Today, we will:

- Do some more example problems – op-amps
- Continue reviewing the pdf module: **op-amps (active filters, clipping circuits)**
- Discuss input and output impedance in more detail

[Current cannot flow into V_n]

Example: Op-amp circuits

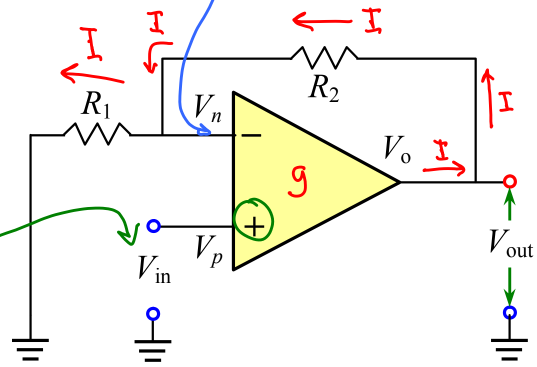
Given: The circuit shown, with

- $R_1 = 20\ \text{k}\Omega$
- $R_2 = 80\ \text{k}\Omega$

$V_o = g(V_p - V_n)$ (+) (−)

The supply voltages to the op-amp are +15 V and –15 V (not shown).

[I remember this because V_{in} goes into V_p (+) not V_n (−)]



To do:

(***a***) Is this is an *inverting* or a *noninverting* amplifier?

(***b***) For an *ideal* op-amp, when V_{in} = 1.50 V DC, calculate V_n in Volts.

$V_n \cong V_p = V_{in} \rightarrow \boxed{V_n = 1.50\text{ V DC}}$

(***c***) For an *ideal* op-amp, calculate the gain G of the circuit.

For noninverting amplifier, $G = 1 + \frac{R_2}{R_1} = 1 + \frac{80\text{ k}\Omega}{20\text{ k}\Omega} = \boxed{5}$

[Note: $G \neq R_2/R_1 = 4$
Here, $G = 1 + R_2/R_1 = 5$]

(***d***) For a *real* op-amp, when V_{in} = 1.50 V DC, calculate V_{out} in Volts.

$V_{out} = GV_{in} \cong 5(1.50\text{ V}) = \boxed{7.50\text{ V}}$ [actual voltage will differ, but by negligible microvolts, since $g \neq \infty$]

(***e***) For a *real* op-amp, when V_{in} = 4.20 V DC, calculate V_{out} in Volts.

- $V_{out} = GV_{in} \cong 5(4.20\text{ V}) = 21.0\text{ V}$ ✗ No — op-amp cannot output more voltage than the supply voltage!

[The op-amp will saturate] →

- So, since $V^+_{supply} = 15.0\text{ V}$, we expect $V_{out} \cong 1\text{ V}$ lower, $\boxed{V_{out} \cong 14\text{ V}}$

Additional: Calculate the current I (in mA) through resistor R_1

- See circuit diagram above, where we label current I and its direction
- Ohm's law: $\Delta V = IR \rightarrow I = \frac{\Delta V}{R_1} = \frac{1.50\text{ V} - 0\text{ V}}{20{,}000\ \Omega}\left(\frac{\text{A}\cdot\Omega}{\text{V}}\right)\left(\frac{1000\text{ mA}}{\text{A}}\right) = 0.075\text{ mA}$

Answer → $\boxed{I = 0.075\text{ mA}\ (75\ \mu\text{A})}$ → This is very small because R_1 is so big

[One reason why we use large R's in these circuits]

