# EE40
# Lecture 6
# Josh Hug

7/2/2010

# General Info

- HW2 due today at 5PM
- HW3 out, due TUESDAY at 2PM
- There will be an optional pre-midterm HW available Tuesday
- No lecture Monday
- Labs as usual on Tuesday
- No lab Wednesday
- Midterm next Friday in class
  - **12:10-1:30 [be on time!]**
  - No electronic devices
  - One 8.5”x11” (or A4) sheet of paper
    - Handwritten anything you want, both sides

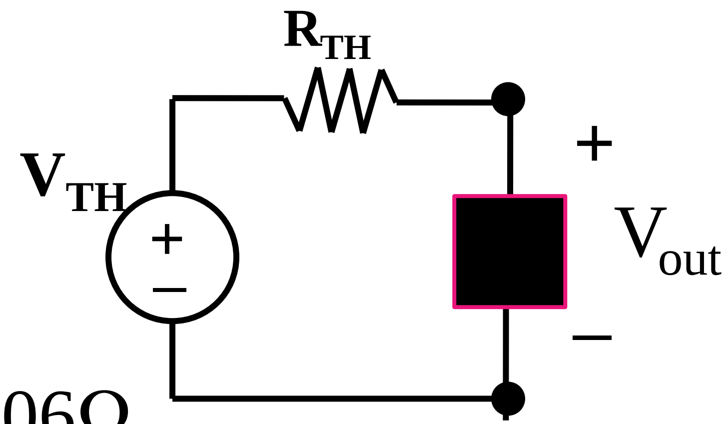
# Op-Amps – How Good Are They Exactly?

- We've been studying ideal op-amps
- Of course, real Op-Amps aren't perfect
  - For example, you can't drive every device in the universe from a real op-amp
- How do we precisely state the quality of a voltage source?
  - Look at its Thevenin equivalent
  - Lower Thevenin resistance is better

# Example: Batteries

- Real voltage sources, like batteries, have a limit to how much current they can draw
  - Called “internal resistance”
  - This internal resistance often varies with charge status, load attached, temperature, and more
  - Just like Thevenin resistance

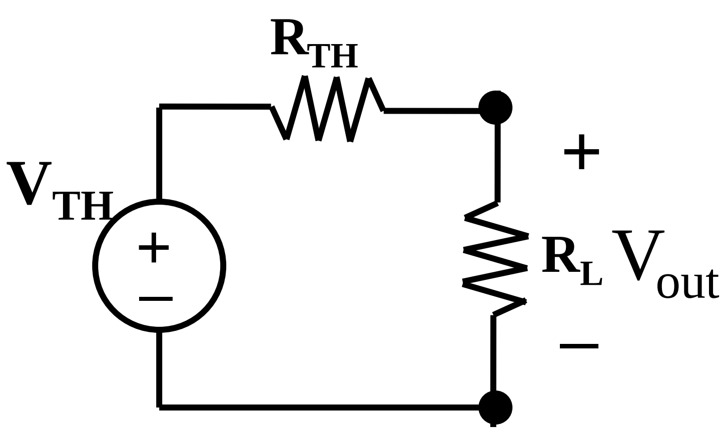
e.g., a car battery supplies 12 Volts, and can supply at most 200 amps, what is its internal resistance?




$12V/200A=0.06\Omega$

# 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:
  - $\frac{99}{100} V_{TH} = \frac{R_L}{R_L+R_{TH}} V_{TH}$
  - $R_L = 99 R_{TH}$

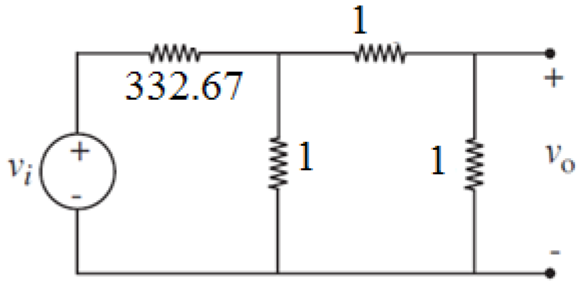


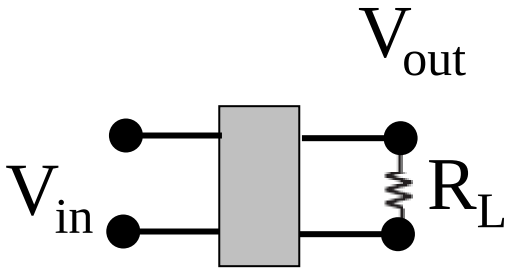

So basically, for loads which are more than 99 times the Thevenin resistance, you get >99% of the Thevenin voltage

