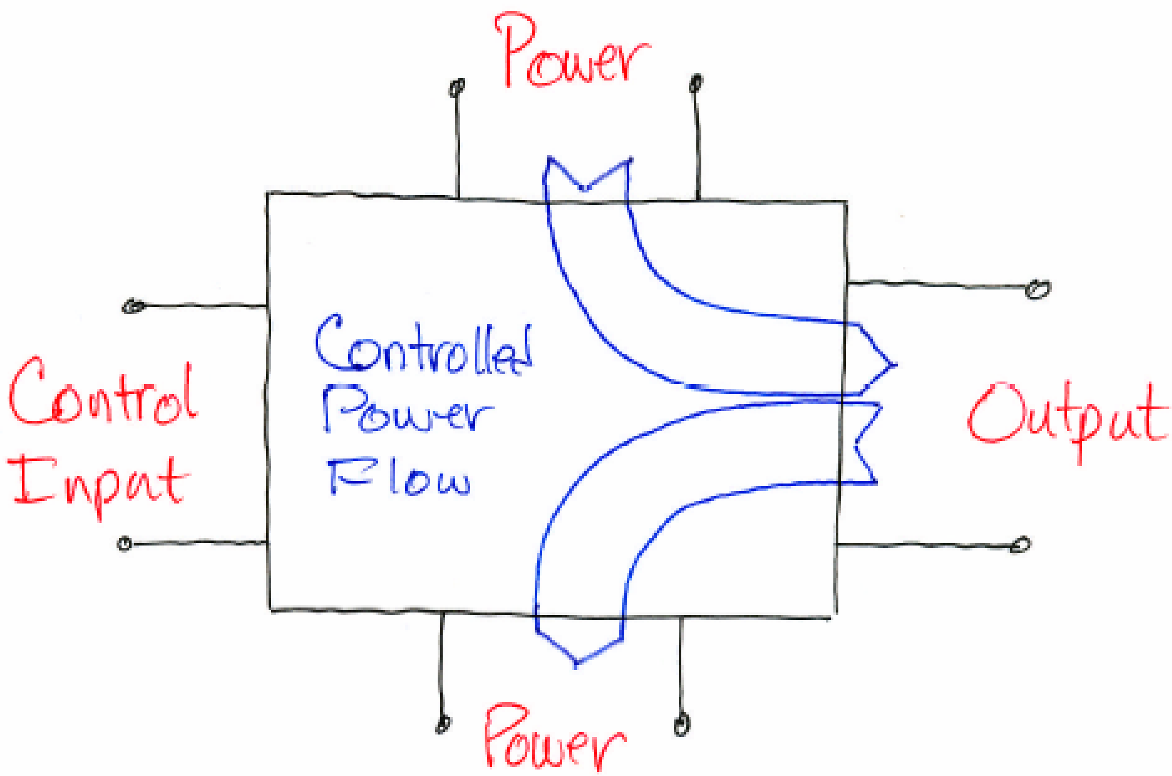
6.002 - Lecture 07

Operational Amplifiers (Op Amps)

- Amplifiers Revisited
- Op Amps
- Ideal Op Amps
- Nonidealities
- Op-Amp Based Amplifiers

