EE40
Lecture 4
Josh Hug

6/28/2010

For those of you watching the webcast…

- We started today with a bunch of blackboard problems
- Hopefully they are legible online, let me know if they're not
- Scanned copies of my notes will be available online within a day or so

iClicker Logistics

- Everyone should go register their iClicker at iClicker.com
- Directions will be posted on the website, but it's pretty easy
- Your student ID is just the first letter of your first name, and then your entire last name, example:
  - John Quincy Onahal-Menchura would have ID "JONAHAL-MENCHURA"
  - Just to be safe, enter your ID in all capital letters

Late HW Logistics

- Reminder: You get 1 late homework with no penalty, and 1 dropped homework
- If you want to turn in a HW late, you must email the readers (CC the email to me as well)
  - Make sure “Late Homework” is in the title
- This will help us with book keeping of who has turned in a late homework
- Late homeworks are due by the next homework deadline
- If you don’t email us, no late credit!

Midterm

- We still have 11 days until the first midterm (July 9th)
- Will cover everything up to and including what we do this Friday (July 2nd)
- You will be allowed one 8.5” x 11” sheet of paper with anything you want to write on it
  - Must be handwritten
  - You can keep it after the exam
- Each midterm you will be allowed to augment your equation collection by 1 additional sheet of paper

Lunch and Webcasts

- If you signed up for lunch, just come up at the end of class and we'll head out together after the post-lecture question battery
- A couple of lunch spots left if you didn't sign up

- Webcasts now available for lectures 1-3, should be linked in the same directory as the actual lectures
- Lecture 2 debugging ("in parallel" vs. "in parallel") coming after class

Important Dates this Week

- Lab #1 on Tuesday
  - Do pre-lab before lab (available on line)
  - Submit prelab in lab
- Lab #2 on Wednesday
- Make up lab to be scheduled if there is a need, most likely on Thursday
- HW2 posted, due Friday at 5 PM
  - It is long, get started early

Secret Office Hours

- By request, holding an extra office hour today
  - 477 Cory, 3:15PM-4:15 PM
- If you're behind and you can come, please do

iClicker HW1

- For those that turned in HW1, approximately how much time did you spend on homework 1?

A. 0-3 hours
B. 3-6 hours
C. 6-9 hours
D. 9-12 hours
E. More than 12 hours

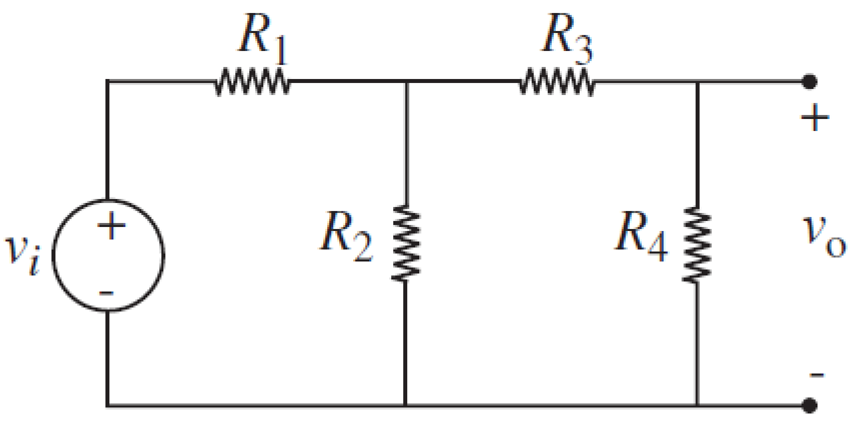
iClicker HW1

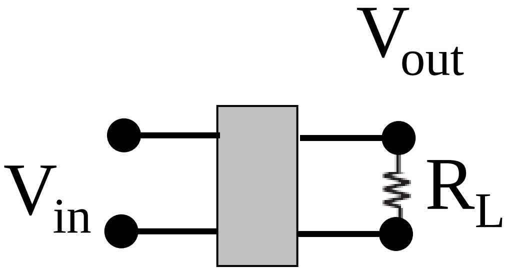
- Did you guys work on the homework solo or with others?

A. I did the homework completely solo
B. I had some, but not much, interaction with others
C. Mostly alone, but then worked in Cory 240 with the impromptu last minute study group
D. Did homework solo, but then went over homework with a group that I'll probably work with again
E. Worked with a group that I'll probably work with again (this is ok!)

