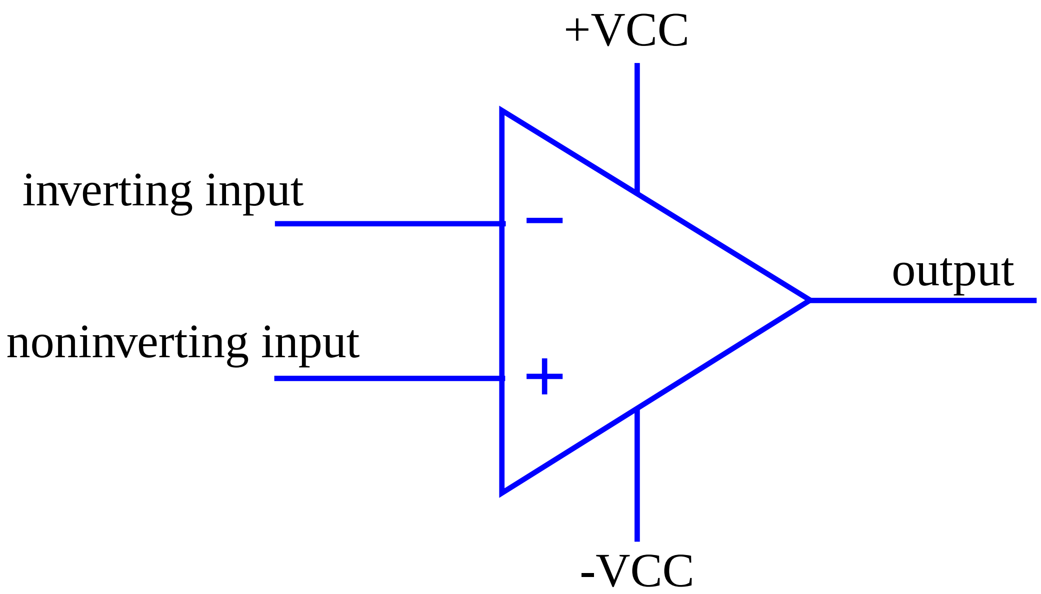
Operational Amplifiers

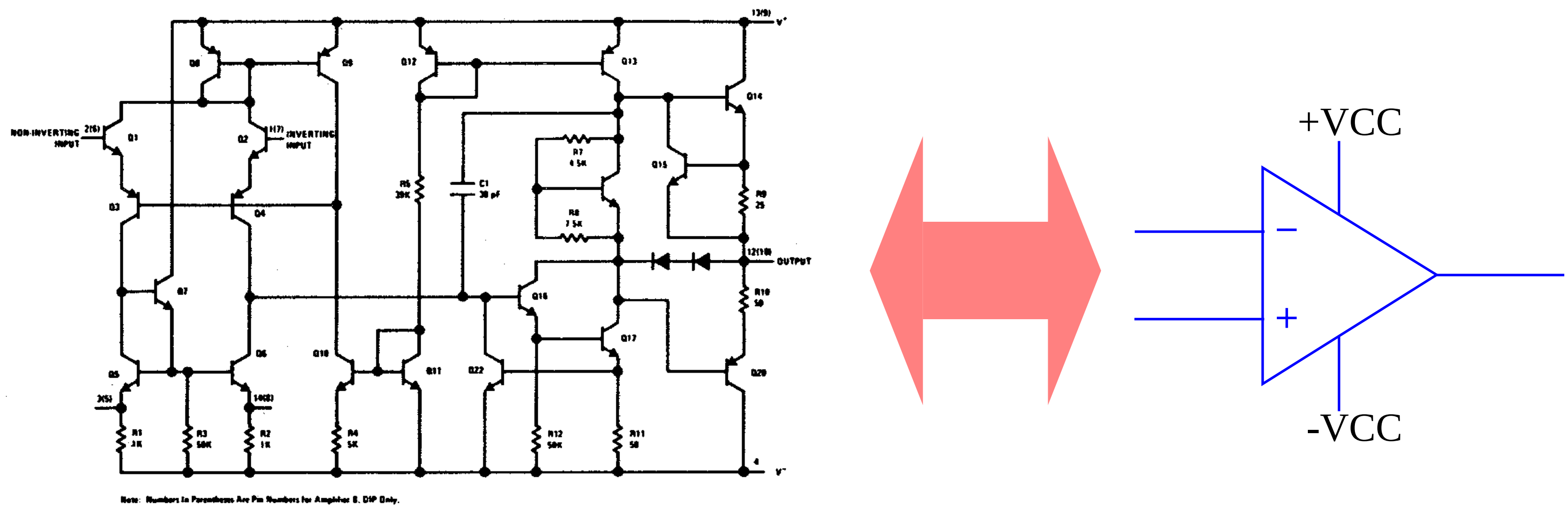
- Universal analog circuit element --- can design almost anything with them
- Easy to design with since they behave very similar to ideal amplifier model



- Differential input and single output amplifier
- Generally use a positive and negative supply voltage
- dc coupled amplifier

