6.200 Circuits and Electronics

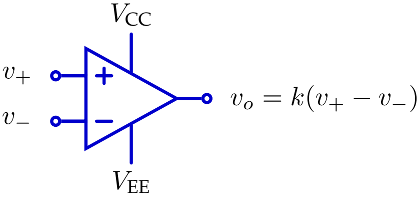
Week 8, Lecture A:

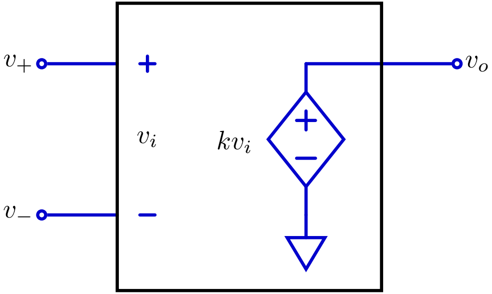
Modularity in Circuits:
Operational Amplifiers

Midterm 1: tonight
PSet 8 releases tonight as well (no hardware, no prelab)

Operational Amplifiers

An operational amplifier ("op-amp") can be modeled* as a voltage-controlled voltage source, where k is intentionally large (typically $\sim 10^5 - 10^7$):

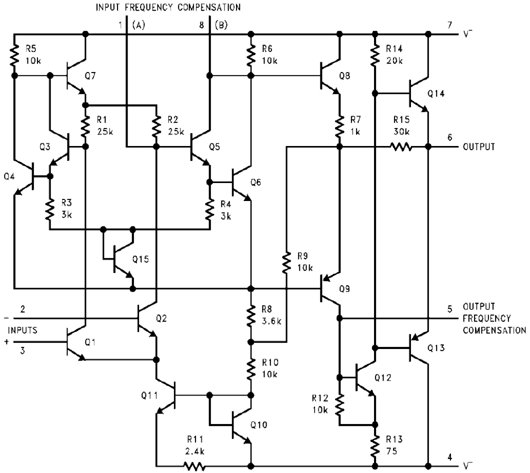




* sometimes

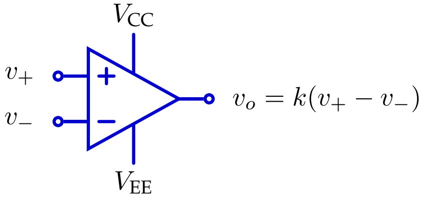
Operational Amplifiers

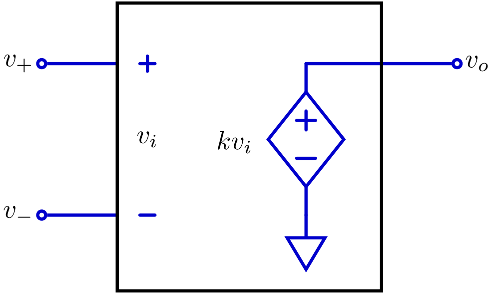
What's *actually* in an op-amp? Here is a more accurate circuit model of a μA709 op-amp:



But that's a pain...

Characterizing an Op-amp (VCVS Model)



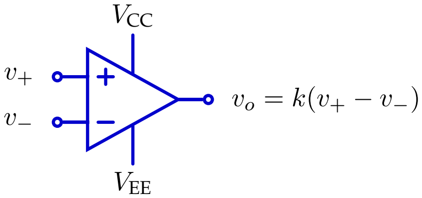


Sketch a graph of v_o versus $(v_+ - v_-)$

Supply Rails

Op-amps derive power from connections to a power supply, and the output voltage is typically constrained by that power supply:

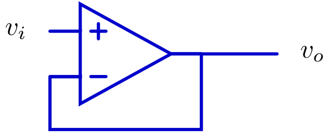
$$V_{\text{EE}} < v_o < V_{\text{CC}}$$



If $k(v_+ - v_-) > V_{\text{CC}}$, then v_o will be V_{CC}.
If $k(v_+ - v_-) < V_{\text{EE}}$, then v_o will be V_{EE}.

