Lecture #7

OUTLINE

- Thevenin/Norton Eq. Cont'd
- Max power transfer theorem
- The operational amplifier ("op amp")
- Feedback
- Comparator circuits
- Ideal op amp
- Unity-gain voltage follower circuit

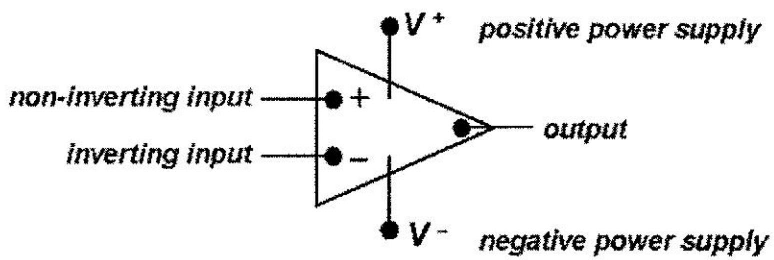
Reading

Complete Ch. 2, Begin Ch. 14, Look at Ch. 11

The Operational Amplifier

- The ***operational amplifier*** ("***op amp***") is a basic building block used in analog circuits.
  - Its behavior is modeled using a dependent source.
  - When combined with resistors, capacitors, and inductors, it can perform various useful functions:
    - **amplification/scaling** of an input signal
    - **sign changing** (inversion) of an input signal
    - **addition** of multiple input signals
    - **subtraction** of one input signal from another
    - **integration** (over time) of an input signal
    - **differentiation** (with respect to time) of an input signal
    - **analog filtering**
    - **nonlinear functions** like exponential, log, sqrt, etc

Op Amp Circuit Symbol and Terminals

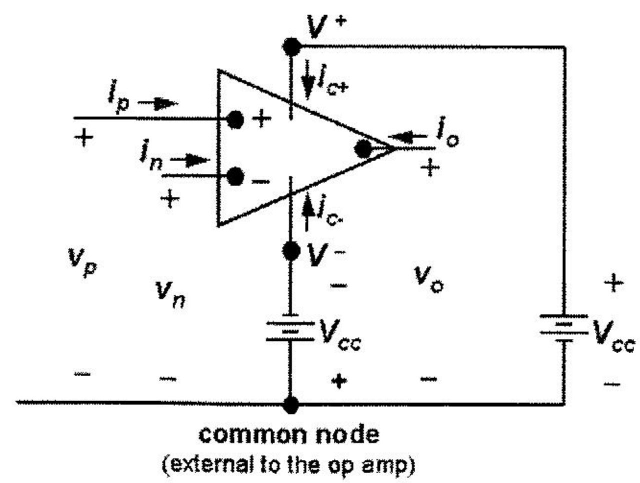


The output voltage can range from V^- to V^+

The positive and negative power supply voltages do not have to be equal in magnitude.

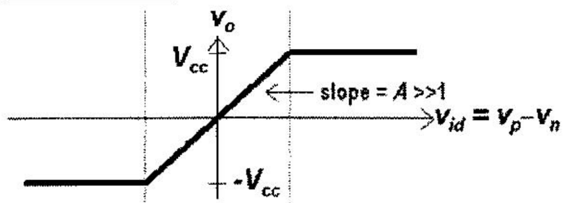
Op Amp Terminal Voltages and Currents

- **All voltages are referenced to a common node.**
- **Current reference directions are <u>into</u> the op amp.**



Op Amp Voltage Transfer Characteristic

The op amp is a differentiating amplifier:



Regions of operation: "negative saturation" "linear" "positive saturation"

- In the ***linear region***, $v_o = A(v_p - v_n) = A\, v_{id}$ where ***A* is the *open-loop gain***
- Typically, $V_{cc} \le 20$ V and $A > 10^4$
  → linear range: $-2\text{ mV} \le v_{id} = (v_p - v_n) \le 2\text{ mV}$