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, say a resistor
- $V_{out} = \frac{R_L}{666.333 + 1000 R_L} V_{in}$

Doesn't work for:

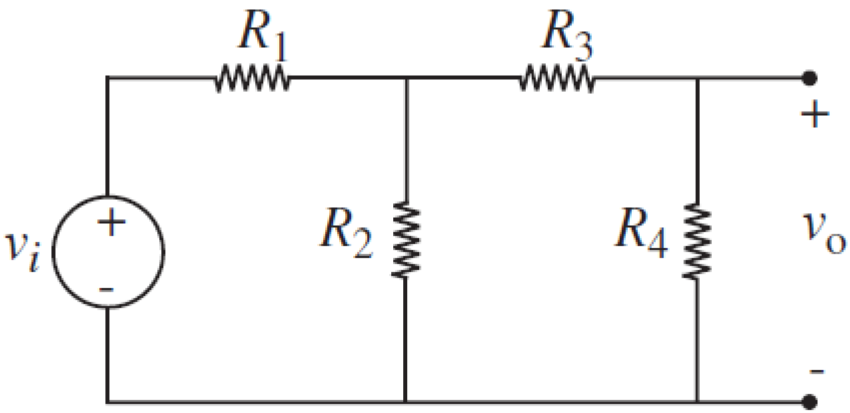
A. Very high R_L

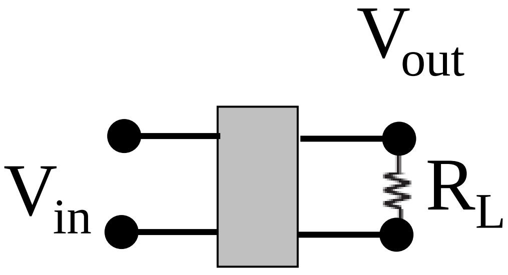
B. Very low R_L

C. Very high or low R_L

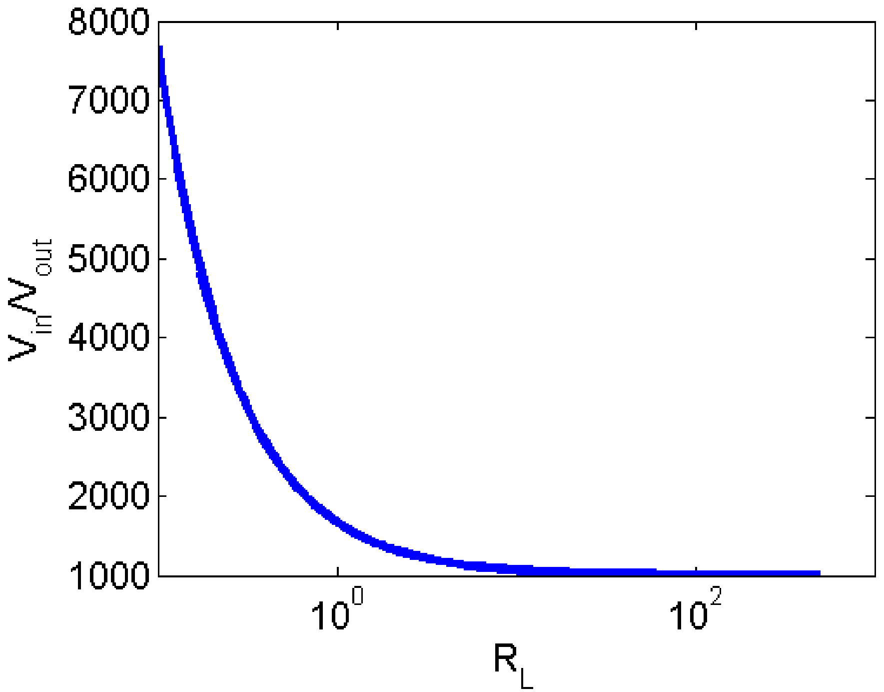
:

- R_1=332.667 Ω, R_2=R_3=R_4=1Ω





- For R_L < 10Ω or so, we have distortion
- Can mitigate this distortion with different resistor values, but there's a better way



