EE40
Lecture 5
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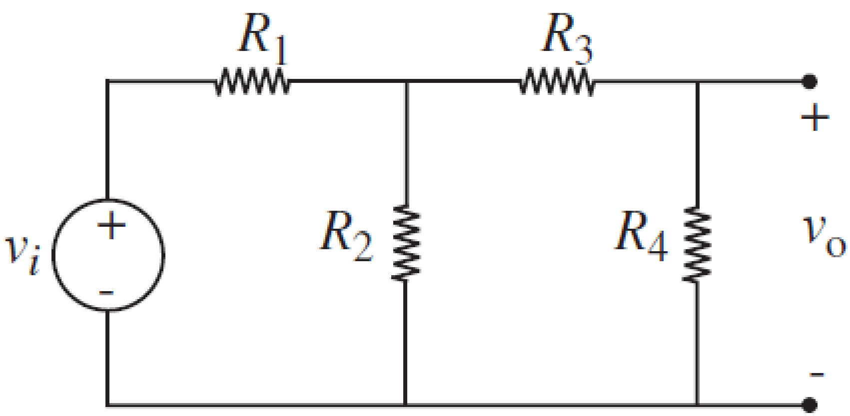
6/30/2010

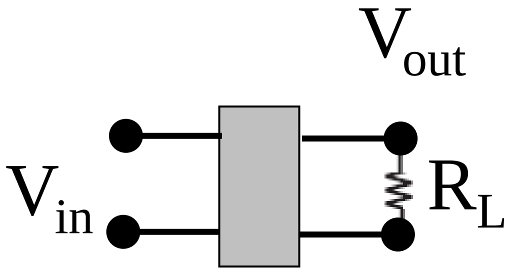
General Info

- Lab #2 today
- HW1 grades up on bspace
- Make up lab next week
  - Date TBA
- Discussions going back to 2 hours
- HW2 still due Friday at 5 PM
  - It is long, you should be half done
  - Get started tonight if you haven't started yet
  - Don't forget about the discussion board
  - Don't forget there are other human beings who are also working on this homework

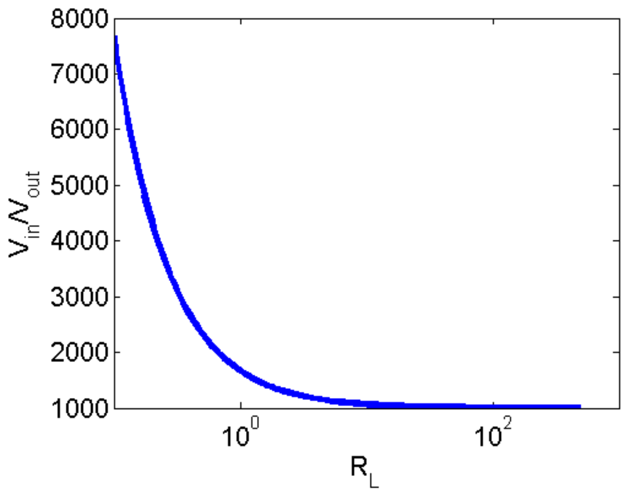
The Need for Dependent Sources

- Suppose you build a circuit such that $v_o = v_i/1000$, to be used as a power supply





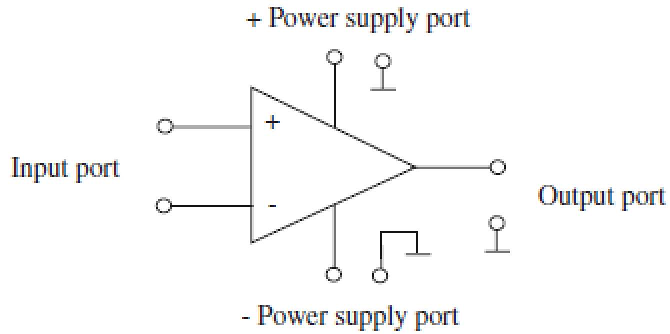
  - E.g. $R_1=332.667\Omega$, $R_2=R_3=R_4=1\Omega$
- Consider what happens when you attach a load to the power supply, for example, a resistor

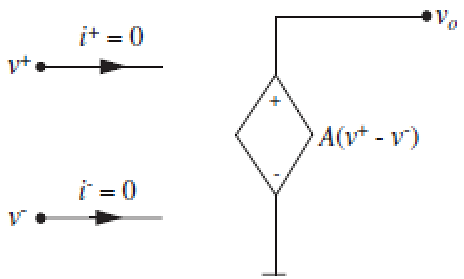


- $V_{out} = \frac{R_L}{666.333+1000R_L} V_{in}$

Operational Amplifiers

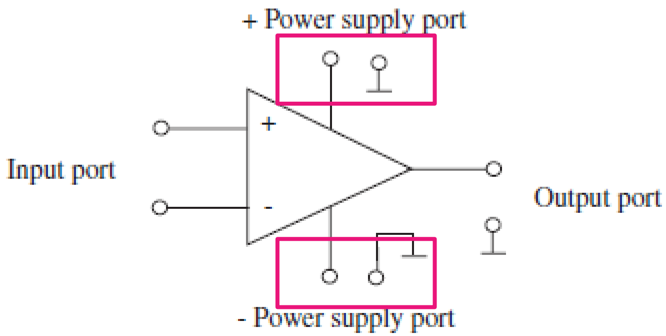
- Dependent Sources are handy
  - Allows for decoupling
- Only one problem:
  - They don't exist
- The "Operational Amplifier" approximates an ideal voltage dependent voltage source
  - Very very cool circuits
  - Analog IC design is hard