Thus, for an op amp to operate in the linear region,

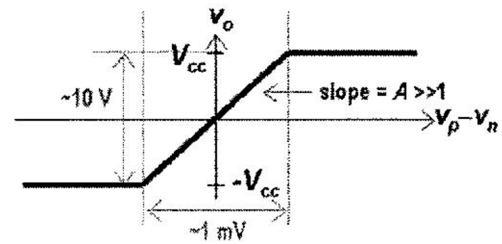
$$v_p \cong v_n$$

(*i.e.* there is a "virtual short" between the input terminals.)

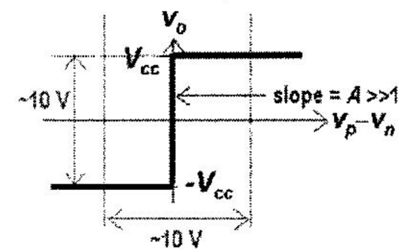
Achieving a "Virtual Short"

- Recall the voltage transfer characteristic of an op amp:

Plotted using different scales for v_o and $v_p - v_n$



Plotted using similar scales for v_o and $v_p - v_n$



Q: How does a circuit maintain a virtual short at the input of an op amp, to ensure operation in the linear region?

A: By using ***negative feedback***. A signal is fed back from the output to the inverting input terminal, effecting a ***stable*** circuit connection. Operation in the ***linear region*** enforces the virtual short circuit.

Negative *vs.* Positive Feedback

Familiar examples of negative feedback:

- Thermostat controlling room temperature
- Driver controlling direction of automobile
- Pupil diameter adjustment to light intensity

Fundamentally pushes toward stability

Familiar examples of positive feedback:

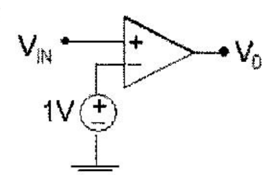
- Microphone "squawk" in sound system
- Mechanical bi-stability in light switches

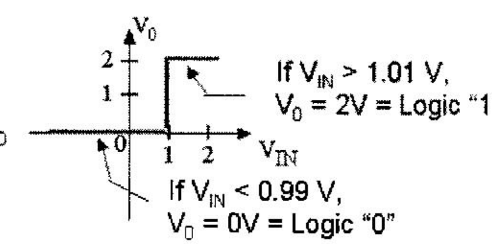
Fundamentally pushes toward instability or bi-stability

Op Amp Operation w/o Negative Feedback

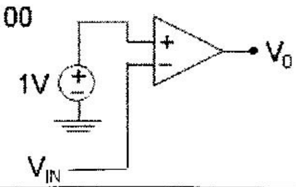
(Comparator Circuits for Analog-to-Digital Signal Conversion)

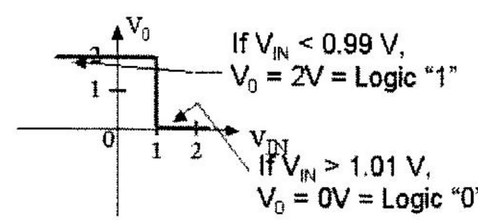
1. Simple comparator with 1 Volt threshold:
   - V^- is set to 0 Volts (logic "0")
   - V^+ is set to 2 Volts (logic "1")
   - A = 100





2. Simple inverter with 1 Volt threshold:
   - V^- is set to 0 Volts (logic "0")
   - V^+ is set to 2 Volts (logic "1")
   - A = 100





