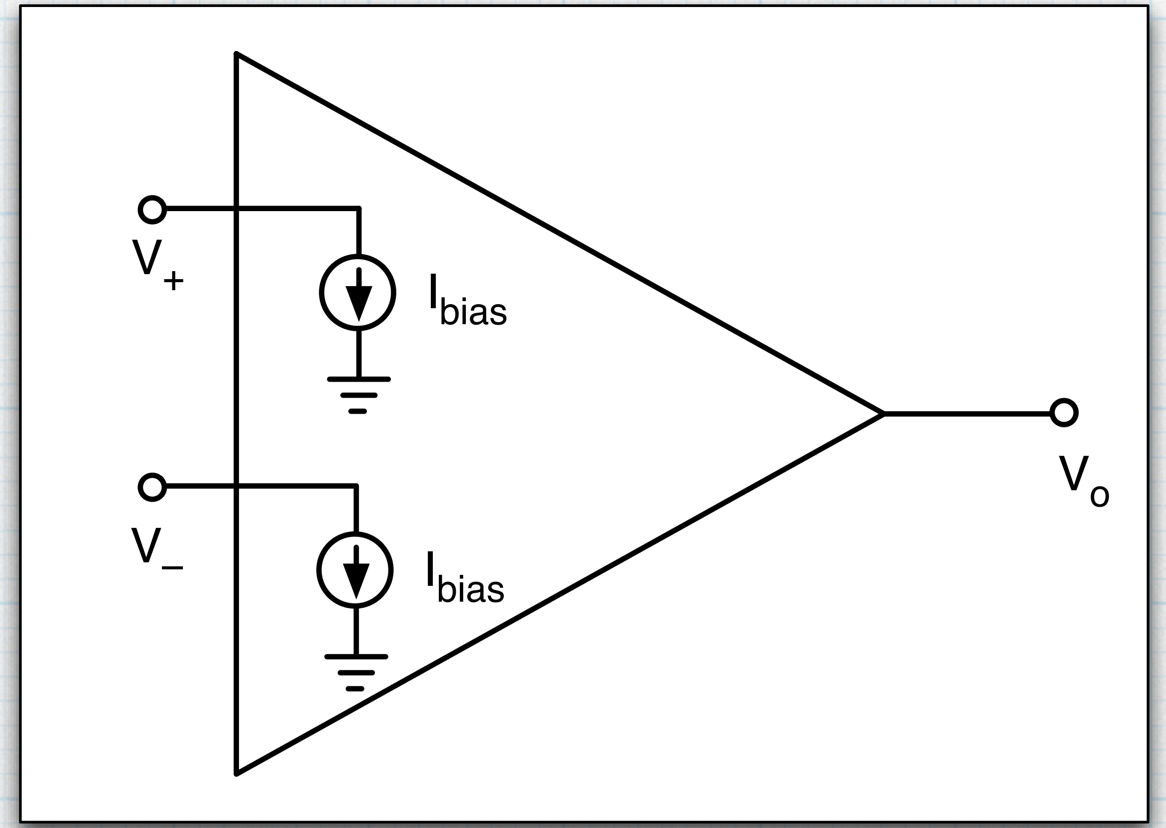
$$= -(5\text{ V})\sin\omega t + 2.5\text{ V}$$

Since voltage offset results from manufacturing variations, it will be a random variable — positive for one amp, negative for another, and maybe zero for a third. So the average over a large number of amps would be zero. However, this gives an improper view of the problem. Instead, we should average the magnitude of the offset. For most op amps, the average of the magnitude is on the order of a few millivolts.