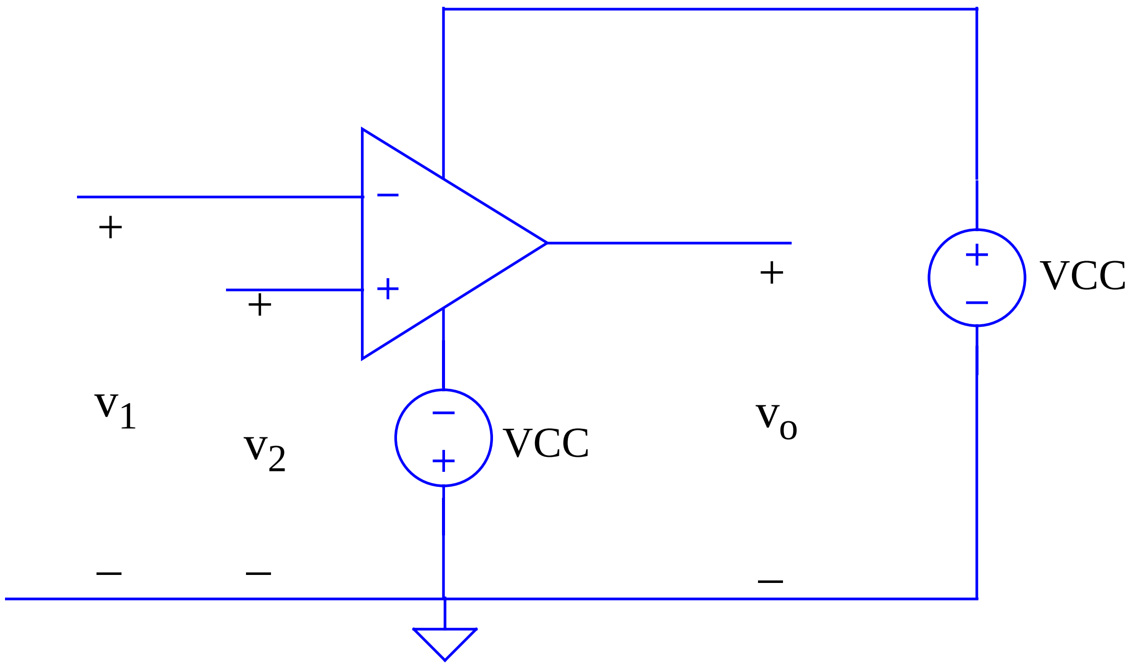
Opamp Model

- System level perspective --- we’ll look at circuits/systems which are built using opamps
- Later we will look at how to design an opamp with transistors, etc.
- But for now we can consider it as a macromodel of the actual circuit behavior



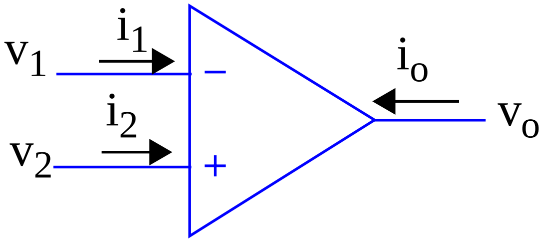
Opamp Terminal Voltages and Currents

- Terminal voltages are specified with respect to the ground of the power supply voltages



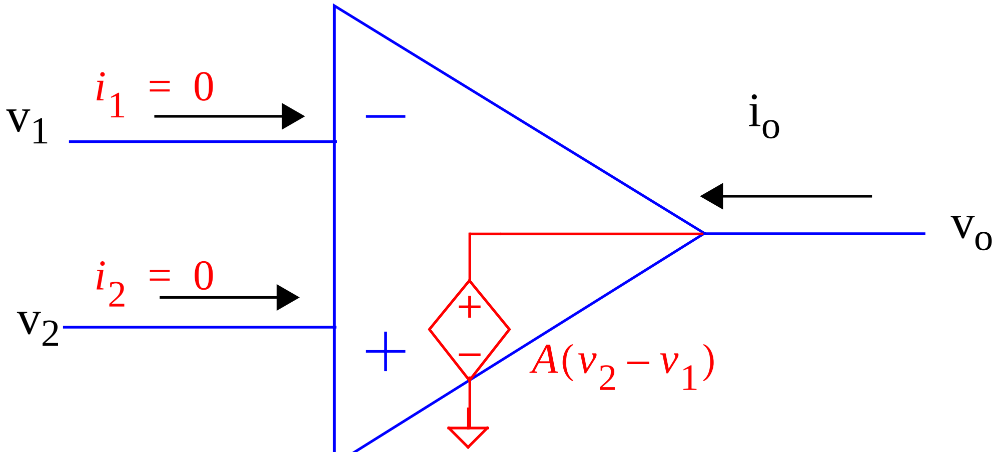
Differential Input

- Amplifies the difference between v_2 and v_1 by a constant gain factor: A



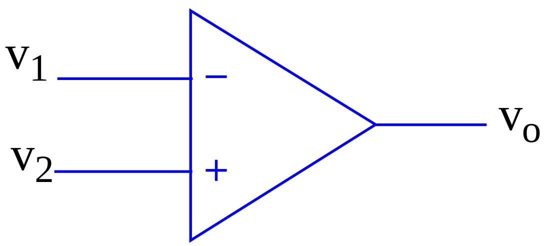
$$v_o = A(v_2 - v_1)$$

- A nearly ideal model has infinite input impedance and zero output impedance



Open Loop Gain

- If A is large, any slight difference in v_2 and v_1 will cause a large output voltage
- The magnitude of the output voltage is limited by the supply voltages
- Output voltage is likely to saturate when used in this way
- To behave like an amplifier, the difference in the input voltages must be really small

