LAST TIME:
- SEMICONDUCTORS
- DIODES
- BIPOLAR JUNCTION TRANSISTORS
- COMMON EMITTER AMPLIFIER

TODAY: CH. 28
- OPERATIONAL AMPLIFIERS
- NEGATIVE FEEDBACK
- GOLDEN RULES FOR THE OP AMP
- NON-IDEAL BEHAVIORS — A FEW EXAMPLES OF "REALISTIC" PARAMETERS

NEXT TIME: CH. 29
- OP AMP APPLICATIONS IN ANALOG ELECTRONICS
  - AMPLIFIER
  - INVERTING AMP
  - ADDITION & SUBTRACTION OF SIGNALS
The operational amplifier is a circuit made of many (dozens) of transistors. Its purpose is to behave in a very simple way, I am not going to teach you how they work. But I want you to understand both the ideal notion (how the perfect op amp is supposed to behave) and a few of the shortcomings of real op amps. It is difficult to design a good op amp, and generally you (don't) get what you (don't) pay for.

**Ideal Op Amp**

\[ V_{\text{out}} = A(V_+ - V_-) \]

"Open Loop" Gain

**Ideally:**

- **Large (Infinite) Gain,** \( A \to \infty \).
- \( V_+ \) and \( V_- \) sense voltages without drawing any current (infinite input impedance).
- \( V_{\text{out}} \) is independent of the load — can supply as much current as needed (zero output impedance).
- \( V_{\text{out}} \) responds instantly to changes in \( V_+ - V_- \) (infinite slew rate).
- \( V_{\text{out}} = 0 \) if \( V_+ = V_- \) (zero offset).

**Real Op Amps Violate These Assumptions:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ideal</th>
<th>Typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain, ( A )</td>
<td>( \infty )</td>
<td>( 10^5 ), but depends on frequency</td>
</tr>
<tr>
<td>Output Impedance</td>
<td>0</td>
<td>10 ( \Omega )</td>
</tr>
<tr>
<td>Input Impedance</td>
<td>( \infty )</td>
<td>10 ( \text{M( \Omega )} )</td>
</tr>
<tr>
<td>Slew Rate</td>
<td>( \infty )</td>
<td>1 ( V/\mu\text{s} )</td>
</tr>
<tr>
<td>Offset</td>
<td>0</td>
<td>May require external adjustment</td>
</tr>
</tbody>
</table>
WHERE DOES THE POWER COME FROM?

THE SUPPLY IS OFTEN OMITTED IN CIRCUIT DIAGRAMS, DON'T FORGET THAT IT'S THERE!

TYPICAL SUPPLY:

- Zero point (ground) is defined halfway between the "rails" at ±Vs.
- The symbol Vcc is often used for the total supply voltage (2Vs).

SUPPLY TO OP AMP:

IMPLICATIONS

I. \(-Vs < V_{out} < Vs\) (\(V_{out} \) "between the rails")

II. KCL: \(i_+ + i_- - i_{out} \neq 0\)
Q: WHAT IS THE OP AMP GOOD FOR?
A: THIS IS BEST ANSWERED WITH AN EXAMPLE USING NEGATIVE FEEDBACK.

\[ V_{\text{out}} = A(V_+ - V_-) = A(V_{\text{in}} - V_{\text{out}}) \]
\[ V_{\text{out}} = \left( \frac{A}{1+A} \right) V_{\text{in}} \]

For \( A \gg 1 \), \( V_{\text{out}} = V_{\text{in}} \)

Q: WHY USE A BUFFER?
A: TO CONNECT A HIGH OUTPUT IMPEDANCE TO A LOW INPUT IMPEDANCE:

\[ V_{\text{out}} = \frac{A}{1+A} V_{\text{in}} \]

\[ V_{\text{out}} \propto \frac{1}{\text{load resistance}} \]

STABILITY: WHAT IF \( V_{\text{in}} \) CHANGES? IS EQUILIBRIUM MAINTAINED?

1. \( V_{\text{in}} > V_{\text{out}} \Rightarrow V_+ > V_- \) GAIN \( \rightarrow \) \( V_{\text{out}} \uparrow \) RAPIDLY \( \{ \) EQUILIBRIUM MAINTAINED! \( \}
2. \( V_{\text{in}} < V_{\text{out}} \Rightarrow V_+ < V_- \) GAIN \( \rightarrow \) \( V_{\text{out}} \downarrow \) RAPIDLY \( \} \)
GOLDEN RULES FOR ANALYZING IDEAL OP AMPS IN CIRCUITS WITH NEGATIVE FEEDBACK*

I. $V_{out}$ DOES WHATEVER IT MUST TO MAKE $V_+ = V_-$. 

II. CURRENT = 0 AT BOTH INPUTS.

THAT'S ALL!

*NEGATIVE FEEDBACK MEANS THE OUTPUT IS CONNECTED, SOMETIMES THROUGH RESISTORS OR OTHER COMPONENTS TO THE INVERTING INPUT.
EXAMPLE — A SIMPLE AMPLIFIER

USE THE GOLDEN RULES:

I. \( V_{IN} = V_+ = V_- \)

II. NO CURRENT AT INVERTING INPUT \( \Rightarrow \)

\[ V_- = V_{OUT} \cdot \frac{1}{1k + 9k} = \frac{1}{10} V_{OUT} \]

\[ \therefore V_{OUT} = 10 V_{IN} \]

Q: WHAT IF GAIN \( A = 100 \)? ASSUME THE AMPLIFIER IS OTHERWISE IDEAL.

A: \[ V_{OUT} = 100 \left( V_+ - V_- \right) = 100 \left( V_{IN} - \frac{1}{10} V_{OUT} \right) = 100 V_{IN} - 10 V_{OUT} \]

\[ \Rightarrow V_{OUT} = \frac{100}{11} V_{IN} = \boxed{9.1 V_{IN}} \]
IF TIME PERMITS—AN EXAMPLE BJT CIRCUIT.

(a) Find $V_1$.

(b) Find $i_c$.

\[ I_c = \beta I_b = 10 \text{A} \]

(If this is true, $V_1 = 10V - 15\Omega \cdot 1A = -5 V$)

ASSUME ACTIVE MODE:

\[ I_b = \frac{10V + 0.6V - 0.6V}{15\Omega} = 10 \text{mA} \]

\[ I_c = 10 \text{mA} + \frac{2}{3} \text{A} = 0.677 \text{A} \]