Amplifiers



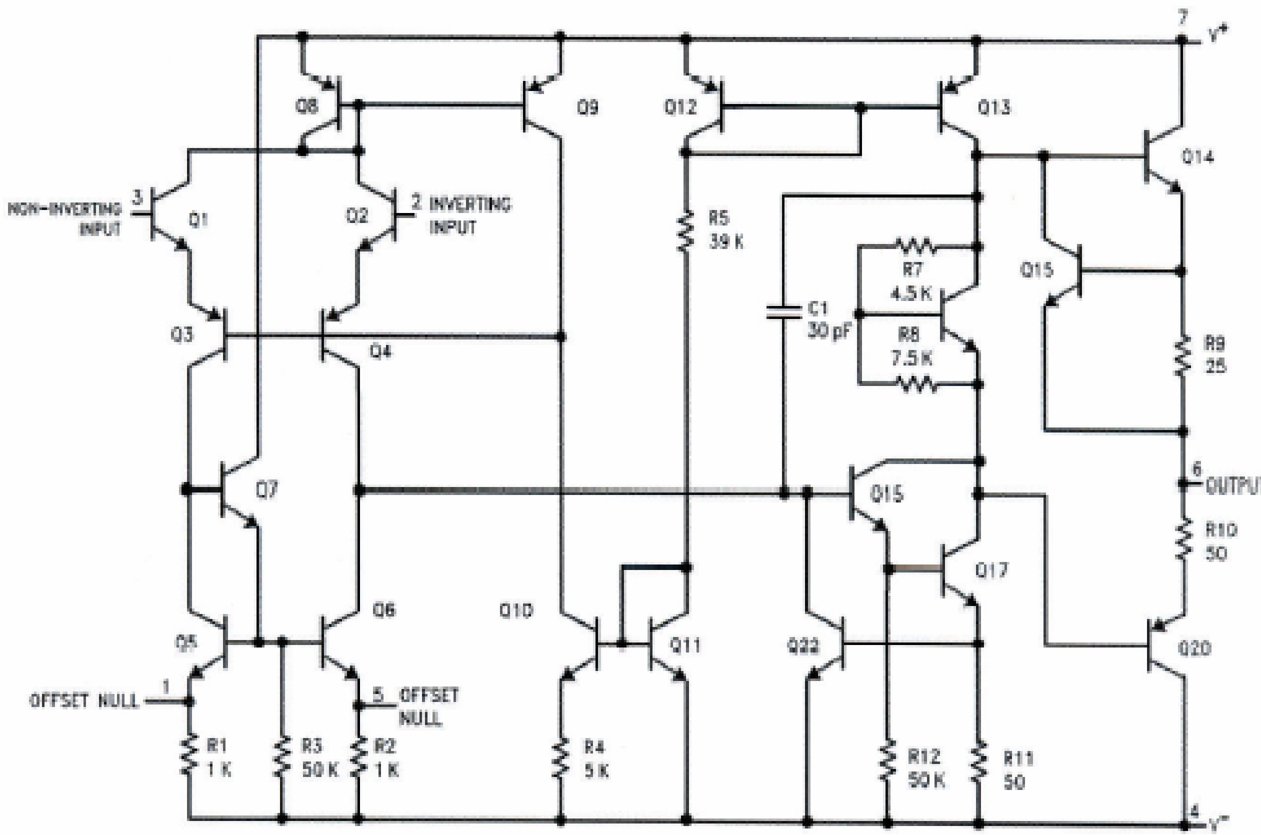
- Amplifier is a three- or four-port device.
- Provides voltage, current and/or power gain.
- Fundamental building block in analog signal processing systems such as: audio and video, communications, instrumentation and control, and so on.

Amplifier Wish List

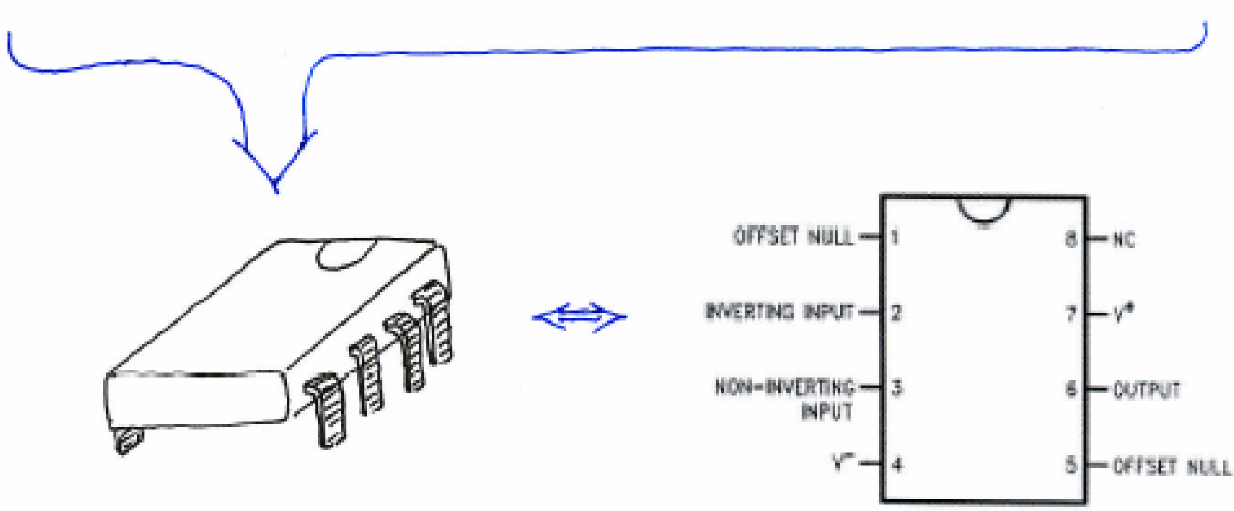
- High voltage, current and power gain
- Linear operation
- Stable operation
- Wide bandwidth ↔ fast response
- Differential input
- Low noise
- High input resistance ↔ low input current
- Low output resistance
- High power handling capability
- Low loss ↔ high efficiency
- Wide temperature operating range
- Minimal manufacturing variation
- Single small package

Op amp provide many of these features.