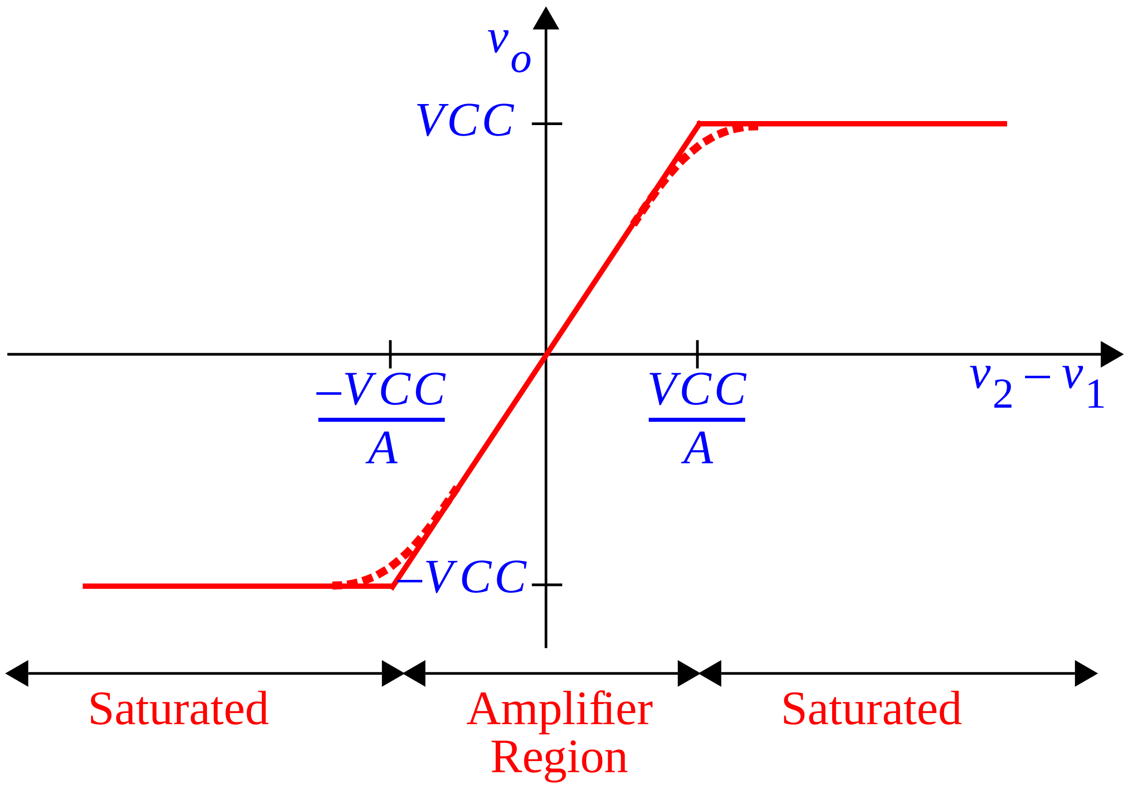


$$v_o = A(v_2 - v_1)$$

$$-VCC \le v_o \le VCC$$

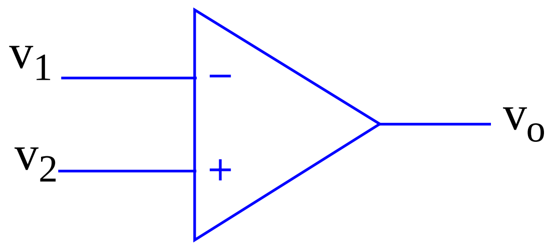
Input-Output Transfer Function

- Opamp open loop gain, A, can be as high as ~10^4 to 10^6
- VCC is generally no more than 20 volts
- So the linear region of amplifier operation is quite narrow



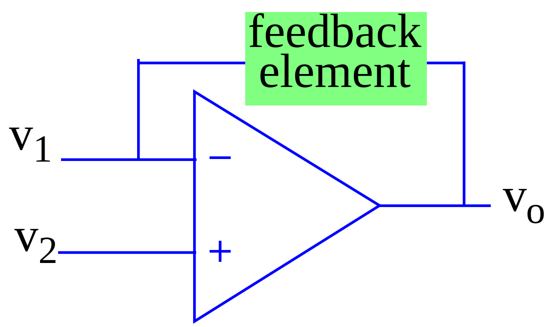
Open Loop Gain

- But even if our signals are really small in magnitude, we can't use an opamp in an open loop configuration because the gain cannot be tightly controlled



$$v_o = A(v_2 - v_1)$$

- For these reasons (and others that we will soon get to) negative feedback is used to design circuits with accurate/precise gain

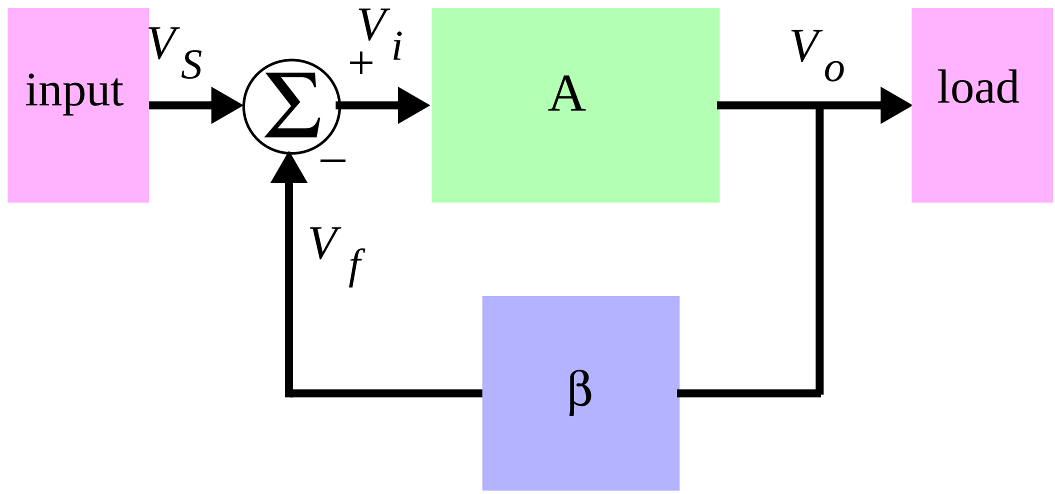


$$v_o = A(v_2 - v_1)$$

- With negative feeback, the difference between v_2 and v_1 becomes very close to zero

