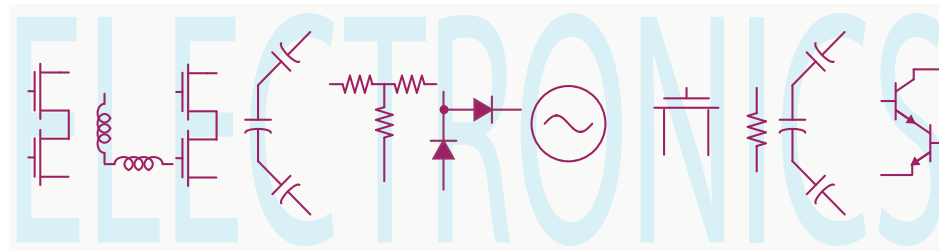


EE 42/100
Lecture 8: Op-Amps



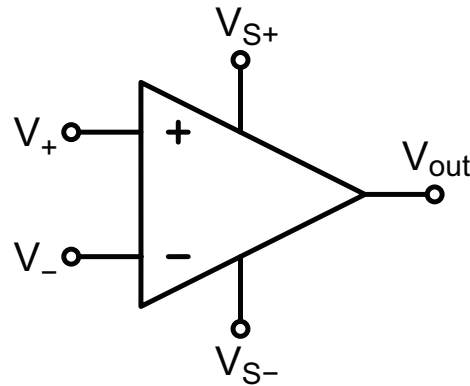
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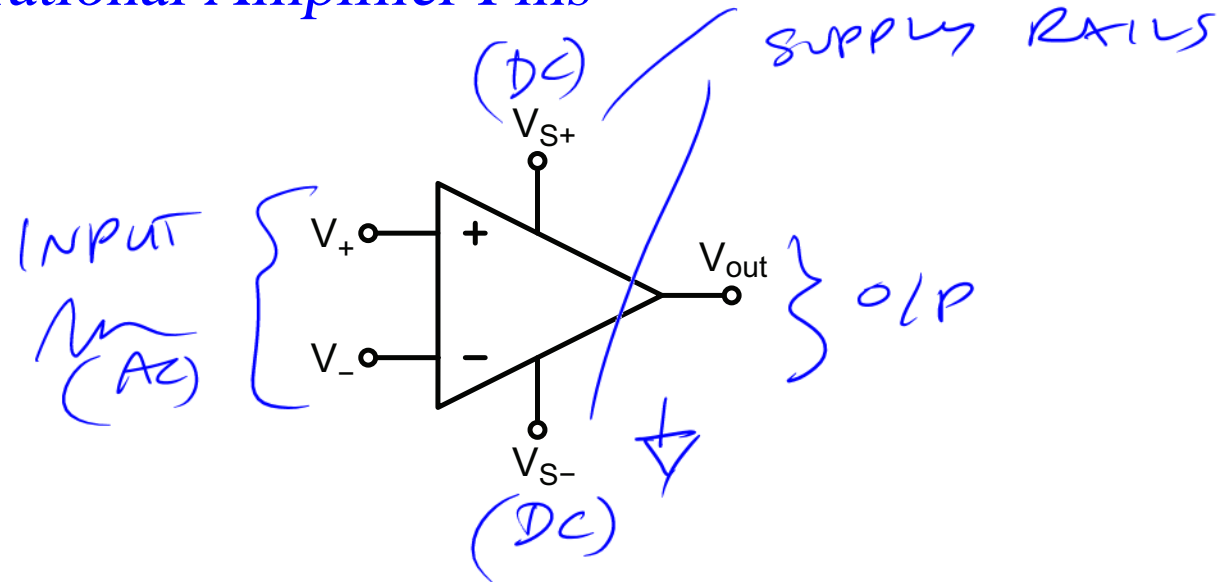
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Operational Amplifiers



- Invented in 1941 by Bell Labs engineer Karl D. Swartzel Jr. using vacuum tubes. It found wide application in WW-II.
- First monolithic IC op-amp was designed by Bob Widlar at Fairchild Semiconductor.
- The 741 op-amp is perhaps the best known op-amp in the world. Many other op-amps use the same pin configuration as the 741.
- The output voltage is usually millions of times larger than the voltage presented at the inputs.
- Op-amps are ubiquitous low cost components used in countless applications for analog signal processing (gain, filtering, signal conditioning).