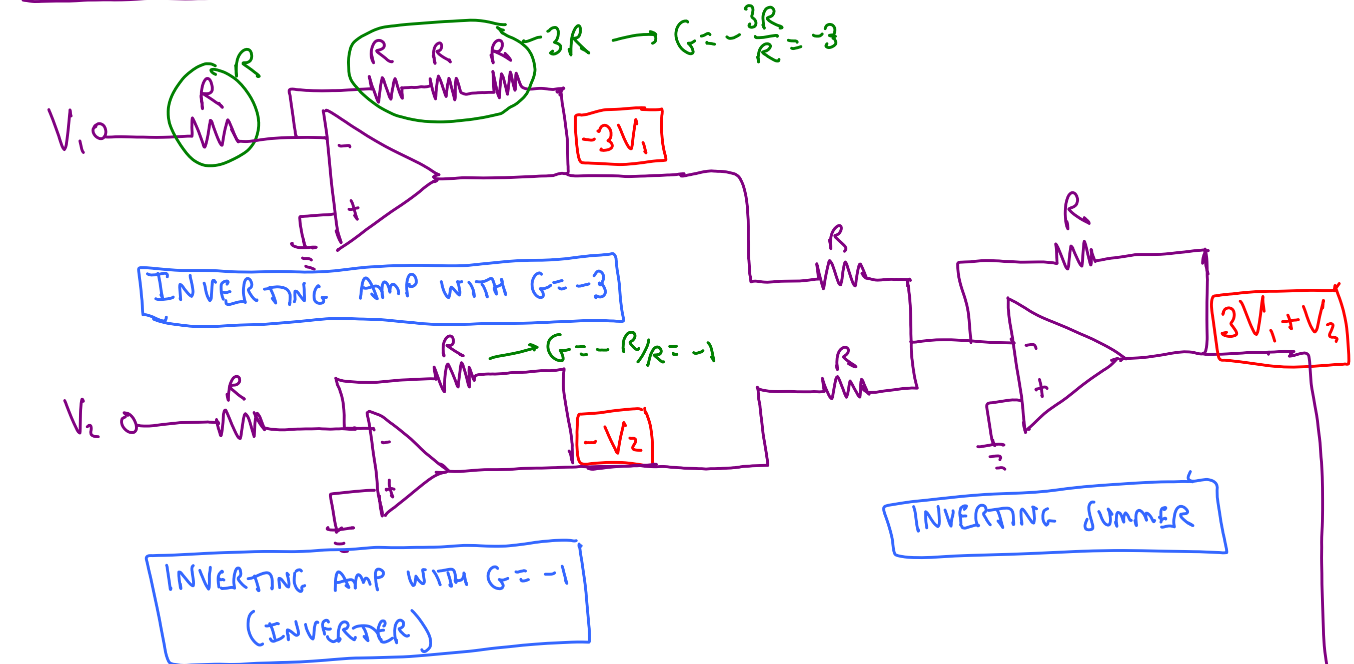
Example: Op-amp circuits

Given: Two voltage input signals, V_1 and V_2 are to be combined to produce an output voltage: $V_o = 4(3V_1 + V_2)$.

To do: Design a circuit that will produce this output, using only op-amps and resistors. Use *inverting* amplifiers [which deal with noise better than noninverting amplifiers], as will be discussed later. Assume that the only resistors you have are 20 kΩ.