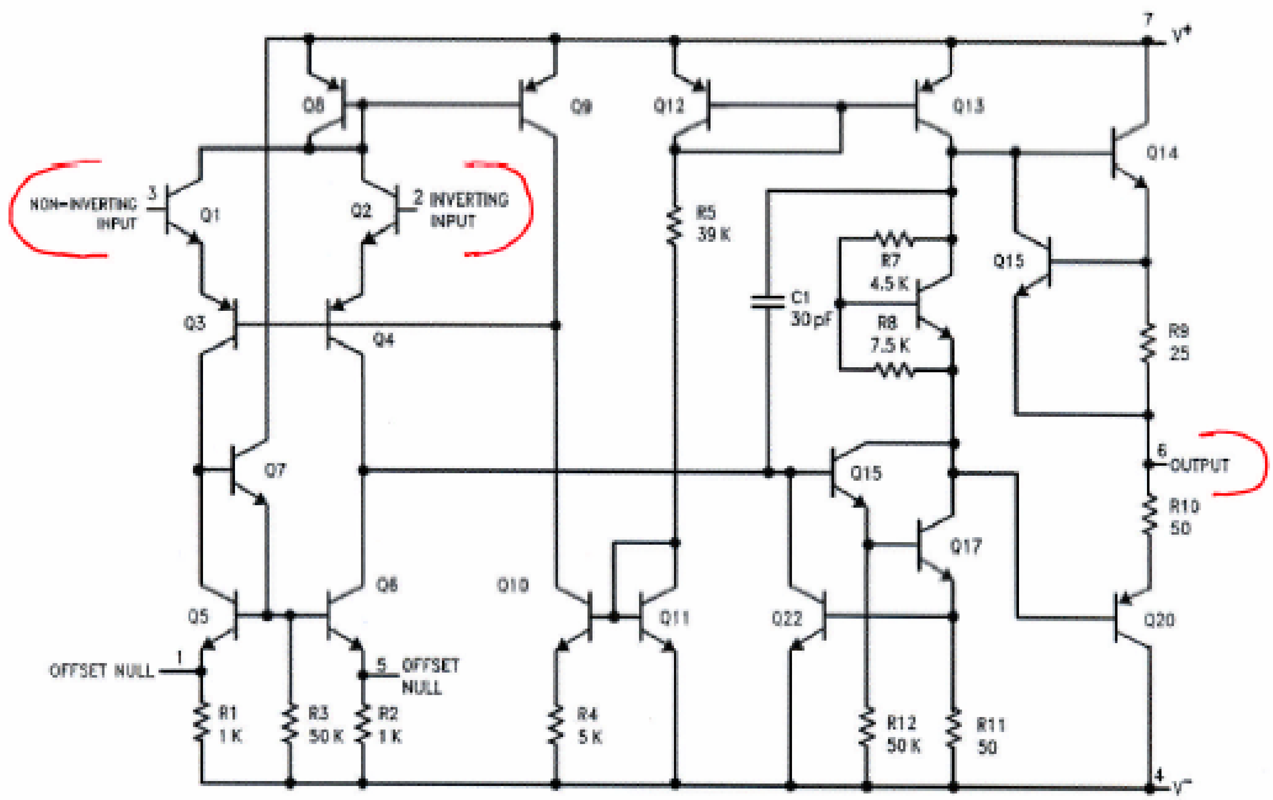
741 Operational Amplifier



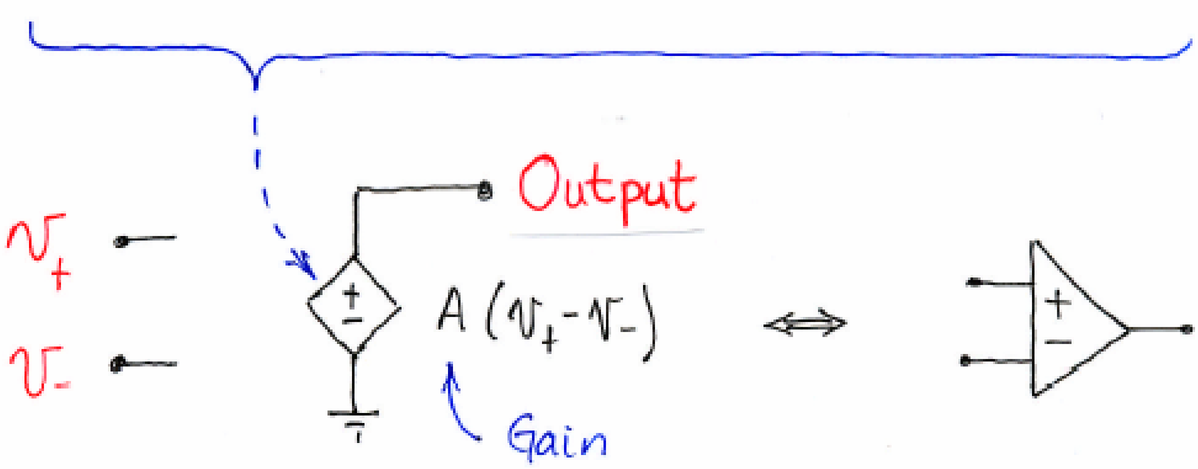
National Semiconductor LM741 Operational Amplifier