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

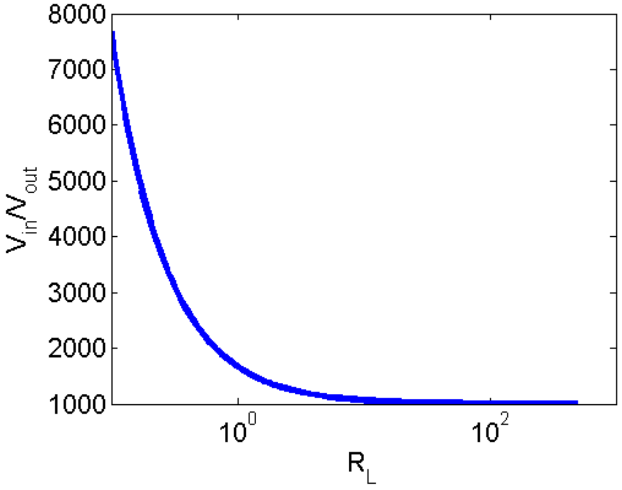
# Source Quality Example

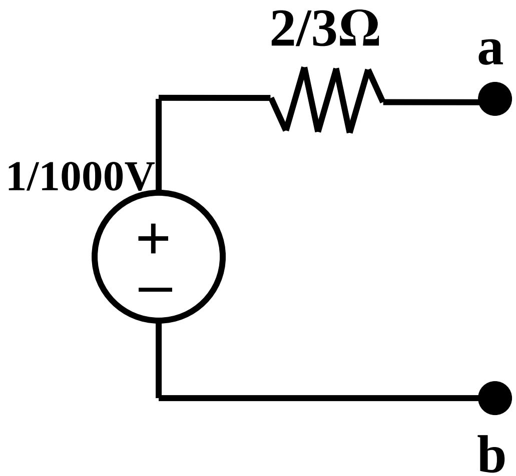
- Everyone's favorite resistive power supply again, $v_o = v_i/1000$