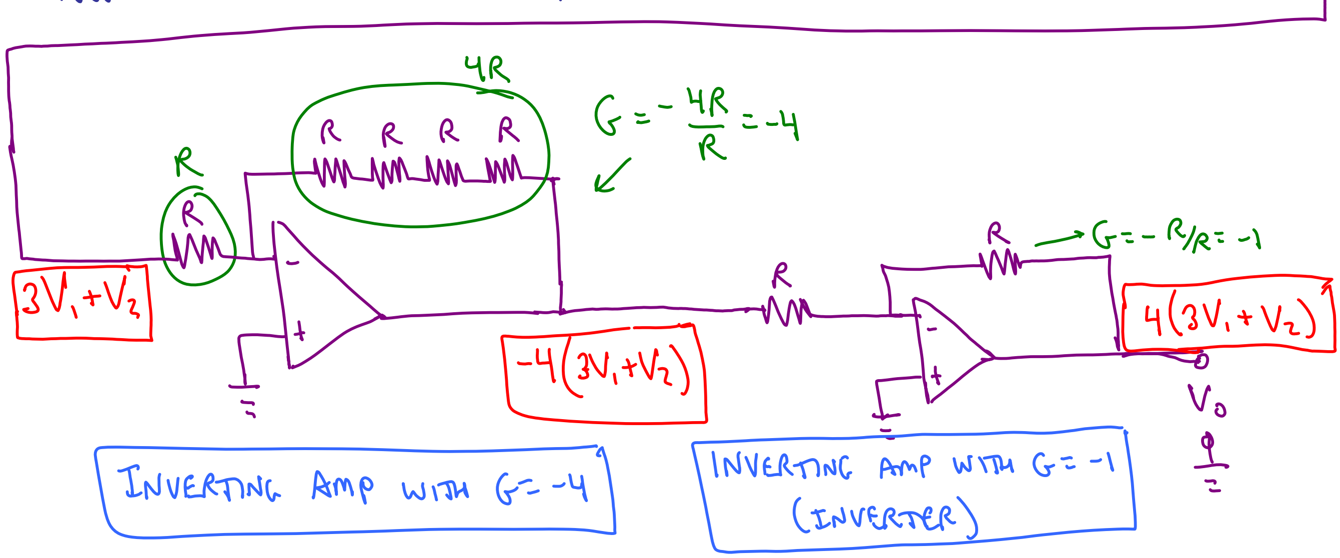
Solution: • Our goal is $V_o = 4(3V_1 + V_2)$ There are many options

• Brute Force Method (one step at a time):



• We multiplied V_1 by -3, multiplied V_2 by -1, added (and inverted) them.

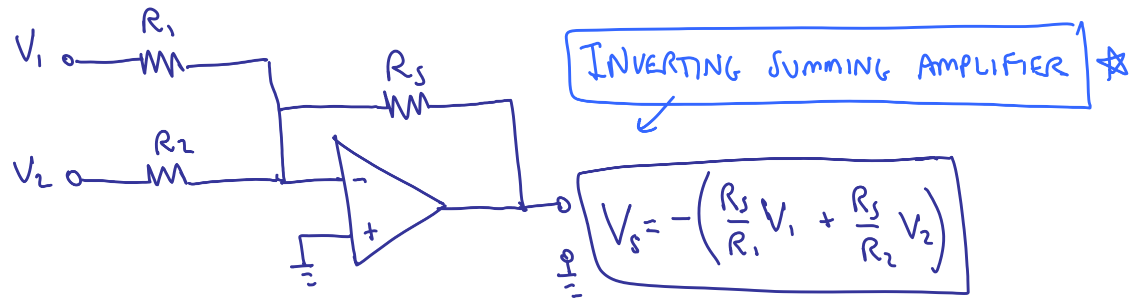
• Now we still need to multiply the sum by 4:



• Finally, invert to get the desired result

- The above (brute force) circuit requires $\boxed{5 \text{ op-amps and } 16 \text{ resistors}}$
- We can do much better (less complicated circuit with fewer components)
- E.g., combine the <u>amplification</u> and the <u>summing</u>