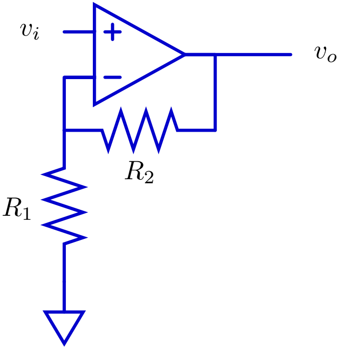
Closing the Loop

Many useful applications of op-amps involve connecting them in *feedback*, where the output affects one of the input terminals. For example, consider the following configuration:



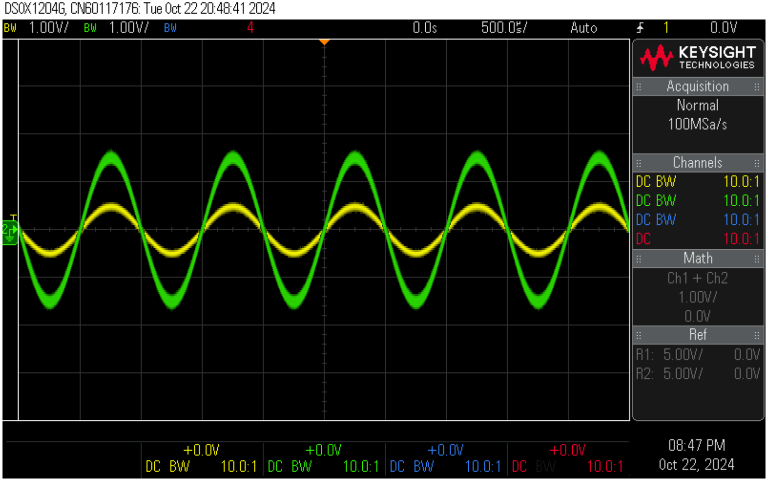
What is v_o (in terms of v_i)? Use the VCVS model from the previous slides.

Another Op-Amp Circuit



What is v_o (in terms of v_i)? Use the VCVS model from the previous slides.

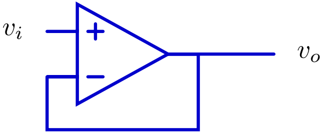
Hmmmmm....



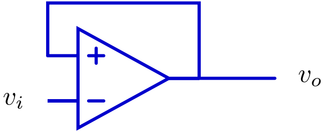
DSOX1204G, CN60117176: Tue Oct 22 20:48:41 2024
BW 1.00V/ BW 1.00V/ BW 4
0.0s 500.0us/ Auto 1 0.0V
KEYSIGHT TECHNOLOGIES
Acquisition
Normal
100MSa/s
Channels
DC BW 10.0:1
DC BW 10.0:1
DC BW 10.0:1
DC 10.0:1
Math
Ch1 + Ch2
1.00V/
0.0V
Ref
R1: 5.00V/ 0.0V
R2: 5.00V/ 0.0V
+0.0V DC BW 10.0:1
+0.0V DC BW 10.0:1
+0.0V DC BW 10.0:1
+0.0V DC BW 10.0:1
08:47 PM
Oct 22, 2024

Negative Feedback

Most of the useful circuits we'll see moving forward involve feedback. But the presence of the + and - signs on the inputs imply that something is different between the following:



$$v_o = \frac{k}{1+k} \approx 1$$

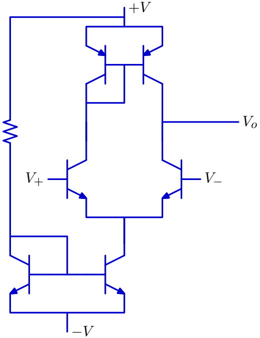


$$v_o = \frac{-k}{1-k} \approx 1$$

But the analysis produces the same answer! The VCVS model alone isn't enough to explain the difference here; we need to go deeper...

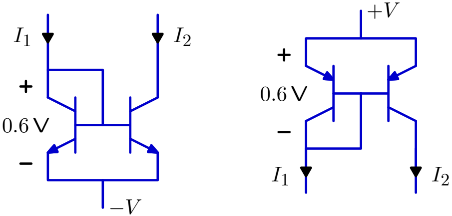
“Thinking” Like an Op-Amp

In fact, both of the systems from the previous page have metastable points at $v_o \approx v_i$. However, in order to understand the difference, we need to think about **temporal dynamics**, and what happens when the system moves away from that metastable point. Let’s consider a slightly-more-complicated op-amp model. Let’s start with a small op-amp:

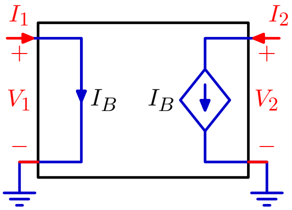


Common Transistor Patterns

A *current mirror* sets its output current to equal its input current.

