(S03-057)

6.002 Lecture Notes
Thursday April 24, 2003
Joel Schindall

First, a few general thoughts regarding this unit on operational amplifiers (op-amps).

How do engineers (and others) deal with design and analysis of large, complex systems?
- Break large systems into [relatively] independent subsystems
  - Sometimes called "modules," or "blocks," or "layers."

This happens all the time.
- Divide automobile into engine, transmission, power steering, braking, electrical
  - Different cross-sections depending on questions asked
    - Electrical contains elements from engine, transmission, etc.
    - Reference is "Zen and the Art of Motorcycle Maintenance
      - By Robert Persig.
- In software design, divide software into layers
  - e.g. BIOS, then DOS or Windows (op sys), then word processor (app)
- In hardware design, divide circuit into blocks (block diagram)
  - Radio has antenna, RF, LO, mixer, IF, detector, amp, PA.

Many mechanical designs use high gain amplifier plus negative feedback
- Power steering
- Cruise control
- Control of many biological processes
- PEOPLE (you and me)
  - Catching a baseball
  - Wheelchair tennis
  - Lifting your arm to a set position (we'll try this in class!)

Development of integrated circuits led to design of integrated op-amps
- Credited to Bob Pease, MIT '61, in late '60's
  - Devices were 702, 709, 741 (still used!)
  - Pease still at National Semiconductor, still writes informative columns
- Excellent example of compartmentalization
- Could achieve result with fewer transistors but
  - Gain block is easy to design with
  - Transistors are "cheap" to incorporate on IC
  - Mass production is efficient
  - Feedback allows consistent transfer function despite op-amp inaccuracies
    - (see homework problem 10.1)

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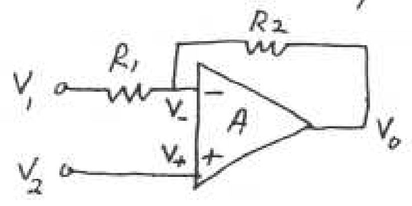
Quick review of simple op-amp configurations

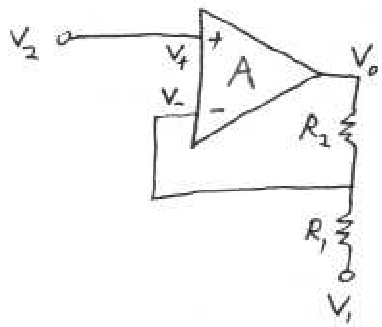
(A)



With $V_2 = 0$, this is an inverting amplifier

For $A \gg \frac{R_2}{R_1}$, $V_- \approx V_+$ and $V_o = -\frac{R_2}{R_1} V_1$

(B)



With $V_1 = 0$, this is a non-inverting amplifier

For $A \gg \frac{R_1 + R_2}{R_1}$, $V_- \approx V_+$ and ~~$V_o =$~~

$$V_o = \left(1 + \frac{R_2}{R_1}\right) V_2$$

from voltage across R_1 from voltage across R_2

What if we use (A) with $V_1 = 0$ and input is V_2?

Then it's the identical circuit to (B), just drawn differently

What if we use (B) with $V_2 = 0$ and input is V_1?

Then it's the identical circuit to (A), just drawn differently

By superposition

$$V_o = -\frac{R_2}{R_1} V_1 + \left(1 + \frac{R_2}{R_1}\right) V_2$$

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Actual op-amp circuits have <u>output</u> <u>resistance</u>

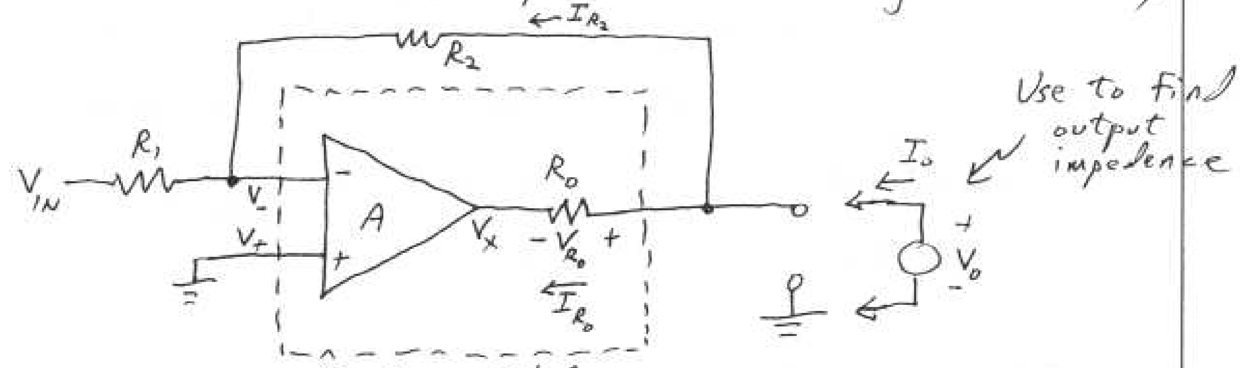
[Show 741 schematic diagram]