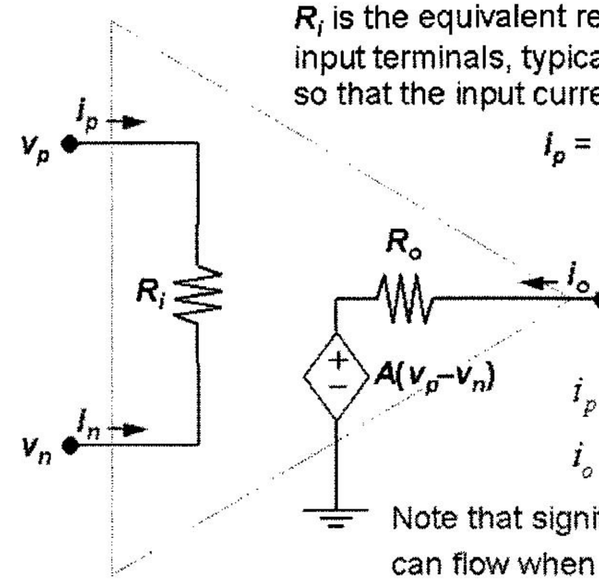
Op Amp Circuits with Negative Feedback

Q: How do we know whether an op amp is operating in the linear region?

A: We don't, *a priori*.

- Assume that the op amp is operating in the linear region and solve for v_o in the op-amp circuit.
  - If the calculated value of v_o is within the range from $-V_{cc}$ to $+V_{cc}$, then the assumption of linear operation *might* be valid. We also need stability – usually assumed for negative feedback.
  - If the calculated value of v_o is greater than V_{cc}, then the assumption of linear operation was invalid, and the op amp output voltage is saturated at V_{cc}.
  - If the calculated value of v_o is less than $-V_{cc}$, then the assumption of linear operation was invalid, and the op amp output voltage is saturated at $-V_{cc}$.

Op Amp Circuit Model (Linear Region)



R_i is the equivalent resistance "seen" at the input terminals, typically very large (>1MΩ), so that the input current is usually very small:

$$i_p = -i_n \cong 0$$

$$i_p + i_n + i_o + i_{c+} + i_{c-} = 0$$

$$i_o \cong -(i_{c+} + i_{c-})$$

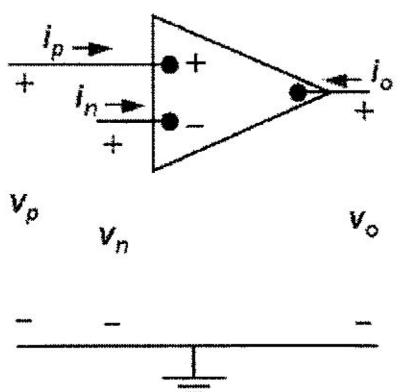
Note that significant output current (i_o) can flow when i_p and i_n are negligible!

Ideal Op Amp

- Assumptions:
  - R_i is large (≥10^5 Ω)
  - A is large (≥10^4)
  - R_o is small (<100 Ω)

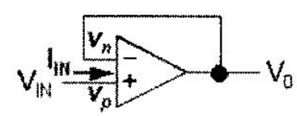
$$i_p = -i_n = 0$$
$$v_p = v_n$$

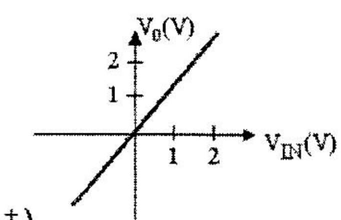
- Simplified circuit symbol:
  - power-supply terminals and dc power supplies not shown



Note: The resistances used in an op-amp circuit must be much larger than R_o and much smaller than R_i in order for the ideal op amp equations to be accurate.

Unity-Gain Voltage Follower Circuit





$v_p = v_n \rightarrow$ $V_0 = V_{IN}$

(valid as long as $V^- \leq V_0 \leq V^+$)

Note that the analysis of this simple (but important) circuit required only one of the ideal op-amp rules.

Q: Why is this circuit important (*i.e.* what is it good for)?

A: A "weak" source can drive a "heavy" load; in other words, the source V_{IN} only needs to supply a little power (since I_{IN} = 0), whereas the output can drive a power-hungry load (with the op-amp providing the power).