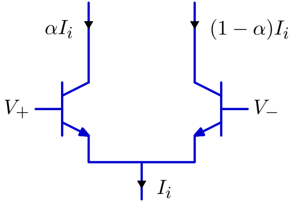


It can be represented by a current-controlled current source:



Common Transistor Patterns

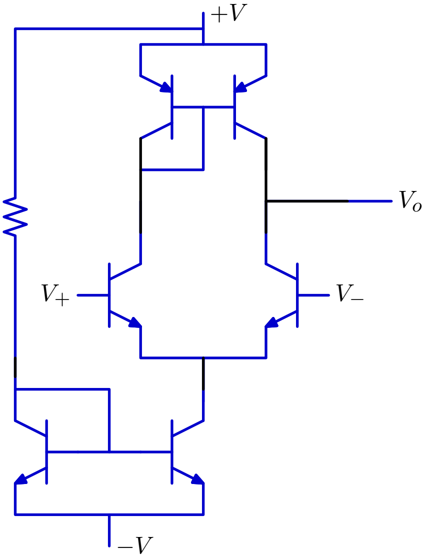
A pair of transistors can be used to split a current.

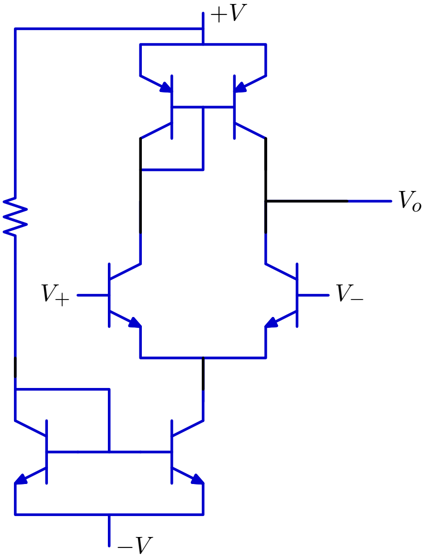


The fraction α is proportional to $e^{(V_+ - V_-)/v_T}$, where $v_T \approx 26\text{mV}$.

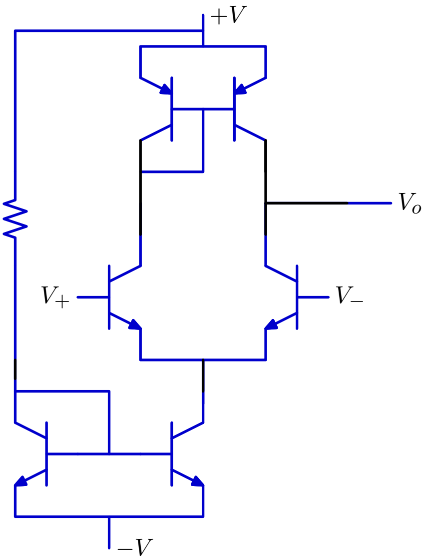
This "differential amplifier" can be represented by two voltage-controlled current sources.

