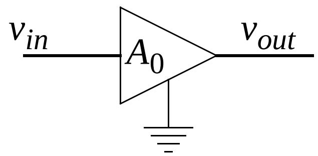
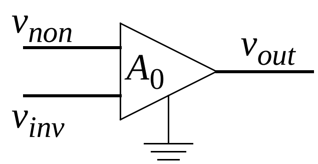
Amplifiers

- An amplifier is a four terminal device that produces an output voltage (or current) proprtional to the input.
- The schematic symbol can represent amplification of a factor A_0 when both input and output are referenced to ground.



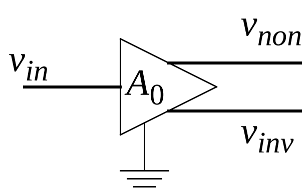
$$v_{out} = A_0 v_{in}$$

- A differential amplifier uses two inputs and amplifies the difference between the inputs.



$$v_{out} = A_0(v_{non} - v_{inv})$$

- Differential drivers create a differential output.

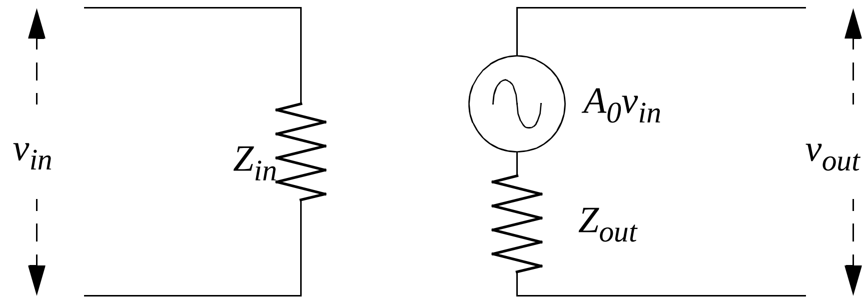


$$(v_{non} - v_{inv}) = A_0 v_{in}$$

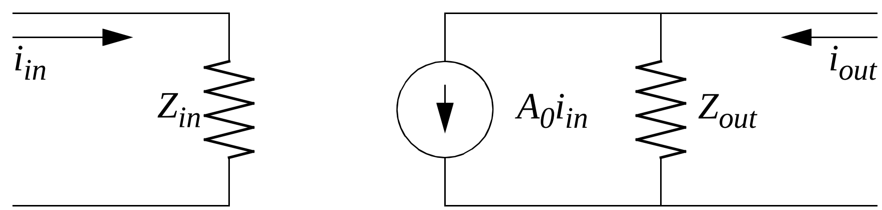
- Real amplifiers are limited to output within the range of the power supply to the amplifier. These output limits are called the *rails*.

Amplifier Equivalent Circuits

- An amplifier can be represented as a Thevenin equivalent circuit for a voltage amplifier.



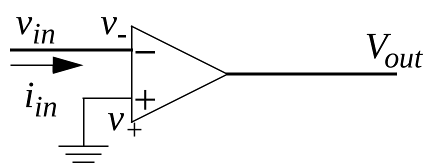
- A current amplifier can be repreesented as a Norton equivalent circuit.

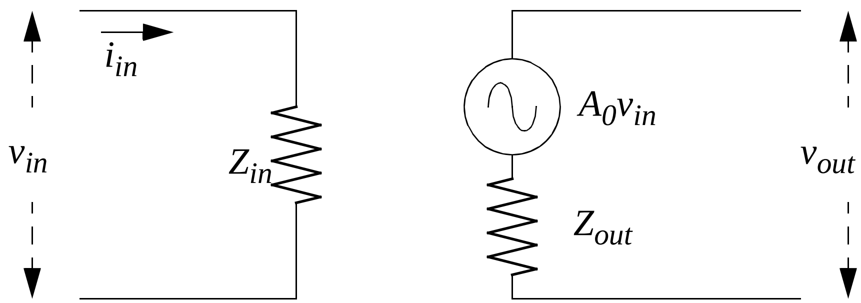


- Amplifiers can also use current in and voltage out or voltage in and current out.

Input Impedance

- The impedance for an amplifier is calculated on one input. If there are two then the other is treated as ground.





$$Z_{in} = \frac{v_{in}}{i_{in}}$$

- The input impedance is equal to transistor base/gate impedance including any internal feedback.

Bipolar input (741) - 2 MΩ.

JFET input (TL071) - 10^{12} Ω.

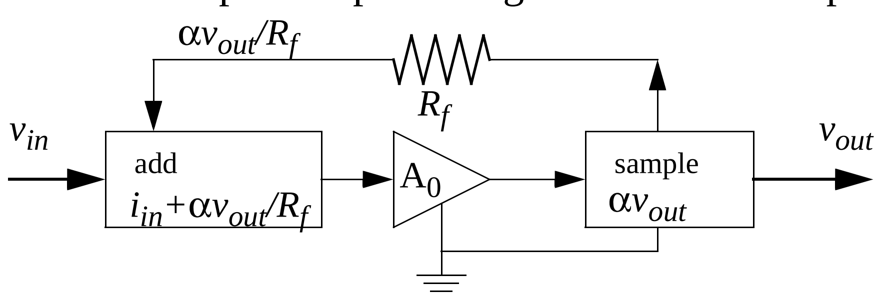
Operational Feedback

Types of Feedback

Sample output	Type of input	Name
Voltage	Voltage	Voltage feedback
Current	Voltage	Current feedback
Voltage	Current	Operational voltage feedback
Current	Current	Operational current feedback

Operational Voltage Feedback

- Operational voltage feed back samples output voltage and adds it to input as current.

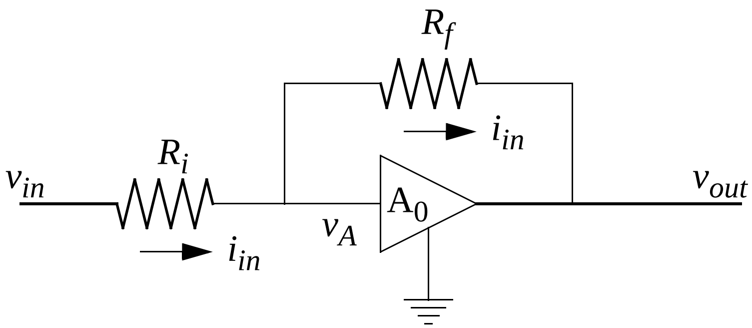


- If the input impedance for the amplifier A_0 is very large, no current can flow into the amplifier compared to the input and feedback, so the input must cancel the feedback. $i_{in} = \frac{\alpha v_{out}}{R_f}$

Feedback Gain

- An input resistor can set the current i_{in}.

$$i_{in} = \frac{v_{in} - v_A}{R_i}$$



- The input current must all go through the feedback resistor. $i_{in} = \dfrac{v_A - v_{out}}{R_f}$
- The amplifier gain gives $v_{out} = A_0\, v_A$. $\dfrac{v_{in} - v_{out}/A_0}{R_i} = \dfrac{v_{out}/A_0 - v_{out}}{R_f}$
- Solving for the gain with feedback. $A = \dfrac{v_{out}}{v_{in}} = \dfrac{1}{(R_i/R_f)(1/A_0 - 1) + 1/A_0}$
- For very large gain, $A_0 >> 1$, and the gain is negative. $A = \dfrac{-R_f}{R_i}$
- If the amplifier gain is much greater without feedback, $A_0 >> A$, $Av_{in} = A_0 v_A$ $v_{in} \gg v_A$, then the input to the amplifier must be very small and is called a *virtual ground*.

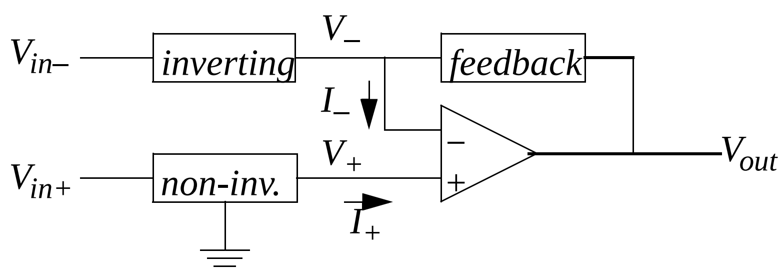
Op Amp Rules

- 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 citcuit.
- 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

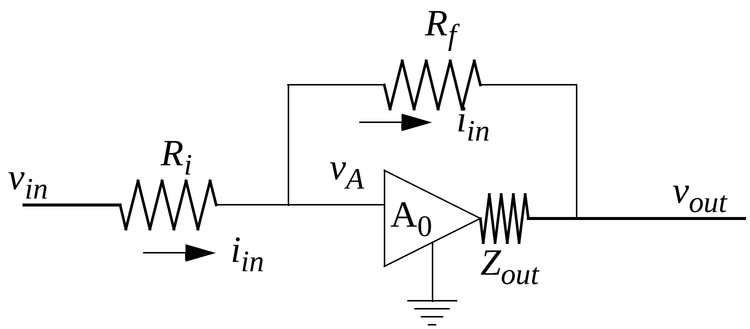
1. $I_+ = I_- = 0$. ***The input currents are 0.***

2. $V_+ - V_- = 0$. ***The input voltage difference is 0 when there is negative feedback.***



Output Impedance

- Intrinsic output impedance Z_{out} is measured with no feedback by Thevenin equivalence.
- Operational voltage feedback reduces the output impedance.

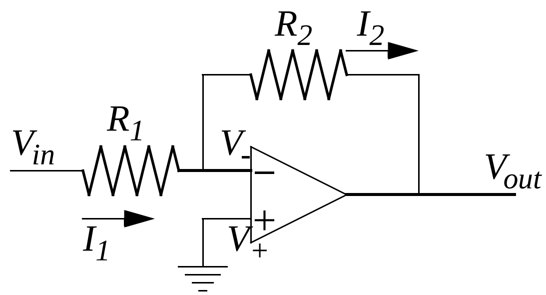


- The output impedance is: $Z'_{out} = v_{th} / i_s$.
- The thevenin output voltage is: $v_{th} = -i_{in} R_f$.
- With v_{out} shorted to ground, $v_A = i_{in} R_f$.
- Internally the voltage drop is $i_s Z_{out} = A_0 v_A = A_0 i_{in} R_f$.

$$Z'_{out} = \frac{-i_{in}R_f}{A_0 i_{in} R_f / Z_{out}} = \frac{-Z_{out}}{A_0}$$

Inverting Amplifier

- The basic inverting amplifier uses 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:

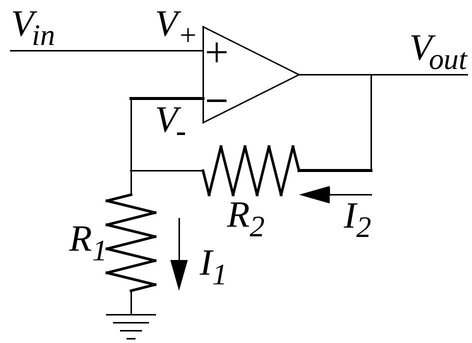
$$Z_{in} = R_1$$

- 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

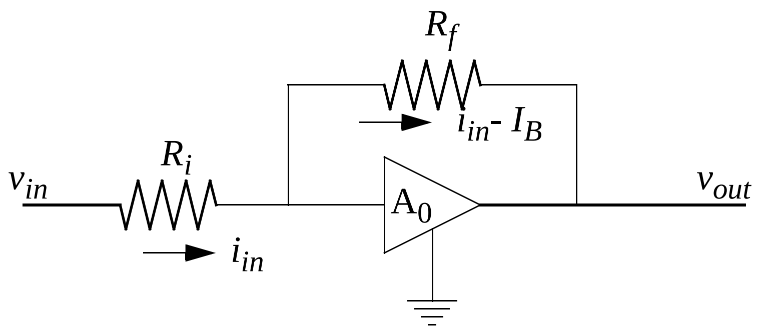
$$A = \frac{V_{out}}{V_{in}} = \frac{I_1 R_2 + I_1 R_1}{I_1 R_1} = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1}$$

- Input impedance based on op-amp only $Z_{in} > 10^{8-12}\Omega$
- Output impedance again uses operational feedback.

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

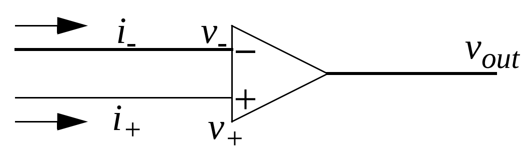
Input Current

- The bias current = common-mode input current, $I_B = (I_+ + I_-)/2$.
- The bias current causes a voltage drop across the feedback resistor.



- Typical values: Bipolar 10-100 nA, FET 10-100 pA.
- With small feedback resistors, bias current can be neglected.

- Offset current = differential-mode input current, $I_B = (I_+ - I_-)/2$.
- Typical values: $I_{io} = 0.1 I_B$ to $0.5 I_B$.



Offset Voltage

- An ideal amplifier gives an output of 0 for an input of zero.
- For a differential amplifier the input is the difference $v_{in} = v_{+} - v_{-}$.

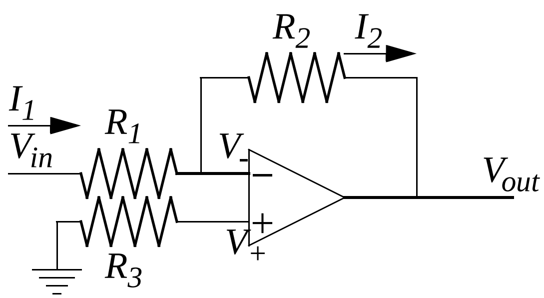
- For a real amplifier, if $v_{+} = v_{-}$, then v_{out} usually saturates to V_{CC} or V_{EE}.
- There is a finite difference called the offset voltage, $V_{io} = v_{+} - v_{-}$ needed for $v_{out} = 0$.

- Typical values for offset voltage are 0.1 to 10 mV, with temperature dependence 1 to 10 μV/°C.
- "Precision" op-amps have V_{io} on the order of 10 μV or less and temperature dependence less than 1 μV/°C.

Common Mode Gain

- Differential amplifiers have some amplification A_{CM} for signals in common to to both inputs.
- High gain amplifiers can have A_{CM} on the order of 1.

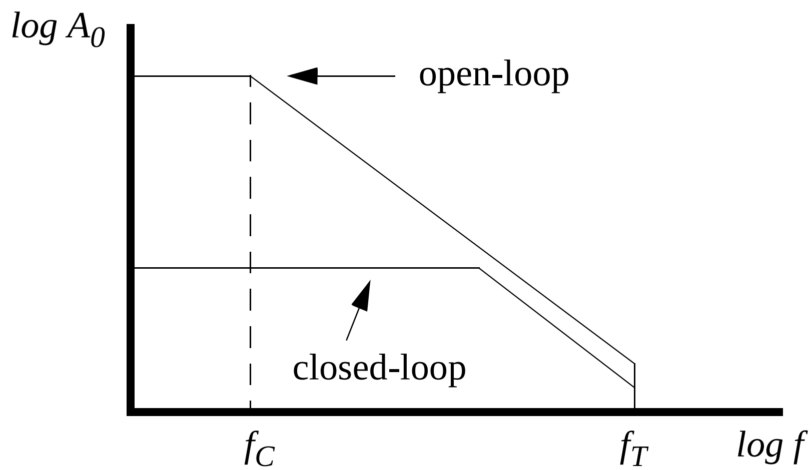
- A *common mode rejection ratio* defines the ability of an amplifier to suppress common mode signals.
- The typical CMRR = A_0 / A_{CM} = 60 to 120 dB.
- The input bias current adds to the common-mode gain, but can be corrected.



- The bias current is pulled into the inverting input through both R_1 and R_2. If R_3 is equal to the parallel equivalent of R_1 and R_2 the voltage drops will cancel.

High Frequency Gain

- Integrated circuit amplifiers provide large gain, eg. $A_0 = 10^4$ to 10^6, or 80 to 120 dB.
- Amplifiers act like low-pass RC filters, including a phase shift at the breakpoint or corner frequency f_C, so the gain is a function of frequency.
- Amplifiers typically have a hard threshold f_T as well.
- Open-loop gain is measured with no feedback. Closed-loop includes the feedback , so the gain is limited by the feedback resistor.



BODE PLOT

- The typical maximum frequency is f_T = 0.1 to 10 MHz.
- For a “compensated” op-amp, $f_C = f_T / A$.

Slew Rate

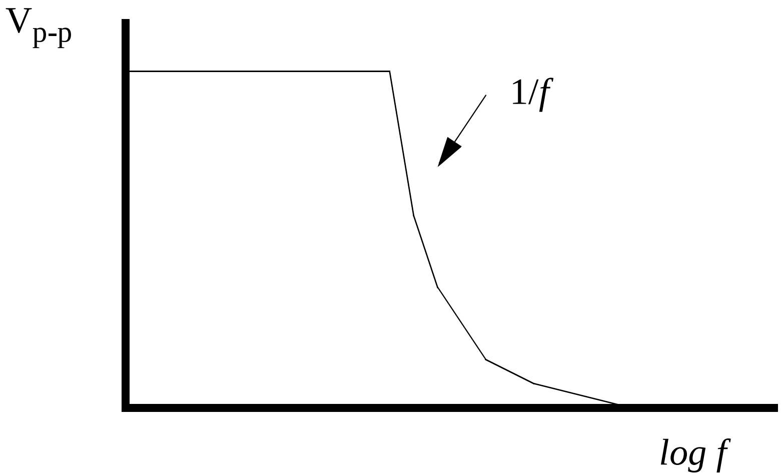
- Slew rate measures the ratye of amplifuer response to a changing input voltage.
- Typical S = 1 to 10 V/µs. “High-speed” op-amps have S = 100 to 1000 V/µs.
- An input sine wave with $\omega = 2\pi f$ and amplitude A

$$A \cos \omega t$$

has a maximum slope

$$A\omega = 2\pi A f$$

The peak-to-peak voltage must be less than $S/\pi f$.



- Slew rate is particularly important in digital applications, such as square-waves with rapid voltage changes.