But the negative feedback causes op-amp to do "whatever it takes" to achieve $-\frac{R_2}{R_1} V_{IN}$ (inverting case)

This significantly reduces the effective output resistance

[but not under all conditions, as we shall demonstrate]

Let's examine op-amp with negative feedback
Will use external output resistor to gain visibility



Op-Amp with R_0

Can make Thevenin equivalent

With $V_{IN}=0$, connect V_0 to output and calculate I_0

V_0 at output $\rightarrow \frac{R_1}{R_1+R_2} V_0$ at V_-

Which produces $-A\frac{R_1}{R_1+R_2} V_0$ at V_x

So $V_{R_0} = V_0 - \left[-A\frac{R_1}{R_1+R_2}V_0\right] = V_0\left[1+A\frac{R_1}{R_1+R_2}\right]$

and $I_{R_0} = \frac{V_0}{R_0}\left[1+A\frac{R_1}{R_1+R_2}\right]$

$$I_0 = I_{R_0} + I_{R_2} = \frac{V_0}{R_0}\underbrace{\left[1+A\frac{R_1}{R_1+R_2}\right]}_{\approx A\frac{R_1}{R_2}} + \underbrace{\frac{V_0}{R_2}}_{\text{small}}$$

So $\frac{V_0}{I_0} \approx \frac{R_0}{A\left[\frac{R_1}{R_2}\right]}$ inverse gain

What is going on?

V_o at output pulls right end of R_o "up" by V_o volts

But this pulls V_- up by $\frac{R_1}{R_1+R_2}$ volts, which

is approx the inverse gain of the amplifier

This ~~pro~~ is amplified by the op-amp, pulling

the left side of R_o down by $A \times$ [inverse gain]

If gain = 100 and $A = 10^5$

left side of R_o goes down by 1000 V_o

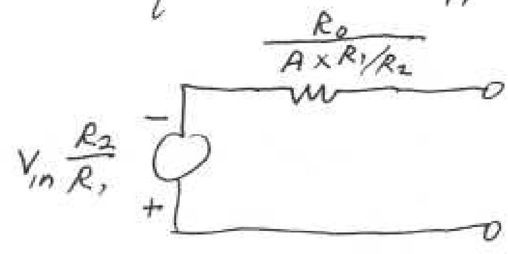
So R_o pulls 1001 times the current that it

would pull if connected to ground

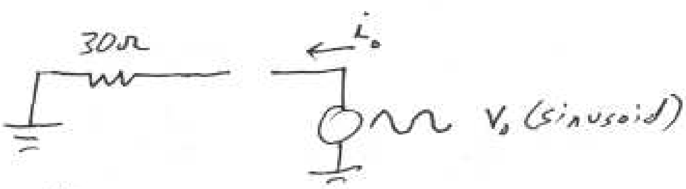
Feedback makes R_o ~~not~~ act like $\frac{R_o}{1001}$

