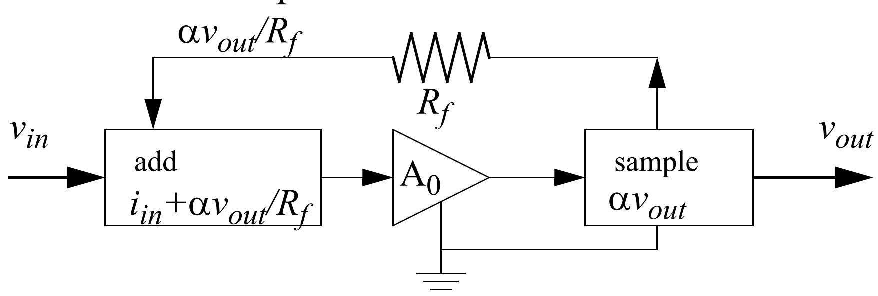
Operational Feedback

Types of Feedback

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

Operational Voltage Feedback

- Sample output voltage and add it to input as current:

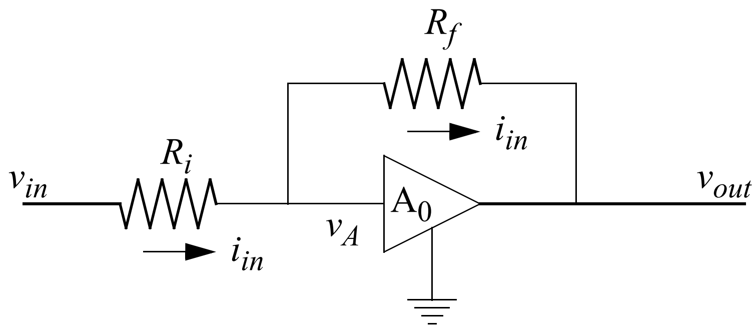


- If the input impedance for the amplifier A_0 is very large, no current can flow into the amplifier compared to the input and feedback, so the input must cancel the feedback.

$$i_{in} = \frac{\alpha v_{out}}{R_f}$$

Feedback Resistor

- 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.

$$i_{in} = \frac{v_A - v_{out}}{R_f}$$

- The amplifier gain gives $v_{out} = A_0\, v_A$, so: $\dfrac{v_{in} - v_{out}/A_0}{R_i} = \dfrac{v_{out}/A_0 - v_{out}}{R_f}$

Feedback Gain

- Solving for the gain with feedback:

$$A = \frac{v_{out}}{v_{in}} = \frac{1}{(R_i/R_f)(1/A_0 - 1) + 1/A_0}$$

- If $A_0 >> 1$:

$$A = \frac{-R_f}{R_i}$$

- The gain in an operational voltage feedback amplifier is negative.
- If the amplifier gain is much greater without feedback, $A_0 >> A$:

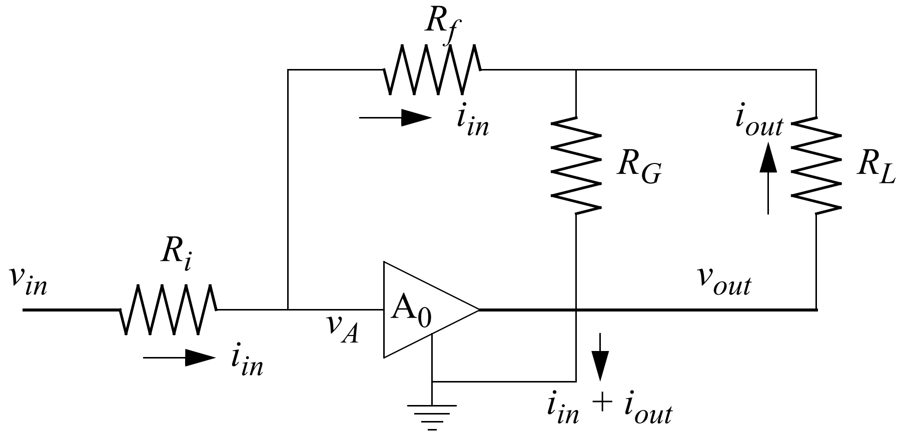
$$A v_{in} = A_0 v_A$$

$$v_{in} \gg v_A$$

- The input to the amplifier must be very small: *virtual ground*.

Operational Current Feedback

- Resistors are used to sample the output current and add to the input.



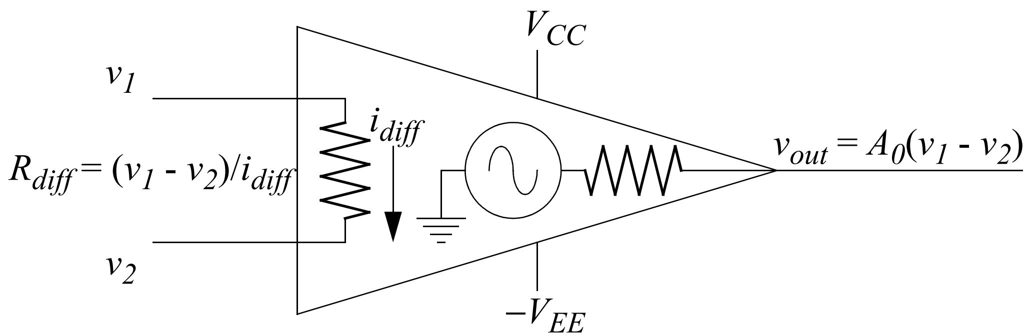
- With a very large A_0 and v_A a virtual ground:

$$i_{in}R_f = -(i_{in} + i_{out})R_G$$

$$i_{out}/i_{in} = -(R_f + R_G)/R_G$$

Operational Amplifier

Schematic Representation



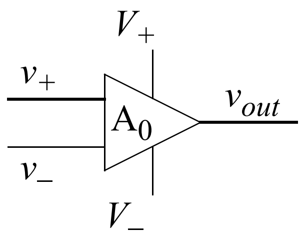
Ideal Op-Amp

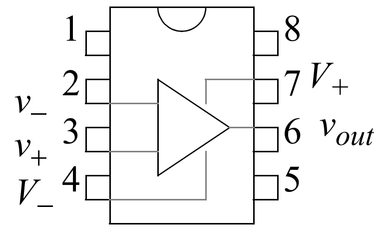
1. Input Impedance, $Z_{in} = \infty$.
2. Output Impedance, $Z_{out} = 0$.
3. Voltage Gain, $A_0 = \infty$.
4. Common Mode Gain, $A_{CM} = 0$.
5. Offset Voltage V_{io}, if $v_+ = v_-$, $v_{out} = 0$.
6. Slew Rate, $S = \infty$.

Ideally, all of these are independent of temperature and power supply.

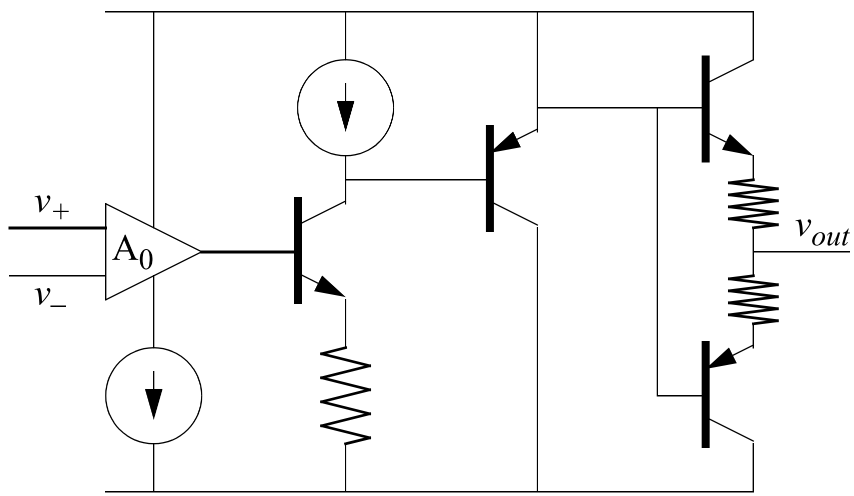
Integrated Circuit OpAmp

- Schematic symbol:



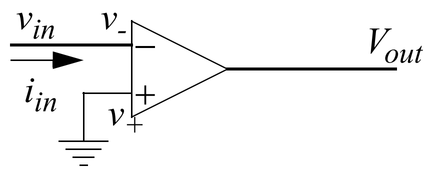


- Actual amplifier has a differential input stage with constant current sink, second stage amplifier with negative feedback for common mode signals, output stage amplifier and follower for high gain.



Input Impedance

- Impedance is calculated on one input when the other is ground.

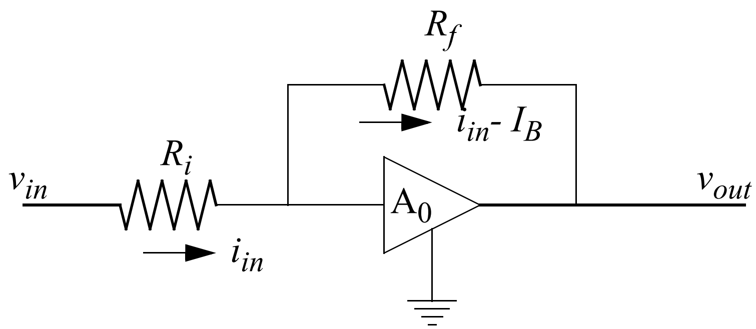


$$Z_{in} = \frac{v_{in}}{i_{in}}$$

- Equal to transistor base/gate impedance with feedback.
- Bipolar input (741) - 2 MΩ.
- JFET input (TL071, 081) - 10^{12} Ω.

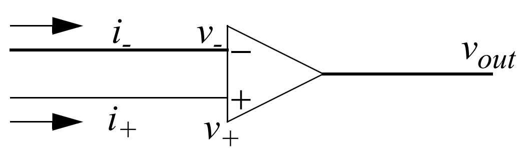
Input Current

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



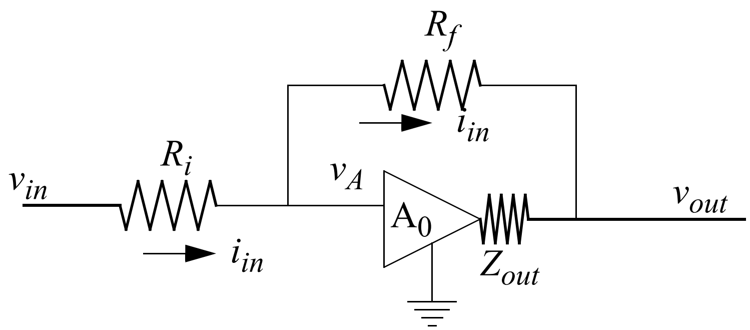
- Typical values: Bipolar 10-100 nA, FET 10-100 pA.
- With small feedback resistors, bias current can be neglected.

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



Output Impedance

- Operational voltage feedback reduces the output impedance.

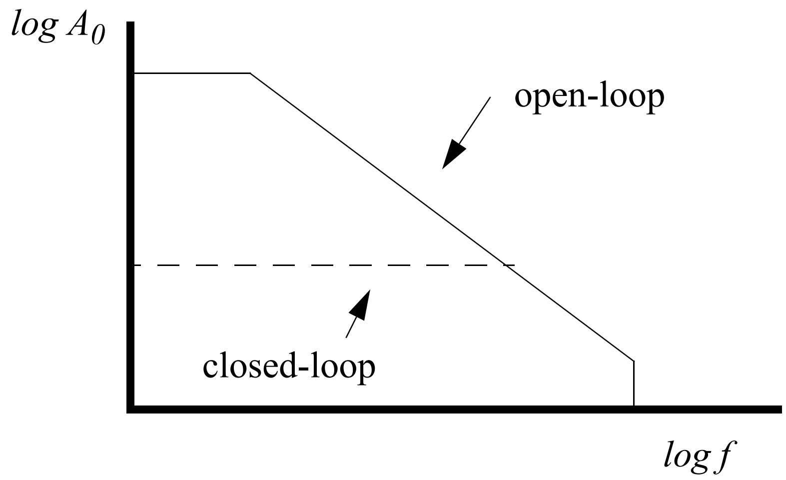


- The output impedance is: $Z'_{out} = v_{th} / i_s$.
- The Thevenin output voltage is: $v_{th} = -i_{in} R_f$.
- With v_{out} shorted to ground, $v_A = i_{in} R_f$.
- Internally the voltage drop is $i_s Z_{out} = A_0 v_A = A_0 i_{in} R_f$.

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

Voltage Gain

- Typical $A_0 = 10^4$ to 10^6, = 80 to 120 dB.
- Gain is a function of frequency.
- Open-loop gain is measured with no feedback. Closed-loop includes the feedback, so the gain is limited by the feedback resistor.

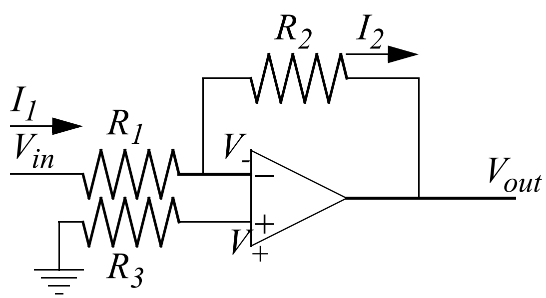


BODE PLOT

- Op-amps act like low-pass RC filters, including a phase shift at the break frequency f_B.
- Typical maximum frequency is $f_T = 0.1$ to 10 MHz.
- For a "compensated" op-amp, $f_B = f_T / A$.

Common Mode Gain

- Typical CMRR = A_0 / A_{CM} = 60 to 120 dB.
- Corresponding gain makes A_{CM} on the order of 1.
- Input bias current adds to 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.

Offset Voltage

- If $v_+ = v_-$, then v_{out} usually saturates to V_{CC} or V_{EE}.
- The difference $V_{io} = v_+ - v_-$ needed for $v_{out} = 0$.
- Typical values 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 with temperature dependence less than 1 µV/°C.

Slew Rate

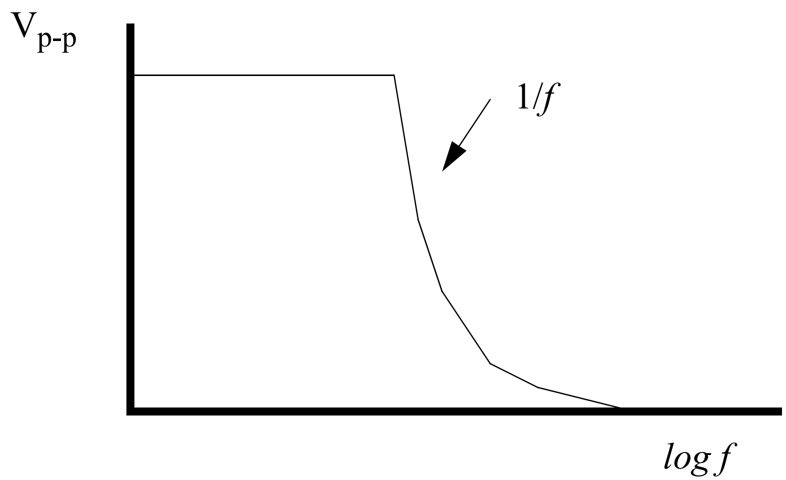
- Slew rate measures the speed that the op-amp can respond to a changing input voltage.
- Typical S = 1 to 10 V/μs. "High-speed" op-amps have S = 100 to 1000 V/μs.
- An input sine wave with $\omega = 2\pi f$ and amplitude A

$$A \cos \omega t$$

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 - square-waves with rapid voltage changes.