Simple Op Amp Model

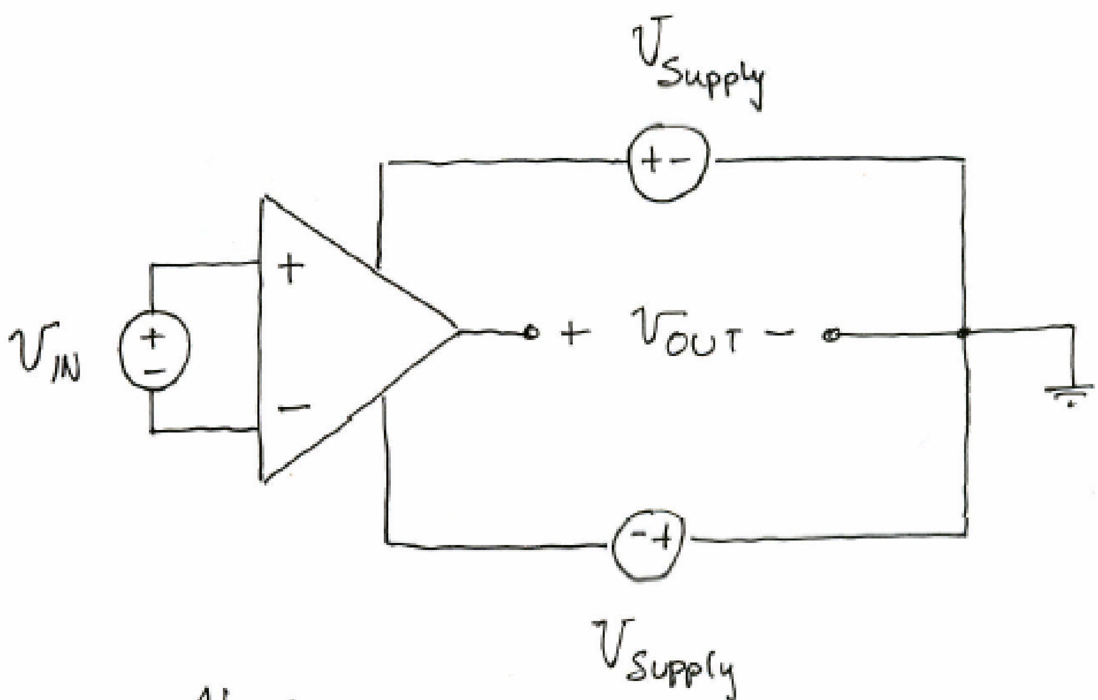


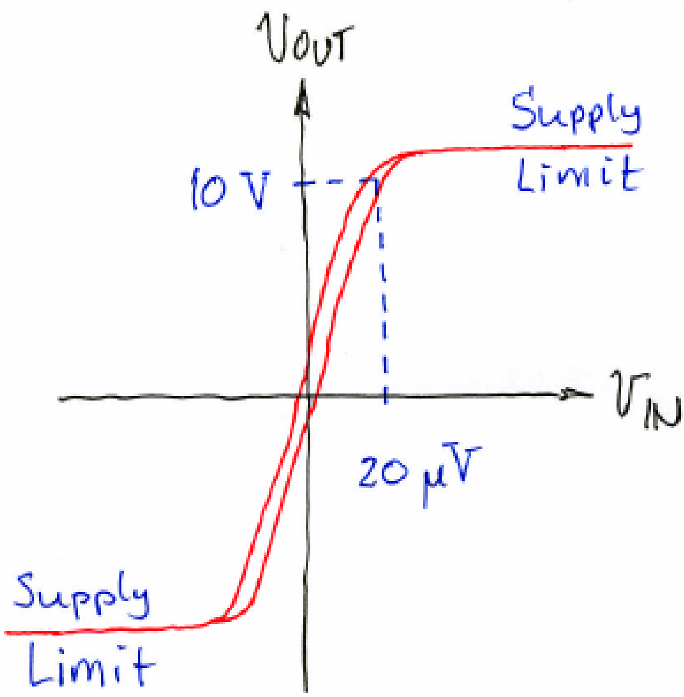
National Semiconductor LM741 Operational Amplifier



