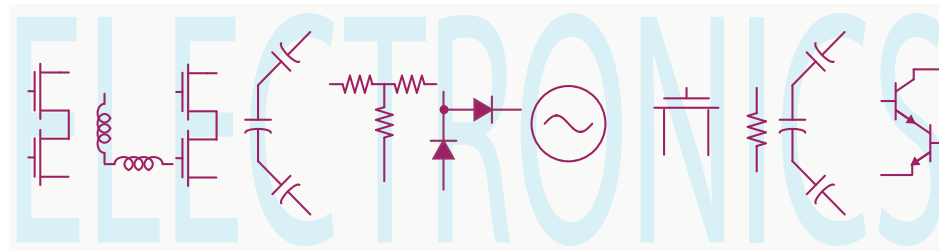


EE 42/100
Lecture 10: Op-Amp Based Circuits



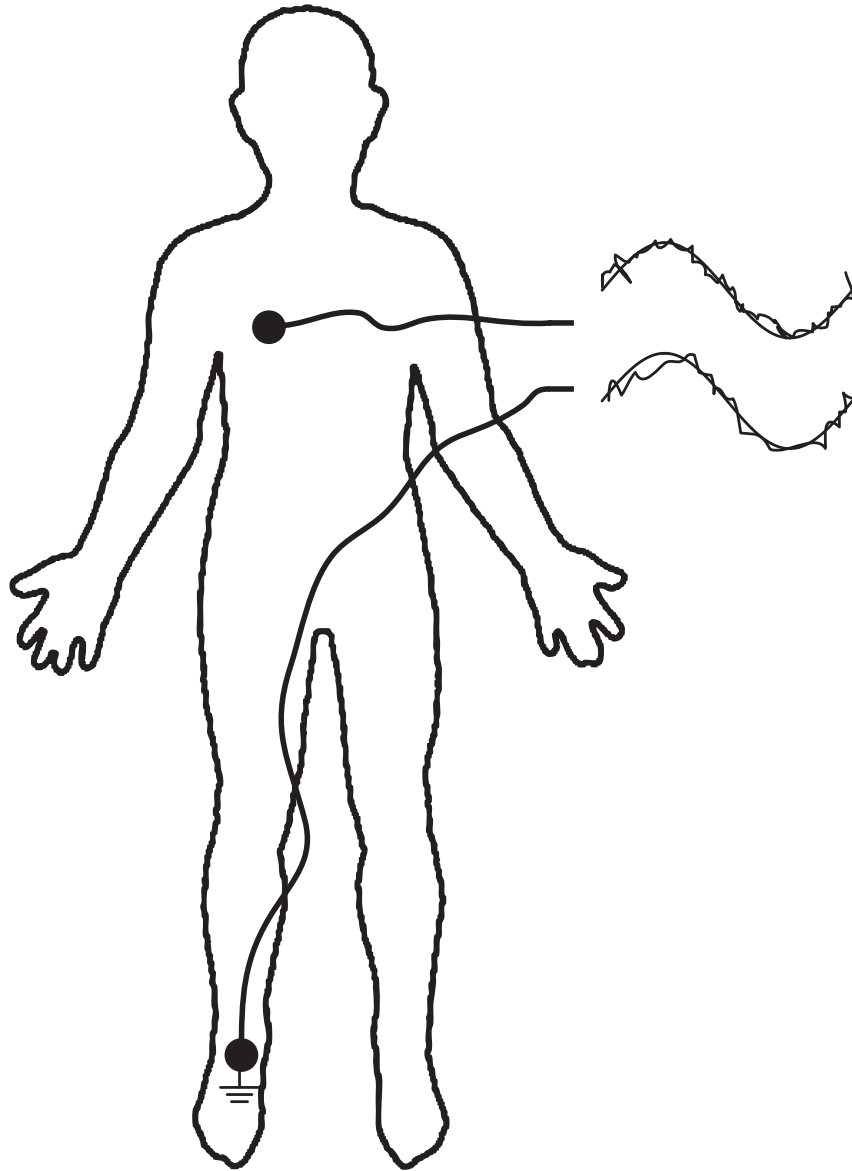
Rev B 2/22/2012 (3:01 PM)