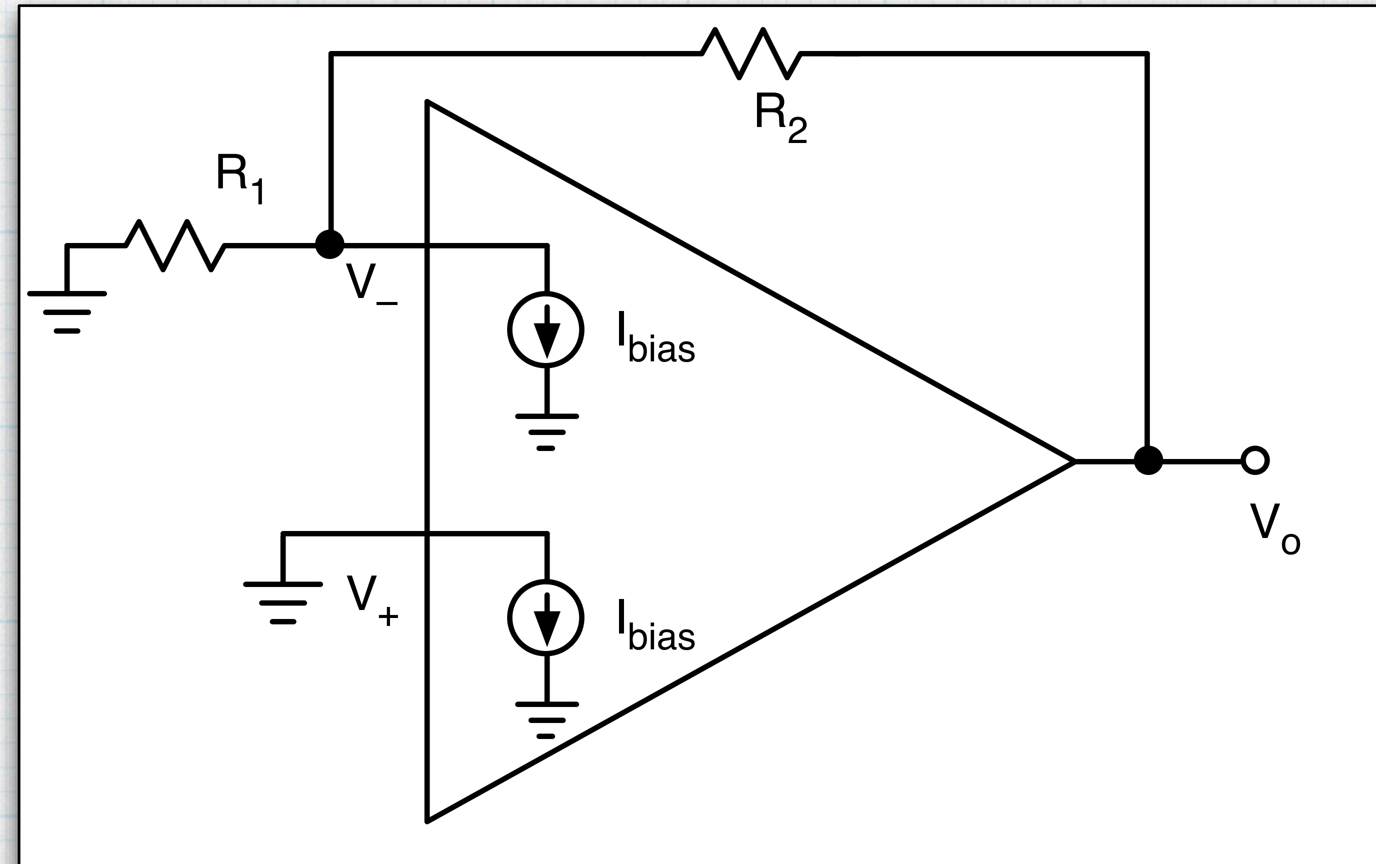
It is possible to buy “high-precision” amps, that have smaller offset voltages, but you pay more than you would for general-purpose amps.

Bias current

Some older op amps (ones using bipolar transistors) require a small amount of current inflow in order to work properly. Again, we can't yet understand the details, but the effect is easy to model — add a pair of current sources at the inputs.