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



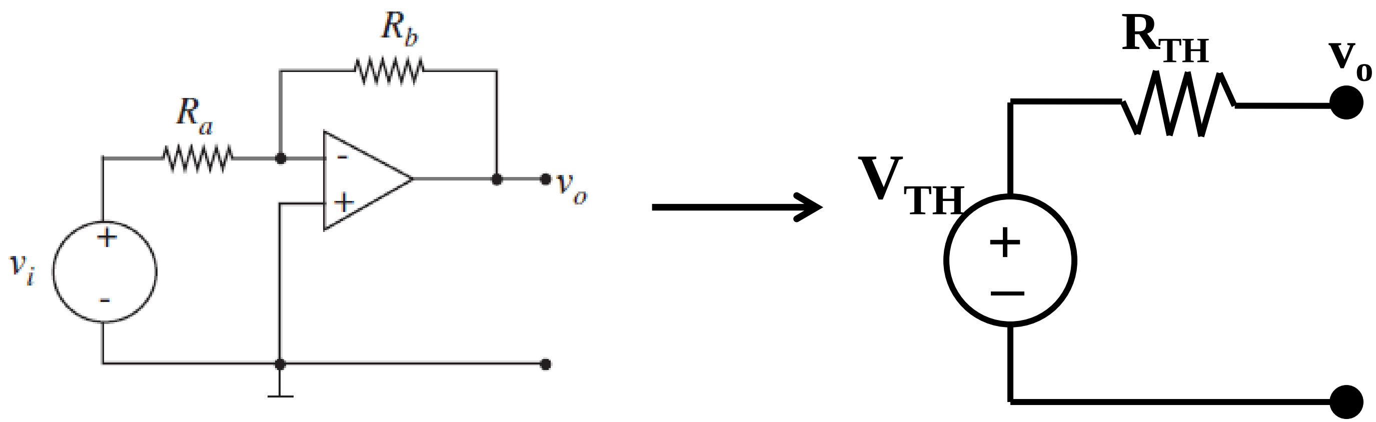




$R_L$=99*2/3Ω=66Ω

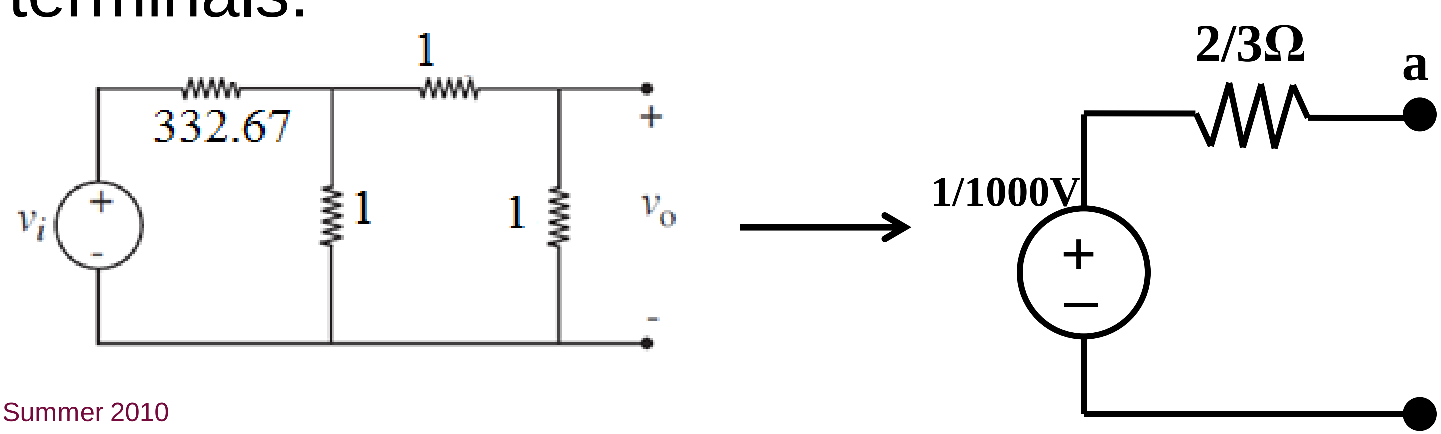
66Ω load gets 99% of $V_{TH}$

# Thevenin Equivalents of Op-Amp circuits

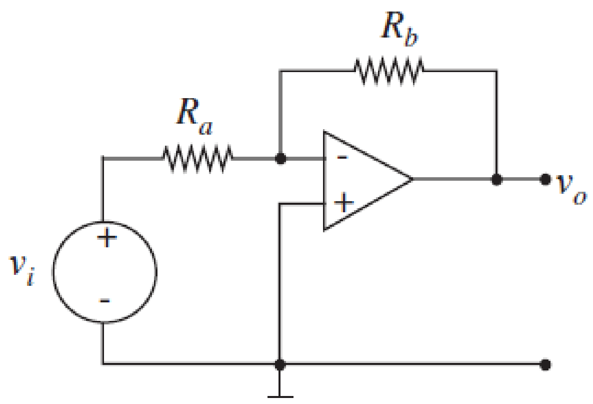
- Can find Thevenin equivalent of an op-amp circuit at its output terminals:

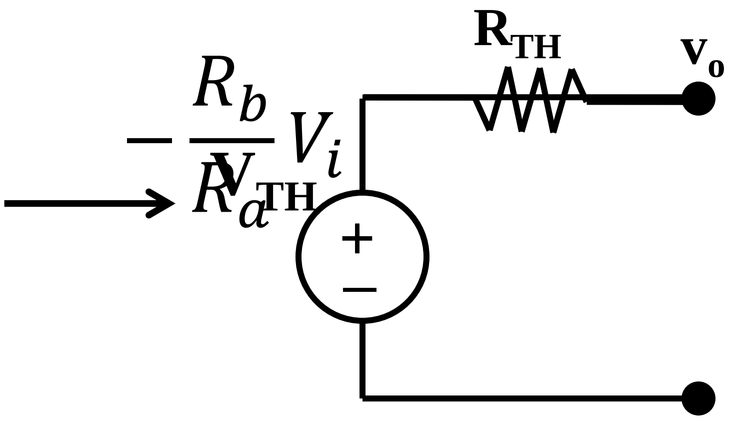



- Just like finding Thevenin equivalent of a simple resistor based voltage attenuator at its output terminals:



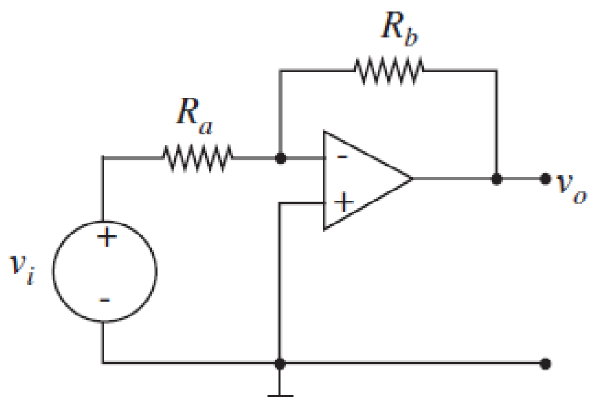
# Thevenin of Inverting Amplifier



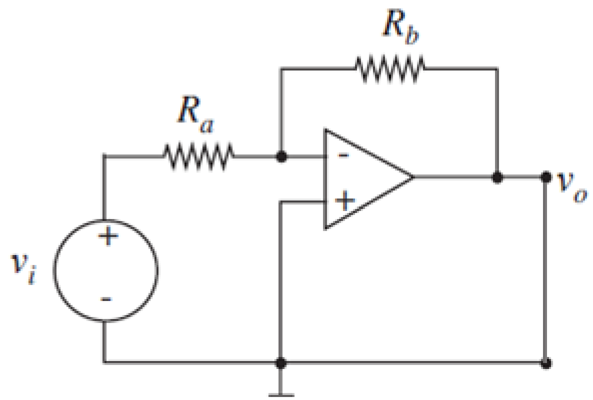




- Assuming that the op-amp here is IDEAL, what's the best way to find the Thevenin equivalent circuit?
  - We've already derived that it's a perfect voltage source!

