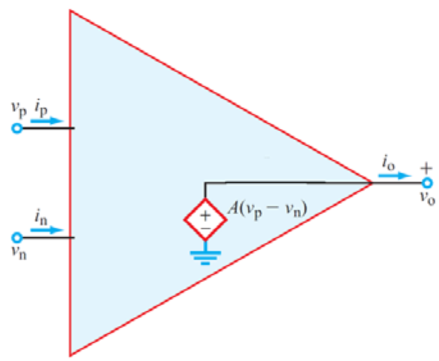
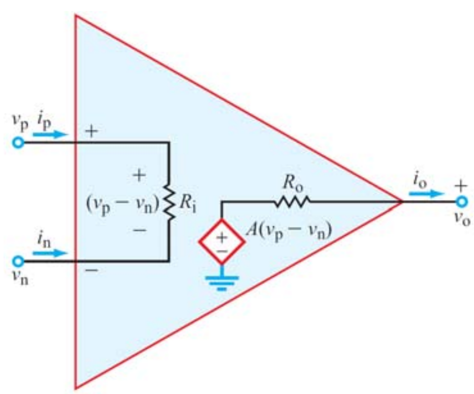
How can we model gain?

- Question: We just said that the output of an Op Amp is $A_V \cdot (V_p - V_n)$. How can we model this for designing / analyzing a circuit?
- Answer: We can use a “dependent” voltage source to model the output, where the output voltage is a function of the input voltage



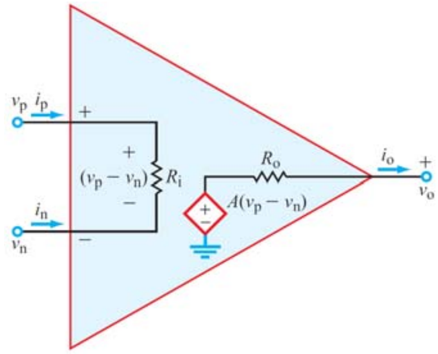
Equivalent Circuit and Specifications



Parameter	Typical Range	Ideal Op Amp
Open-loop gain A	10^4 to 10^8 (V/V)	∞
Input resistance R_i	10^6 to 10^{13} Ω	∞ Ω
Output resistance R_o	1 to 100 Ω	0 Ω
Supply voltage V_{cc}	5 to 24 V	As specified by manufacturer

- In other words, Op Amps are *really* close to ideal.
- Note that the output voltage swing is typically limited to around V_{CC}

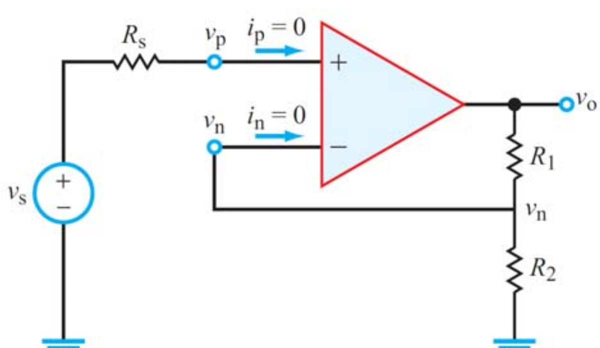
But how should we use an Op Amp?



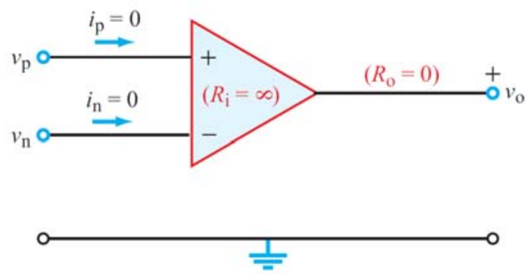
- The gain is huge, and the dynamic range is limited. This would normally limit the input signal to a few μV!
- Additionally, the gain is usually very poorly controlled, and can vary a lot with temperature, etc., and from part to part.
- Instead, we use "negative feedback" to bring the gain under control.

