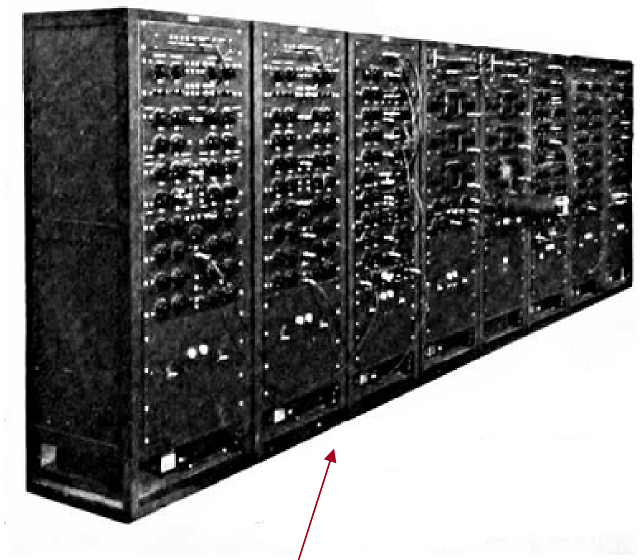
ELEN 50 Class 15 – Operational Amplifiers

S. Hudgens

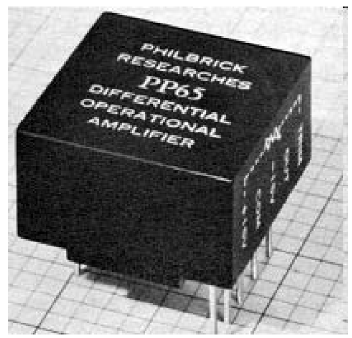
First, a little history

The operational amplifier (op amp) is a DC-coupled, very high-gain, feedback amplifier which has become an important circuit element in many electronic devices. It was invented in 1941 at Bell Laboratories and the first op amps were constructed using vacuum tube technology.



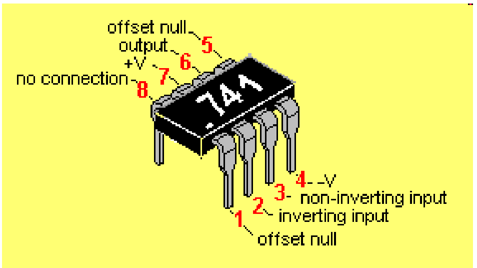
They were also very expensive (about \$28 each in 1952 → ~ \$230 in today's dollars) – and mostly used in analog computers….its not likely you've ever seen one of these.

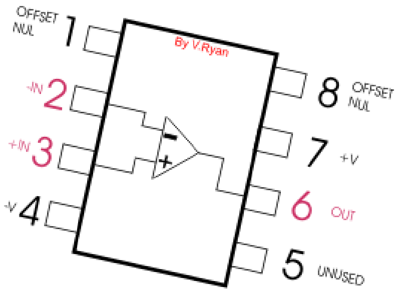
With the invention of transistors in the late 1940s …and their wide commercial availability in the 60s and 70s , op amps using discrete transistors and other circuit elements became available….replacing vacuum tubes. The op amps were still pretty big!

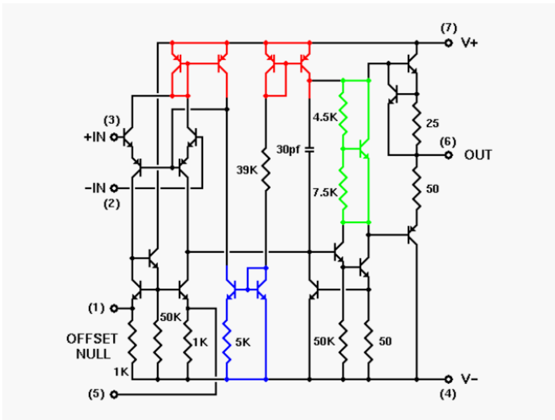


The op amp shown above was made by Philbrick Researches in the 1960s. The op amp was contained in an epoxy cube about 2 inches on an edge – and was still quite expensive. Since mainframe digital computers had largely replaced analog computers by the 1970s, op amps were used primarily as instrumentation amplifiers.

Today, integrated circuit versions of op amps are available and they are very inexpensive – about $0.20 each in single unit quantities.







The internal circuitry of the 741 op amp.

This is what's inside a 741 op amp …20 transistors and 11 resistors for $0.20 … retail in single unit quantities! This is the op amp you will use in the next lab.

Just for Fun

Robert John (Bob) Widlar (pronounced *wide-lar*; born on November 30, 1937 in Cleveland; died February 27, 1991 in Puerto Vallarta, Mexico) was an American electronic engineer and a pioneer of linear (analog) integrated circuit (IC) design. Widlar invented the basic building blocks of linear ICs like the Widlar current source, the Widlar bandgap voltage reference and the Widlar output stage. From 1964 to 1970, Widlar, together with David Talbert, created the first mass-produced operational amplifiers ICs (μA702, μA709), the first integrated voltage regulator IC (LM100), the first operational amplifiers employing full internal compensation (LM101), field-effect transistors (LM101A), and super-beta transistors (LM108). These were all predecessors of the op amp you will use in the ELEN 50 lab. Each of Widlar's circuits had "at least one feature which was far ahead of the crowd" and became a "product champion" in its class. They made his employers, Fairchild Semiconductor and National Semiconductor, the leaders in linear integrated circuits.