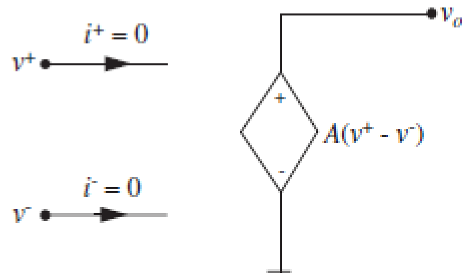


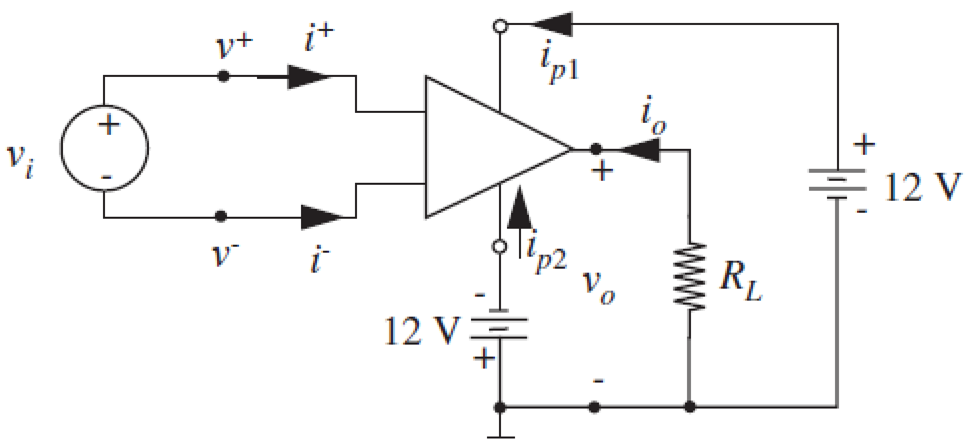


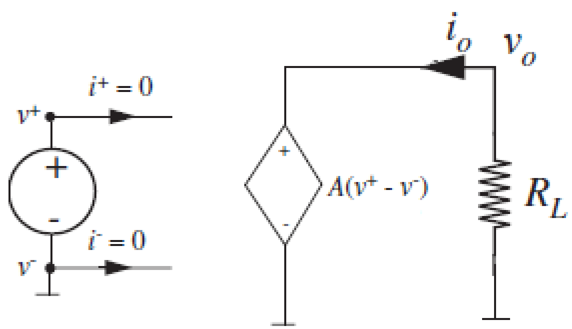
Most Obvious Op-Amp Circuit

We'll ignore power supply ports for now







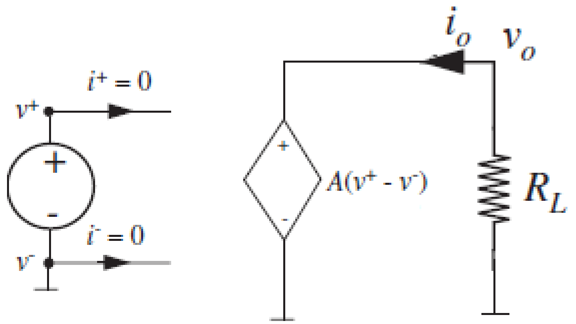


$v_o = Av_i$ e.g. A=1/1000

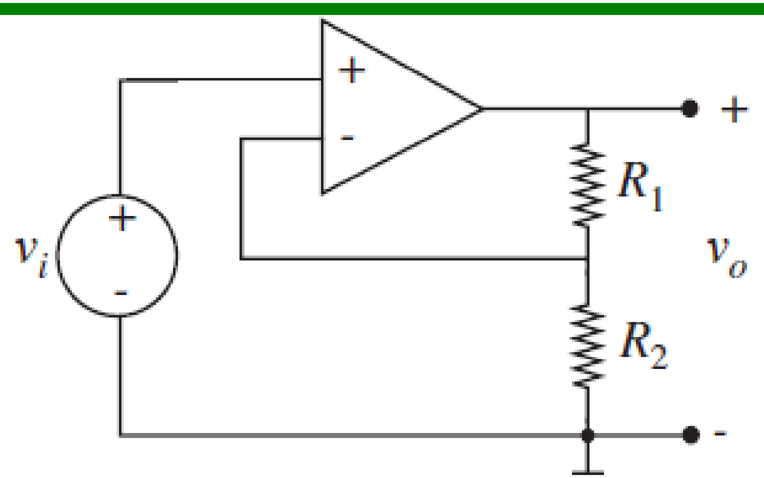
One Problem

- The "open loop gain" A is:
  - – Hard to reliably control during manufacturing
  - – Typically very large (A > 1,000,000)
  - – Fixed for a single device
- Negative feedback helps us overcome these issues