Building a Better Attenuator

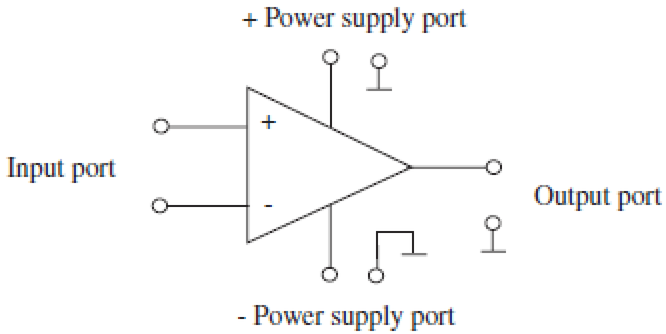
- Using any ideal basic circuit element that we've discussed, what's the best possible circuit we can design so that $V_{out}=v_{in}/1000$?

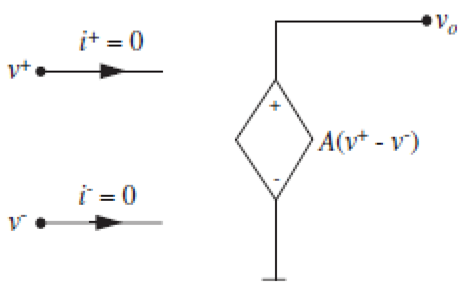
Dependent Sources

- Dependent sources are great for decoupling circuits!
- Only one problem:
  – They don't exist

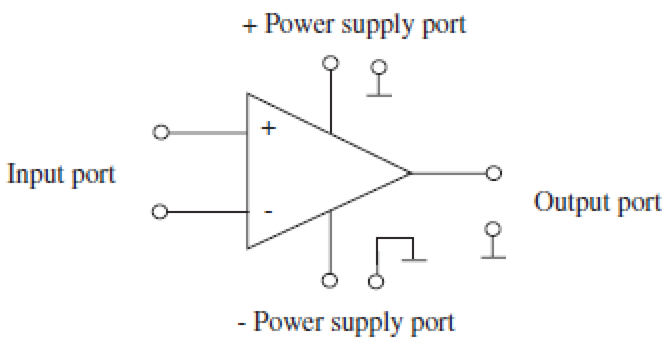
Operational Amplifiers

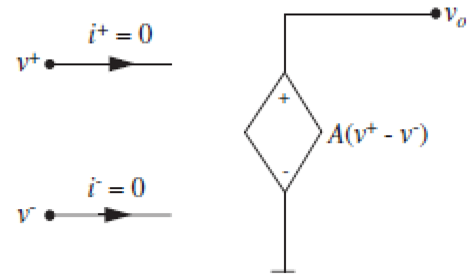
- Dependent Sources are handy
  - Allows for decoupling
- Only one problem:
  - They don't exist
- The "Operational Amplifier" approximates an ideal voltage dependent voltage source
  - Very very cool circuits
  - Analog IC design is hard