Power supply terminals not shown

Op Amp Behavior



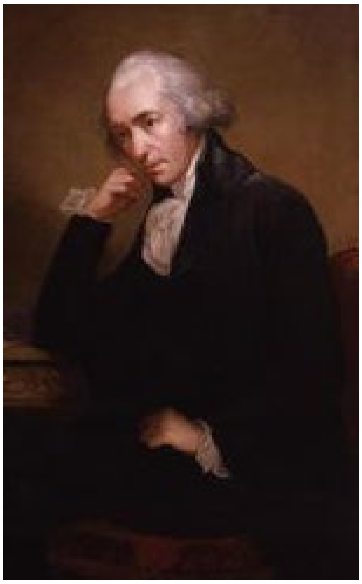


Voltage Gain $\approx 5 \cdot 10^5$

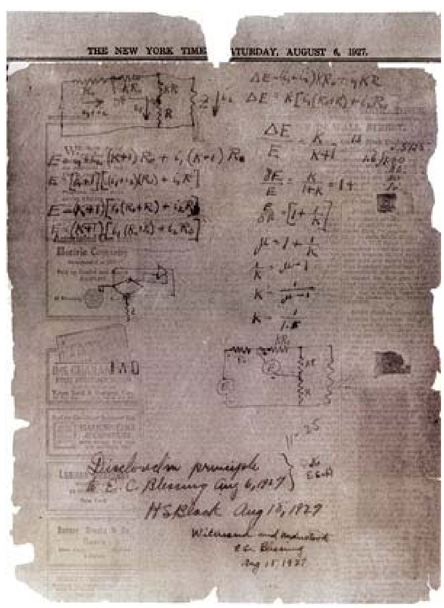
Non-Linear

Temperature Dependent

Negative Feedback



James Watt invents the steam engine speed governor in 1788. It uses negative feedback



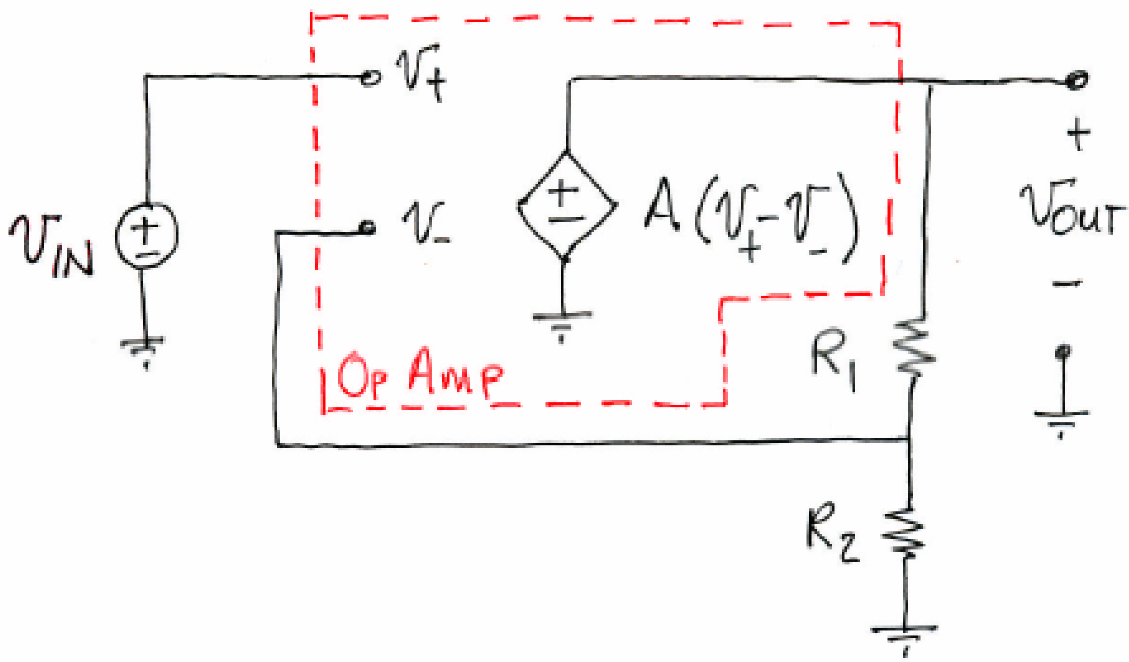
Harold Black invents the negative feedback electronic amplifier in 1927 while working at Bell Labs.