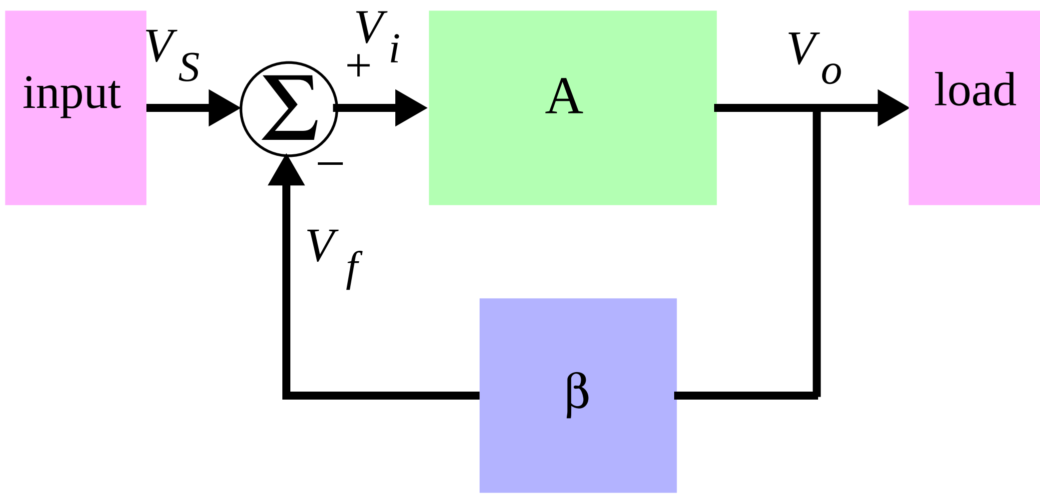
Negative Feedback: Closed-Loop Gain

- Important concept for all types of systems, including electronics



Negative Feedback

- Makes the input voltage to A practically zero when closed loop gain is large

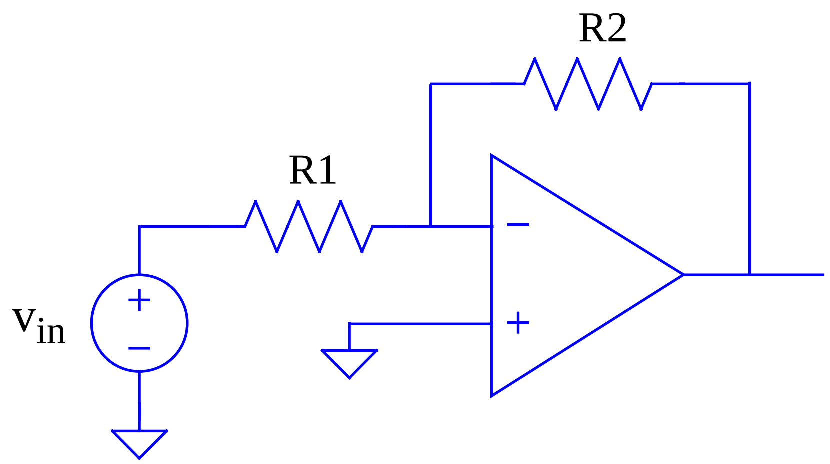


Desensitize Loop Gain to Changes in A

- Assuming that feedback factor, β, can be controlled by elements such as resistors, then the gain (closed-loop) is no longer sensitive to changes in the open loop gain, A

Inverting Amplifier

- Resistors can be used to create a controlled, smaller gain
- One of the most common configurations is an inverting amplifier

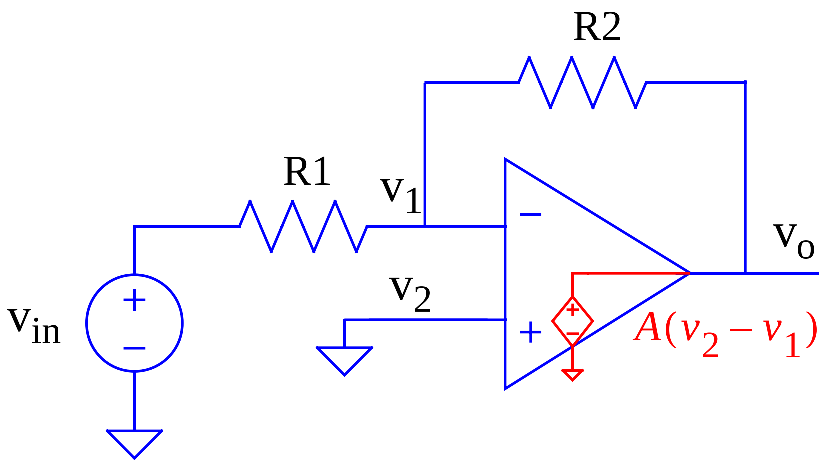


- If it's operating in the linear region (as an amplifier), $v_o = -A(v_1 - v_2)$
- With really large open loop gain, feedback should force $(v_2 - v_1) \to 0$

- Assume that feedback works, and amplifier is operating in its linear region:
  1) Solve equations; 2) check assumption

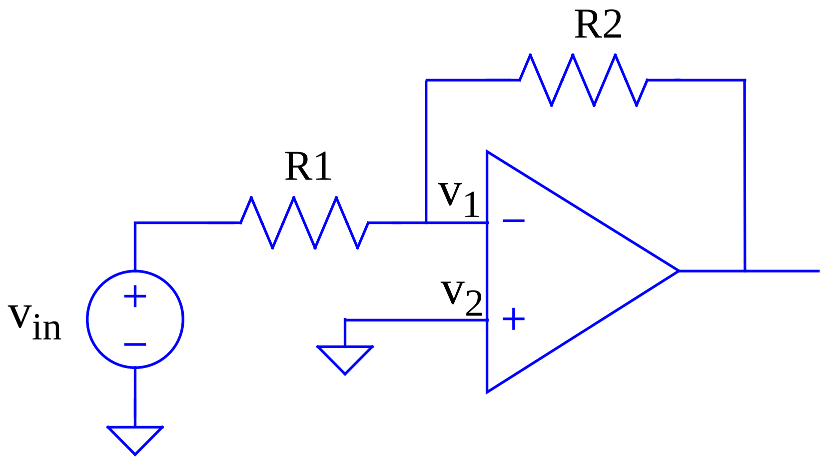
Inverting Amplifier with Ideal Opamp Model