$$v_o = Av_i$$



Simple Op-Amp Circuit with Negative Feedback



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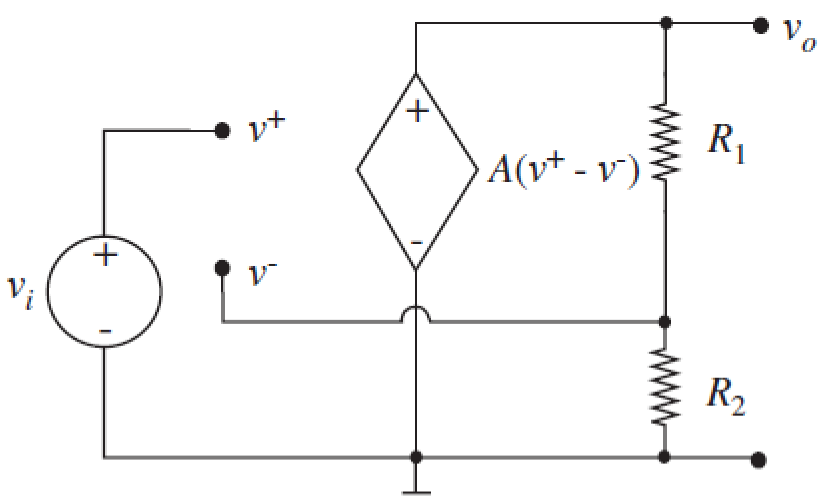
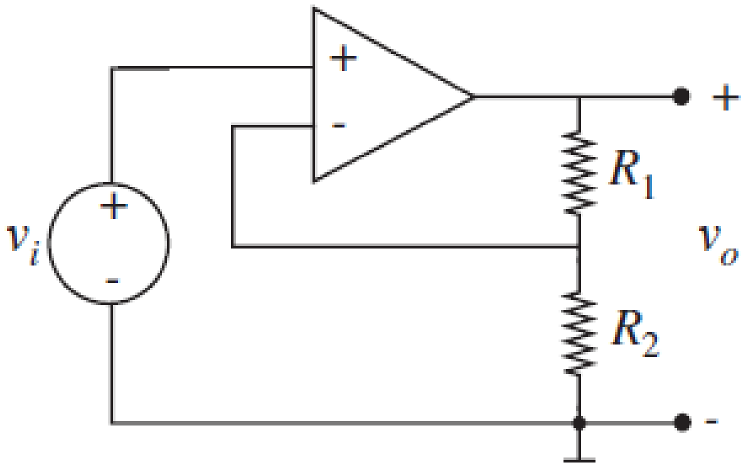


On the board:

$$v_o = \frac{Av_i}{1 + A\frac{R_2}{R_1+R_2}}$$

Negative Feedback Op-Amp Circuit

$$v_o = \frac{Av_i}{1 + A\frac{R_2}{R_1+R_2}}$$



(a)