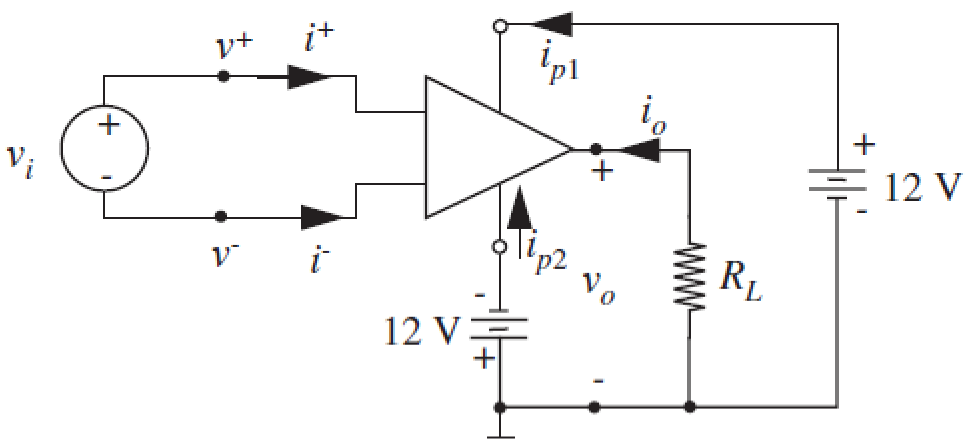


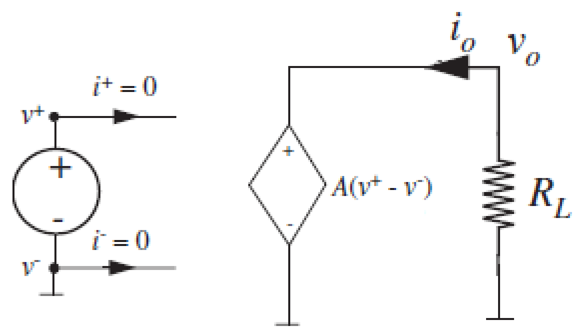


Most Obvious Op-Amp Circuit







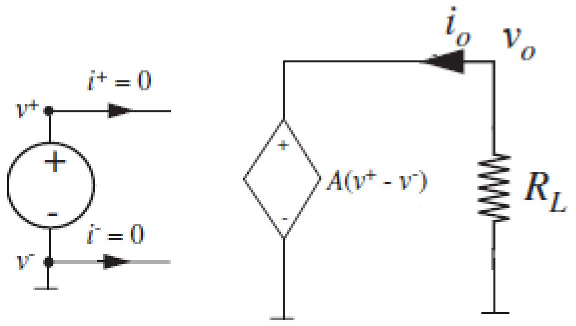


$$v_o = Av_i$$

One Problem

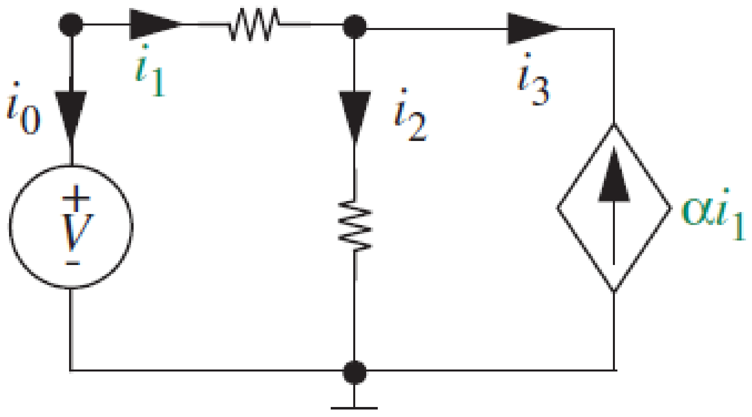
- The "open loop gain" A is:
  - Hard to reliably control during manufacturing
  - Typically very large (A > 1,000,000)
  - Fixed for a single device
- For example, if you needed $V_o = V_{in}/1000$ within 2%, you'd need a high quality op-amp with A=1/1000
- Could spend a lot of time and money addressing these, but there is a better way

$$v_o = Av_i$$



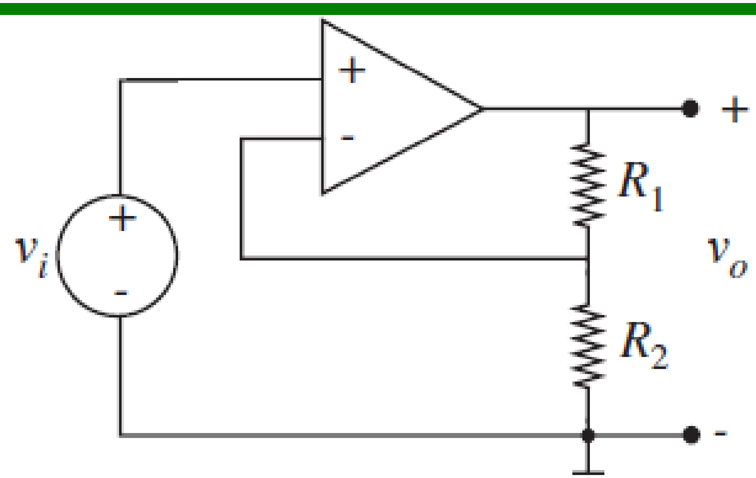
Feedback

- Recall before that I mentioned that dependent sources can provide feedback to their controlling input, e.g.:

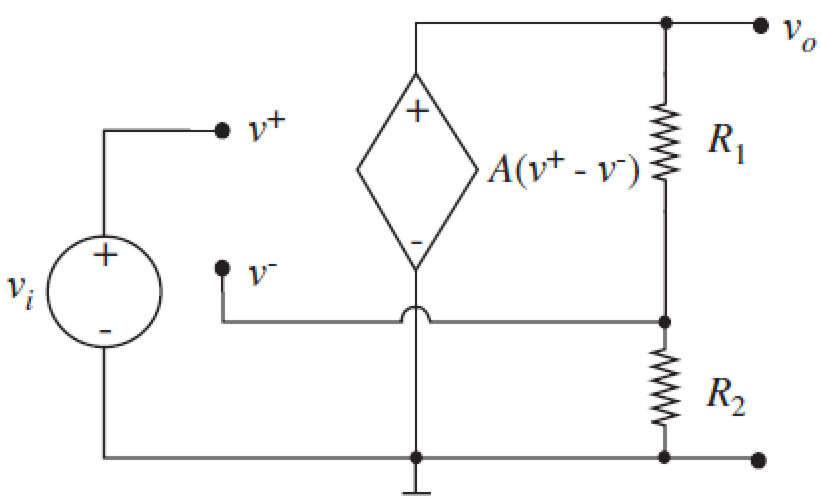


- Remember also that these can be a little tricky to analyze

Simple Op-Amp Circuit with Negative Feedback



(a)

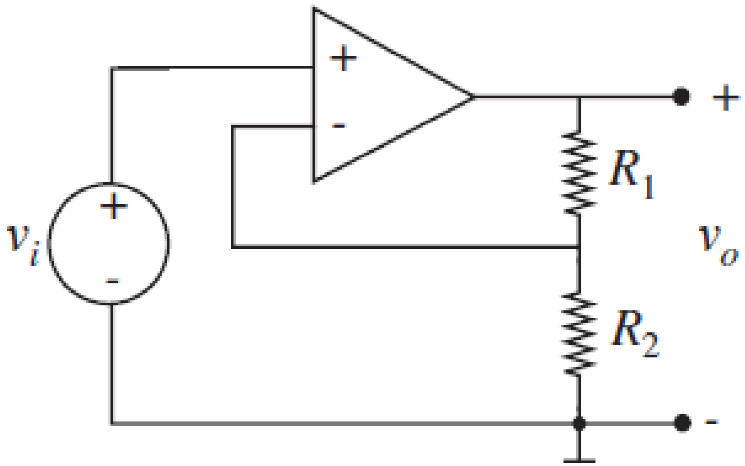


On the board:

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

Negative Feedback Op-Amp Circuit

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



(a)