To see the effect of the bias current, hook up an inverting amp.



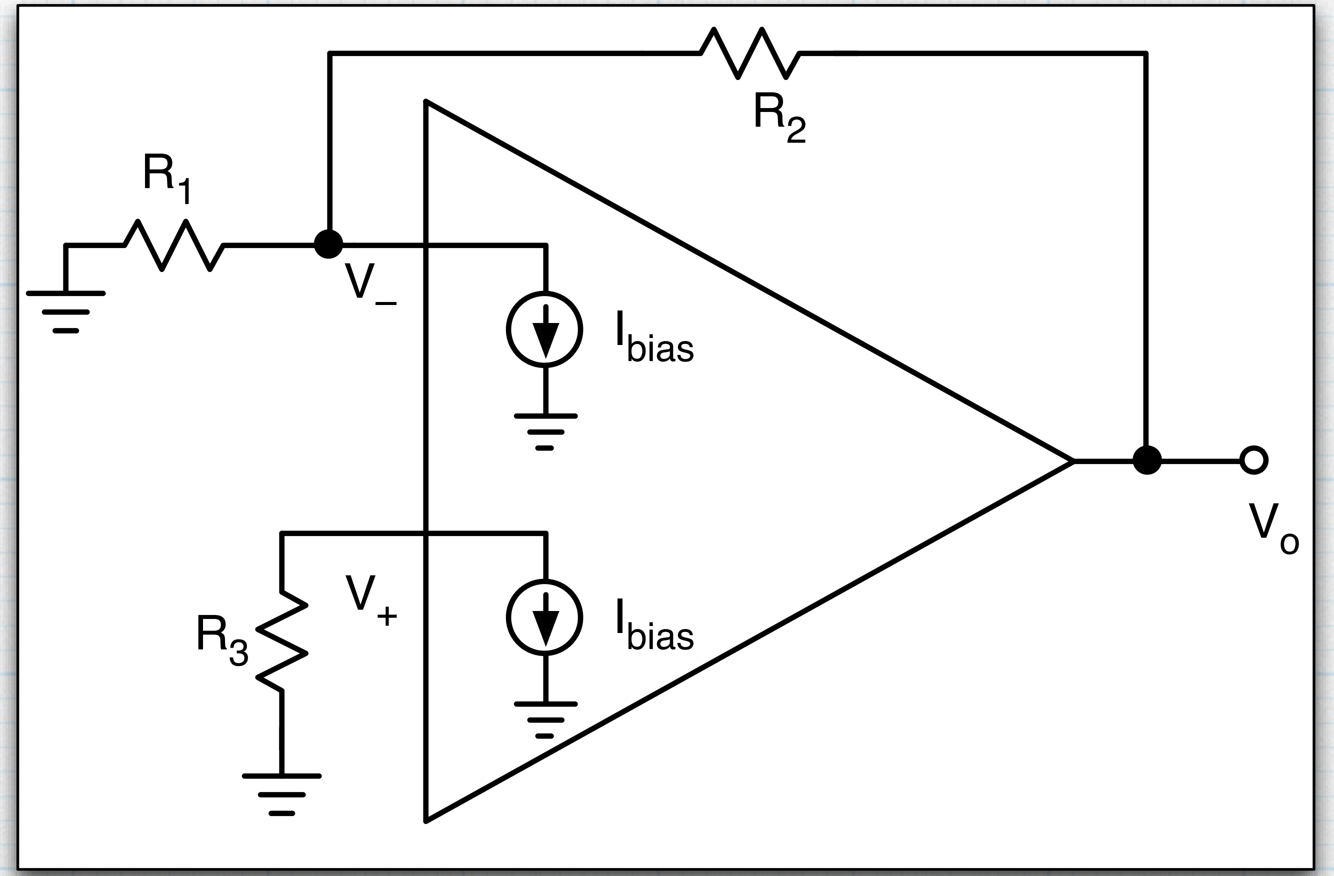
Using virtual ground: $V_{-} = V_{+} = 0$.