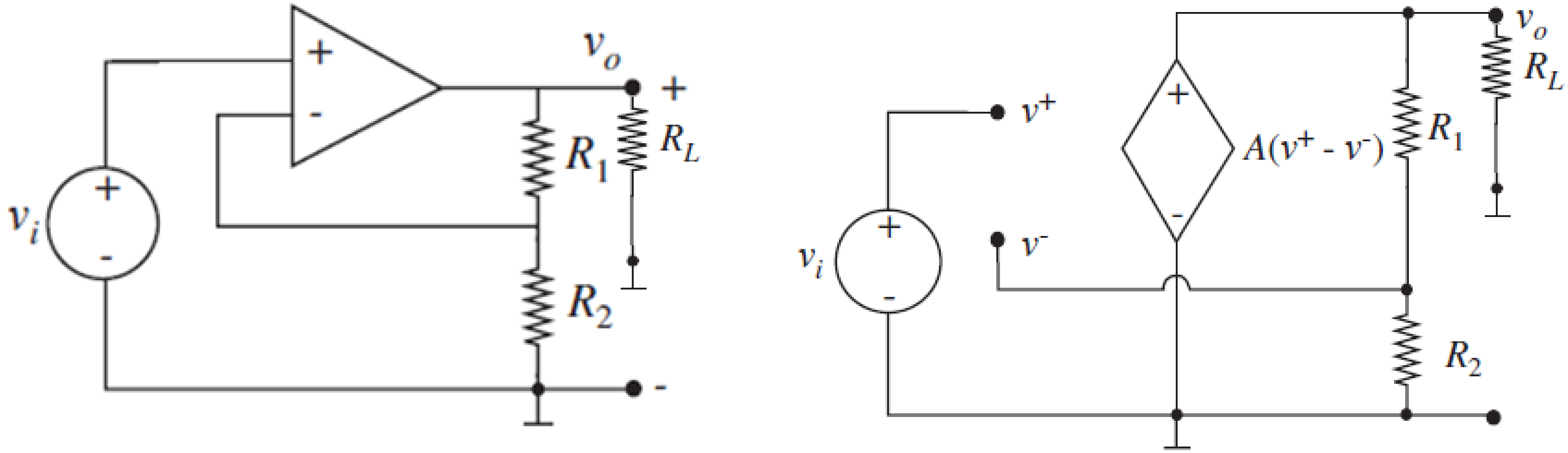
Assuming A is very big…

$$v_o = \frac{Av_i}{A\frac{R_2}{R_1+R_2}}$$

$$v_o = \frac{v_i}{\frac{R_2}{R_1+R_2}}$$

$$v_o = v_i\frac{R_1+R_2}{R_2}$$

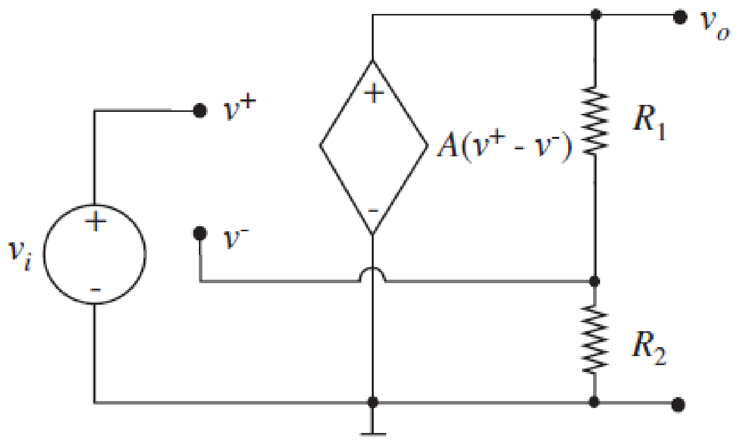
Op-Amp Circuit



- Output voltage is independent of load!
- One op-amp fits all, just tweak your resistors!
- Output is independent of A!

$$v_o = v_i \frac{R_1 + R_2}{R_2}$$

Wait, so whoa, how did that happen?



$$v_o = \frac{Av_i}{1 + A\frac{R_2}{R_1+R_2}}$$

- Let's consider what happened to v^-:

$$v^- = \frac{Av_i}{1 + A\frac{R_2}{R_1+R_2}} \times \frac{R_2}{R_1+R_2}$$

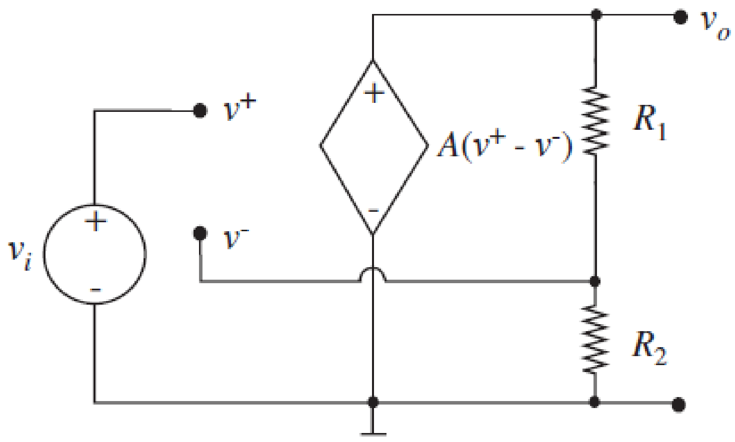
$$v^- = v^+ \frac{AR_2}{R_1 + R_2 + AR_2}$$

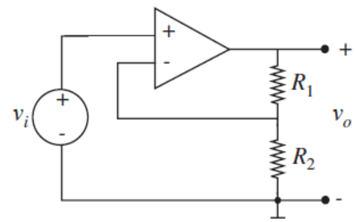
and for large A…

$$v^- = v^+(1 - \varepsilon)$$

Where ε represents some tiny number

The Voodoo of Analog Circuit Design





(a)

$$v_o = \frac{A v_i}{1 + A\frac{R_2}{R_1+R_2}}$$

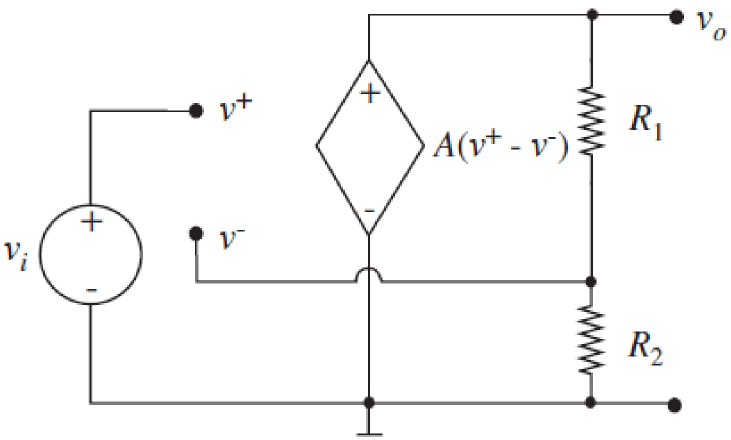
For large A:

$$v_o = v_i \frac{R_1 + R_2}{R_2}$$

$$v^- = v^+(1 - \varepsilon)$$

- The “negative feedback” forces v^- to be extremely close to v^+
- This very tiny difference between v^- and v^+ gives us v_o