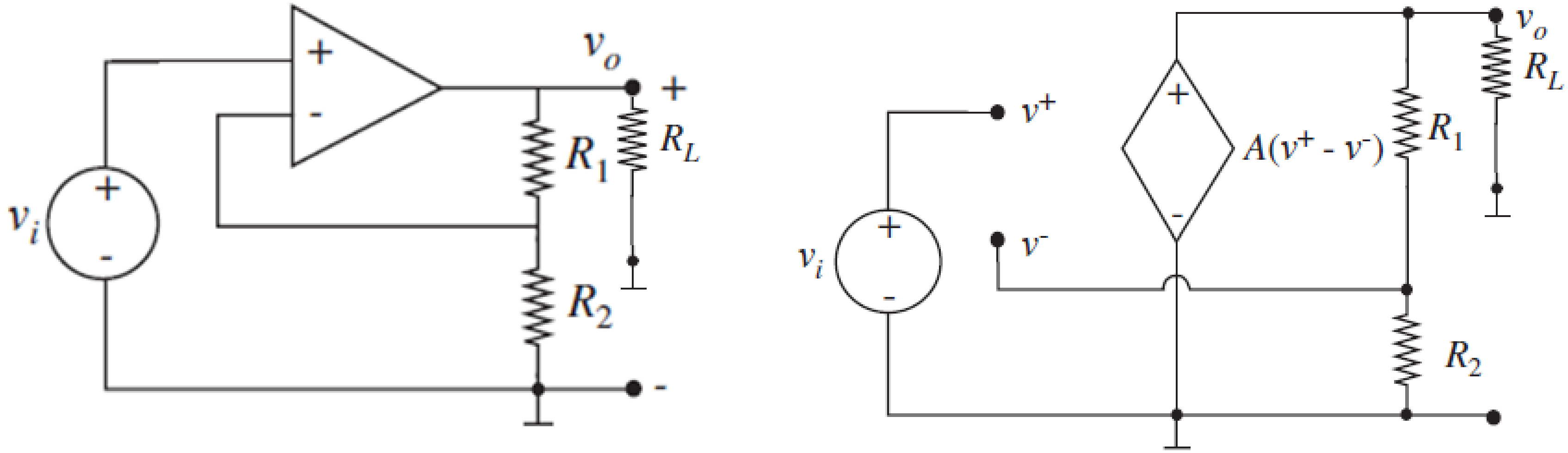
Assuming A is very big…

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

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

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

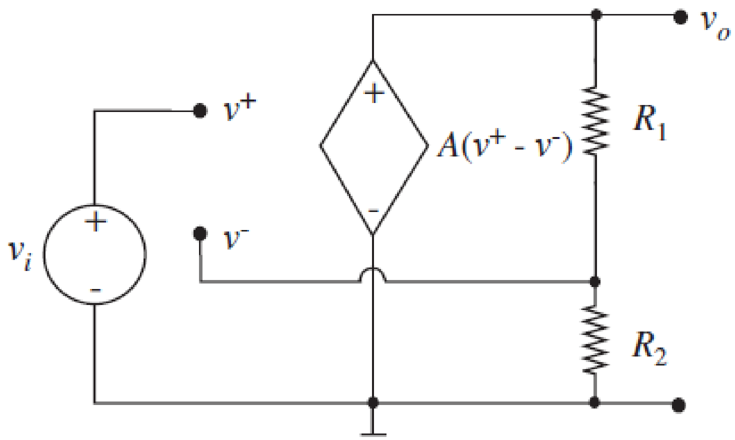
Op-Amp Circuit



- 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^-:

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

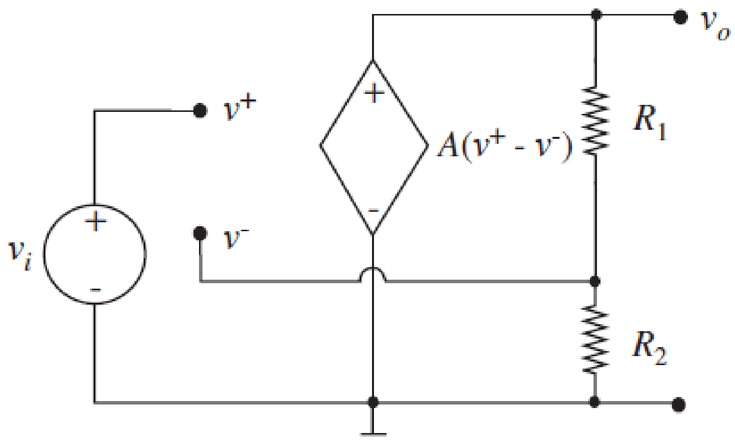
$$v^- = v^+ \frac{AR_2}{R_1 + R_2 + AR_2}$$

and for large A…

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

Where ε represents some tiny number

The Voodoo of Analog Circuit Design



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

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

Consequence of Negative Feedback

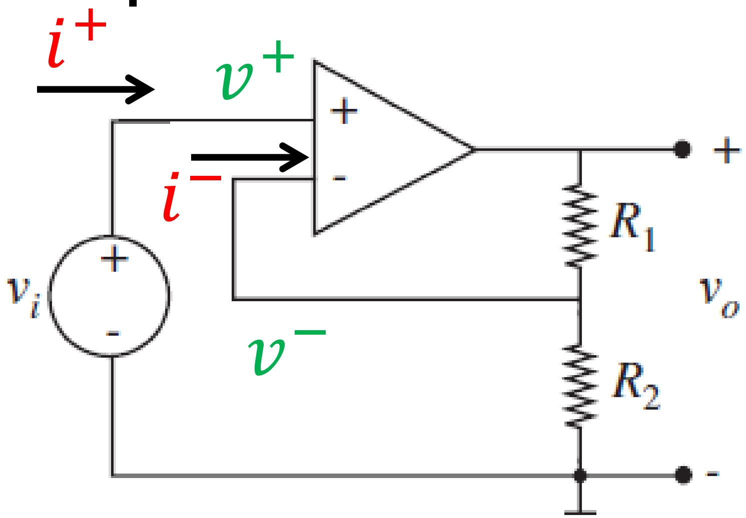
- In any circuit where v_o is connected back to v^- (and not to v^+), we have the property that $v^- = v^+(1+\varepsilon)$
- We'll approximate this by assuming that $v^- = v^+$
  - Of course it's not actually equal, otherwise the op-amp would not do anything
  - However with A>1,000,000, this approximation is incredibly acscurate
    - Less error from this approximation than component variation, temperature variation, etc.