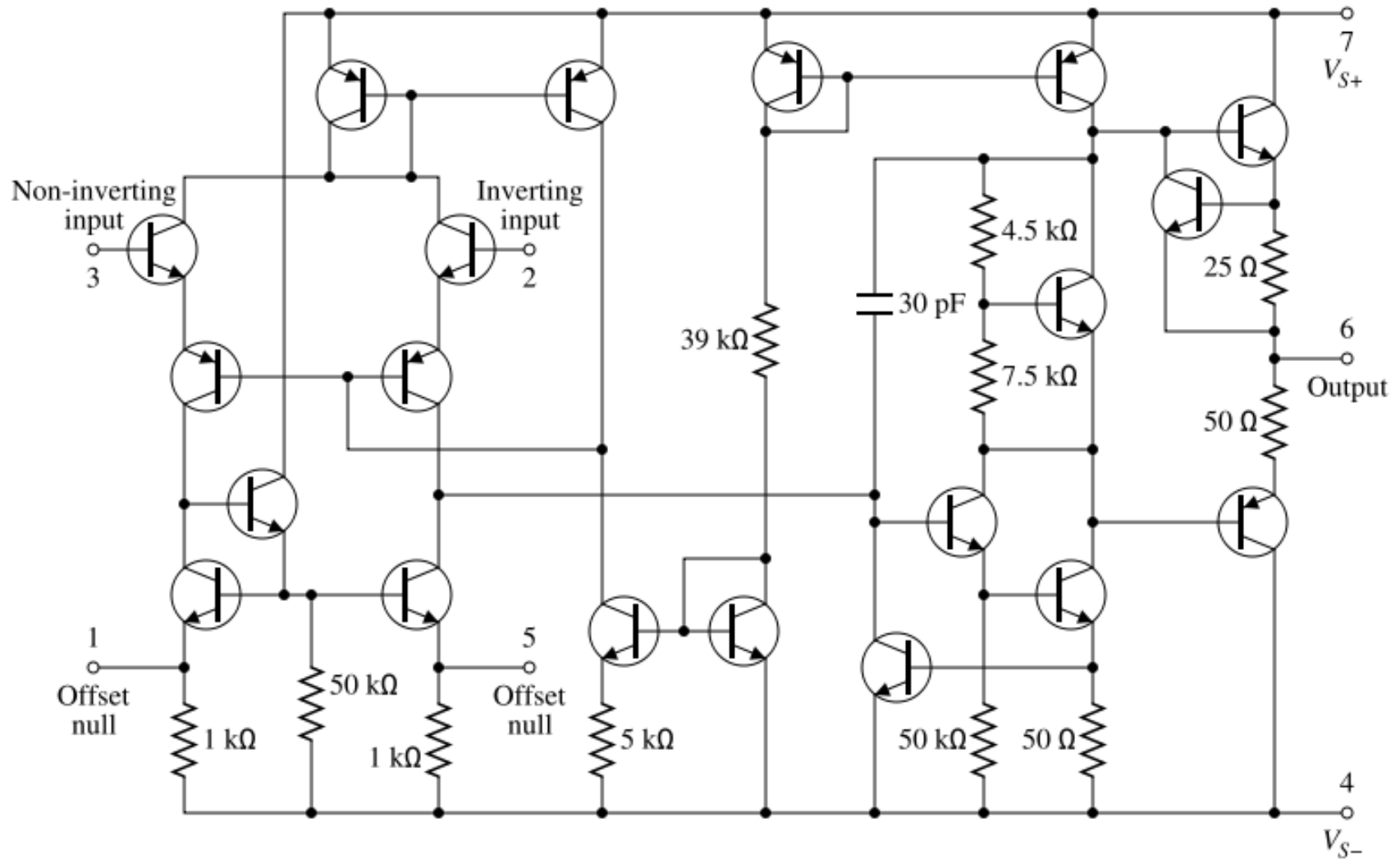
Operational Amplifier Pins



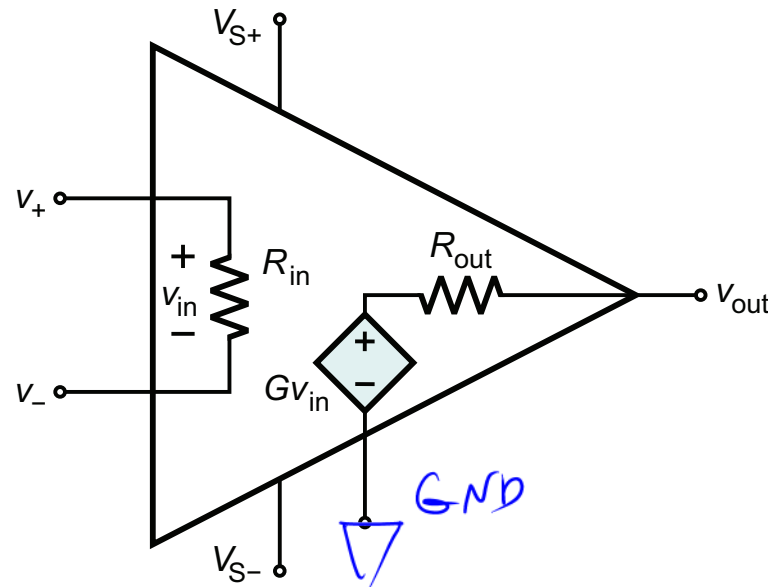
- The op-amp has 6 pins. There are the supply pins, where we connect a positive and negative voltage, and three signal pins, the two inputs, and an output. There is also a ground pin (not shown).
- The signal pins are usually AC voltages whereas the supply voltages are DC voltages.
- Some op-amps work with a single supply, in which case the negative rail is ground.
- Commonly known as the op-amp, is a high gain amplifier with a *differential input*.