- Assume $i_2 = i_1 = 0$



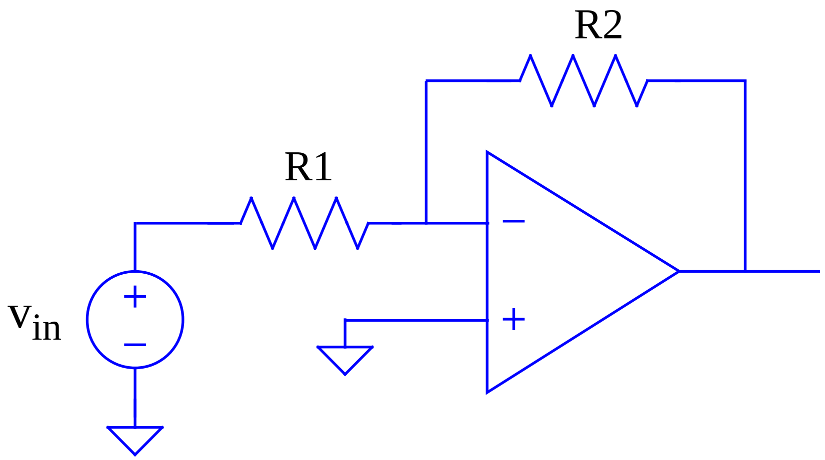
Virtual Ground

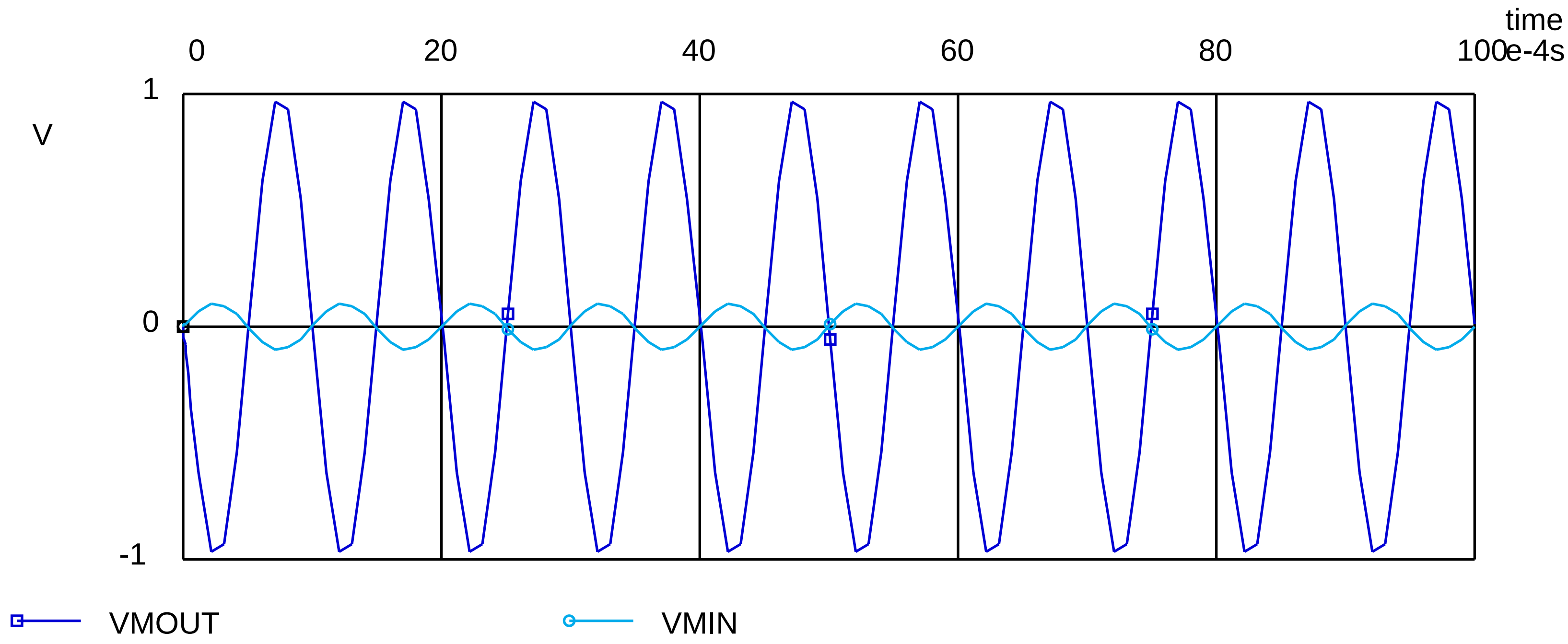
- If the open loop gain is infinite, then v_1 is a virtual ground
- This can further simplify the analysis



Inverting Amplifier

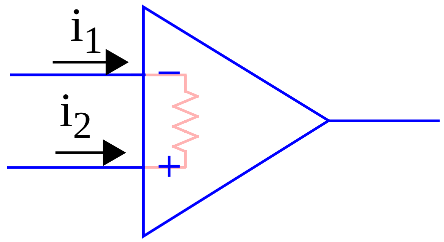
- For a dc input, the inverting amplifier has a negative output voltage
- For an ac input, the output is 180° out of phase with the input