# But if you really want to…




$$V_{OC} = -\frac{R_b}{R_a} V_{in}$$



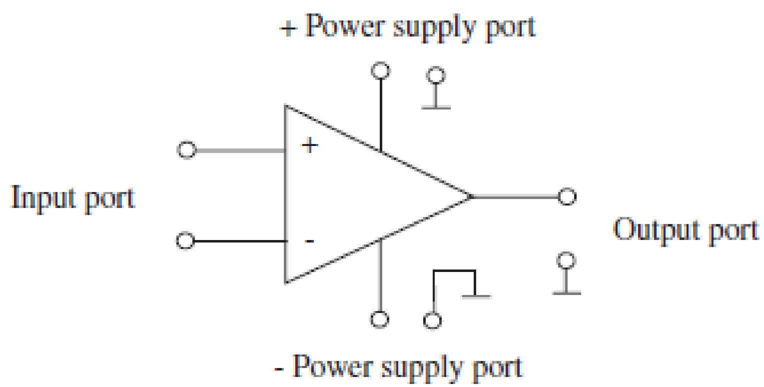

$$I_{SC} = \frac{V_{out}}{0} = \infty$$

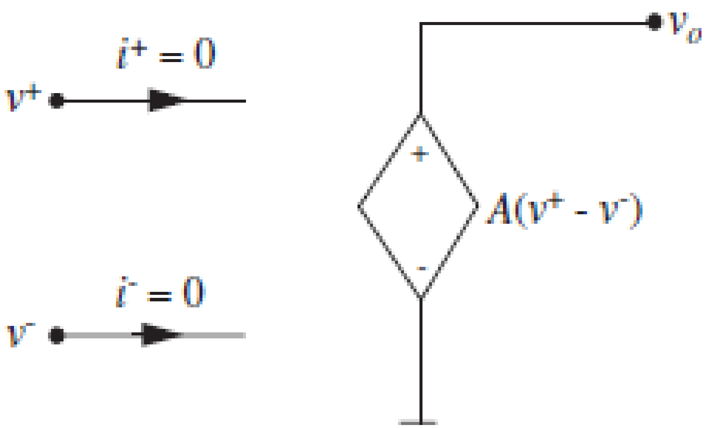
$$R_{TH} = \frac{V_{OC}}{\infty} = 0$$

Technically you should take limits here but we are lazy…

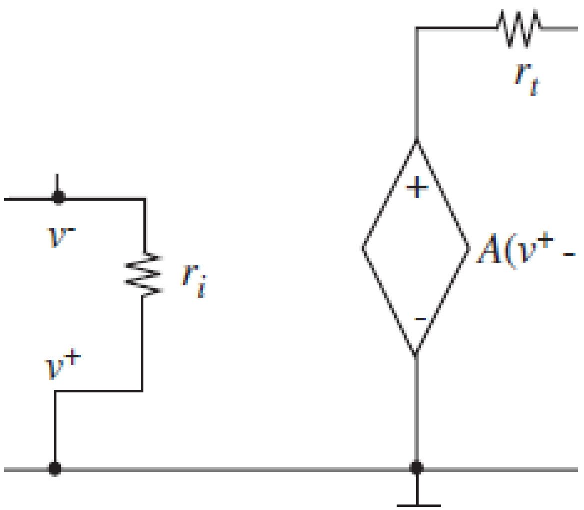
# What's wrong?

- Our op-amp model is missing something
  - That's why it's the "ideal" op-amp model
  - We'll now introduce the "resistive" op-amp model



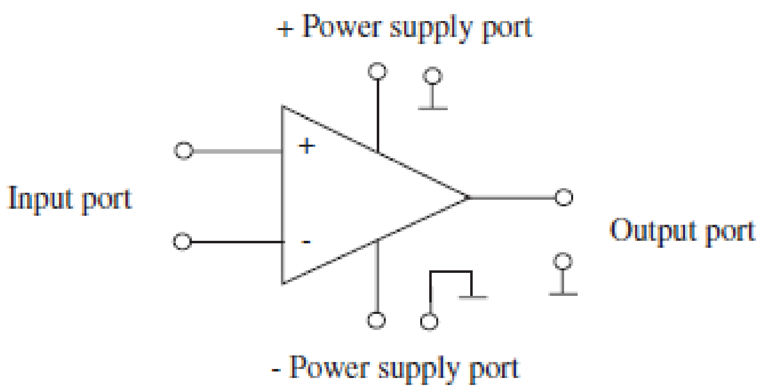



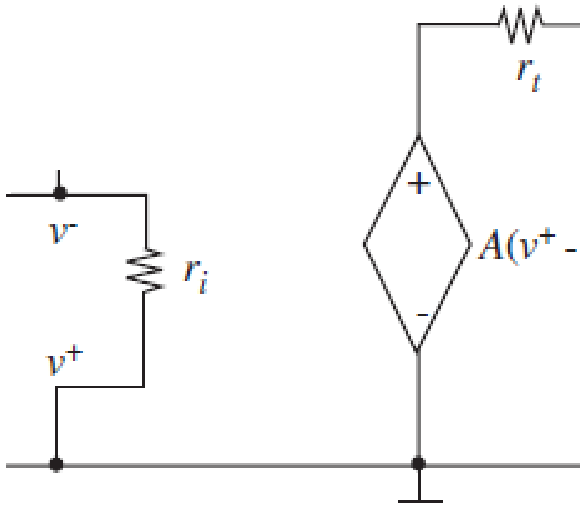

Ideal




Resistive Op-Amp Model

# Resistive Op-Amp model

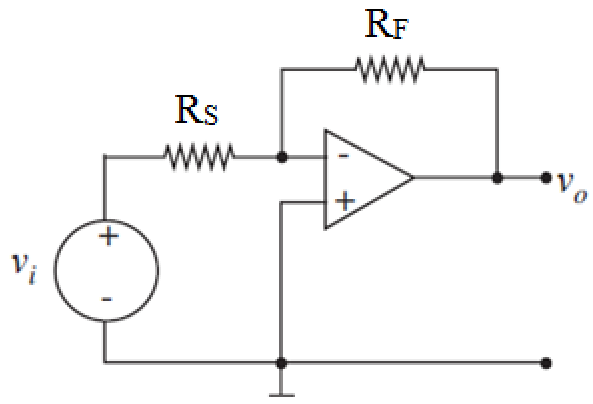



- Takes in to account the fact that
  - Some current flows into the input terminals
  - The op-amp cannot source all device in the universe (output resistance is non-zero)

# Output Resistance of Inverting Op-Amp

- On board (using resistive model of op-amp)