$$v_o = A \cdot (v^+ - v^-)$$

Classic 741 Schematic

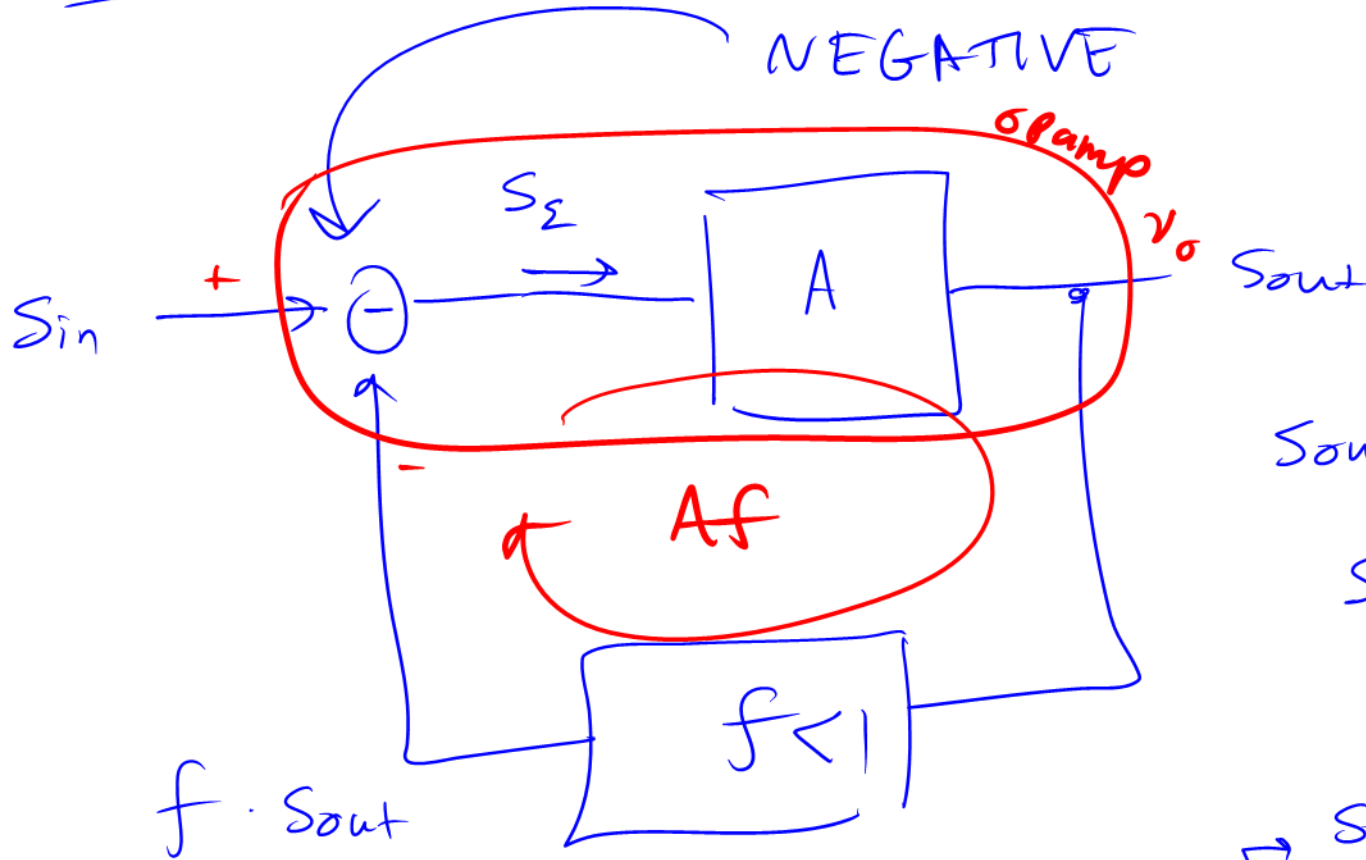


Equivalent Circuit Model (hard)



- We model the complex op-amp by using the simple equivalent circuit shown above. The most salient features are the high gain A (typically a million or more), very high input resistance R_{in} , and low output resistance R_{out} .
- Because of the large gain, only a few microvolts of input signal is required to saturate the op-amp output. Thus the amplifier is very impractical if used without *feedback*. In fact, the gain of the