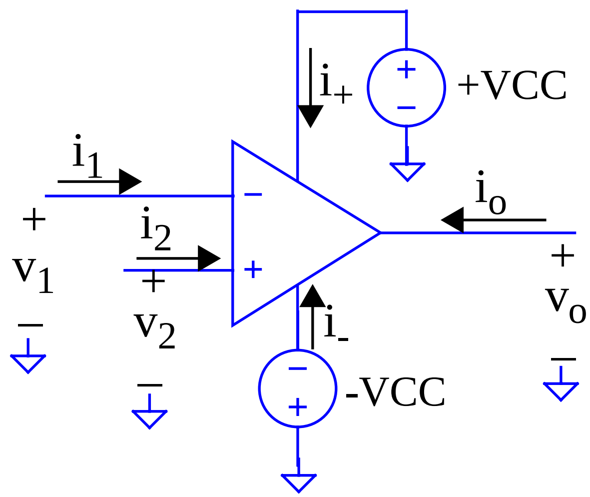


Opamp Currents and Input Impedance

- Due to the transistors used to build an opamp, the input currents, i_2 and i_1 are practically zero --- input resistance of amplifier is huge, especially for MOS!
- For the ideal opamp we assume, $i_2 = i_1 = 0$, and R_{in} of opamp is infinite

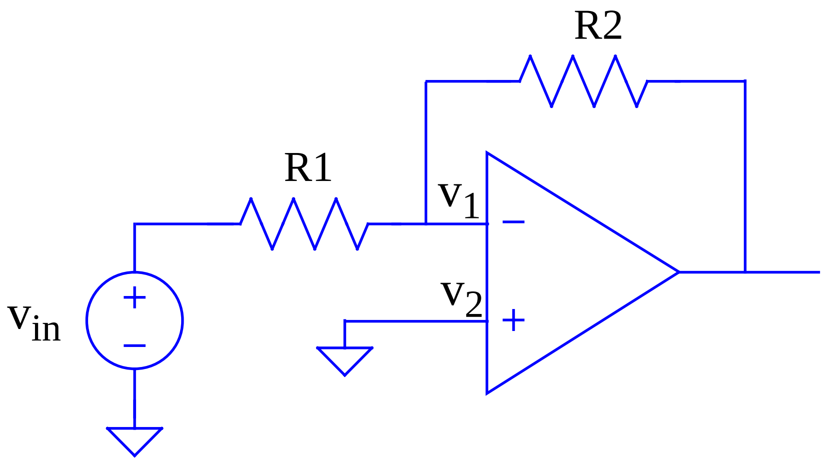


- All circuit elements are charge conserving, so i_o is coming to/from the power supplies:



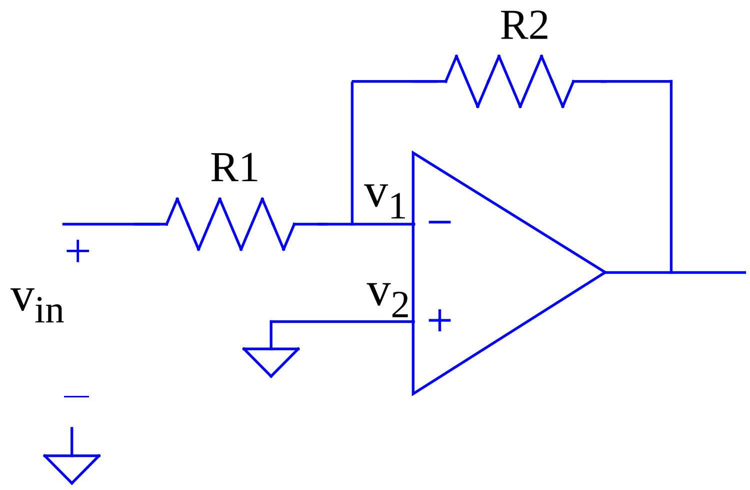
Feedback and Input Impedance

- Feedback can be used to change the input impedance of the amplifier circuit too
- What's the input impedance (Thevenin equivalent) of an inverting amplifier?



Input Impedance

- Sometimes want large values of R_1 for increasing input impedance. Why?

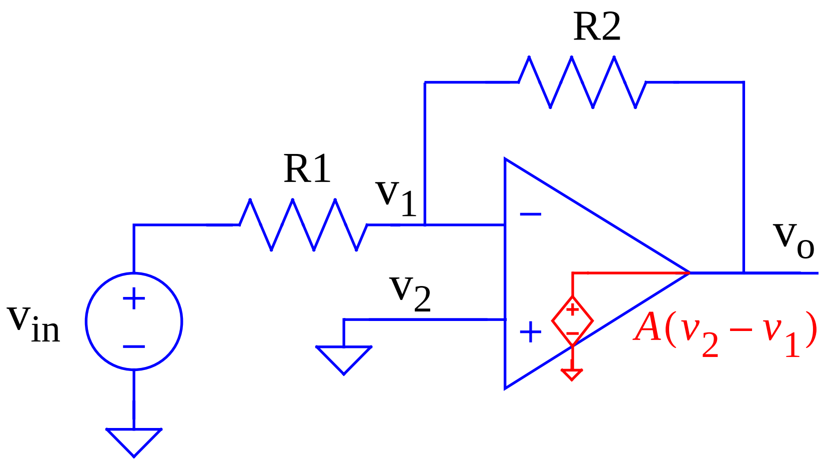


- But then gain is set by R_2, and we can't make it arbitrarily large. Why?

Output Impedance

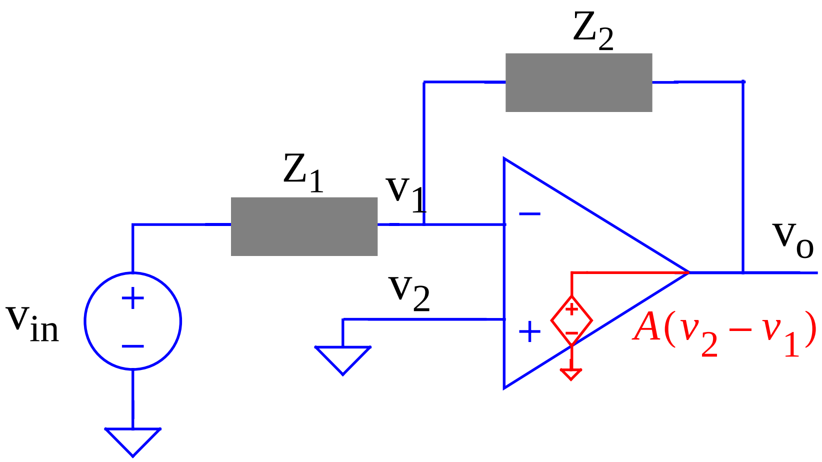
- We generally want a small output impedance. why?