In general,



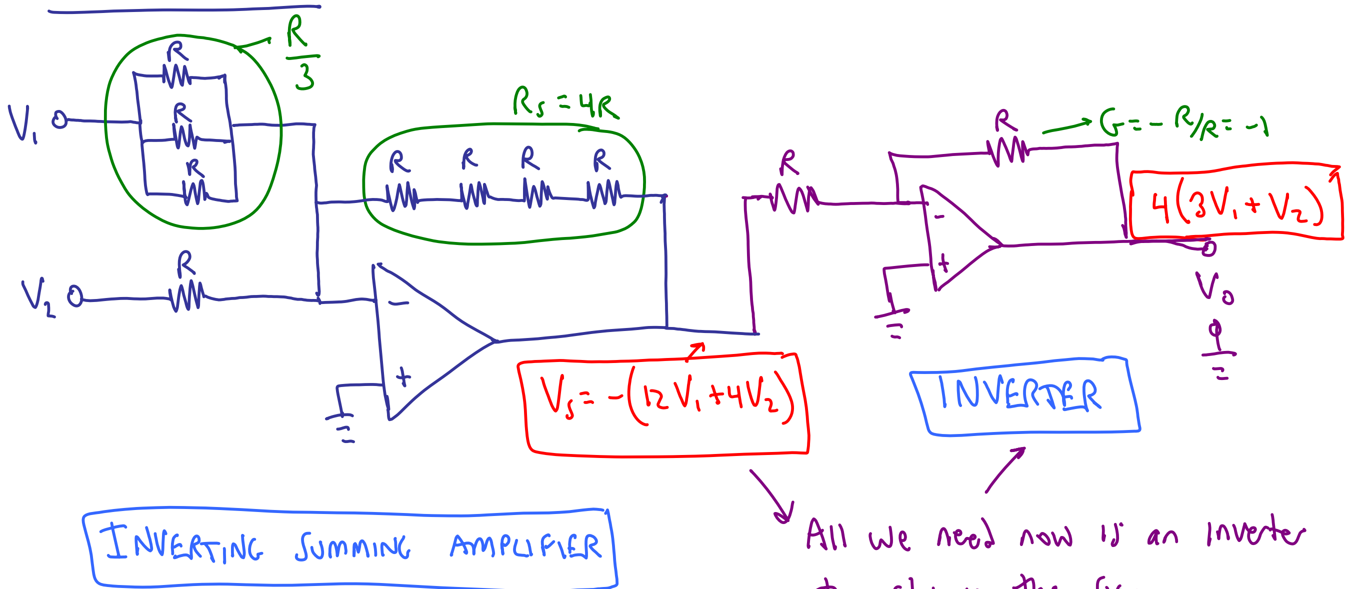
$$\boxed{V_s = -\left(\frac{R_s}{R_1}V_1 + \frac{R_s}{R_2}V_2\right)}$$

- Here, we choose $\frac{R_s}{R_1} = 12$ so that V_1 gets multiplied by 12

  & $\frac{R_s}{R_2} = 4$ so that V_2 gets multiplied by 4

  because $V_o = 4(3V_1 + V_2) = 12\,V_1 + 4\,V_2$

- <u>Revised circuit:</u>

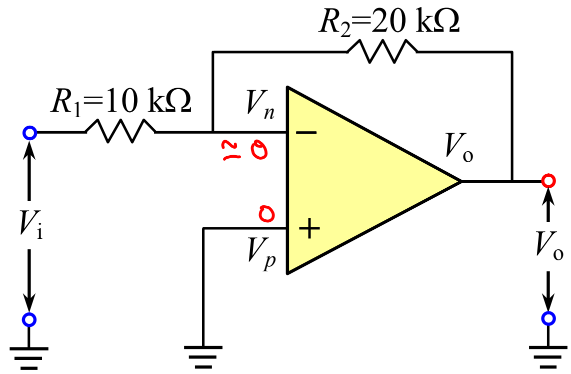


All we need now is an inverter to change the sign

Now we are using only $\boxed{2 \text{ op-amps and } 10 \text{ resistors}}$ (much better than the brute force method)

Example: Op-amp circuits

Given: The circuit shown to the right.



(*a*) To do: Calculate V_o in terms of V_i.

Solution: This is an inverting amplifier

with $G = -\frac{R_2}{R_1} = \frac{-20}{10} = -2$

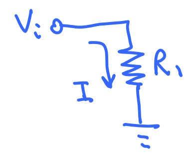
So, $\boxed{V_o = -2V_i}$

(*b*) To do: Calculate the input impedance of the amplifier.