Approach to Op-Amp Circuits

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

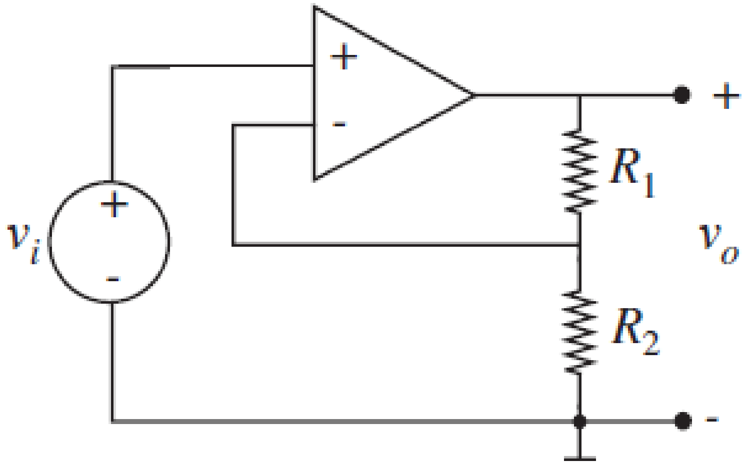
  } "Summing-point constraint"

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



(a)

Example using the Summing-Point Constraint



(a)

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

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

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

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

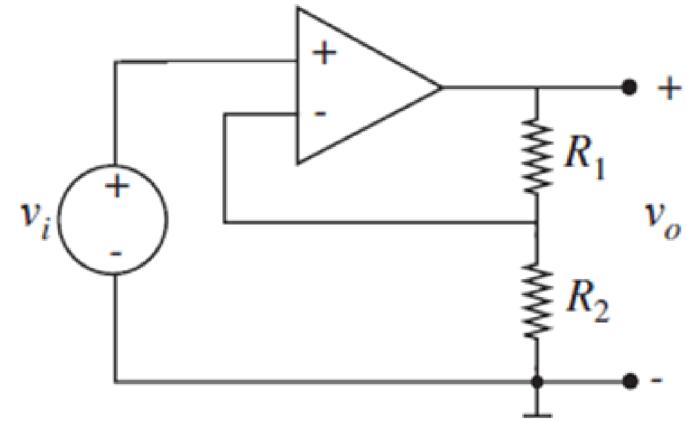
$$\begin{aligned} v_o &= v_i + i_{R_1} R_1 \\ &= v_i + v_i R_1 / R_2 \\ &= v_i \frac{R_1 + R_2}{R_2} \end{aligned}$$

Summing-Point Constraint

- You don’t have to use the summing-point constraint
- However, it is **much** faster, albeit trickier
- This is where building your intuition helps, so you can see where to go next

