How can we model gain?

- **Question**: We just said that the output of an Op Amp is $A_V(V_p - V_n)$. How can we model this for designing / analyzing a circuit?

- **Answer**: We can use a “dependent” voltage source to model the output, where the output voltage is a function of the input voltage.

**Equivalent Circuit and Specifications**

- In other words, Op Amps are really close to ideal.
- Note that the output voltage swing is typically limited to around $V_{CC}$. 

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical Range</th>
<th>Ideal Op Amp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-loop gain $A$</td>
<td>$10^4$ to $10^8$ (V/V)</td>
<td>$\infty$</td>
</tr>
<tr>
<td>Input resistance $R_i$</td>
<td>$10^6$ to $10^{13}$ Ω</td>
<td>$\infty$ Ω</td>
</tr>
<tr>
<td>Output resistance $R_o$</td>
<td>1 to 100 Ω</td>
<td>0 Ω</td>
</tr>
<tr>
<td>Supply voltage $V_{CC}$</td>
<td>5 to 24 V</td>
<td>As specified by manufacturer</td>
</tr>
</tbody>
</table>
But how should we use an Op Amp?

- The gain is huge, and the dynamic range is limited. This would normally limit the input signal to a few \( \mu V \! \)!
- Additionally, the gain is usually very poorly controlled, and can vary a lot with temperature, etc., and from part to part.
- Instead, we use “negative feedback” to bring the gain under control.

What is negative feedback

- Conceptually, it is taking a “piece” of the output, and providing it to the \( V_N \) or “inverting” input
- Since the output is \( A_v \cdot (V_P - V_N) \), the larger the output, the more the feedback “piece” works to reduce the output.
- Overall, this reduces the “effective” gain of the amplifier.
- In fact, if we assume \( A_v \) is \( \infty \), then the ultimate result is that \( V_P \) must be \textit{equal} to \( V_N \)
Ideal Op Amps with Negative Feedback

Start with the following “golden rules”

- \( V_P = V_N \) (due to effect of infinite gain and negative feedback)
- \( I_P = I_N = 0 \) (due to infinite input resistance of ideal Op Amp)
- Since the output has zero output resistance, you won’t actually need a KCL at the output node, since the output voltage is entirely determined by the input voltages and feedback conditions

Non-inverting Amplifier

KCL at node \( v_n \):

\[
\frac{v_n - v_o}{R_1} + \frac{v_n}{R_2} = 0
\]

\( v_n = v_P = v_s \)

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

\( v_o \) (max) = \( V_{cc} \)

Interestingly, the gain of the Op Amp, \( A_v \), no longer appears in the equation. This is a benefit of feedback with nearly ideal amplifiers… we can achieve the desired result purely by the choice of external components
**Inverting Amplifier**

KCL at \( v_n \):
\[
\frac{v_n - v_s}{R_s} + \frac{v_n - v_o}{R_f} + i_n = 0.
\]
\( v_n = v_p = 0 \)

\[
G = \frac{v_o}{v_s} = -\left( \frac{R_f}{R_s} \right).
\]

**Voltage Follower or Buffer**

\( v_o = v_p = v_s \)

\( v_o \) is immune to input and load resistors
Design Exercise: Touch Screen Sensor

- Assume the following:
  - The supply voltage to the touch screen is 5V
  - We want the output to vary from 0V for a touch on the right to 10V for a touch on the left

\[
\text{Output Circuit}
\]

5V

Tap point To output circuit

\[
76
\]

Design Exercise: Touch Screen Sensor

- We want a non-inverting amplifier with a gain of 2

\[
V_o = \frac{R_1 + R_2}{R_2} V_i
\]
Design Exercise: Current Source

• In the multi-touch version, we needed a current source

• In this next exercise, we’ll use an Op Amp to convert a battery (which is a voltage source) into a current source

Remember the golden rules for an ideal Op Amp

– \( V_+ = V_- \)
– \( I_{in} = 0 \)

We have to use negative feedback to use the golden rules

Since \( I_{in} = 0 \), then \( I_1 = I_2 \).
In other words, we have made a constant current source with an output current of \(-V_s / R_s\)
Optional Exercises: Summing Amplifier

Optional Exercises: Difference Amplifier