Modeling An Op-Amp





Modeling An Op-Amp



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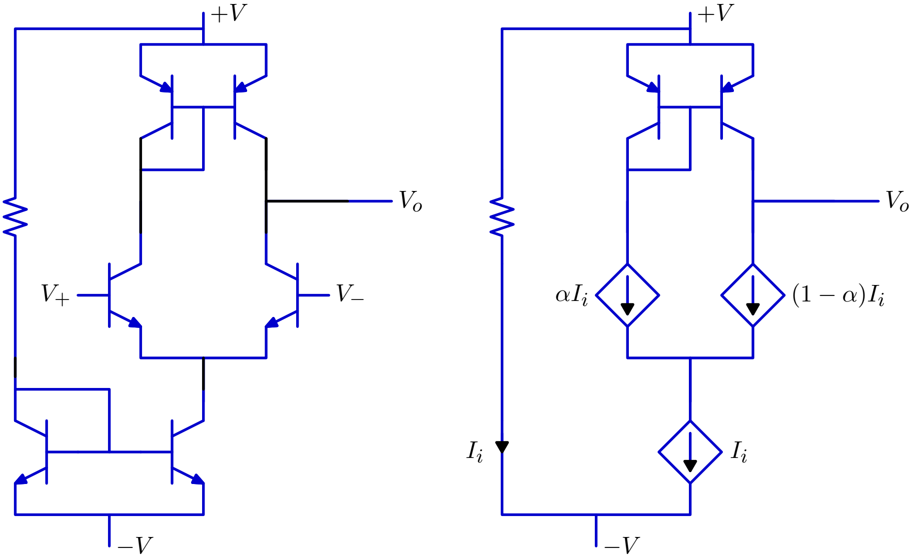
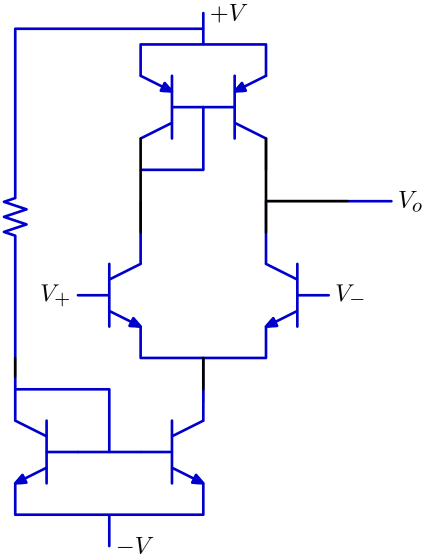
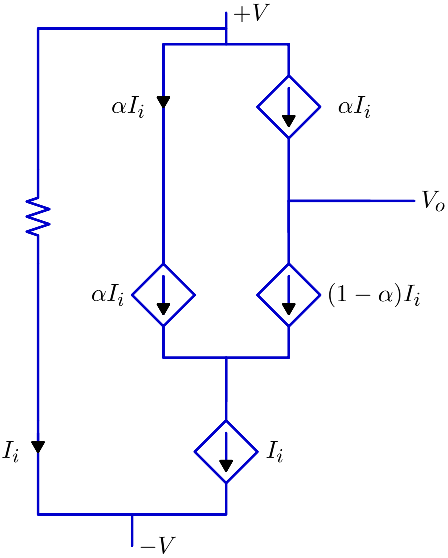
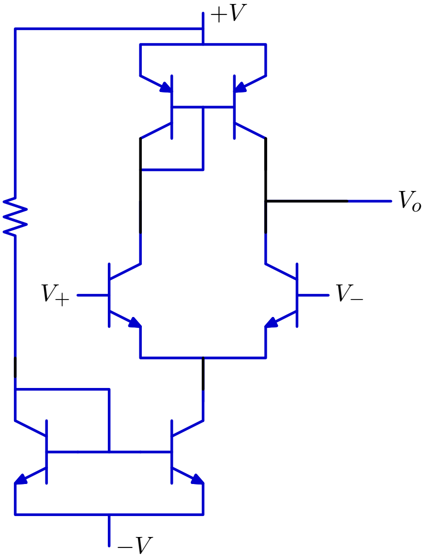


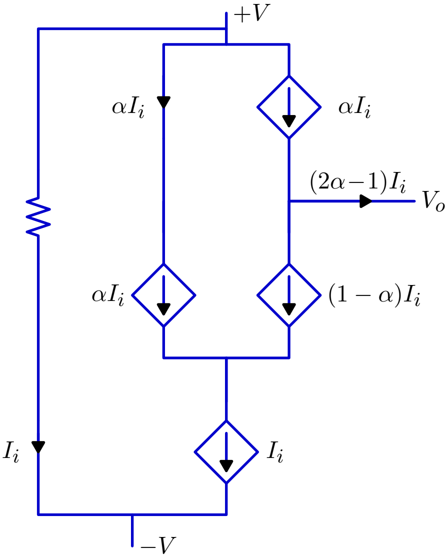
Modeling An Op-Amp





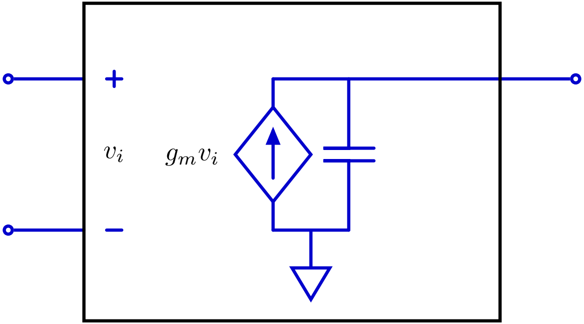
Modeling An Op-Amp





Modeling Time Dynamics

This leads us to a model of the op-amp that can explain the difference:



How does this circuit behave in the negative-feedback vs positive-feedback case?

Like we do with a lot of things, the important thing to remember is not this model, but the consequence of it: negative feedback drives the input potentials together (linear VCVS model applies!), positive feedback drives them apart.