Op-Amp Circuits

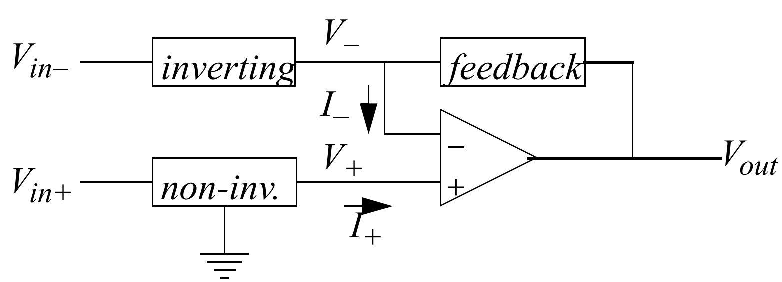
Op-Amps with Negative Operational Feedback

- Op-amps have very high input impedance, so the input current is nearly zero. For most circuits it can be treated as equal to zero compared to other currents in the circuit.
- Op-amps have very large gain. Circuits that use negative operational feedback take advantage of the large gain and feedback to keep both input voltages at the same value compared to other voltages in the circuit.

Two Rules for Op-amp Circuits

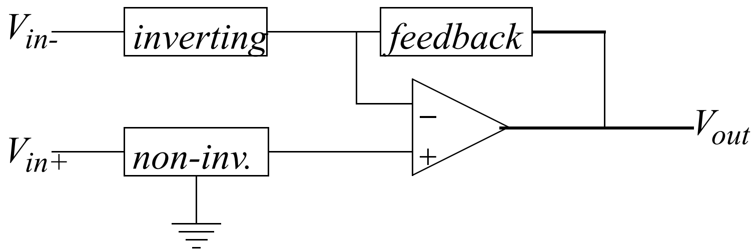
1. $I_+ = I_- = 0$. ***The input currents are 0.***

2. $V_+ - V_- = 0$. ***The input voltage difference is 0.***



Op-Amp Analysis

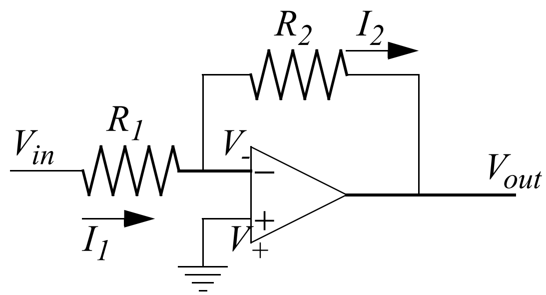
- Find the voltage at the non-inverting input and use rule two to assign that same voltage to the inverting input.
- Find the current flowing at the inverting input from any voltage source.
- Use rule one to send all the current at an input flowing into the feedback network
- Use the current through the feedback network to find a voltage drop to the output.



- The non-inverting, inverting and feedback networks can be complex impedances, semiconductors, or other active components.

Inverting Amplifier

- Use a resistor for input and feedback.



- From the op-amp current rule, since $I_{-} = 0$, $I_1 = I_2$.
- From the op-amp voltage rule, since $V_{+} = 0$, $V_{-} = 0$.
- Ohm's law gives $I_1 = V_{in}/R_1$ and $V_{out} = -I_1 R_2$.
- The gain for the amplifier is

$$A = \frac{V_{out}}{V_{in}} = \frac{-R_2}{R_1}$$

- Input impedance, v_{-} is a virtual ground:

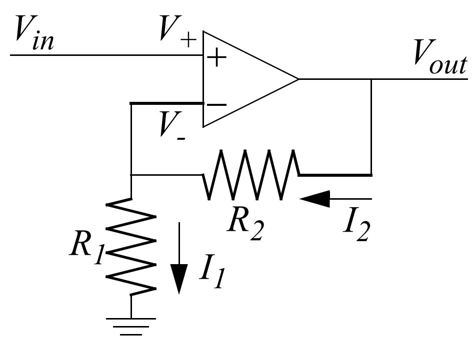
$$Z_{in} = R_1$$

- Output impedance using operational feedback

$$Z'_{out} = \frac{-Z_{out}}{A_0} \ll 1\Omega$$

Non-inverting Amplifier

- Use the positive input for the signal to get positive gain.