op-amp is a very poorly controlled parameter, often varying wildly with temperature or from part-to-part. How do you design with such an imperfect component? *Feedback*.

CLOSED LOOP FEEDBACK



$$S_{out} = A \cdot S_{\epsilon}$$

$$S_{\epsilon} = \frac{S_{out}}{A}$$

$$S_{out} = \frac{S_{in}}{f + \frac{1}{A}}$$

$$S_{out} = \frac{A}{1 + Af} \cdot S_{in}$$

$$S_{out} \approx \frac{A}{Af} S_{in} = \boxed{\frac{S_{in}}{f}}$$

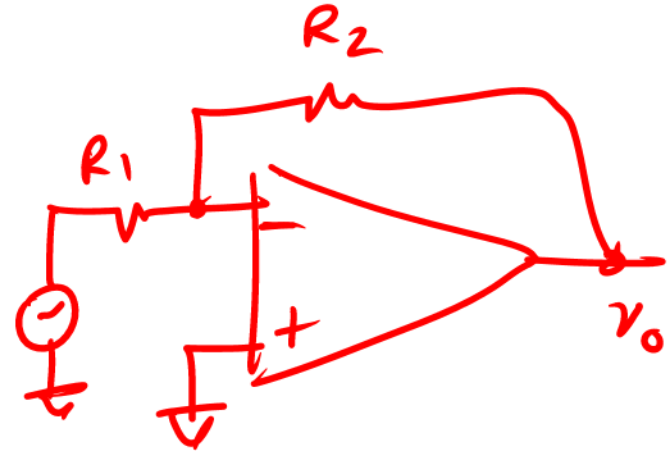
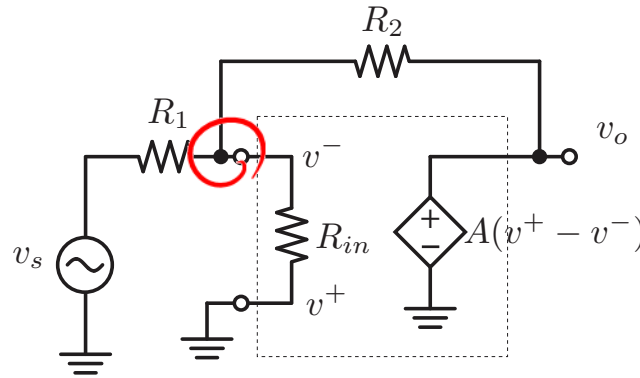
$$S_{\epsilon} = S_{in} - f S_{out} = \frac{S_{out}}{A}$$