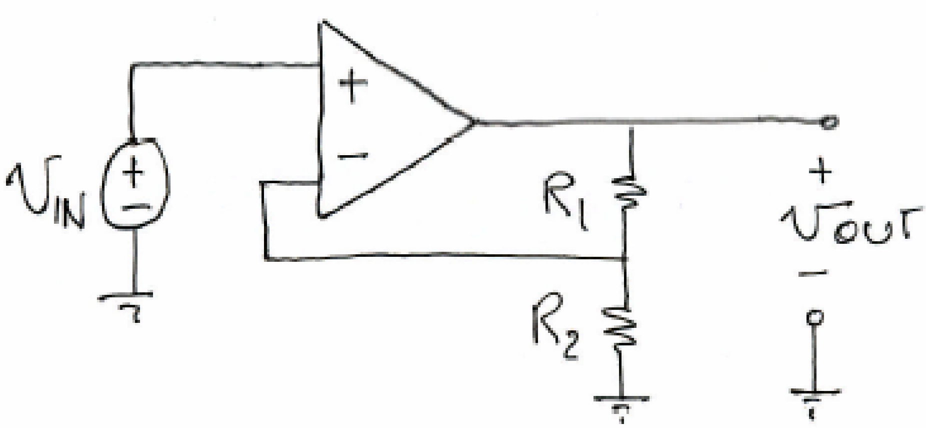
Natural occurrences are ubiquitous in biology, for example in body temperature, blood glucose and blood pressure regulation

Pictures courtesy of Wikipedia and WPI

A Practical Amplifier

Use negative feedback to trade gain for more ideal performance.





Power supply connections not shown.

Analysis

Node Method: $\frac{v_-}{R_2} + \frac{v_- - A(v_+ - v_-)}{R_1} = 0$ ($v_+ \to v_{IN}$)

$$v_- = \frac{A R_2}{R_1 + (A+1) R_2} v_{IN}$$

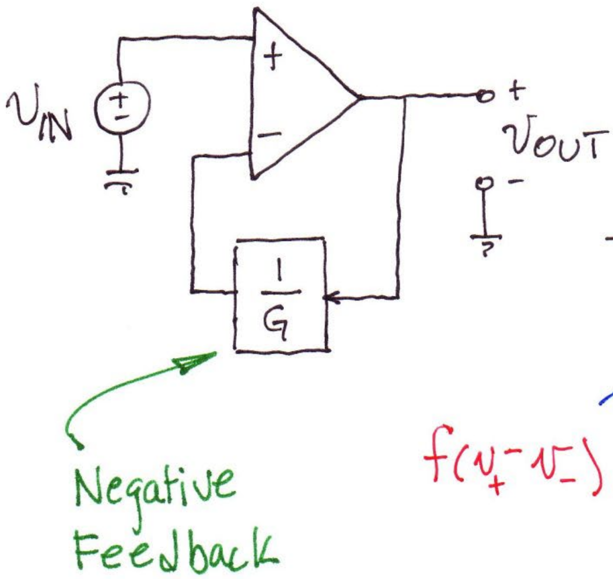
$$V_{OUT} = A(v_+ - v_-) \quad (v_+ \to v_{IN})$$