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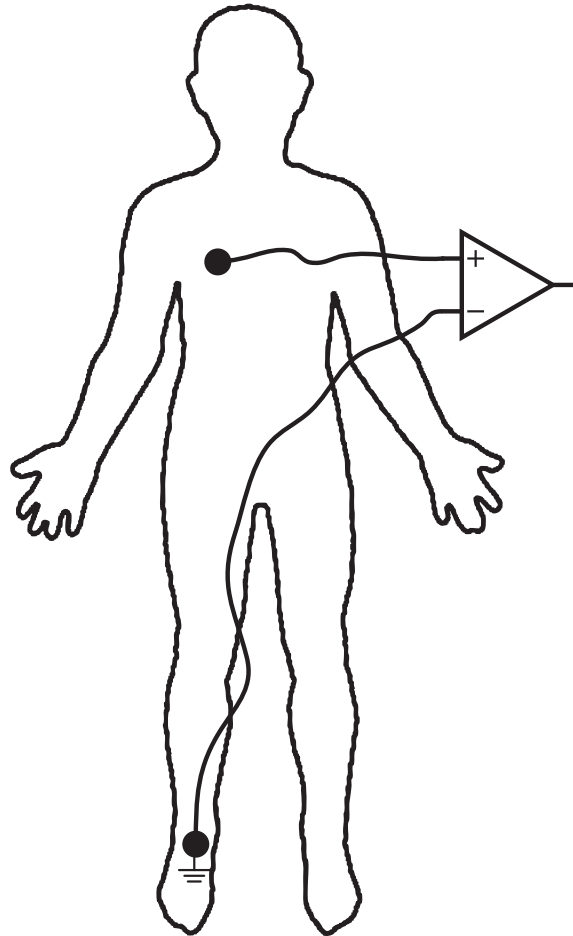
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Differential Amplification and Noise



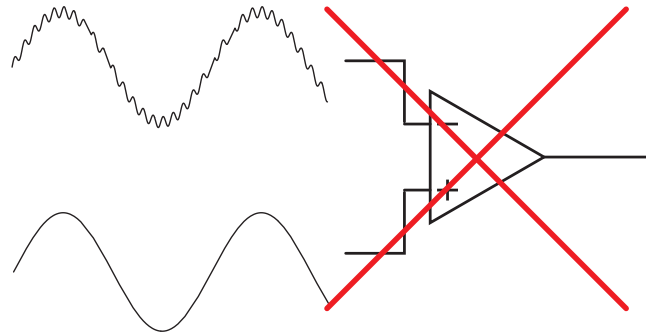
- In many systems, the desired signal is weak but it's accompanied by a much larger undesired signal. A good example is the ECG measurement on the human body. The human body picks up a lot of 60 Hz noise (due to capacitive pickup) and so a very weak ECG signal (mV) is accompanied by a large signal ($\sim 1V$) that we wish to reject.
- Fortunately the noise pickup is in *common* with both leads of the ECG because the body is essentially an equipotential surface for the noise pickup. If we take the difference between two points, it disappears.

Common-Mode and Differential-Mode Gain



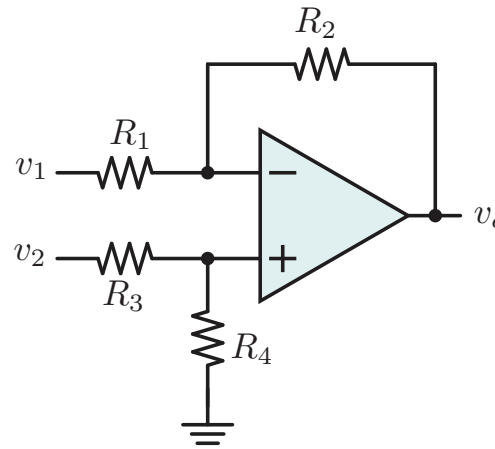
- We thus need an amplifier that can detect a small *differential mode* voltage in the presence of a potentially very strong *common mode* voltage.