The Voodoo of Analog Circuit Design

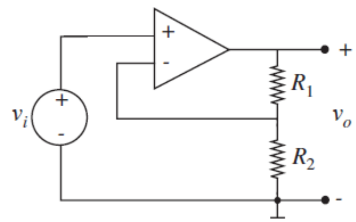


$$v_o = \frac{A v_i}{1 + A\frac{R_2}{R_1+R_2}}$$

For large A:

$$v_o = v_i \frac{R_1 + R_2}{R_2}$$

For this circuit:



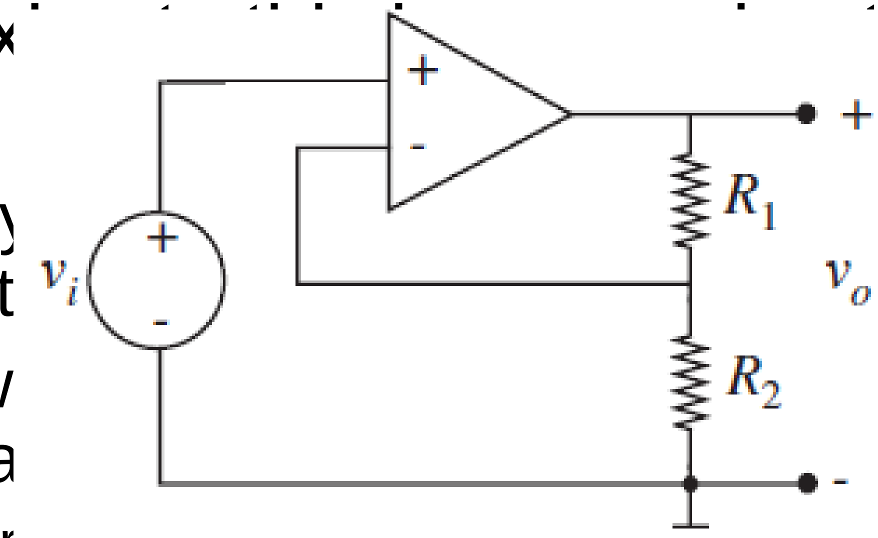
(a)

$$v^- = v^+(1 - \varepsilon)$$

- No longer focus on how op-amp drives the output, but instead on how it drives its own input!
- The gain "A" disappears, since if it's really big, the op-amp just forces $v^- = v^+$

Consequence of Negative Feedback

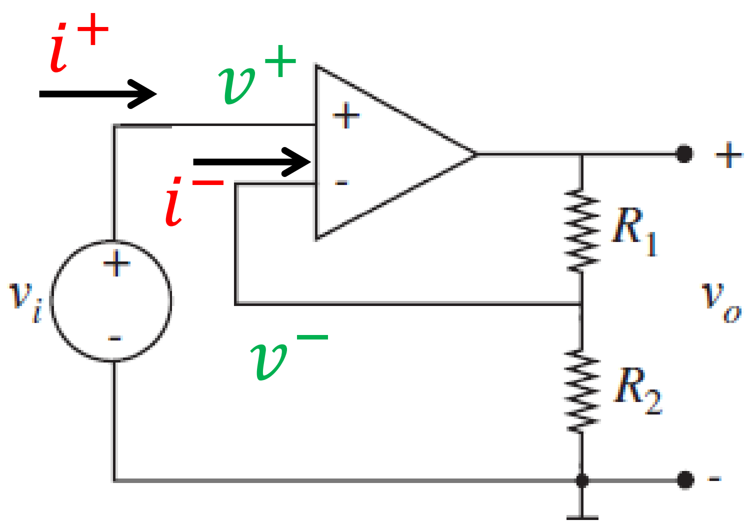
- This input forcing property generalizes to all circuits with “negative feedback”
- Specifically, in any circuit where v_o is connected back to v^- (and not to v^+), we have the property that $v^- = v^+(1-\varepsilon)$
- We’ll approx… …hat $v^- = v^+$
  – Not actually… …p would not do anyt…
  – However w… …mation is incredibly a…
    - Less error… …ponent variation, t…



(a)

Approach to Op-Amp Circuits

- An op-amp connected in a negative-feedback configuration does the following:
  - Forces $v^- = v^+(1-\varepsilon)$
  - Can approximate by $v^- = v^+$
- Our prior approach was to replace the op-amp by dependent source and solve
- This opens up a new approach