- What is the output impedance for the idealized amplifier?



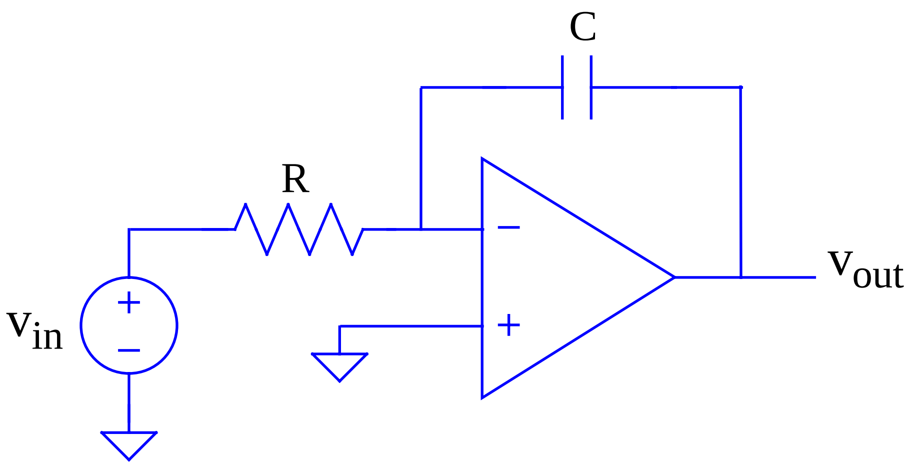
Complex Impedances in Opamp Circuit

- We can analyze the inverting amplifier the same way if the external elements include impedances and admittances (functions of s or jω)



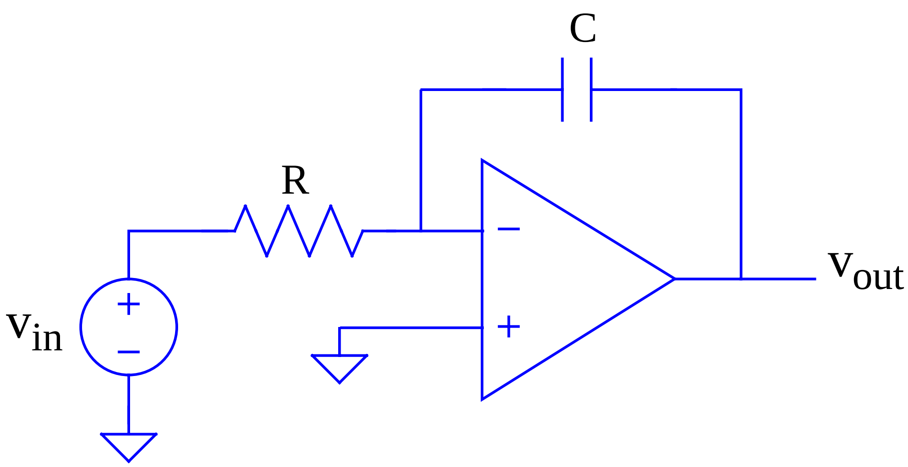
Example: Integrating Amplifier

- Integrating amplifiers are used in various applications: e.g. analog computing
- We can analyze this circuit in the time domain or the frequency domain:



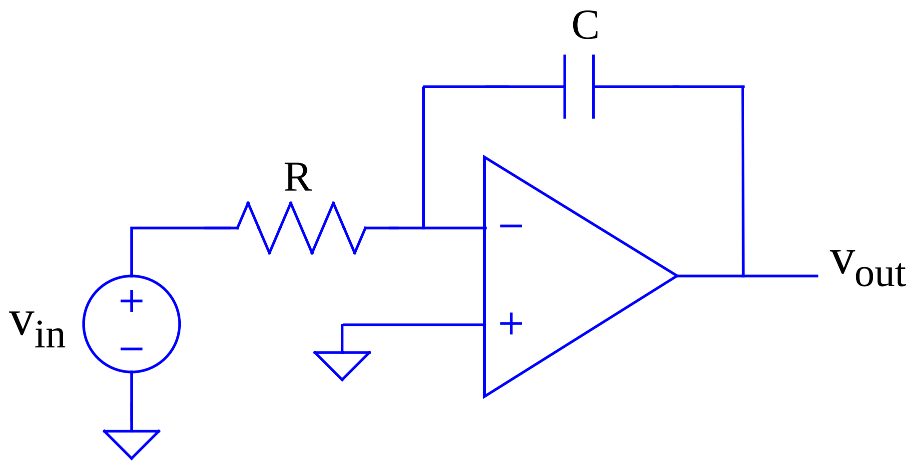
Example: Integrating Amplifier

- What is the frequency domain response?
- Where's the pole?