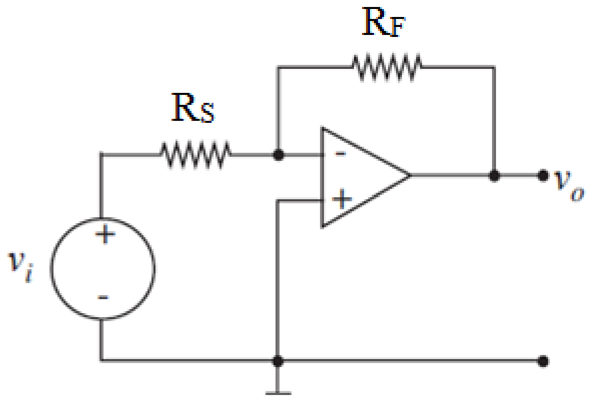

$$R_{out} \cong \frac{R_t}{A\frac{R_s}{R_s + R_f}}$$

- Output Resistance
  - Tells us how small our load can be before we start losing signal fidelity

# Input Resistance

- Resistance at the input terminals of a device
- Tells us how much current will be generated for a fixed input voltage
  - Useful, for example, to find power needed to power a device (at that input)

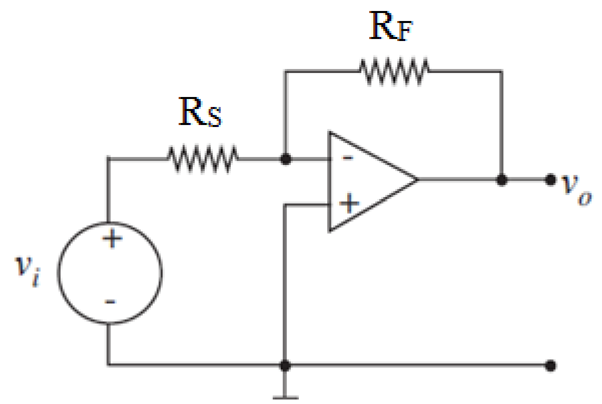
$$R_{in} = R_s$$



# Input Resistance of Inverting Amplifier

- What is the input resistance of an inverting amplifier using ideal op-amp model?

$$R_{in} = R_s$$



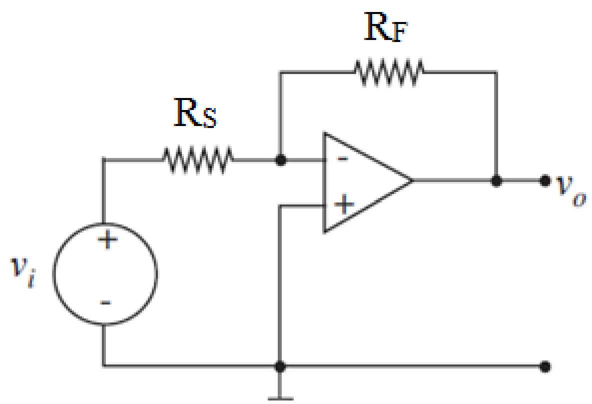

- What is the input resistance of an inverting amplifier using resistive op-amp model?

$$R_i = r_i \parallel (R_f + r_t) \parallel \left( \frac{R_f + r_t}{A} \right)$$

(See sec 15.42 in book)

$$R_{in} \cong R_s$$

# Why are these quantities useful?

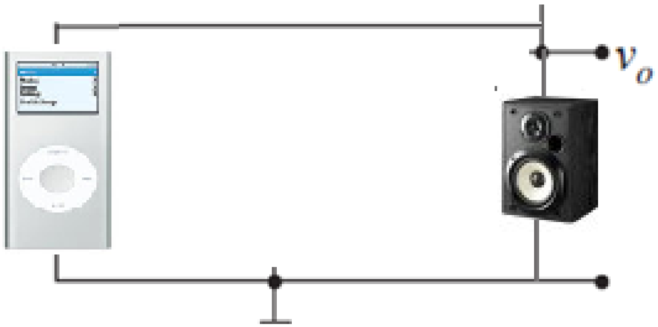



$$R_{in} \cong R_s$$

$$R_{out} \cong \frac{R_t}{A\,\frac{R_s}{R_s + R_f}}$$

- Input resistance tells us how much current (power) our input signal needs to provide
- Output resistance says how small of a load we can drive

# Why are these quantities useful?

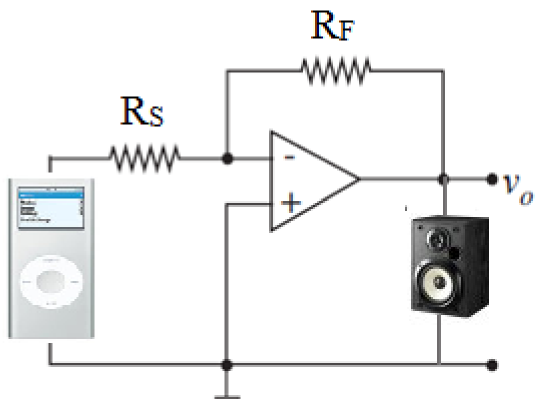



- An iPod provides roughly 1V signal output with 20Ω internal resistance
- Speakers might be 4Ω resistance
- Connect iPod directly to such speakers
  - Internal resistance dominates