Then: $v_{oDC} = I_{bias}R_2$

So this will be a problem whenever R_2 is large (as in the case of high-gain amps).

It is possible to cancel out the effects of the bias currents by shifting the non-inverting terminal from ground, i.e. having $v_+ \neq 0$. Put a resistor between ground and the non-inverting terminal.

$$\frac{v_-}{R_1} + \frac{v_- - v_o}{R_2} + I_{bias} = 0$$

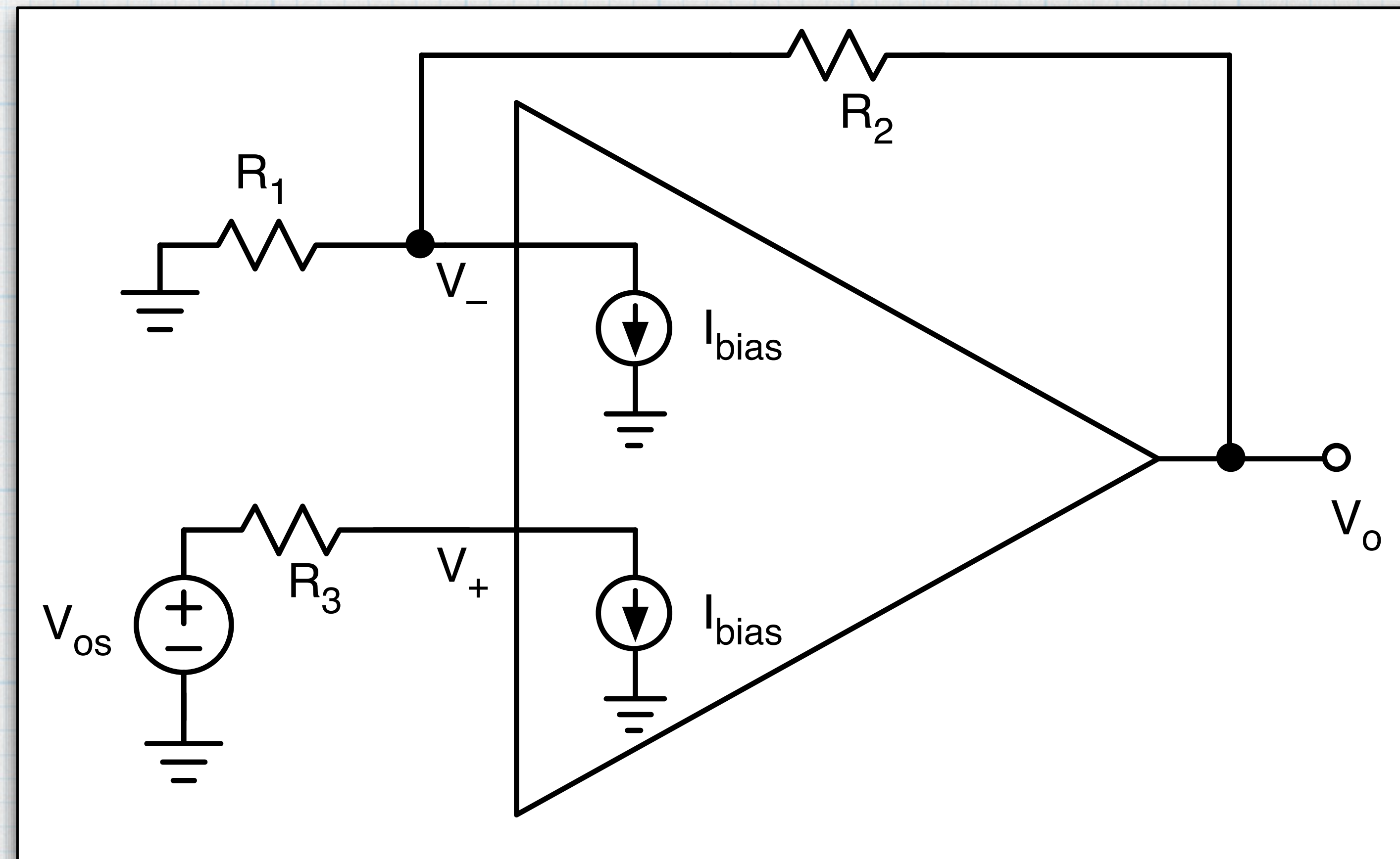


$$v_- = v_+ = -I_{bias} R_3$$

$$v_o = I_{bias}\left(R_2 - R_3 - \frac{R_2 R_3}{R_1}\right)$$

The output will be zero, if we choose $R_3 = R_1 \| R_2$

Although we've treated them separately, offset voltage and bias currents will occur together and we can't necessarily sort them out.



Use superposition (or solve node voltages from scratch, as done below) to see the cumulative effect.

$$\frac{v_-}{R_1} + \frac{v_- - v_o}{R_2} + I_{bias} = 0 \qquad v_- = v_+ = -I_{bias}R_2 + V_{os}$$

$$v_o = \left(R_2 - R_3 - \frac{R_2 R_3}{R_1}\right) I_{bias} + \left(1 + \frac{R_2}{R_1}\right) V_{os}$$

If $R_3 = R_1 \| R_2$ then $v_o = \left(1 + \frac{R_2}{R_1}\right) V_{os}$

We see offset voltage effect only.

Example (like lab)

Set up the inverting circuit with R_2/R_1 =680kΩ/1kΩ with no input and set $R_3 = R_1||R_2$. The bias current effect should be zeroed out. If we then measure the output voltage to be -2.0 V, we can calculate V_{OS}.

$$V_{os} = -2.0\text{V} / 681 = -2.9 \text{ mV}.$$

Then remove R_3 (i.e. make it zero) and measure the output to -0.5 V. Since the bias currents aren't canceled in this case,