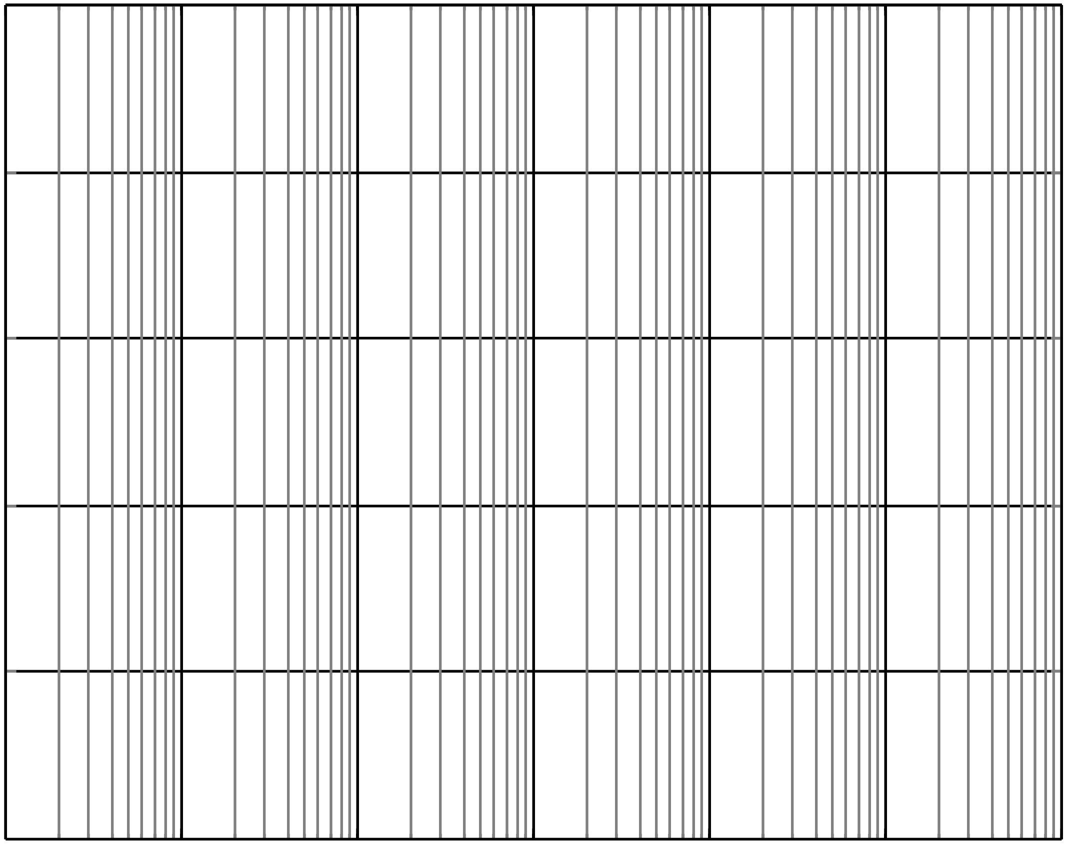
Example: Integrating Amplifier

- What does the frequency response (Bode plot) look like?



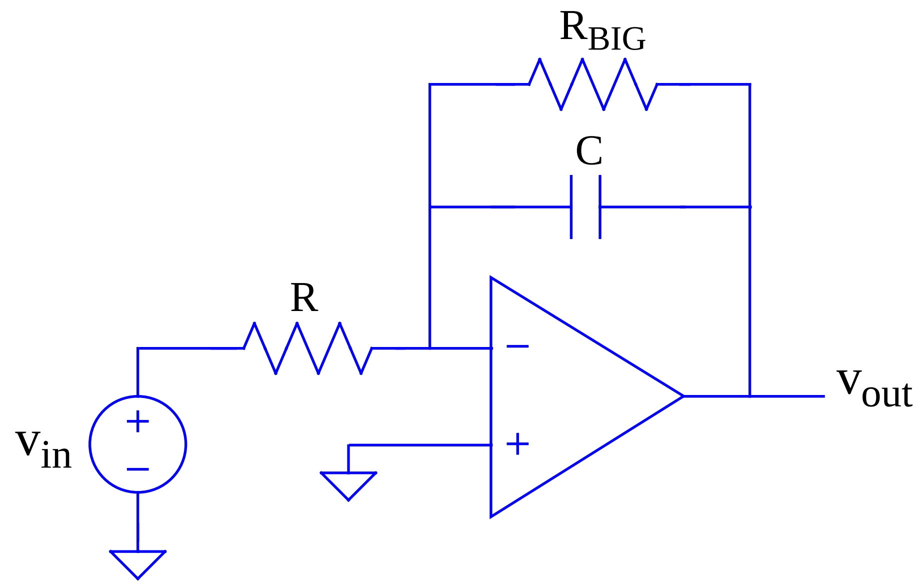
- What is the dc gain? What is the unity gain frequency?

Bode Plot



Integrating Amplifier

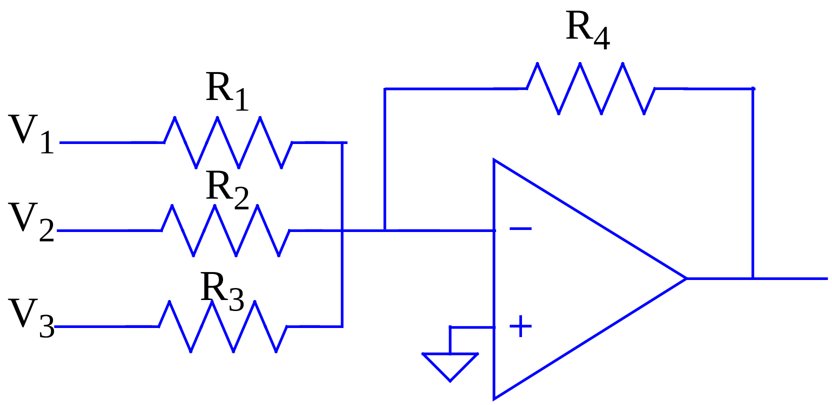
- Without control over the dc gain, a small dc input voltage can saturate the opamp output
- For this reason a large feedback resistor is added to control the dc gain



- But the circuit is no longer a perfect integrator!

Summing Amplifier

- A variety of opamp circuits are based on the inverting amplifier configuration



Noninverting Opamp

- The noninverting amplifier is analyzed in the same manner as the inverting one