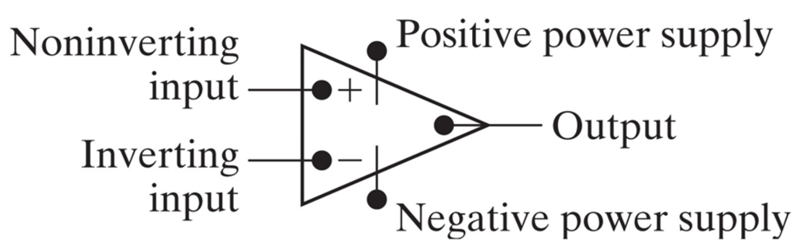
From Wikipedia

There are many Bob Widlar stories on the Internet – he was an analog design genius and one of the most “colorful characters” in Silicon Valley in the old days.

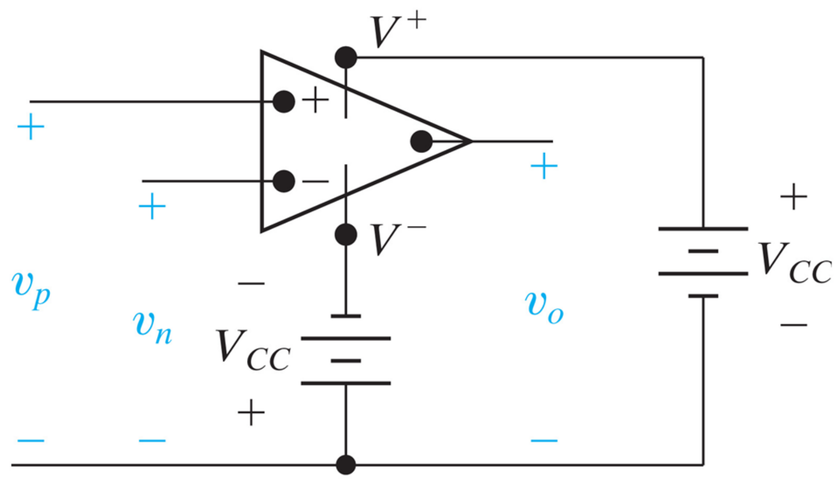
What Are Op Amps?

In this circuits course, we will deal with op amps as an abstraction – regardless of what is actually inside of the physical op amp. From our perspective an op amp is just another circuit element, as shown below:

It's different from circuit elements we've studied so far -- it has five terminals – three of which are very important

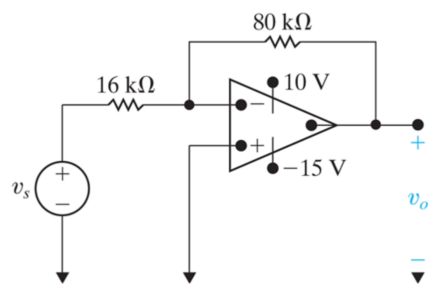


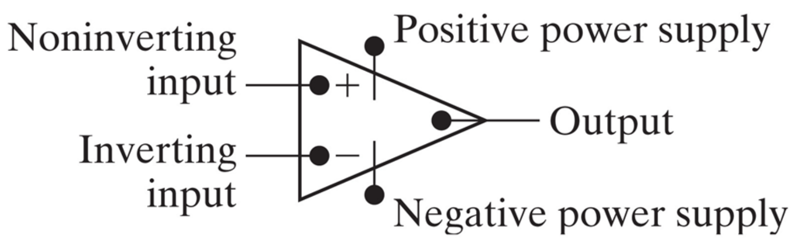
There are two power supply connections, two input connections, and one output connection. Also…the operational amplifier is an **<u>active circuit element.</u>** It's not like a resistor which is a passive element – although it is actually very much like a dependent voltage source. In fact you could represent an operational amplifier as a dependent voltage source whose output is equal to a gain factor G times the difference between two input voltages.