$$V_{speaker} = \frac{4}{20+4} \times 1V = 0.17V$$

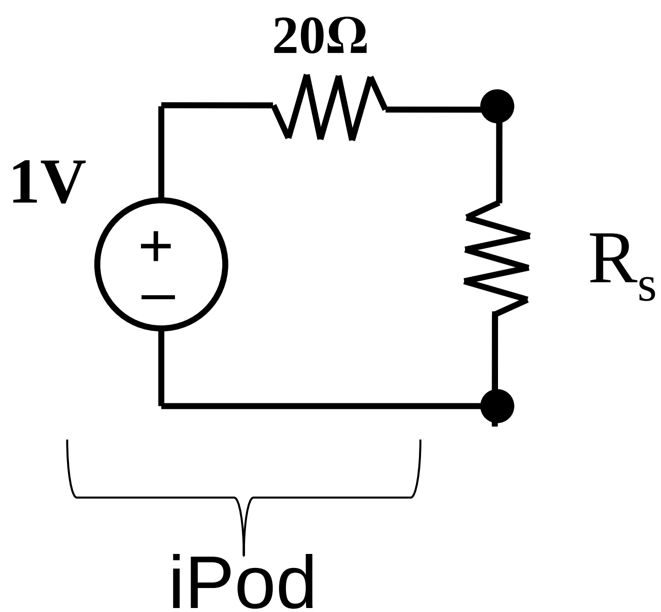
$$P_{speaker} = 0.17^2/4\Omega = 0.0072\ Watts$$

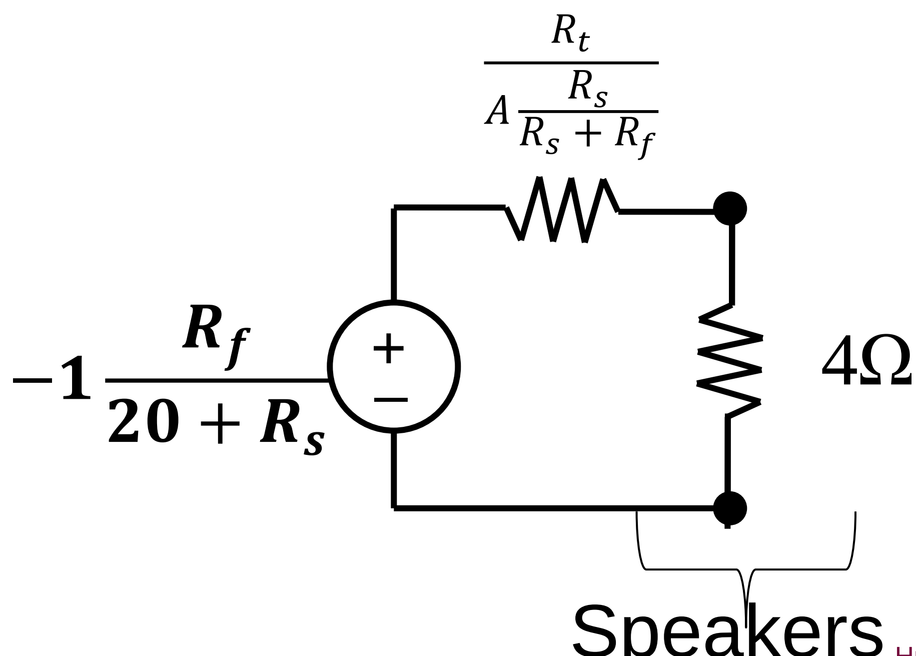
# Why are these quantities useful?