What is negative feedback

- Conceptually, it is taking a "piece" of the output, and providing it to the V_N or "inverting" input
- Since the output is $A_V \cdot (V_P - V_N)$, the larger the output, the more the feedback "piece" works to reduce the ouput.
- Overall, this reduces the "effective" gain of the amplifier.
- In fact, if we assume A_V is ∞, then the ultimate result is that V_P must be *equal* to V_N



Ideal Op Amps with Negative Feedback



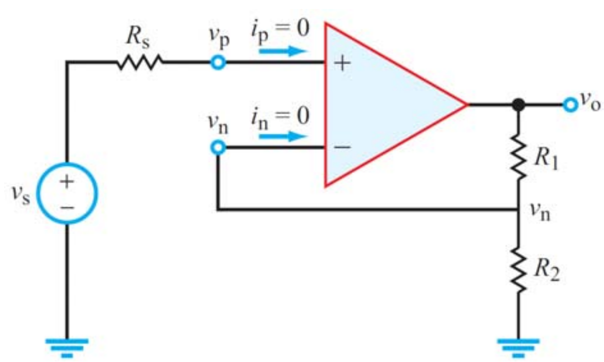
Ideal Op Amp

- Current constraint $\quad i_p = i_n = 0$
- Voltage constraint $\quad v_p = v_n$
- $A = \infty \quad R_i = \infty \quad R_o = 0$

Start with the following "golden rules"

- $V_P = V_N$ (due to effect of infinite gain and negative feedback)
- $I_p = I_n = 0$ (due to infinite input resistance of ideal Op Amp)
- Since the output has zero output resistance, you won't actually need a KCL at the output node, since the output voltage is entirely determined by the input voltages and feedback conditions

Non-inverting Amplifier



KCL at node v_n:

$$\frac{v_n - v_o}{R_1} + \frac{v_n}{R_2} = 0$$

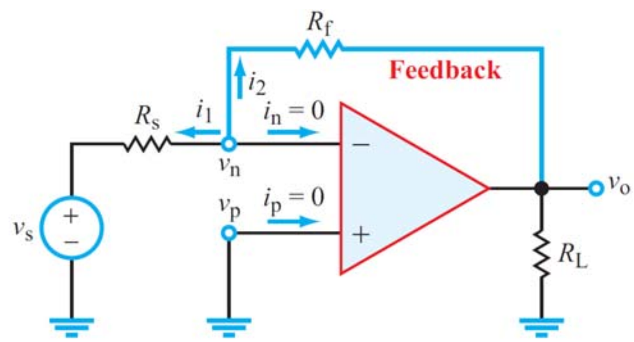
$$v_n = v_p = v_s$$

$$\boxed{v_o = \frac{R_1 + R_2}{R_2} v_s}$$

v_o (max) = V_{cc}

Interestingly, the gain of the Op Amp, A_V, no longer appears in the equation. This is a benefit of feedback with nearly ideal amplifiers… we can achieve the desired result purely by the choice of external components

Inverting Amplifier

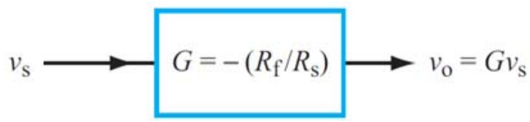


KCL at v_n:

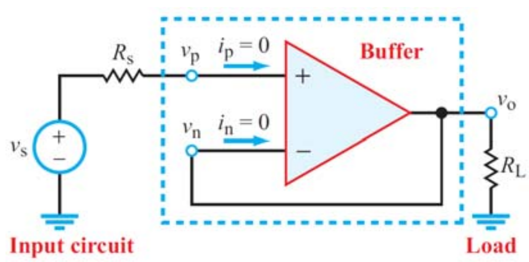
$$\frac{v_n - v_s}{R_s} + \frac{v_n - v_o}{R_f} + i_n = 0.$$