common node

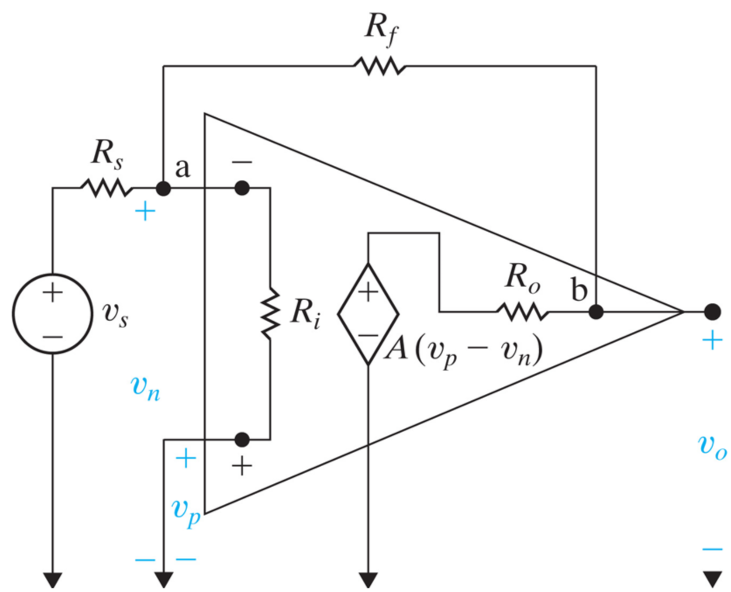
The power supply is made up of two voltage sources – plus and minus with respect to the common ground node, and the input and output voltages are all referenced to the common node as shown. In most op amp circuits we won't bother showing the power supply connections and all voltages will be referenced to an assumed "ground" connection as shown below.





The power supply connections are needed to make the op amp work, but, otherwise not significant except they provide a limit to the output voltage. The output voltage cant be more positive or negative than the power supply voltage.

Schematically, we can consider the op amp to be made up of an input resistor, an output resistor, and a voltage controlled voltage source:

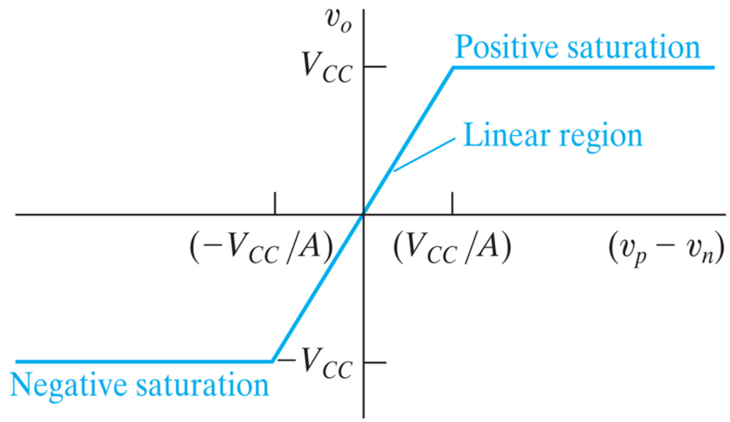


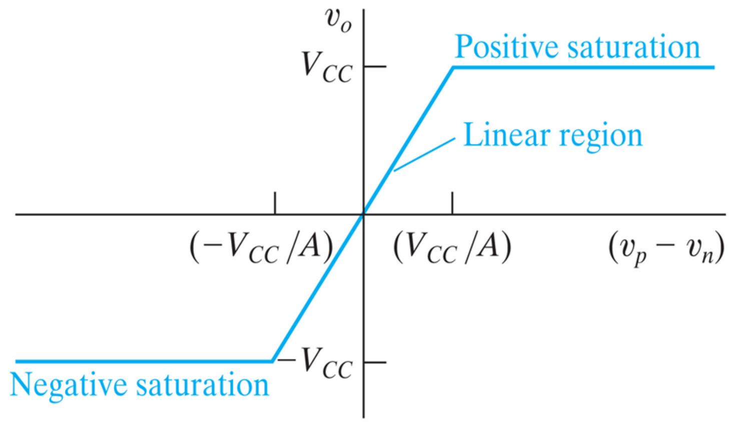
The amplification factor or open loop gain of the op amp is very large …usually greater than 10^4 (and often larger) and it has a differential input – meaning that the op amp <u>amplifies the voltage difference</u> between the inverting and non-inverting inputs. Thus, the voltage output of the op amp, v_0 , is given by:

$$\boxed{v_0 = A\,(v_p - v_n)}$$

Here, v_p is the voltage on the positive or noninverting input, v_n is the voltage on the negative or inverting input, and A is the (huge) open loop gain of the amplifier.

Because of the high open loop gain, and the fact that the output voltage can never be larger (positive or negative) than the power supply voltage, the bare op amp has a voltage transfer characteristic as shown:





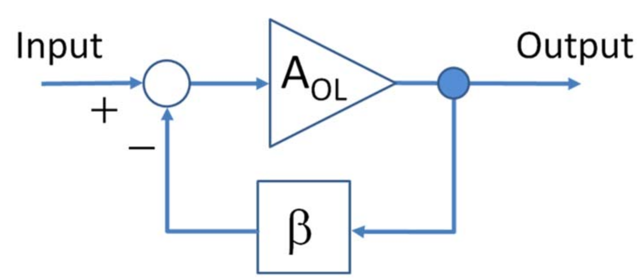
The very narrow range of (v_p –v_n) [a few mV or smaller] over which the op amp is operating in the linear region is a consequence of the high open loop gain. <u>This doesn't sound like a very useful device!</u>

It is, however, a very useful device if we use negative feedback.

Negative Feedback

Op amps are almost never used as high-gain, “open loop” amplifiers. Instead, they are used in **negative feedback circuits** where a portion of the output is fed back to the inverting input. Negative feedback has several beneficial consequences as we will see.