$$S_{in} = \left(f + \frac{1}{A} \right) S_{out}$$

Example Calculation

$$\begin{aligned} v_o &= A(v^+ - v^-) \\ &= A(0 - v^-) \\ &= -Av^- \end{aligned}$$

$$v^- = \frac{v_o}{-A}$$



- The above example shows a typical op-amp configuration where the output signal is fed-back to the negative input terminals. This is called negative feedback.
- This seems strange at first because we are subtracting the output from the input, but as we shall see, this is a self-regulation mechanism that results in a very precise amplifier.
- Write KCL at the input node of the amplifier

$$(v^- - v_o)G_2 + v^- G_{in} + (v^- - v_s)G_1 = 0$$

$$\frac{(v^- - v_o)}{R_2} + \left(\frac{v^- - 0}{R_{in}} \right) + \left(\frac{v^- - v_s}{R_1} \right) = 0$$

Voltage Gain of Circuit

- But the output voltage in this case is simply given by $v_o = -Av^-$, where A is very large, which means that $v^- = -v_o/A$ is a very small voltage

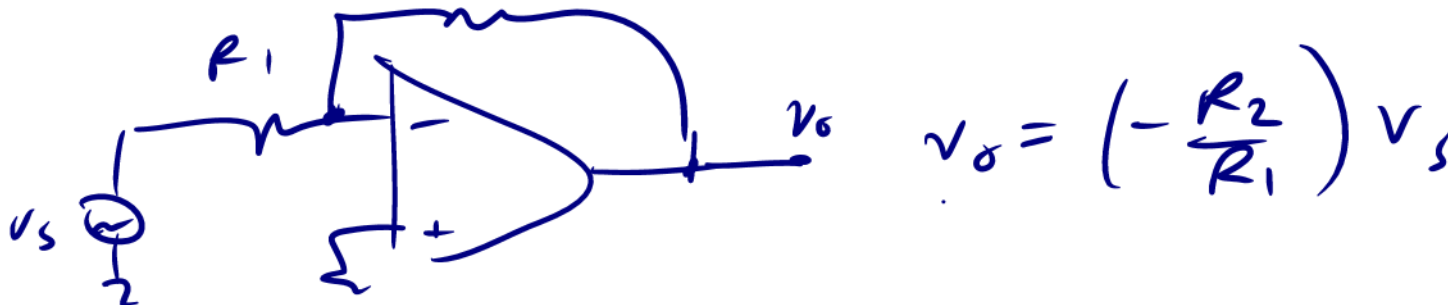
$$\left(\frac{-v_o}{A} - v_o\right)G_2 + \left(\frac{-v_o}{A}\right)G_{in} + \left(\frac{-v_o}{A} - v_s\right)G_1 = 0$$

- which allows us to write the complete expression for gain

$$\frac{v_o}{v_s} = \frac{-AG_1}{G_2(A+1) + G_{in} + G_1}$$

- Assuming that the op-amp has a very large gain, the above equation simplifies

$$\frac{v_o}{v_s} \approx \frac{-\cancel{A}G_1}{G_2(\cancel{A}+1)} \approx \frac{-G_1}{G_2} = \left(\frac{-R_2}{R_1}\right)$$