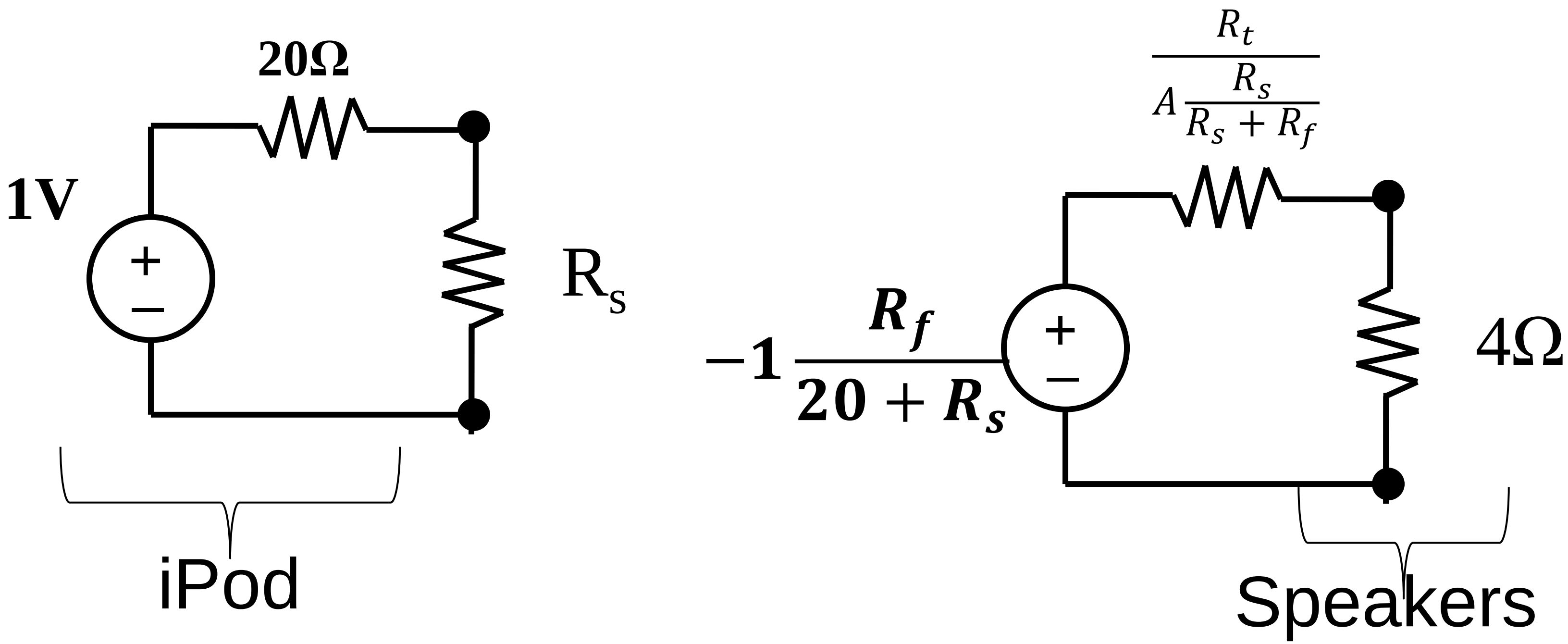

$$R_{in} \cong R_s$$

$$R_{out} \cong \frac{R_t}{A\frac{R_s}{R_s + R_f}}$$



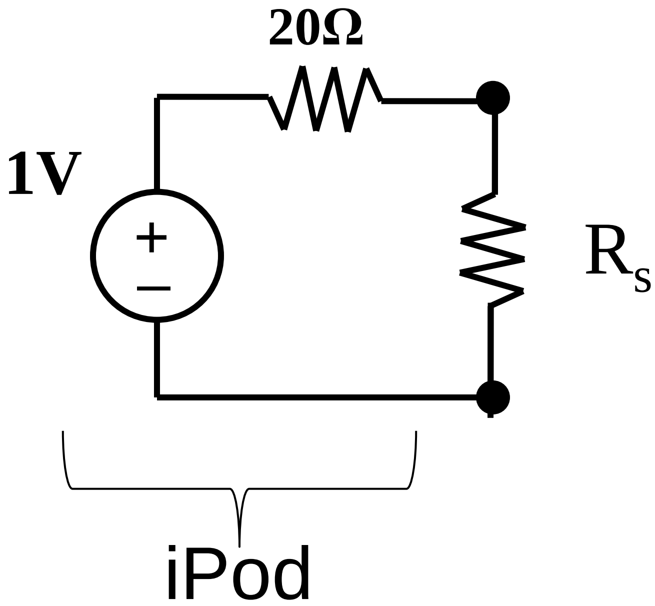



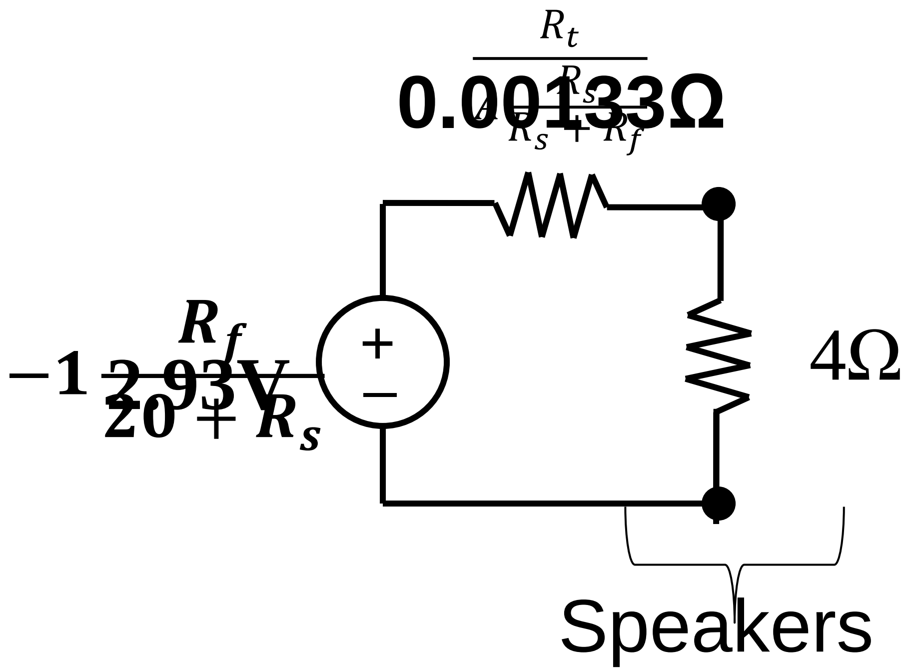
# Bad Amplifier (Small $R_s$)




- Very small $R_s$
  - iPod must supply 50mW
  - Output resistance is large (can’t drive speakers)