Solution: ✯ $\boxed{\text{The input impedance of an inverting amplifier is} \approx R_1}$ Since $V_n \approx V_p = 0$

∙Here, $\boxed{\text{Input impedance} \approx R_1 = 10\ k\Omega}$

[This is what V_i "sees" →



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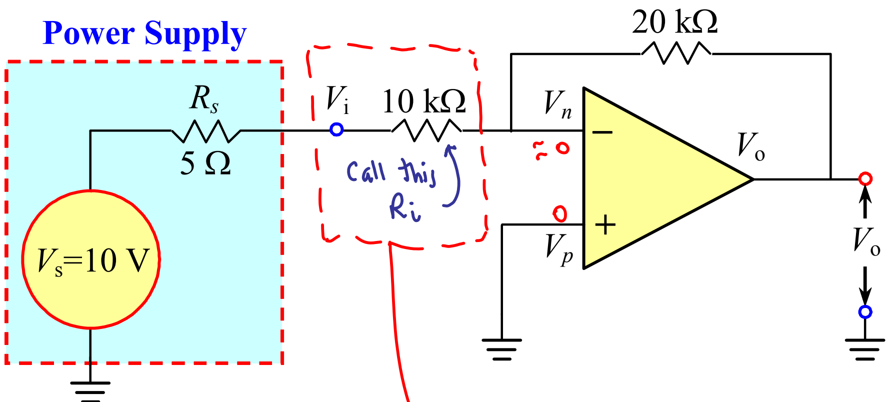
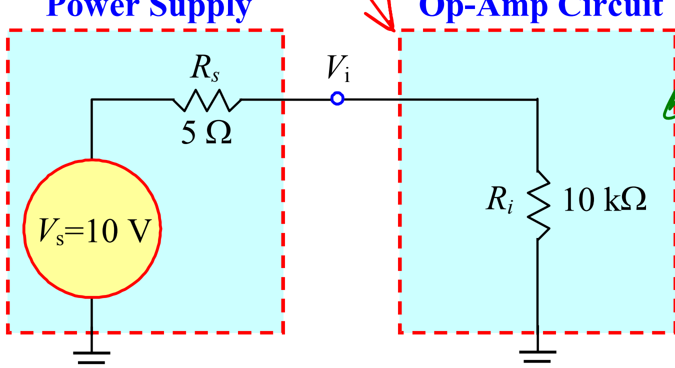
(*c*) To do: Suppose V_i is supplied by a cheap power supply with an output impedance of 5.0 Ω. The power supply is adjusted to provide exactly 10 V (V_s = 10 V). Thus, V_i = 10 V when there is *no load* on the supply. Calculate the voltage V_i when this power supply is connected to the above op-amp circuit (i.e., we add a *load* to the power supply).

Solution:

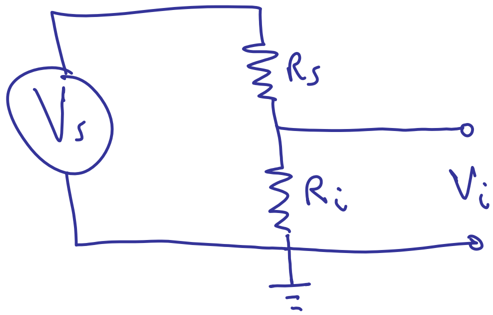


Since the input impedance of an inverting amplifier op-amp circuit is equal to R_1, the input impedance here is 10 kΩ. Thus, the equivalent circuit (from the power supply's point of view) is:



[The input impedance acts like a resistor in series with the output impedance resistor of the power supply.]