The schematic idea of negative feedback



In circuits where the op amp is constrained by negative feedback to operate in the linear region we can write:

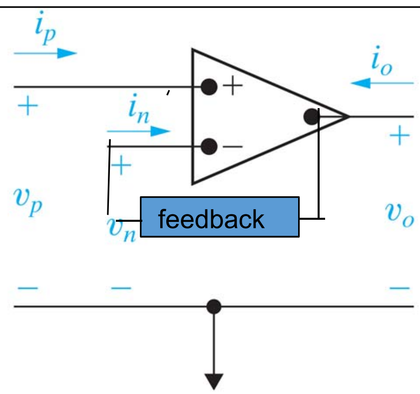
$$(v_p - v_n) \sim 0.$$

Do you see why this is true?

For circuit analysis, we'll assume the open loop gain is infinite so, for the analysis, we can assume that there is no voltage difference between v_p and v_n when the amplifier is operating in the linear region. We will also assume that the input impedance of the two inputs is infinite. These two conditions for an ideal op amp using negative feedback can be written:

$$\boxed{v_p = v_n \qquad\qquad i_p = i_n = 0}$$

These two ideal op amp equations are very important. You should write them down (or at least think about them) every time you are solving a circuit with op amps !



The ideal op amp “Golden Rules” when used in a negative feedback circuit

$$i_p = 0$$

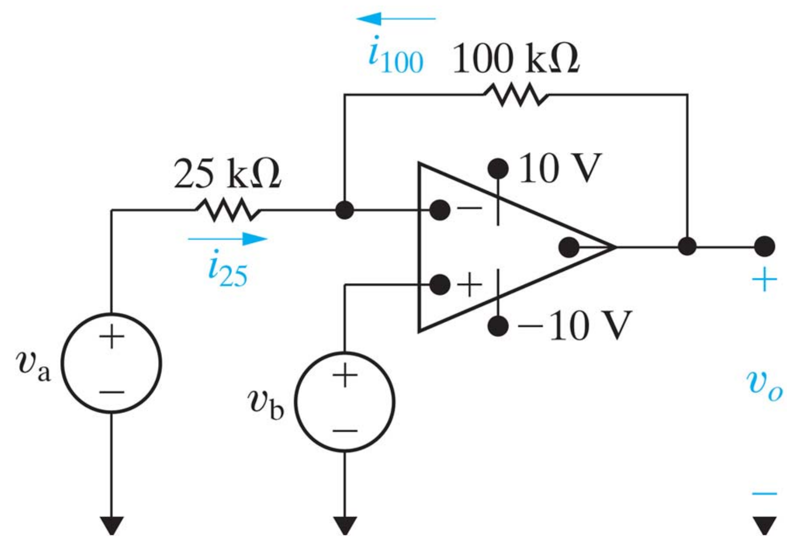
$$i_n = 0$$

$$v_p = v_n$$

Because the ideal op amp has infinite input resistance

Because of negative feedback and the assumption that the ideal op amp has infinite open loop gain

Here's an illustration of a negative feedback circuit with an op amp – calculate the output voltage, v0, if va = 1V and vb = 0V

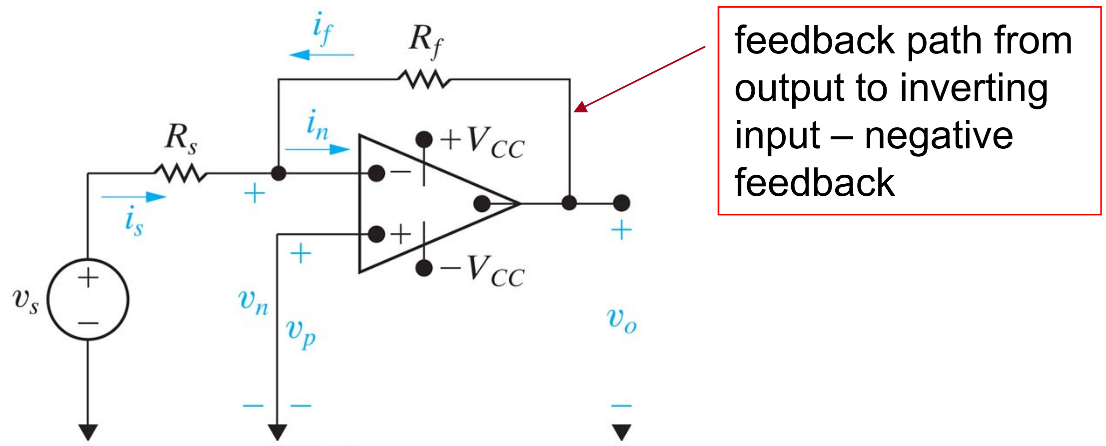


Using what we have already learned about ideal op amps in negative feedback circuits:

$$\boxed{v_p = v_n \qquad\qquad i_p = i_n = 0}$$

The "op amp Golden rules"

we can analyze this circuit.