# Good Amplifier



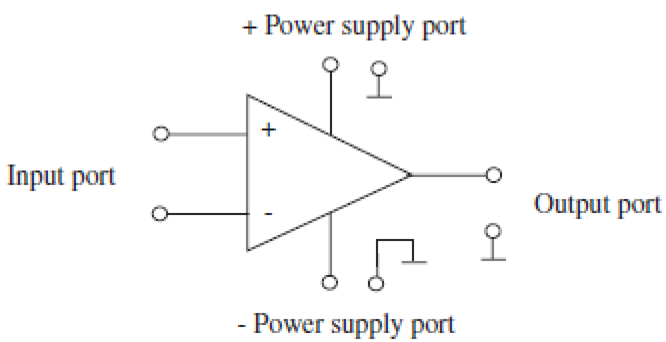



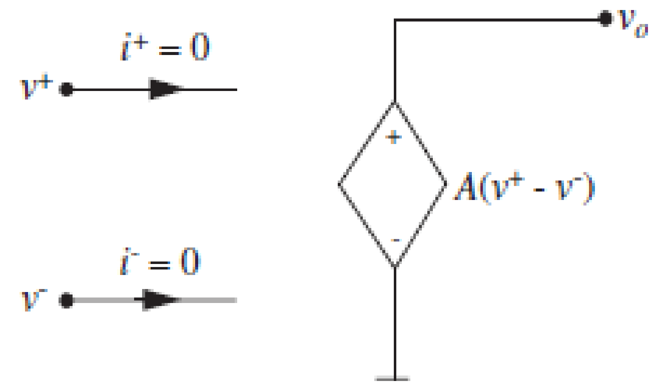

Must provide 1 mW

- $R_s$=1000, $R_f$=3000, $A=10^6$, $R_t$=1000

# Op-Amp Saturation

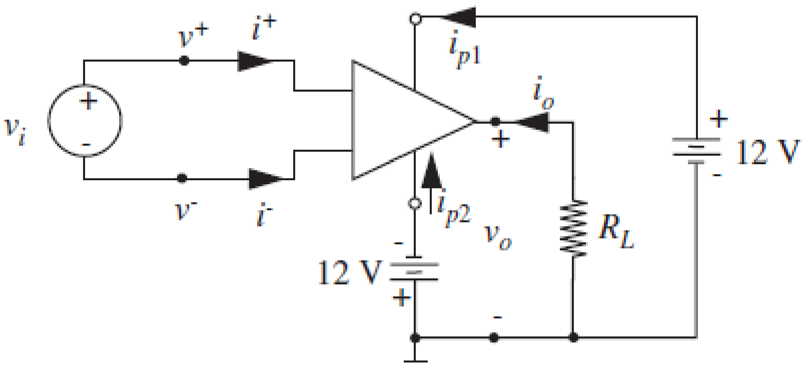
- Remember those power ports we've been ignoring?

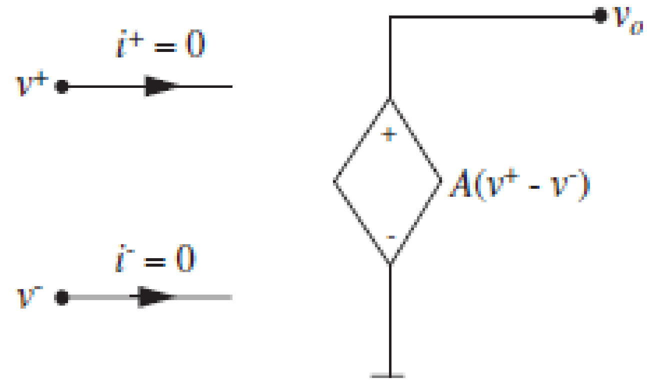



- They specify the maximum and minimum voltage that our op-amp can deliver
  - If $v_{min} < A(v^+ - v^-) < v_{max}$
    - Op-Amp output is $A(v^+ - v^-)$
  - If $A > v_{max}$,
    - Op-Amp output is $v_{max}$
  - If $A < v_{min}$,
    - Op-Amp output is $v_{min}$

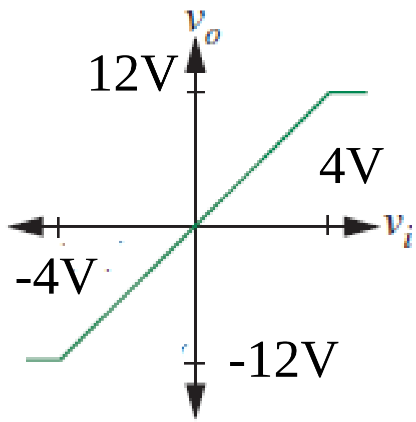
# Op-Amp Saturation Example



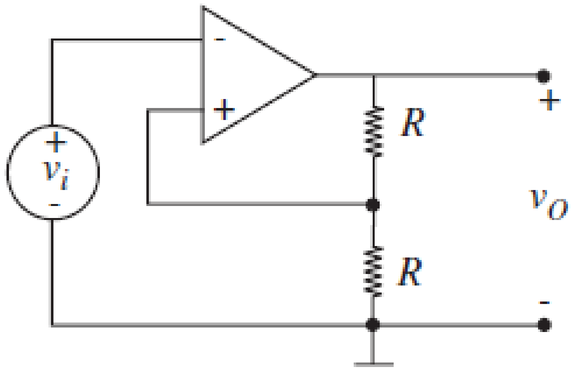




- $v_{max} = 12V, v_{min} = -12V$
- If A=3:

| $V_{in}$ | $V_o$ |
|---|---|
| -5 V | -12V |
| -1V | -3V |
| 2V | 6V |
| 1,512,312V | 12V |



# Positive Feedback




On the board

# That's all forOp-Ampsks

- No class Monday
- Enjoy weekend (doing op-amp problems)