Circuit analysis — this is just a voltage divider circuit!



$$\boxed{V_i = \frac{R_i}{R_i + R_s} V_s}$$

Numbers: For $V_s = 10\text{ V}$ & $R_1 = R_i = 10\text{ k}\Omega$ & $R_s = 5\Omega$

$$V_i = \frac{10{,}000\,\Omega}{10{,}000 + 5\,\Omega}(10\text{ V}) = 9.995\text{ V} \rightarrow \boxed{V_i = 9.995\text{ V}}$$

Notice that $V_i < V_s$ $(V_i < 10\text{ V})$ → We have reduced the power supply's voltage by adding another circuit downstream

This voltage drop is called input loading ☆

[we are changing the very voltage we are trying to amplify]

Conclusion & Summary

☆ ☆ ☆

Good electronics devices should have:

- Very high input impedance → low input loading
- Very low output impedance → low output loading

☆ This is why good voltmeters, oscilloscopes, A/D cards, etc. have input impedances on the order of tens or hundreds of megaohms

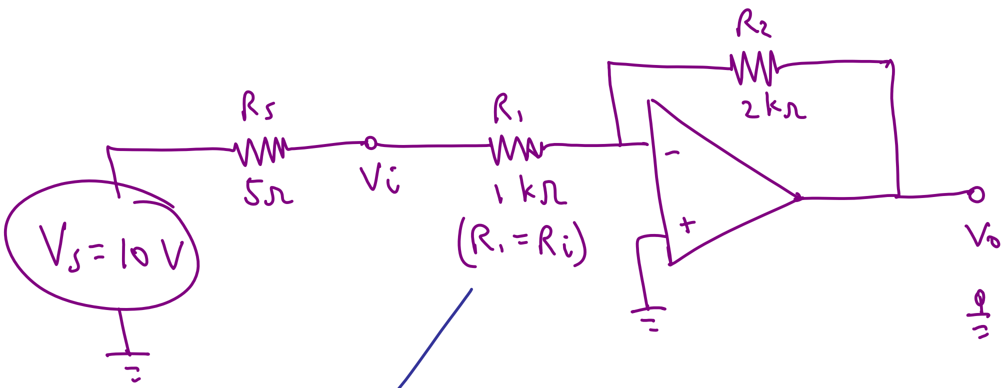
• E.g. If measuring the 10 V power supply with a voltmeter with $R_i = 6.0\text{ M}\Omega$,

$$V_{measured} = \frac{6.0\times10^6\,\Omega}{6.0\times10^6\,\Omega + 5\Omega}(10\text{V}) = 9.999992\text{ V} \approx 10.000\text{ V}$$

Negligible input loading ☆

- On the other hand, low input impedance leads to significant input loading.

- E.g., suppose we use $R_1 = 1\ k\Omega$ instead of $10\ k\Omega$ & $R_2 = 2\ k\Omega$ instead of $20\ k\Omega$



Now, the input impedance is only $1\ k\Omega$ instead of $10\ k\Omega$

$$V_i = \frac{R_i}{R_i + R_s} V_s = \frac{1000\ \Omega}{1000 + 5\ \Omega}(10\ V) = \boxed{9.95\ V = V_i}$$

This is really noticeable input loading

- Also, compare the power dissipated through R_1 for $R_1 = 1\ k\Omega$ & $10\ k\Omega$

$$R = 1\ k\Omega: \quad \dot{W} = VI = \frac{V^2}{R} = \frac{(9.95\ V)^2}{1000\ \Omega}\left(\frac{W \cdot \Omega}{V^2}\right) = 0.099\ W \approx \underline{0.10\ W}$$

$$R = 10\ k\Omega: \quad \dot{W} = \frac{(9.995\ V)^2}{10{,}000\ \Omega}\left(\frac{W \cdot \Omega}{V^2}\right) = 0.0099\ W \approx \underline{0.01\ W}$$

(ten times smaller power)

☆ This is another reason why we like to use large resistors in op-amp circuits (wastes less power)

Typical → $\boxed{10\ k\Omega < R < 100\ k\Omega}$ ☆
(goal)

Extreme cases:

$\boxed{1\ k\Omega < R < 1\ M\Omega}$