- From the op-amp voltage rule, since $V_+ = V_{in}$, $V_- = V_{in}$.
- From the op-amp current rule, since $I_- = 0$, $I_1 = I_2$.
- Ohm's law gives $I_1 = V_{in}/R_1$ and $V_{out} = I_1 R_2 + V_{in}$.
- The gain for the amplifier is $A = \dfrac{V_{out}}{V_{in}} = \dfrac{I_1 R_2 + I_1 R_1}{I_1 R_1} = \dfrac{R_1 + R_2}{R_1} = 1 + \dfrac{R_2}{R_1}$
- Input impedance based on op-amp only

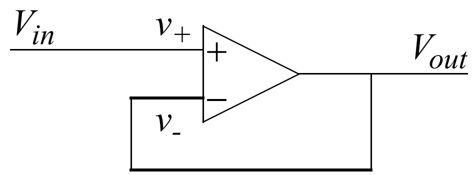
$$Z_{in} > 10^{8-12}\Omega$$

- Output impedance again uses operational feedback

$$Z'_{out} = \frac{-Z_{out}}{A_0} \ll 1\Omega$$

Buffer/Follower

- Non-inverting amplifier without resistors.

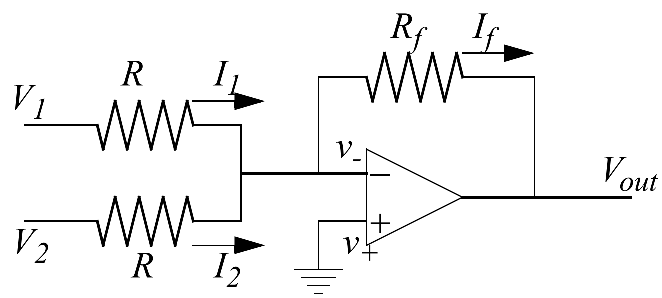


- Effectively, $R_1 = \infty$, and $R_2 = 0$. So, $A = 1 + \frac{R_2}{R_1} = 1$

- This is an op-amp version of a emitter-follower with very high input impedance and very low output impedance.

Summing Amplifier

- Consider two inputs V_1 and V_2 an an inverting amplifier



- From the op-amp rules, $v_- = 0$.

$$I_1 = \frac{V_1}{R} \qquad I_2 = \frac{V_2}{R}$$

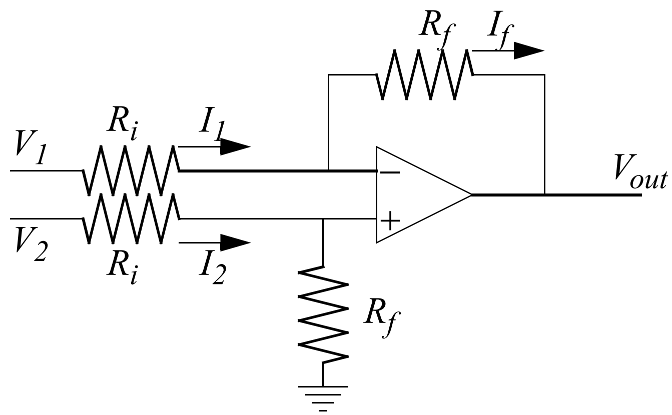
- Using the Kirchoff current law: $I_f = I_1 + I_2$.

$$V_{out} = -I_0 R_f = -(V_1 + V_2)\frac{R_f}{R}$$

- The input voltages are summed and amplified.

Difference Amplifier

- Combine an inverting and non-inverting amplifier



- On the non-inverting side: $I_2 = \dfrac{V_2}{R_i + R_f}$ $\qquad V_A = \dfrac{R_f V_2}{R_i + R_f}$

- On the inverting side: $I_1 = \dfrac{V_1 - V_A}{R_i} = \dfrac{(R_i + R_f)V_1 - R_f V_2}{(R_i + R_f)R_i}$

- The output is:

$$V_{out} = -I_1 R_f + V_A = \frac{-[(R_i + R_f)V_1 - R_f V_2]R_f}{(R_i + R_f)R_i} + \frac{R_i R_f V_2}{(R_i + R_f)R_i}$$

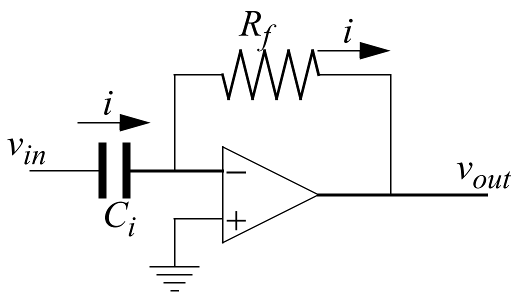
- This can be reduced to

$$V_{out} = \frac{R_f}{R_i}(V_2 - V_1)$$

Differentiator

- An amplifier can utilize the relation between charge and current.