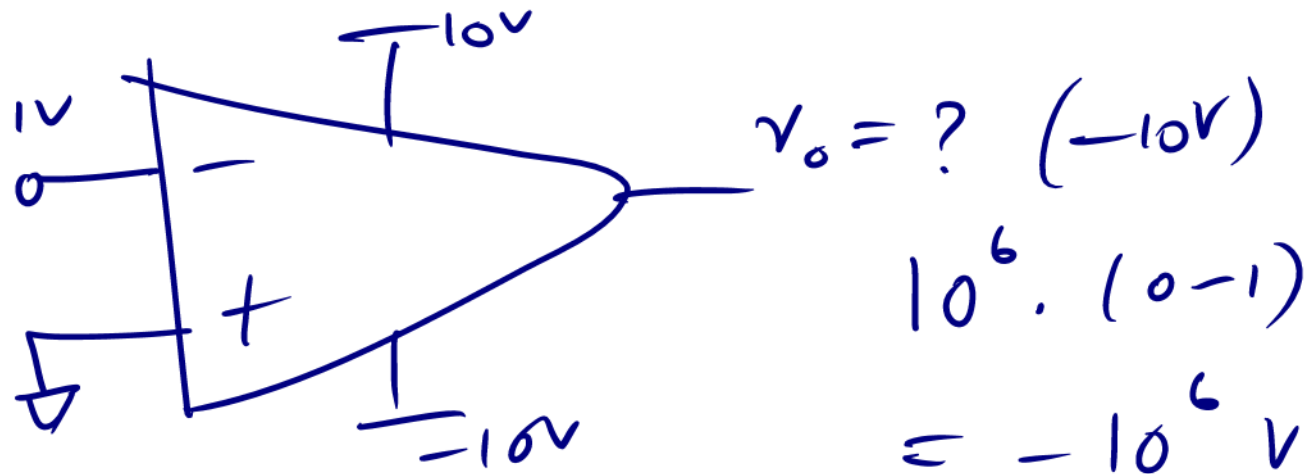


Differential rather than Difference Amplifier

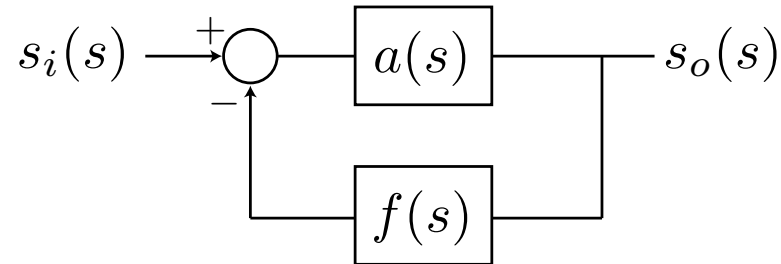
- Why do we call an op-amp a differential amplifier rather than a difference amplifier?
- In the inverting amplifier configuration, we can calculate the effective input voltage by

$$(v^+ - v^-) = \frac{v_o}{A} = \frac{-R_2}{R_1} v_s \approx 0$$

- A *difference* amplifier is perhaps a better name, but somewhat misleading since as we see the input voltage must be small for the op-amp to operate correctly (hence a “differential” voltage).
- We will build a true *difference* amplifier with op-amps later.



Op-Amp Feedback System



- In the derivation we have a nice result that the voltage gain of the overall circuit is just set by the ratio of two resistors, which can be made very precise and can track temperature.
- The internal gain of the amplifier A does not appear in the final expression, which means if it varies due to temperature or from part to part, it plays a negligible role in setting the gain.
- So we sacrificed gain to arrive at a solution that is much more robust. This is the concept of negative feedback and it is used widely in electronic systems (biological, chemical, and mechanical systems use it too).
- The idea is to sample a fraction of the output and compare it to the input. By forcing equality between the sample and the fraction of the output, the gain is determined by the fraction rather than by the raw gain of the amplifier.
- Note that positive feedback is not used, since it has a saturating (rather than regulating) characteristic.

Dynamic Range of Amplifier

- So what did we gain when we designed an op-amp with such a high value of gain? For one, it's an extremely versatile device that can be reconfigured to have any gain range by simply selecting the feedback components (R_1 and R_2).
- *Subtle Point:* Unlike a non-feedback (“open loop”) amplifier, the input linear range can be made larger since regardless of the input voltage source magnitude, the differential input of the op-amp is always small $(v^+ - v^-) = v_o/A \approx 0$.