Because of the high open loop gain of the amplifier, we can assume that the negative feedback forces the node at the inverting input to be equal to the voltage at the noninverting input ….i.e. zero volts.

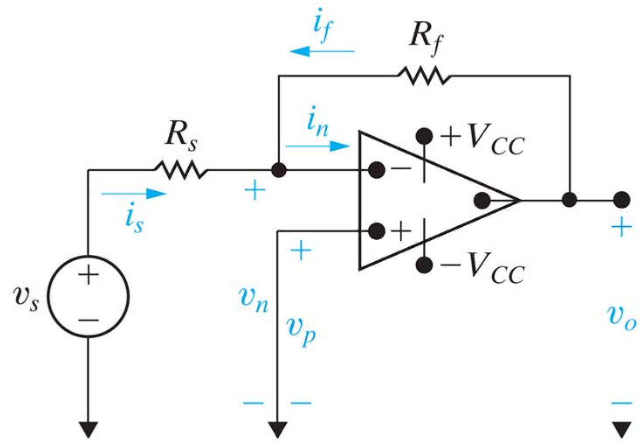
KCL at the inverting node is: $v_s/R_s + v_0/R_f = 0$ (since i_n is zero because op amp input impedance is infinite …i.e. no current goes into the op amp)

Solving for v_0:

$v_0 = -v_s R_f/R_s$ The output voltage is inverted in sign from the input voltage and has a magnitude that has been amplified by the ratio of the feedback resistor to the input resistor.

This is the op amp inverting amplifier configuration….a very typical circuit This is a very useful op amp circuit!

Inverting Amplifier



$$v_0 = - R_f / R_s \ v_s$$

Notice that negative feedback has caused the gain of the amplifier to be determined by the feedback and input resistance only – it doesn't depend on the open loop gain, A …so long as A is large enough (effectively infinite).

If we wanted to make this into a noninverting amplifier, could we just bring the feedback path back to the noninverting input of the op amp? No! This Wont Work! This would produce positive feedback! Not a good idea!

We need negative feedback to cause the two inputs of the op amp to have the same voltage. We can use an op amp in a noninverting configuration (as we will see) …but, in all cases the feedback loop has got to connect to the negative input …to make the feedback negative.

Noninverting Amplifier

Here's the way to make a noninverting amplifier …the feedback still goes to the noninverting input so it's negative feedback, but what was originally the input terminal in the inverting amplifier is grounded and the new input terminal is the noninverting input – which was grounded in the inverting amplifier configuration. We can calculate the gain for this amplifier: Because of the ideal op amp assumptions we can write KCL at node A as:

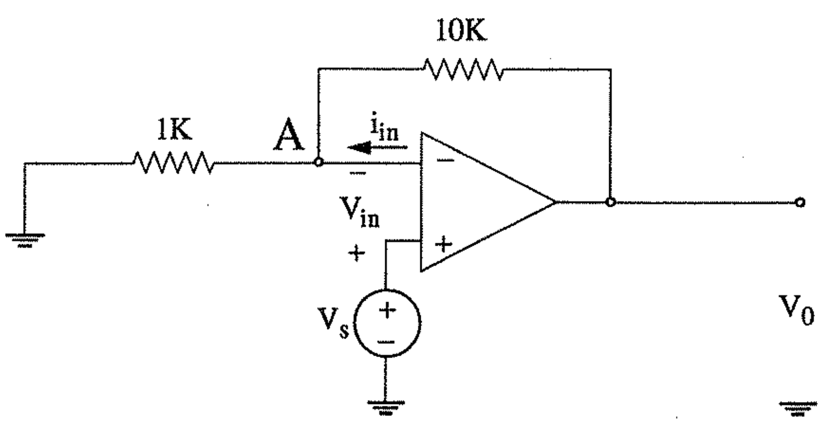
$v_p = v_n$	$i_p = i_n = 0$

$$V_A = V_{in} \quad i_{in} = 0$$

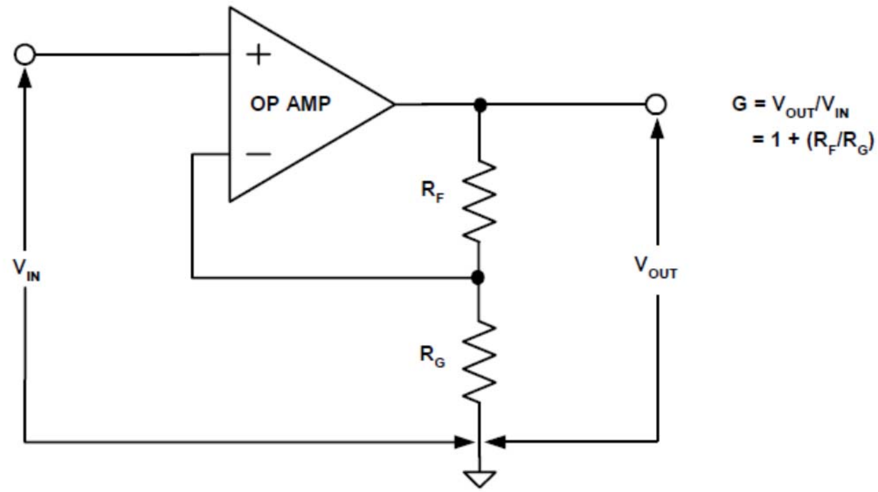
$$so$$

$$-\frac{V_0 - V_{in}}{10K} + \frac{V_{in}}{1K} = 0$$

$$V_0 = V_{in}\left[1 + \frac{10K}{1K}\right]$$



Here’s another way of drawing the non-inverting op amp configuration – which might make the equation for its gain more intuitive:

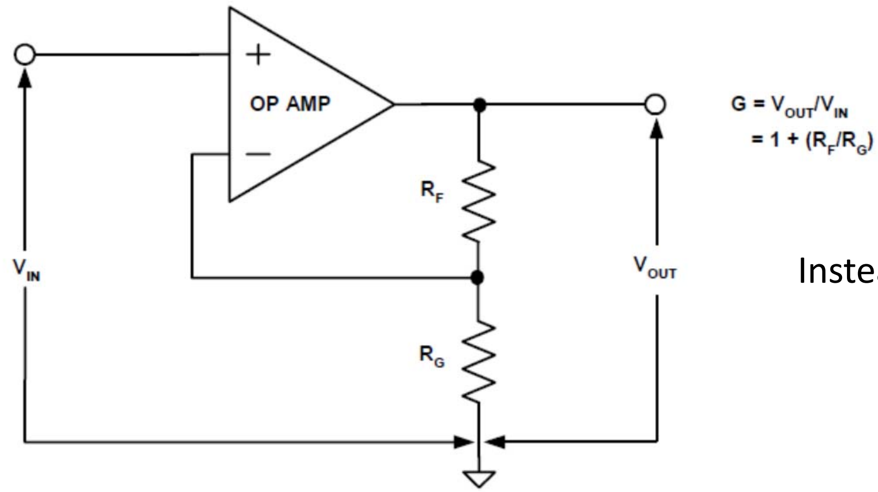


since the op amp golden rule says that $v_p = v_n$ -- because of negative feedback, this means that the voltage across R_G has to be equal to V_{in} ..and the voltage across R_G is just a voltage divider for the output voltage V_{out}

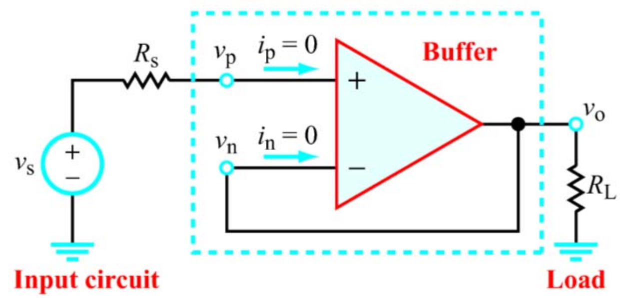
$$so \quad V_{in} = V_{out} \frac{R_G}{R_F + R_G}$$

$$V_{out} = V_{in}\left[1 + \frac{R_F}{R_G}\right]$$

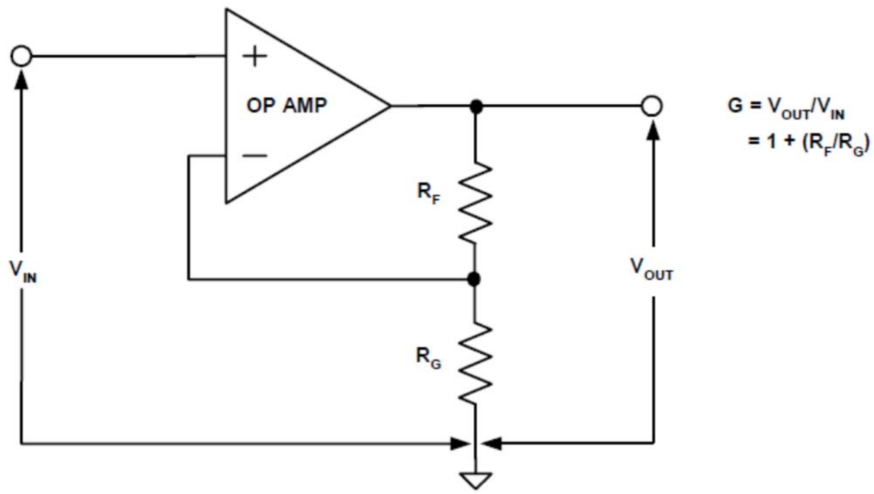
A special version of the noninverting amplifier happens when the feedback resistor is zero:

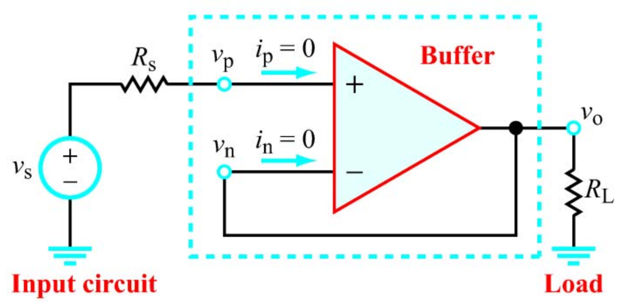


Instead of this ….