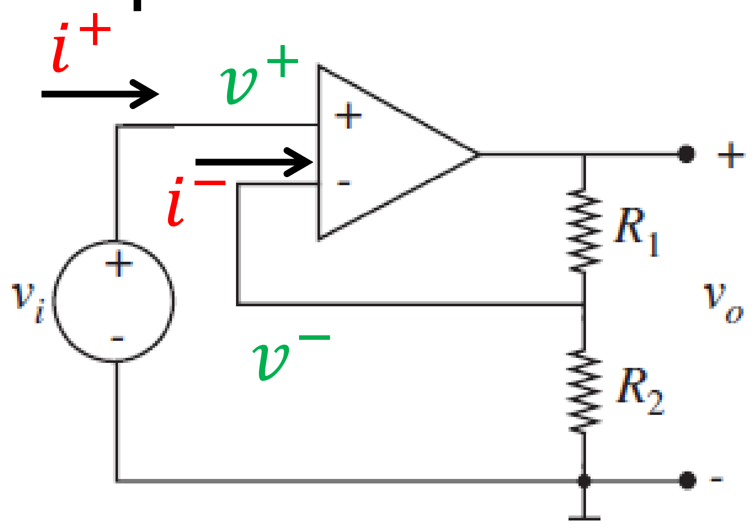


(a)

Approach to Op-Amp Circuits

- If there's only negative feedback:
  - Assume $v^{+} = v^{-}$
  - Assume $i^{+} = 0$ and $i^{-} = 0$

  } "Summing-point constraint"
- If there's no feedback or positive feedback, replace the op-amp with equivalent dependent source and solve



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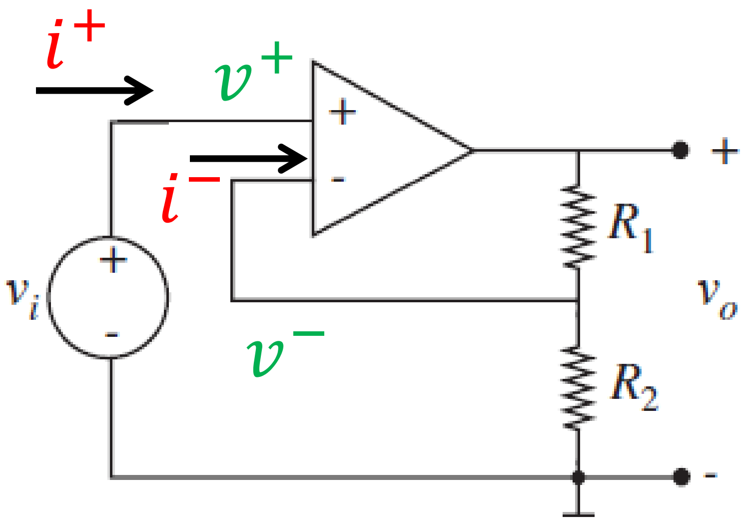
Negative Feedback Amplifiers



(a)

$$v^+ = v^-$$

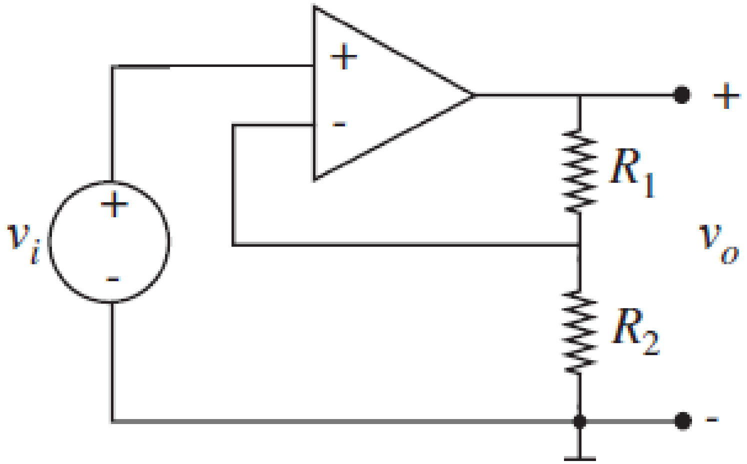
$$i^+ = 0 \text{ and } i^- = 0$$

- Concept was invented on a ferry to Manhattan by **Harold Stephan Black** during his morning commute to Bell Labs in Manhattan in 1927, originally sketched out on a blank spot of his New York Times
- The idea is bizarre, but really epic
  - Completely revolutionized electronics
  - 9 years before patent office believed it

If you're a little lost

- Don't fret, the idea is weird
- At first, just keep in mind the important thing:
  - An op-amp with negative feedback has the properties that
    - $v^+ = v^-$
    - $i^+ = 0$ and $i^- = 0$
- Later, if you want to show that this really works, do an op-amp circuit from scratch by replacing the op-amp with a voltage source, and you'll get the same answer

Example using the Summing-Point Constraint



(a)

$$v^- = v^+ = v_i$$

$$i^- = 0, i^+ = 0$$

$$i_{R2} = \frac{v^-}{R_2} = \frac{v_i}{R_2}$$

$$\begin{aligned} i_{R_1} &= i^- + i_{R2} \\ &= i_{R2} \\ &= \frac{v_i}{R_2} \end{aligned}$$