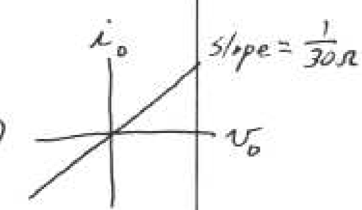
$30\Omega \rightarrow 30$ milliohms

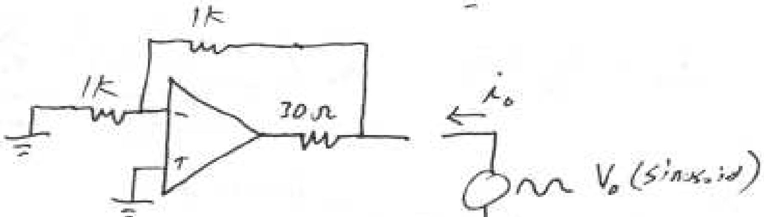
Thevenin equivalent is approx

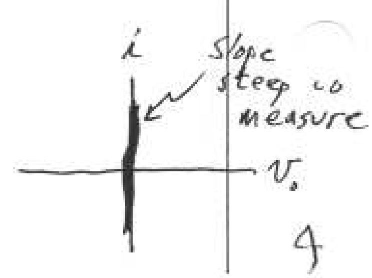


$\boxed{\text{DEMO \#1}}$

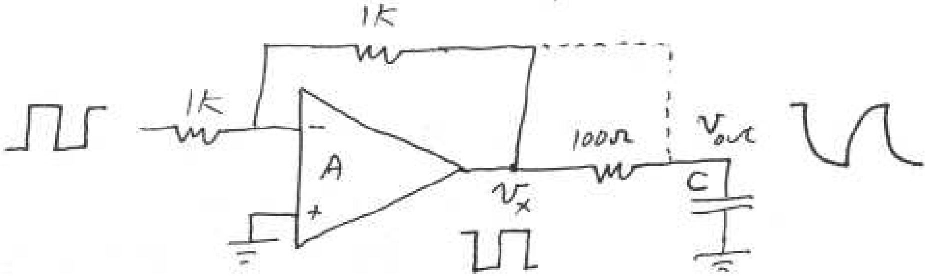








What if we use an op-amp with square wave V_{IN} to drive a capacitor? Start with 100Ω "output resistance" outside the feedback loop



Now connect the feedback directly to the capacitor, as shown by the dotted line

If $A = 10^6$, should reduce output impedance from

$100\,\Omega$ to $200\,\mu\Omega$

Would expect this to force square wave at capacitor, right?

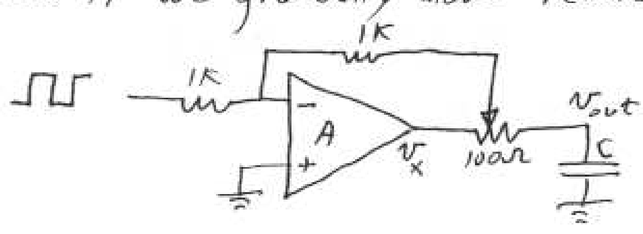
Wrongo!

[Student Fill in waveform here] →

Why is this?

[Discussion in class]

What if we gradually move feedback from V_x to V_{out}



V_{out} starts as and improves to

V_x starts as and moves to to provide additional charging current to C

But eventually the V_x peaks hit the op-amp voltage limits

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Op-Amp ~~an~~ circuit analysis

Start with what you know

(input voltage, etc.)

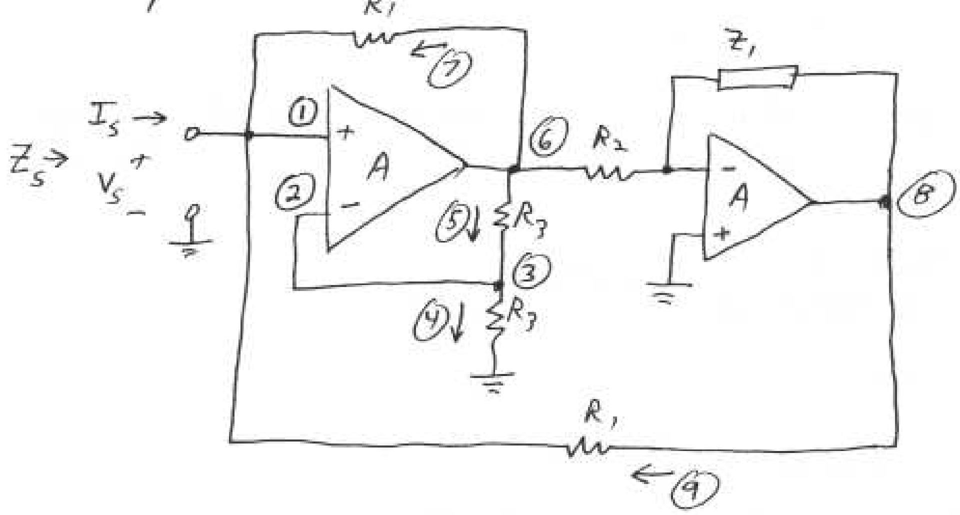
Move where circuit constraints "help" you

$V_+ = V_-$ $\quad i_{in} = 0$ at op-amp
(in active region with feedback)

It's like the game of minesweeper

[describe]

Example "Gyrator"



Flow is from (1) to (2) to ... to (9)

Every step is easy