We have this ….





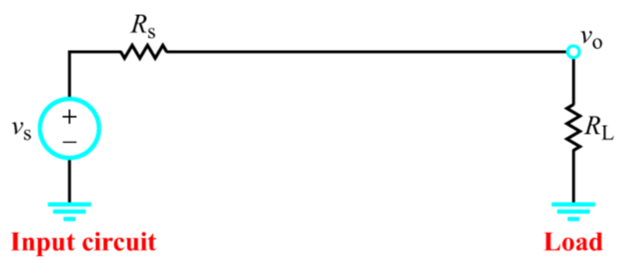
Since:

$$V_{out} = V_{in}\left[1 + \frac{R_F}{R_G}\right]$$

$$V_{out} = V_{in}[1] = V_{IN}$$

The circuit is called a follower …because the output "follows" the input exactly

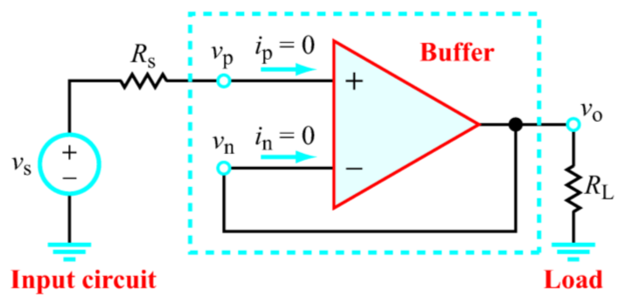
What is a follower (buffer) amplifier used for?



(a) Input circuit connected directly to a load

$$v_0 = \frac{v_s R_L}{R_s + R_L}$$

Signal amplitude is degraded by the presence of a load



(b) Input circuit separated by a buffer

$$v_0 = v_p = v_s$$

No amplitude degradation by attaching load!

Are the expressions we obtained for the inverting and noninverting amplifier configurations valid for all values of v_s, R_f, and R_s ?

$$v_0 = - R_f / R_s \ v_s \qquad\qquad v_0 = [1+R_f/R_s]\ v_s$$

Inverting Noninverting

No …. Because the output voltage can never be larger than the power supply voltage. If we picked the ratio of R_f/R_s to be too large for the value of v_s, v_0 would have to exceed V_{cc}.

So

$$\frac{R_f}{R_s} \le \left|\frac{V_{cc}}{v_s}\right| \quad inverting$$

$$1+\frac{R_f}{R_s} \le \left|\frac{V_{cc}}{v_s}\right| \quad noninverting$$

If the input voltage, v_s or the choices of R_s and R_f result in a situation that violates these equations, the output "saturates" or "clips" at a value of + / - V_{cc}.

$$\frac{R_f}{R_s} \leq \left|\frac{V_{cc}}{v_s}\right| \quad inverting$$

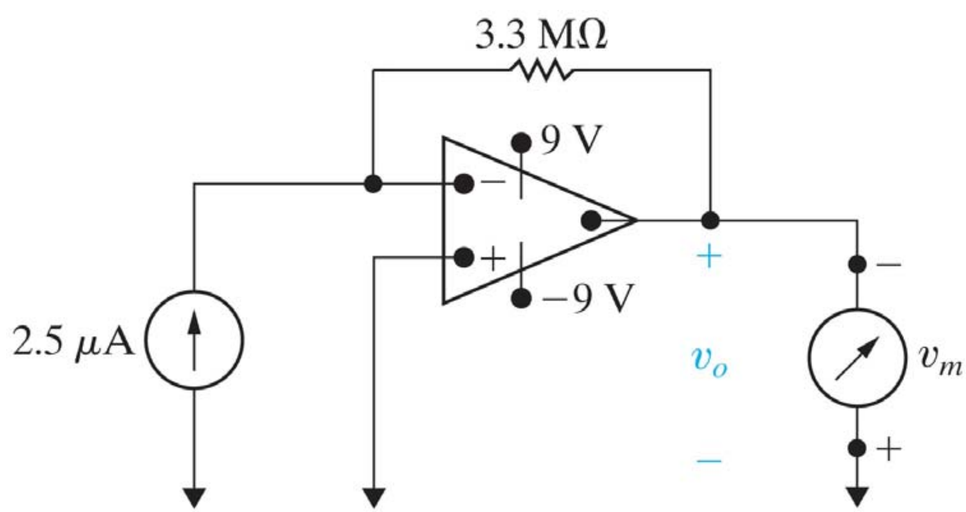
$$1 + \frac{R_f}{R_s} \leq \left|\frac{V_{cc}}{v_s}\right| \quad noninverting$$

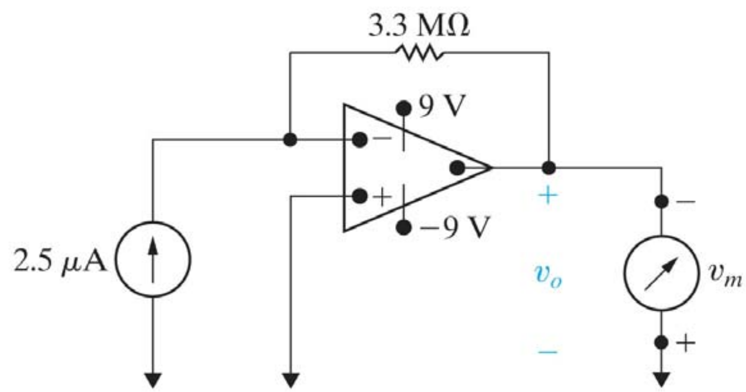
Saturation or clipping is usually not desirable because the amplifier is not behaving linearly – the output is no longer proportional to the input. However, if you wanted to generate a square wave signal at the same frequency as a particular sine wave….just putting the sine wave into an amplifier that was designed to saturate might be a good way to do it.

You might also want to use clipping for “artistic” reasons:

Here…clipping is desirable

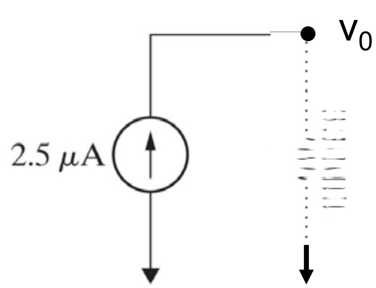
Here's another circuit using an op amp in the inverting amplifier configuration. What is the output voltage, v0? Notice the power supply voltages indicated in the diagram. Is the op amp still within its linear operating region?





$V_m = 8.25V$
so op amp is
still operating
in the linear
region where
output is less
than V_{cc}

This is an interesting type of inverting amplifier circuit – it is a current to voltage convertor. The output voltage is proportional to the input current – and the constant of proportionality is the value of the feedback resistor. So in some respects, it's just like the circuit below. However, it's much better because it acts like a resistor as far as converting current to voltage but it looks like a short circuit load to the current source. In the real world, many current sources (such as light sensing photovoltaic cells) need to be connected to a short circuit load to operate correctly.



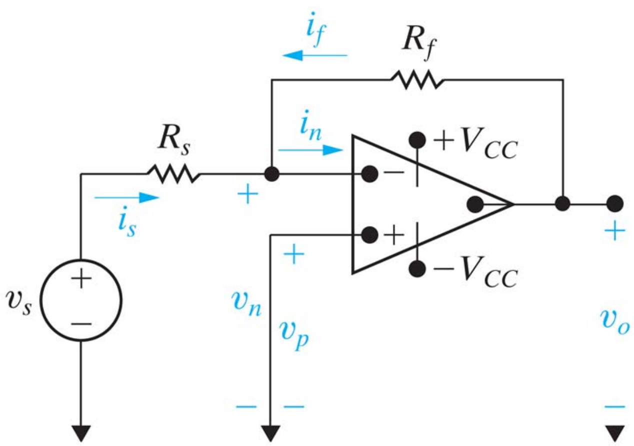
So, just to review:

Ideal operational amplifiers in negative feedback circuits are described by these two “Golden Rule” equations:

$v_p = v_n$ $\qquad$ $i_p = i_n = 0$

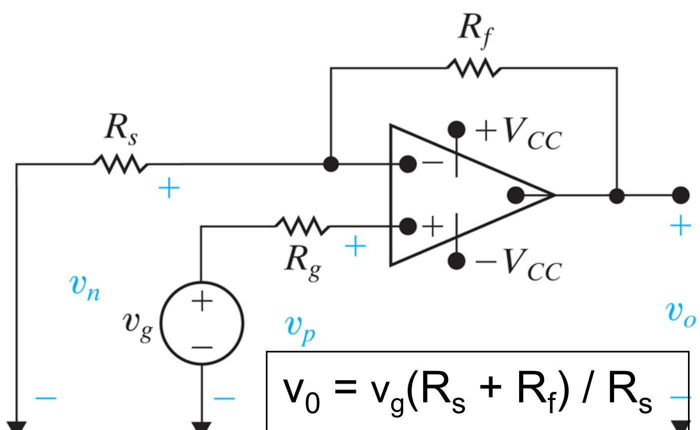
And this results in:

Inverting Amplifier



$v_0 = -R_f / R_s \; v_s$

Non-inverting Amplifier



$v_0 = v_g(R_s + R_f) / R_s$

$= v_g(1 + R_f/R_s)$

We’ll talk about a lot of different kinds of op amp circuits later, but you now know the essentials necessary to understand any op amp circuit.

- Feedback has to exist from the output to (at least) the inverting input – we’ll talk later about allowing for some positive feedback

- Because of the feedback, the op amp golden rules will be valid.

$$\boxed{v_p = v_n \qquad\qquad i_p = i_n = 0}$$

- Using the golden rules and everything else you’ve learned about circuit theory (especially KCL, KVL, and Ohms Law) you can solve op amp circuits.