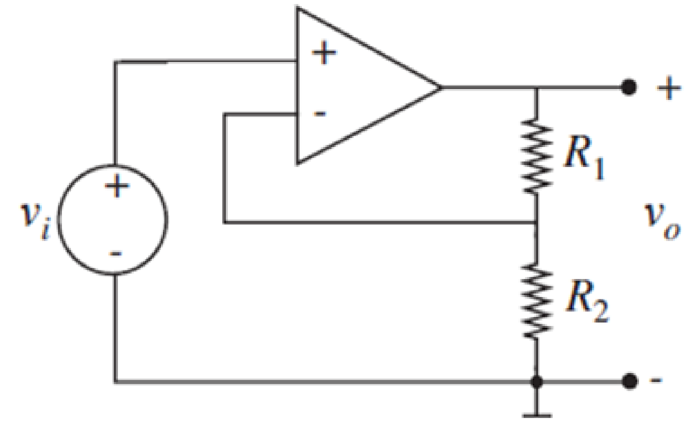
$$\begin{aligned} v_o &= v_i + i_{R_1} R_1 \\ &= v_i + v_i R_1 / R_2 \\ &= v_i \frac{R_1 + R_2}{R_2} \end{aligned}$$

Summing-Point Constraint

- You don’t have to use the summing-point constraint
- However, it is **much** faster, albeit less familiar and thus a little tricky at first

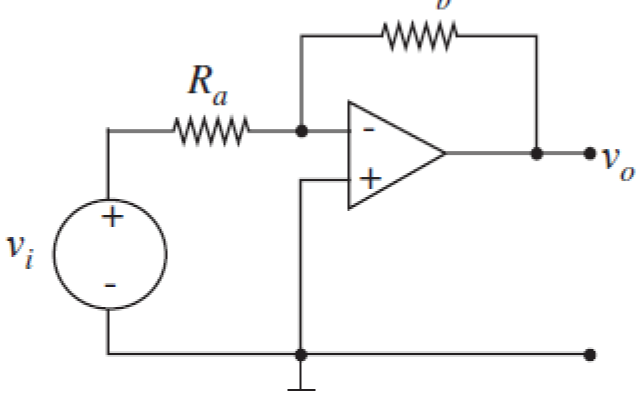
Op-Amp Circuits

- There are a bunch of archetypical circuits, the one we've studied so far is the "non-inverting amplifier"



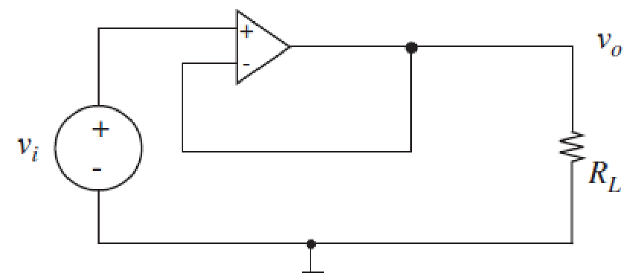
$$v_o = v_i \frac{R_1 + R_2}{R_2}$$

Inverting amplifier



$$v_o = -\frac{R_b}{R_a} v_i$$

Voltage follower



$$v_o = v_i$$

Board Problems Time

- Let's go through some problems on the board

And then we were done…

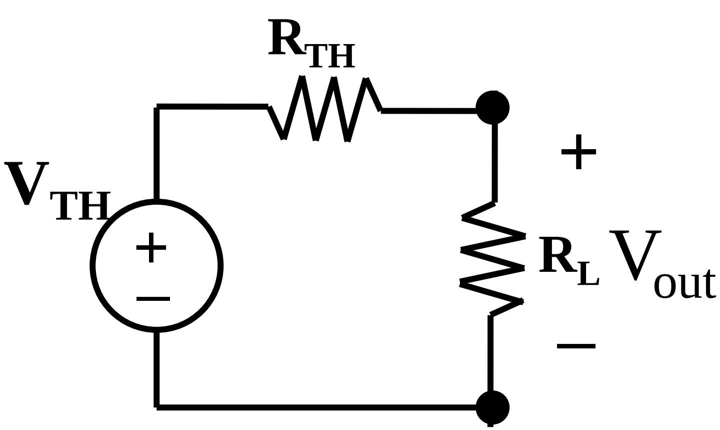
- We did some op-amp problems in class and then called it a day here, next slides will appear on Friday

Op-Amps – How Good Are They Exactly?

- Of course, Op-Amps aren't perfect
  - You can't drive every device in the universe from one op-amp
- How do we measure how good a voltage source is?
  - Looking at its Thevenin equivalent
  - Lower Thevenin resistance is better

Measuring the Quality of a Source

- If you attach a resistive load, then the output voltage is:
  - $V_{out} = \frac{R_L}{R_L + R_{TH}} V_{TH}$
- If you want V_{out} to be 99% of V_{TH}, then:
  - $\frac{99}{100} V_{TH} = V_{TH} \frac{R_L}{R_L + R_{TH}}$
  - $R_L = 99 R_{TH}$