$$v_n = v_p = 0$$

$$\boxed{G = \frac{v_o}{v_s} = -\left(\frac{R_f}{R_s}\right).}$$



Voltage Follower or Buffer

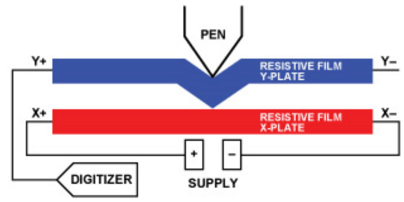


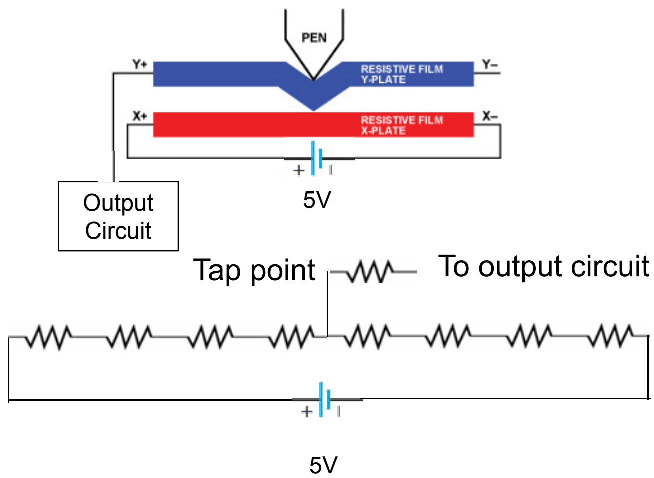
$$v_o = v_p = v_s$$

v_o is immune to input and load resistors

Design Exercise: Touch Screen Sensor

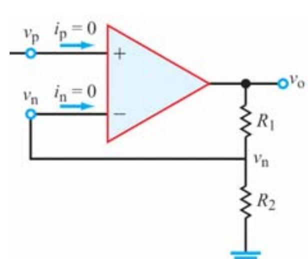
- Assume the following:
  - The supply voltage to the touch screen is 5V
  - We want the output to vary from 0V for a touch on the right to 10V for a touch on the left





Design Exercise: Touch Screen Sensor

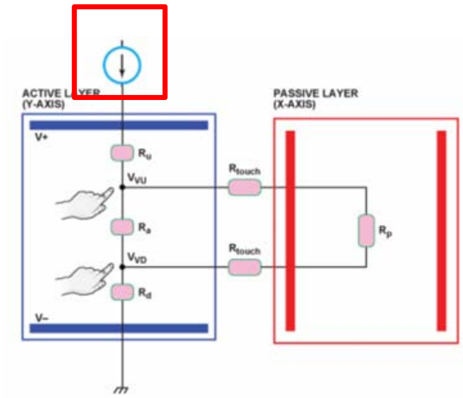
- We want a non-inverting amplifier with a gain of 2



$$\boxed{v_o = \frac{R_1 + R_2}{R_2} v_s}$$

Design Exercise: Current Source

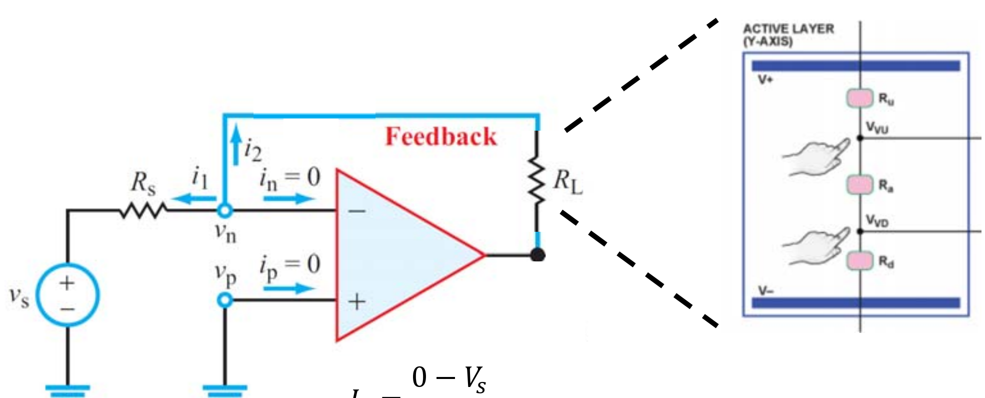
- In the multi-touch version, we needed a current source



- In this next exercise, we'll use an Op Amp to convert a battery (which is a voltage source) into a current source

Design Exercise: Current Source

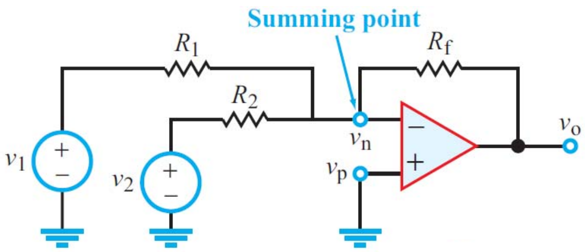
- Remember the golden rules for an ideal Op Amp
  - $V_- = V_+$
  - $I_{in} = 0$
- We have to use negative feedback to use the golden rules



$$I_1 = \frac{0 - V_S}{R_S}$$

Since $I_n = 0$, then $I_1 = I_2$.
In other words, we have made a constant current source with an output current of $-V_S / R_S$

Optional Exercises: Summing Amplifier



Optional Exercises: Difference Amplifier