$$v_o = R_2 I_{bias} + \left(1 + \frac{R_2}{R_1}\right) V_{os}$$

$$I_{bias} = \frac{v_o - \left(1 + \frac{R_2}{R_1}\right) V_{os}}{R_2}$$

$$= \frac{-0.5 \text{ V} - (-2.0 \text{ v})}{680 \text{ k}\Omega} = 2.2 \ \mu\text{A}$$

Note that V_{OS} can be positive or negative, and the bias currents can also be positive or negative, depending on the type of transistors at the input.

A further complication is that the bias currents may be mismatched also, for much the same reason that there is an offset voltage. So we could take the analysis one step further and include current differences. However, these effects are usually very small and not worth extra effort here.

Modern op amps (using CMOS technology) have exceptionally tiny bias currents — so small that we probably don't even need to consider them.

Offset voltages and bias currents are particularly problematic in high-gain amps and integrating circuits.

Some op amps have extra connections that can be used to try to cancel offset voltages (eg. 741). Read the data sheet to see how to use these. We can also use summing amp techniques to try cancel offsets.

	A_o	$V_{S+} - V_{S-}$	I_o (max)	SR	V_{OS}	I_{bias}
LM324	10^5	3 V - 30 V	20 mA	0.5 V/μs	3 mV	20 nA
LMC660	2×10^6	5 V - 16 V	18 mA	1.1 V/μs	3 mV	2 fA
TL082	2×10^5	5 V - 36 V	—	13 V/μs	3 mV	30 pA
NE5532	10^5	5 V - 30 V	38 mA	9 V/μs	0.5 mV	200 nA
OP27	1.8×10^6	44 V	30 mA	2.8 V/μs	30 μV	20 nA
AD843	3×10^4	44 V	50 mA	250 V/μs	1 mV	0.6 nA
LT1028	7×10^6	36 V	30 mA	11 V/μs	40 μV	25 nA