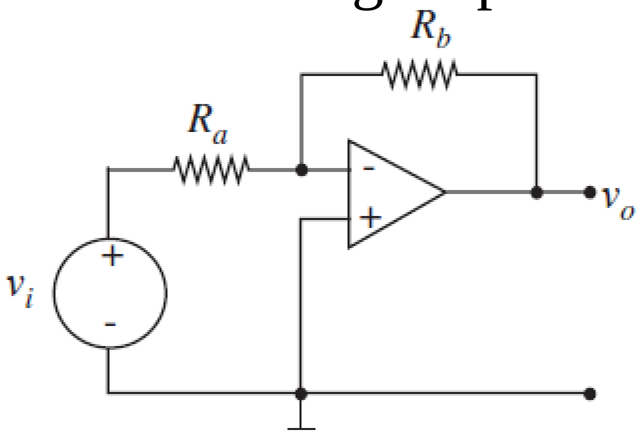
Op-Amp Circuits

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



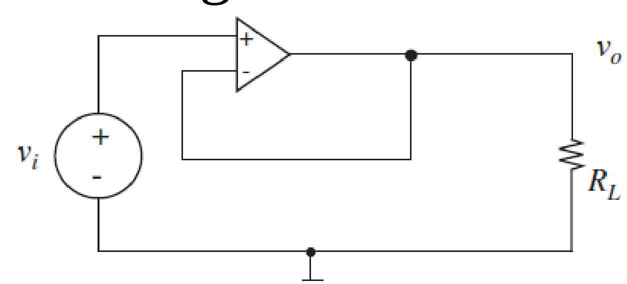
$$v_o = v_i \frac{R_1 + R_2}{R_2}$$

Inverting amplifier



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

Voltage follower



$$v_o = v_i$$

For Next Time

- Lots more op-amp circuits
- Useful for abstractions for analyzing and designing op-amp circuits
- Before we go, a couple of questions

Pacing

- Class Pacing
  A. Way too slow
  B. Too slow
  C. Just right
  D. Too fast
  E. Way too fast

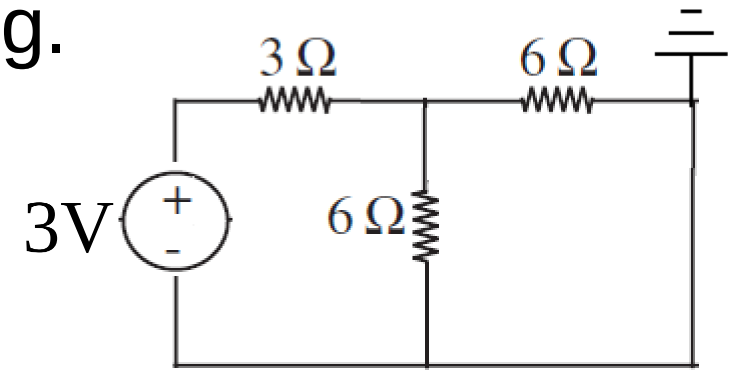
Blackboard

- PowerPoint vs. chalkboard
  A. Almost always prefer PowerPoint
  B. PowerPoint is slightly preferable
  C. Whatever is fine
  D. Chalkboard is a bit better
  E. I’d prefer little to no PowerPoint

Extra Slides

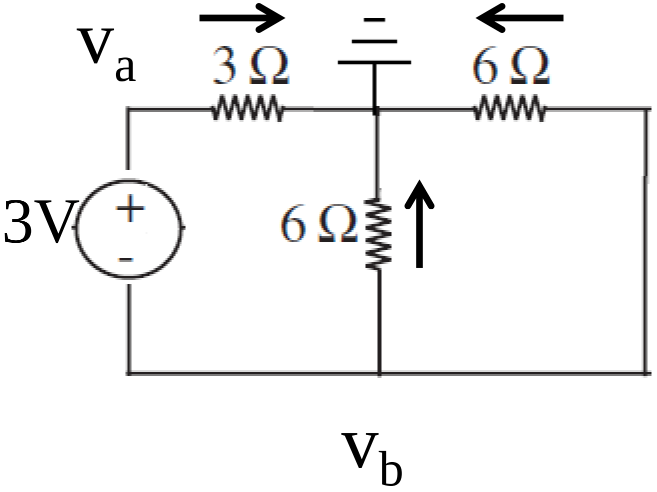
Voltage Sources and the Node Voltage Method

- I didn't point this out explicitly, but whenever you have a voltage source that connects two nodes, and neither of those nodes are ground, e.g.



- Then you have to write KCL for the surface enclosing the two nodes (the book calls these surfaces "supernodes")
- If a node has N voltage sources, the surface will include N nodes

Supernode Example



$$v_a = v_b + 3$$

Treat a and b together as one node, giving KCL:

$$\frac{v_a}{3} + \frac{v_b}{6} + \frac{v_a}{6} = 0$$

If you try to write KCL for node a or b alone, you'll get stuck when you try to write the current from a to b.

Note to Non-Native Speakers

- I try my hardest to make sure the language on homework problems and on tests is clear
- Please don't hesitate to ask me if something seems confusing