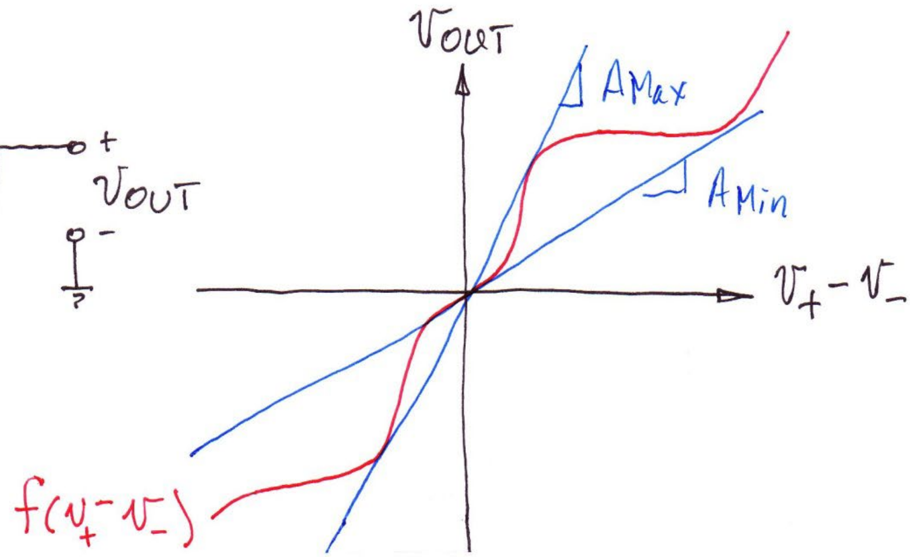
$$= \frac{A \cdot G}{A + G} v_{IN} \qquad G \equiv \frac{R_1 + R_2}{R_2}$$

If $A \gg G$ then $v_{OUT} = G\, v_{IN}$

↑ Dependent only on resistors.

Feedback Benefits





$$v_{OUT} = f\left(v_{IN} - \frac{1}{G} v_{OUT}\right)$$

$$A_{Min}\left(v_{IN} - \frac{1}{G} v_{OUT}\right) \le v_{OUT} \le A_{Max}\left(v_{IN} - \frac{1}{G} v_{OUT}\right)$$

$$\frac{G\, v_{IN}}{1 + G/A_{Min}} \le v_{OUT} \le \frac{G\, v_{IN}}{1 + G/A_{Max}}$$

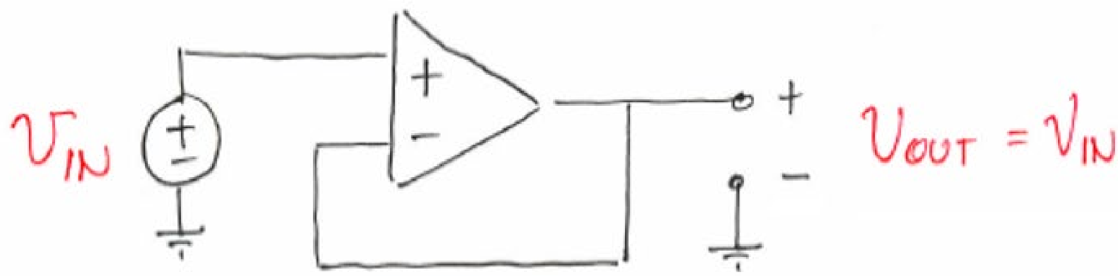
$A_{Max} > A_{Min} \gg G \Rightarrow$ Robust against:

- nonlinear f
- temperature dependent f
- manufacturing variations in f
- aging of f

Only G matters

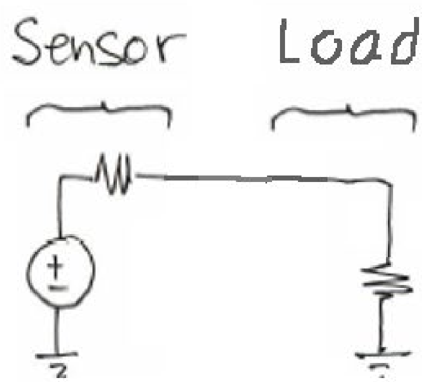
Buffer

$R_1 \to 0$ (Short) $R_2 \to \infty$ (Open)



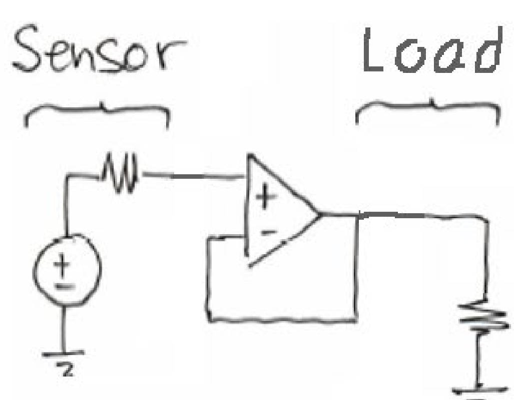
Voltage Gain = 1 Current Gain = ∞ Power Gain = ∞

Problem:



The load reduces the sensor output.