$$I = \frac{dQ}{dt} = C\frac{dV}{dt}$$



- The current is converted to a voltage

$$v_{out} = -iR_f = -R_f C_i \frac{dv_{in}}{dt}$$

- For a sinusoidal input $v_{in} = V_0 \sin\omega t$,

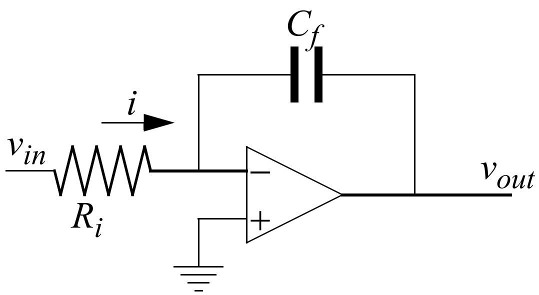
$$\frac{dv_{in}}{dt} = V_0 \omega \cos\omega t$$

$$v_{out} = -R_f C_i V_0 \omega \cos\omega t = -R_f C_i \omega v_{in}$$

- The amplitude increases with increasing frequency

Integrator

- The input current can be converted into a charge



$$i = \frac{v_{in}}{R_i} = -C_f \frac{dv_{out}}{dt}$$

- Solving for v_{out}:

$$v_{out} = \frac{-1}{R_i C_f} \int v_{in} dt + K$$

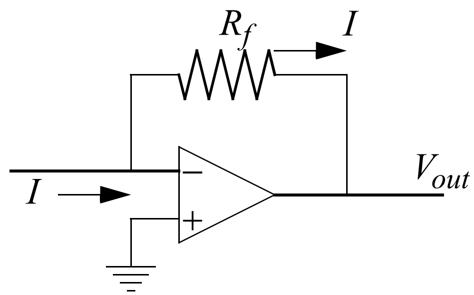
- With a sine wave input

$$v_{out} = \frac{-1}{\omega R_i C_f} v_{in} + K$$

- The amplitude decreases with frequency.

Current-to-Voltage Converter

- Operational feedback relies on current.



$$V_{out} = -R_f I$$

This is used for small input signals such as photonic devices.

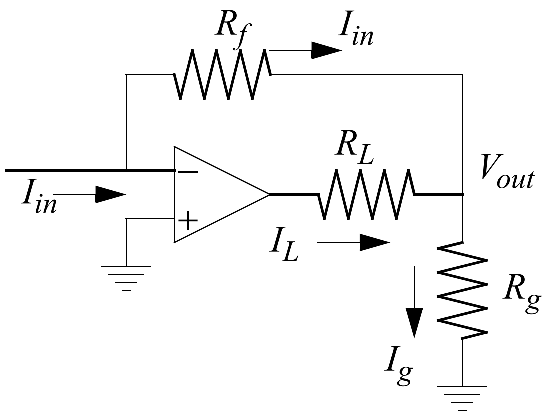
A parallel feedback capacitor can be used to reduce high frequencies.

The output is usually measured in V/μA.

- The op-amp provides low output impedance, hence higher power.

Current-to-Current Converter

- An extra resistor to defines the current.



$$V_{out} = -R_f I_{in}$$

From Kirchoff's Laws:

$$I_g = I_L + I_{in}$$

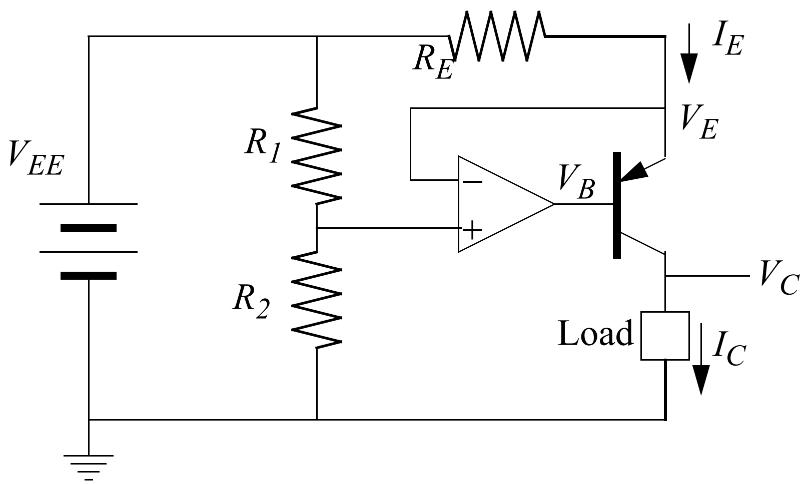
$$V_{out} = R_g I_g$$

Combine the equations:

$$I_L = -I_{in}\left(1 + \frac{R_f}{R_g}\right)$$

Voltage-to-Current Converter

- An op-amp follower can be used to drive a conventional transistor current source.



- R_1 and R_2 form a voltage divider, and the amplifier acts as a buffer. $V_E = \frac{R_2}{R_1 + R_2} V_{EE}$
- The current I_E is defined by R_E; $I_E = \frac{V_{EE} - V_E}{R_E} = \frac{R_1}{(R_1 + R_2)} \frac{V_{EE}}{R_E}$
- The current through the load is $I_C = I_E$.