Don't Do This



- Even though the op-amp output is the difference between the inputs, this circuit does not work for several reasons.
- The op-amp in open loop configuration has very unreliable gain. Also, the gain is probably too high for this application and the amplifier may rail out.
- In closed loop configurations, the op-amp input voltage is nearly zero ($v^+ - v^- \approx 0$). What we need is a way to amplify potentially large voltage differences.

Difference Amplifier



- Using superposition, we can quickly calculate the transfer function. For port 1, the amplifier is simply an inverting stage

$$v_o^1 = v_1 \frac{-R_2}{R_1}$$

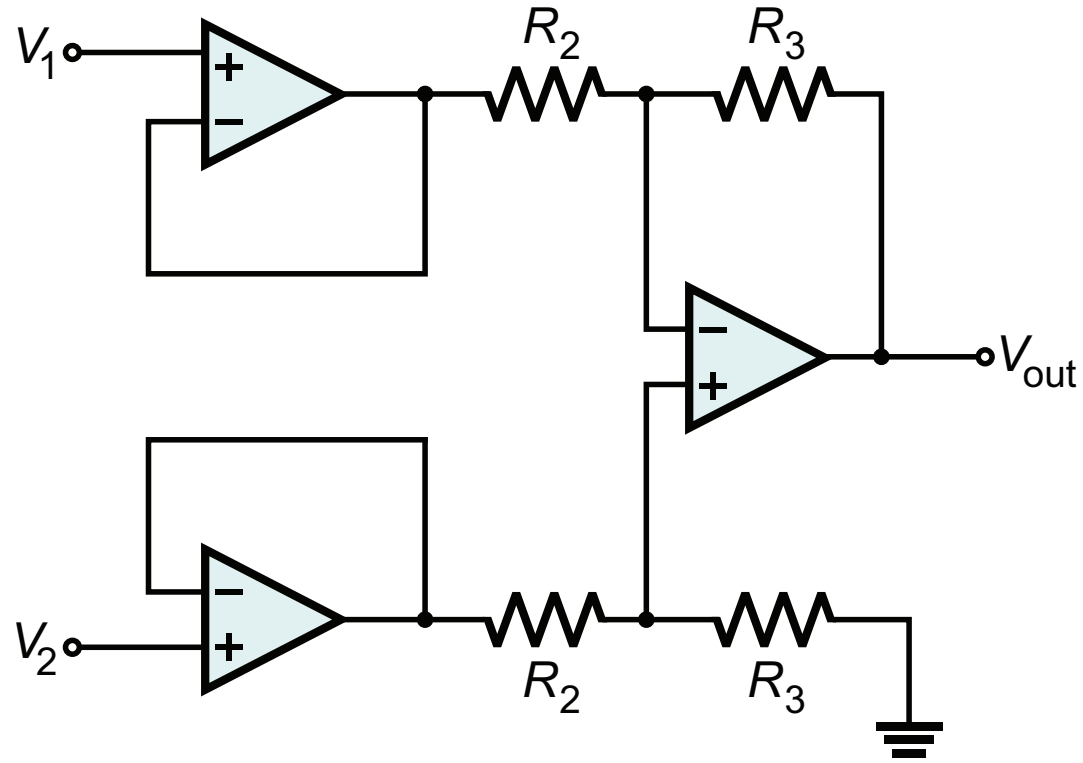
- For port 2, it's a non-inverting stage, except we only tap off a fraction of v_2

$$v_o^2 = v_2 \frac{R_4}{R_3 + R_4} \left(1 + \frac{R_2}{R_1}\right)$$

- Take the sum and set $R_1 = R_3$ and $R_2 = R_4$, we have

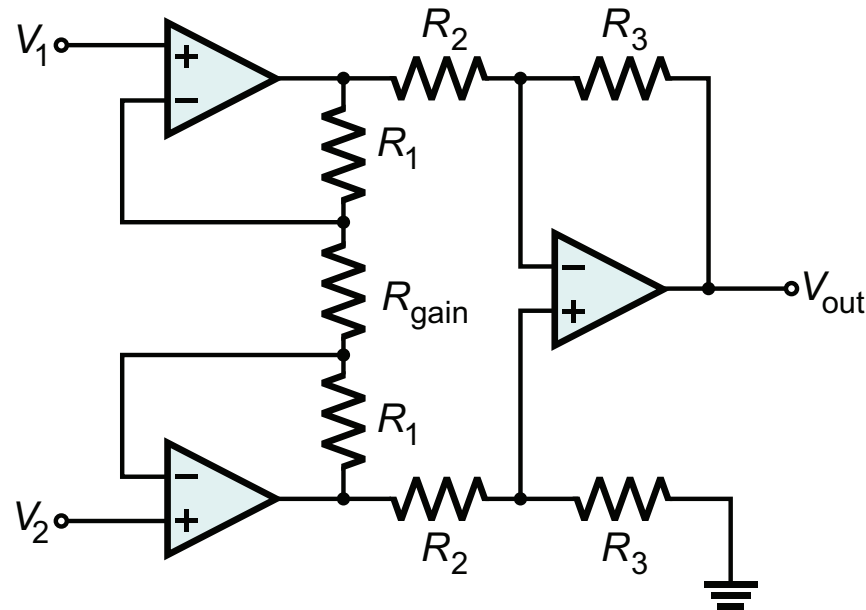
$$v_o = \frac{R_2}{R_1} (v_2 - v_1)$$

Instrumentation Amplifier



- Two unity-gain buffers are used to buffer the input signal. A difference amplifier is used to provide a gain of R_3/R_2 .

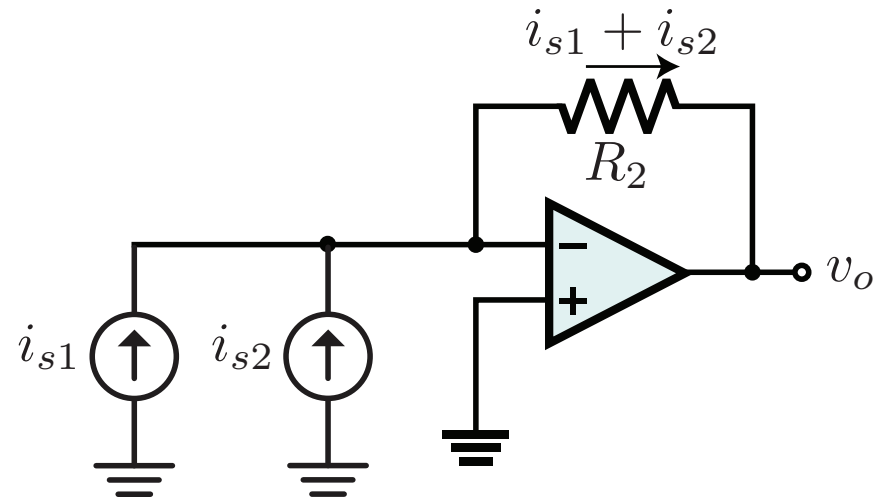
Instrumentation Amplifier Version 2



$$v_o = \left(1 + \frac{2R_1}{R_{gain}} \right) \frac{R_3}{R_2} (v_2 - v_1)$$

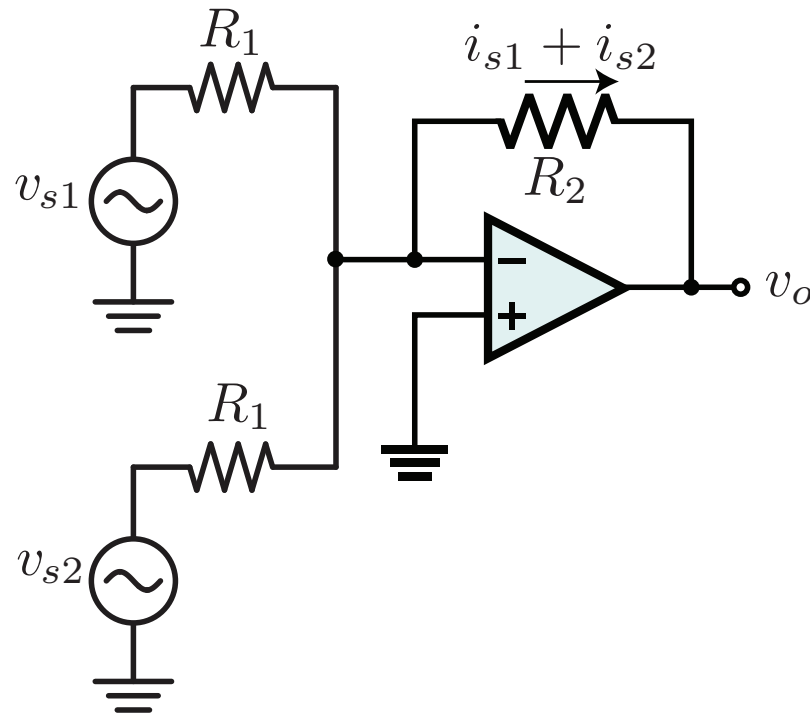
- The input buffers now have gain due to the fact that the circuit is configured as a non-inverting amplifier. Why is the resistor R_{gain} appear between the amplifiers?
- *Subtle:* Note that we could simply put in two resistors to ground, but a more elegant way to realize it is to put in between the top and bottom. For balanced inputs, the resistor is split in two and grounded in the middle (another virtual ground). For unbalanced inputs, no current flows and the resistor is not there, so there's no common-mode gain!

Current Summing Amplifier



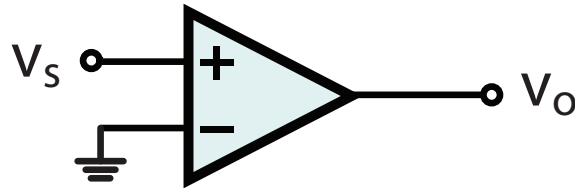
- An important observation is that in the inverting amplifier, the current injected into the negative terminal of the op-amp is routed to the output and converted into a voltage through R_2 . If multiple currents are injected, then the *sum* of the currents is converted to a voltage.

Voltage Summing Amplifier



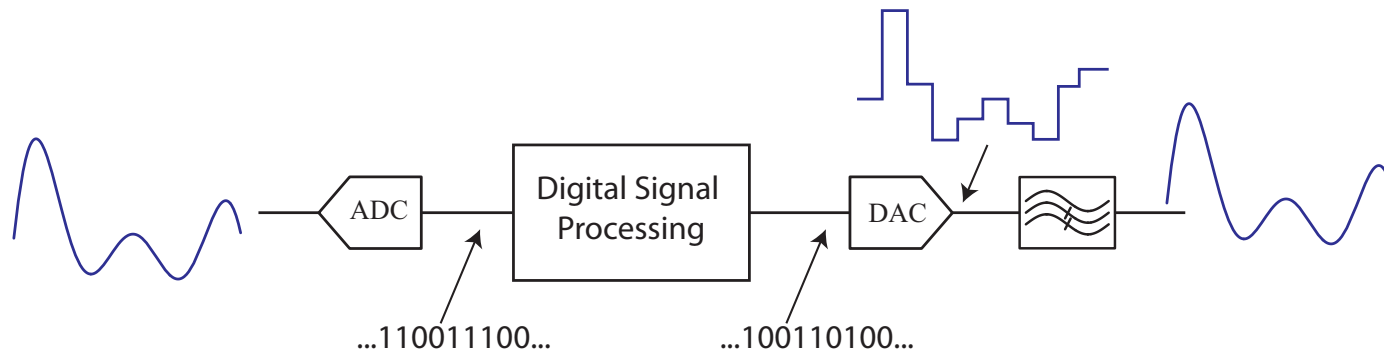
- Each source is converted into a current and then summed in a similar fashion as the currents. Note that the virtual ground means that no current is “lost” when the currents are put in parallel (due to the output resistance).

Comparator / Zero Crossing Detector



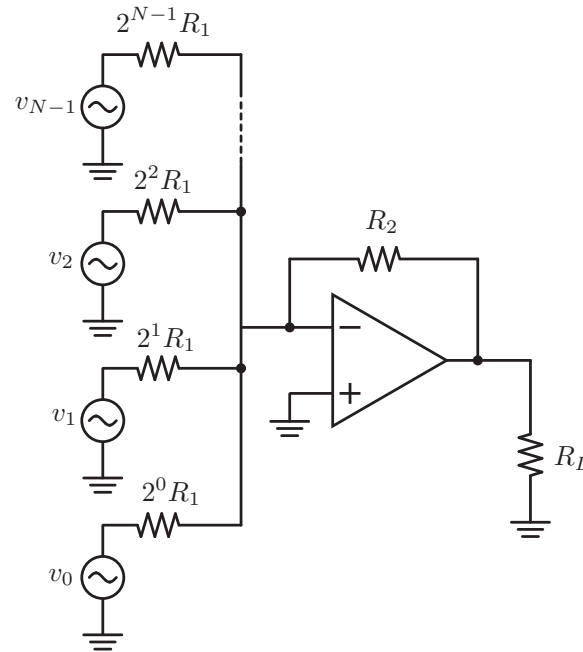
- In theory an op-amp in “open-loop” configuration can be turned into a comparator, a circuit that compares the inputs and produces either a “high” signal ($v^+ > v^-$) or a “low” signal ($v^+ < v^-$). This is useful in converting small analog signals into a digital signal.
- Due to the very high gain of the op-amp, the output rails to one or the other supply as the input crosses zero.
- In practice, a specialized comparator should be used since it can operate much faster than an op-amp.

Digital Signal Processing



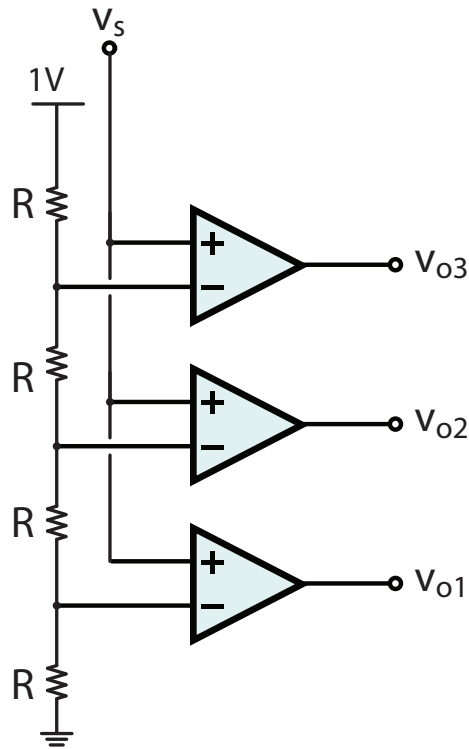
- An Analog-to-Digital Converter (ADC) converts a continuously varying analog signal into digital form (1's and 0's), which can be read into a computer, stored, processed (filtered or otherwise manipulated). [Note: You'll need a pre-filter to avoid aliasing...]
- A Digital-to-Analog Converter (DAC) does the reverse process. A digital input is converted into a continuous waveform. Most DAC's hold their value over the entire clock period ("zero-order hold"). By filtering this data we can reconstruct the original waveform.

Op-Amp Based DAC



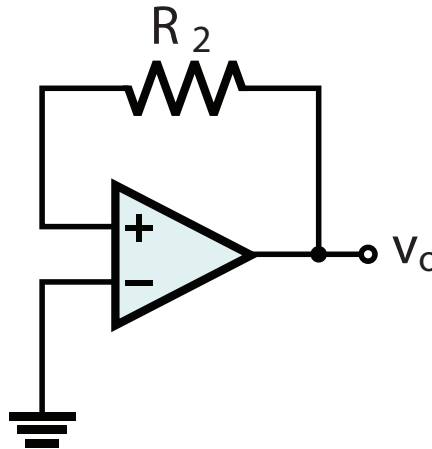
- Each voltage source represents a binary digital. A 1 corresponds to the maximum voltage (rail) and a 0 corresponds to the ground potential.
- Each voltage is converted into a current. We weight the voltage by the binary digit position (2^j). The weighted sum is the desired analog voltage.

Comparator Analog-to-Digital Converter



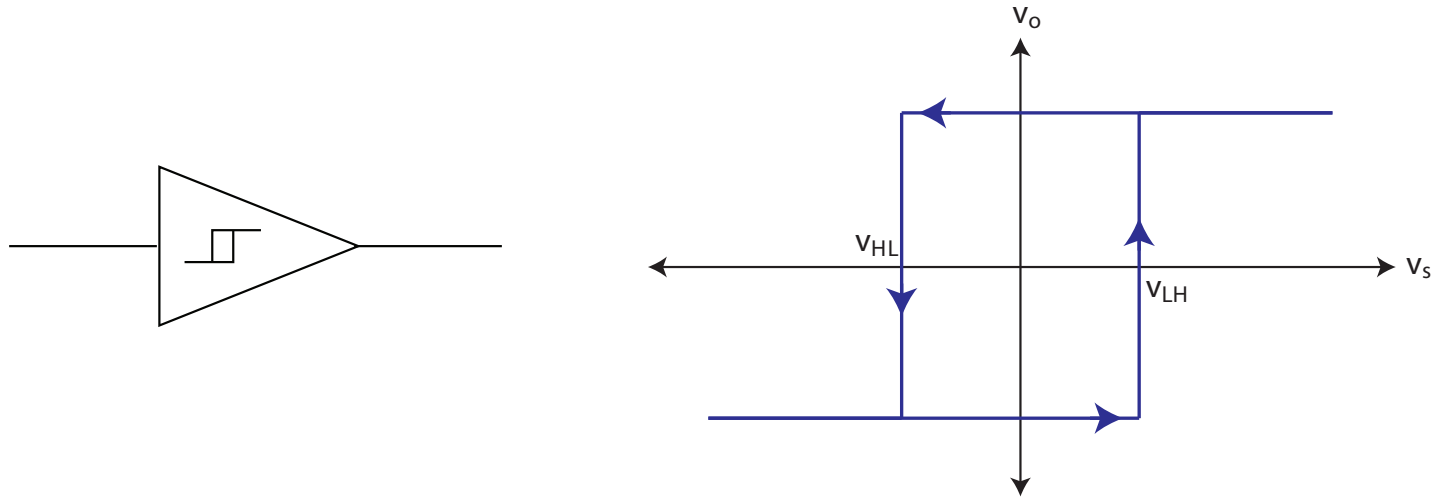
- A very useful circuit is an analog-to-digital converter, or a circuit that quantizes (rounds off) a smoothly varying analog signal into a digital signal (that can be read into a computer and processed using power digital signal processing algorithms).
- The resistor tree is essentially a voltage divider, where the tap points provide a uniform reference voltages for comparison.
- All the comparators with reference voltage below the input go high. The remaining comparators go low. This output can be translated into standard binary.

Positive Feedback



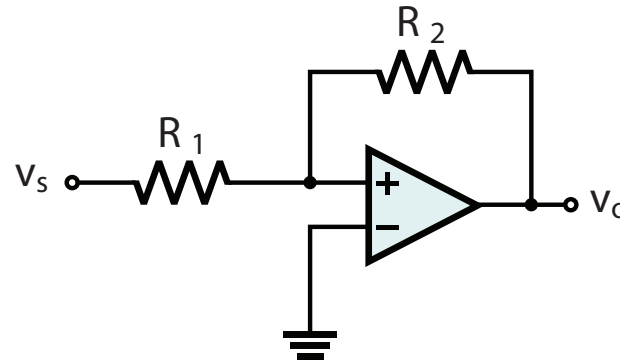
- Most of the circuits we have seen so far use negative feedback. The output is sampled and fed into the *negative* terminal of the op-amp. As we have seen, this leads to a very stable operating point.
- By contrast, when we feed the output back to the positive terminal, as shown above, the output will saturate to the positive or negative rail.
- Suppose that we when we turn on the above circuit, the input is at zero and the output is at zero, so the input differential voltage is zero. That seems stable, right?
- Now suppose a slight perturbation causes the output go to slightly positive. Then due to the large gain, the output would “rail” to the positive supply.
- What would have happened if the voltage perturbation had occurred in the negative direction?

Schmitt Trigger



- The Schmitt Trigger is a circuit that employs positive feedback. It is similar to a comparator, but due to the feedback, it has *hysteresis*. In other words, the transfer characteristics of the amplifier are not static, but depends on the history or past input values.

Schmitt Trigger (cont)



- A Schmitt Trigger can be constructed using an op-amp. The action of the feedback is to set the “comparison” voltage based on the current output voltage.
- The op-amp output will change if v^+ cross zero. At any given time, the voltage v^+ can be found by Nodal analysis (no current flows into the input terminals of an ideal op-amp)

$$\frac{v^+ - v_s}{R_1} + \frac{v^+ - v_o}{R_2} = 0$$

- Solve for v^+ to obtain

$$v^+ \left(\frac{1}{R_1} + \frac{1}{R_2} \right) = \frac{v_s}{R_1} + \frac{v_o}{R_2} \qquad v^+ (R_2 + R_1) = v_s R_2 + v_o R_1$$

$$v^+ = \frac{v_s R_2 + v_o R_1}{(R_2 + R_1)}$$

Schmitt Trigger Thresholds

- We find that v^+ is a function of both the input v_s and the output v_o . This second dependence gives rise to the hysteresis.
- One can say that the input v^+ is an “arm wrestle” between the input and the current output. For instance, if the output is already high, then the input v_s has to come sufficiently low to cause v^+ to cross zero. We can find the “high-to-low” threshold v_{HL} by setting $v_o = V_{sup}$ and solve for $v^+ = 0$

$$v^+ = \frac{v_{HL}R_2 + V_{sup}R_1}{(R_2 + R_1)} = 0$$

$$V_{HL} = -V_{sup} \frac{R_1}{R_2}$$

- Similarly, the “low-to-high” threshold v_{LH} can be found by setting $v_o = -V_{sup}$ and solving for $v^+ = 0$

$$v^+ = \frac{v_{LH}R_2 - V_{sup}R_1}{(R_2 + R_1)} = 0$$

$$V_{LH} = V_{sup} \frac{R_1}{R_2}$$

Schmitt Trigger Application

- First notice that a Schmitt Trigger is a *bi-stable* device, with two stable operating points. It's a memory cell !
- In practice we can build memory cells with far fewer transistors than an op-amp, but this is a useful way to think about the circuit.
- The most common application is to increase the noise immunity of a circuit. In a comparator, there is only a signal threshold voltage. If the input is noisy, then the output will bounce if the noise causes the input to cross the threshold. In a Schmitt Trigger, though, once the output transitions (say high), the threshold to bring the output back down to zero is more negative, which means it's less likely that a noise signal will cause a false transition.