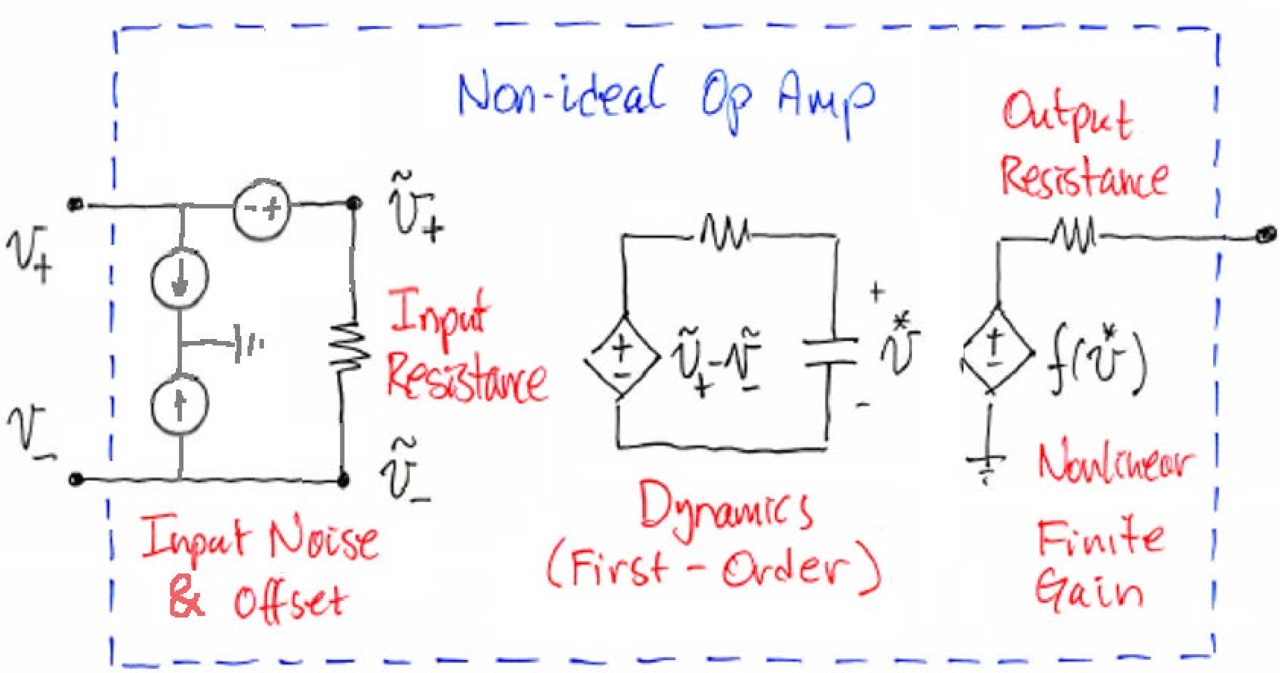
Solution:



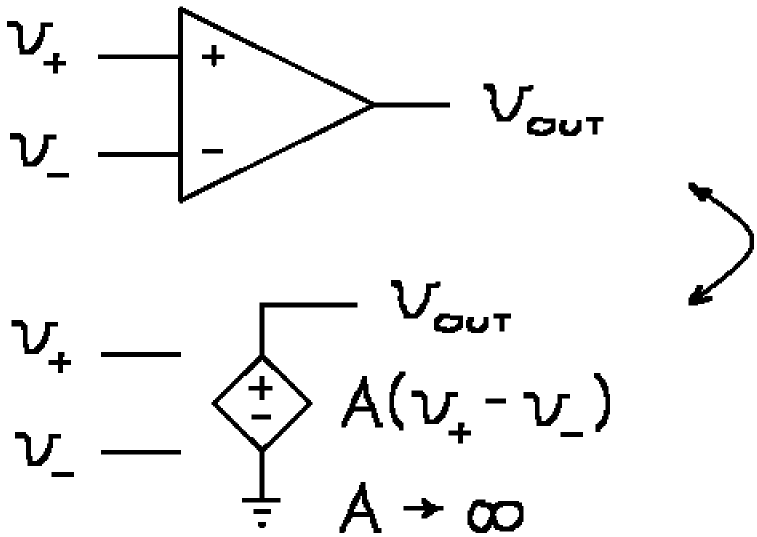
The buffer isolates the sensor from the load.

Common Nonidealities

- Finite, non-linear and non-differential gain.
- Finite bandwidth
- Non-zero output resistance
- Finite input resistance
- Input offsets and noise
- Temperature dependence



Ideal Op Amp



v_+, v_- and v_{OUT} are referenced to ground

- Zero input currents
- Algebraic differential output voltage
- Differential gain $A \to \infty$