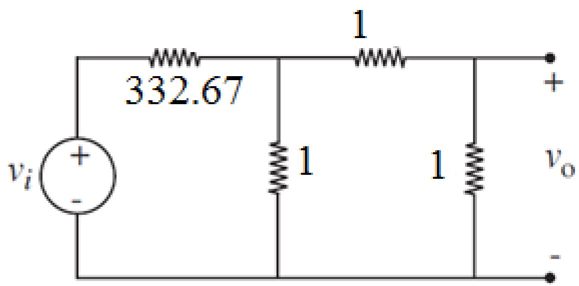


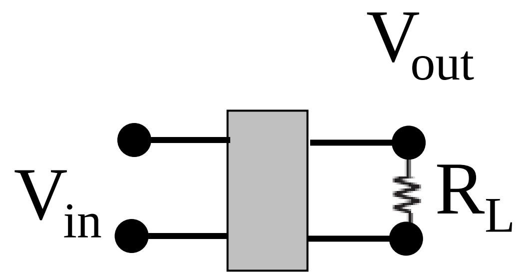
So basically, for loads which are more than 99 times the Thevenin resistance, you get >99% of the Thevenin voltage

Lower R_{TH} is better, can handle smaller loads

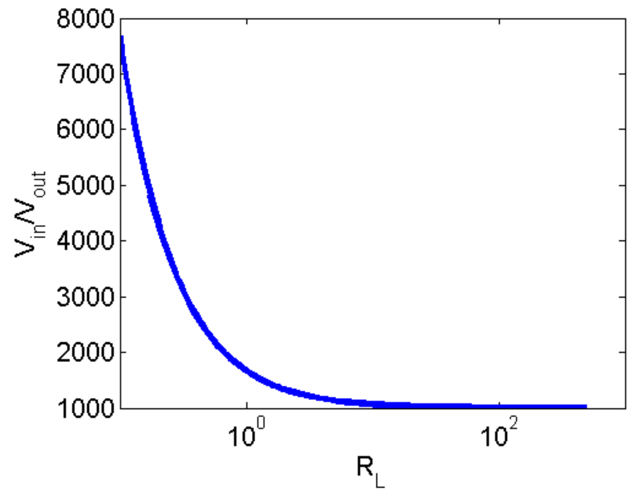
Source Quality Example

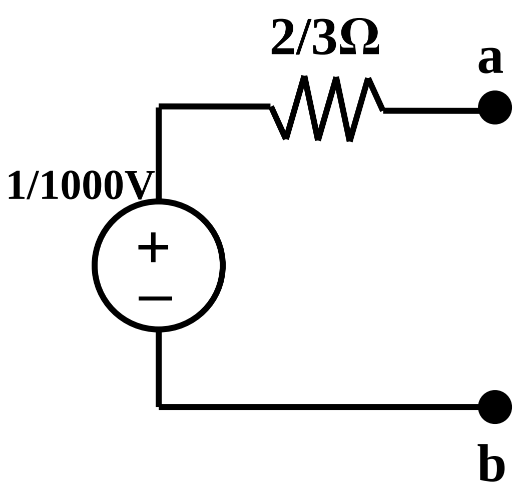
- Suppose you build a circuit such that $v_o = v_i/1000$, to be used as a power supply





- $$V_{out} = \frac{R_L}{666.333 + 1000 R_L} V_{in}$$



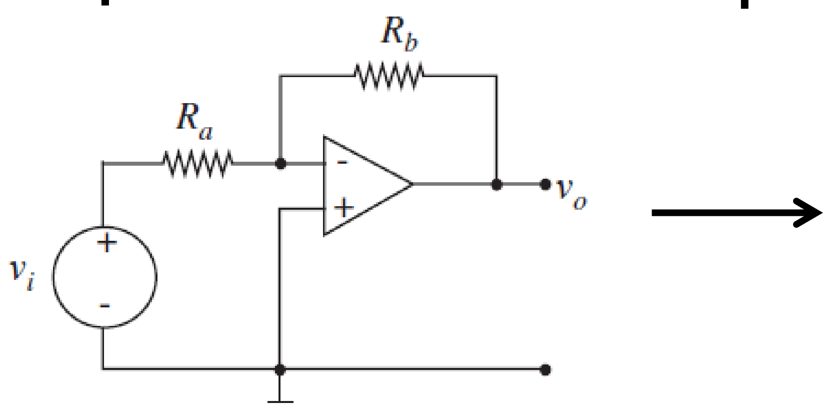


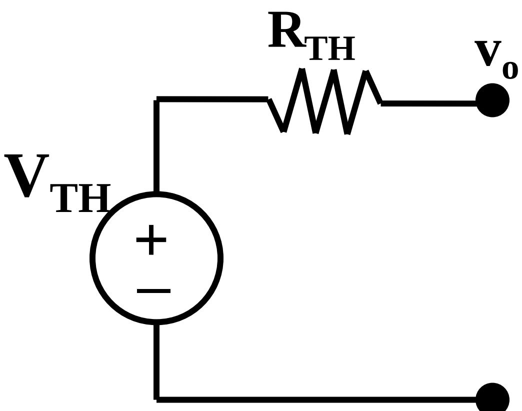
$R_L = 99 \cdot 2/3\Omega = 66\Omega$

66Ω load gets 99% of V_{TH}

Thevenin Equivalents of Op-Amp circuits

- Can look at Thevenin equivalent of an op-amp circuit at its output terminals:





- Just like converting a simple resistor based voltage attenuator: