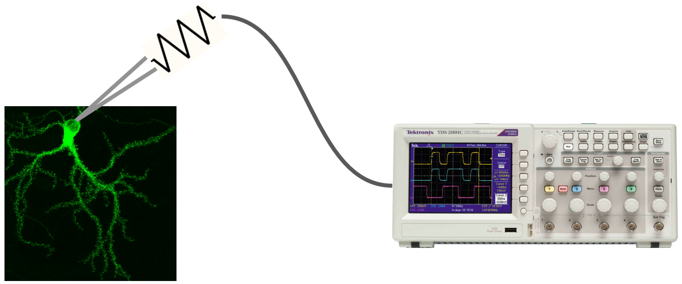
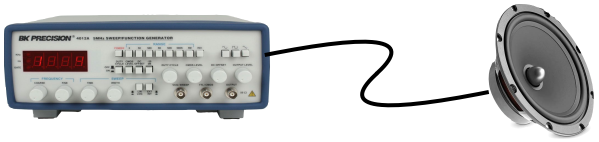
Operational Amplifiers
(Op Amps)

Why Amplifiers?

Problem:
Attenuated Signal

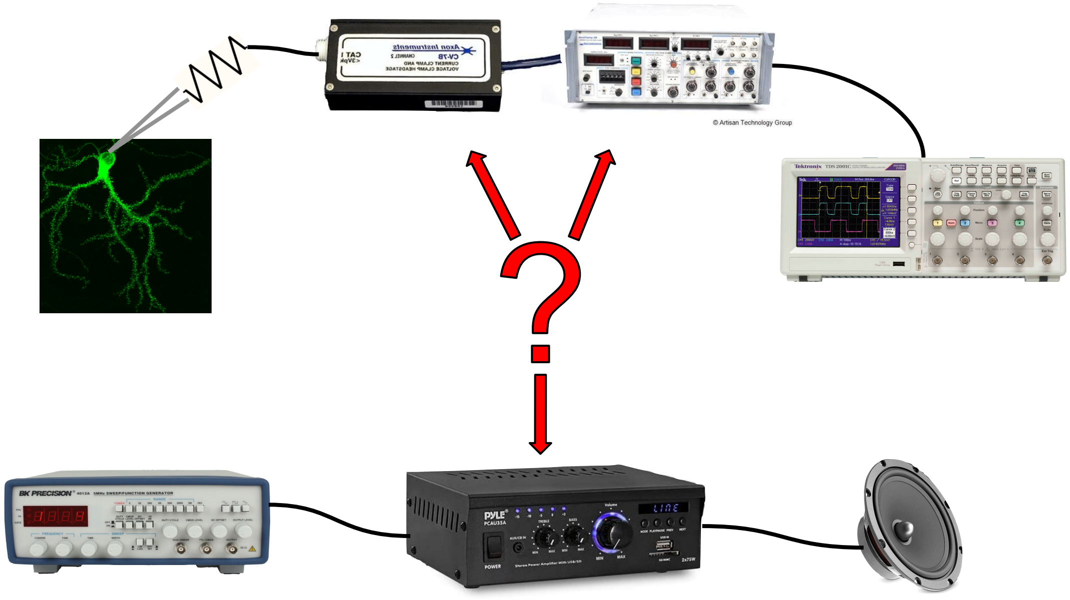


"Very Weak" Source **"Standard" Readout**



"Standard" Source **"Power-Hungry" Readout**

Solution:
Amplifiers



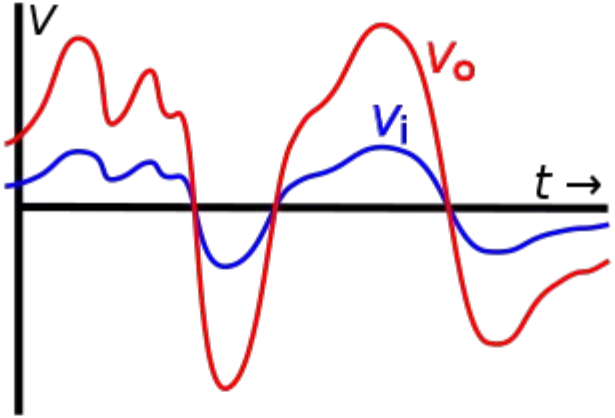
What is an Amplifier?

- Active electronic device that increases the power of a signal
- Input and output signals can be current or voltage and need not be the same type
- Gain is the ratio of output to input. Can have units or be unitless

$$P_{Out} > P_{In}$$

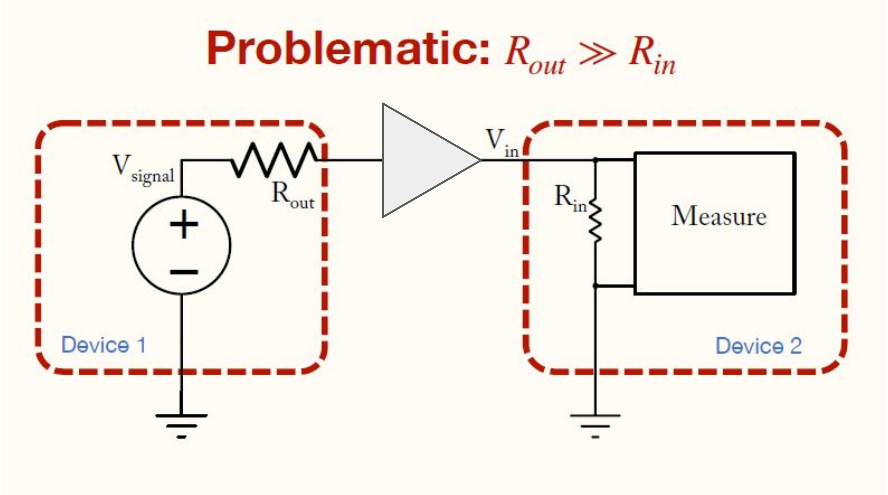
$$I_{Out}V_{Out} > I_{In}V_{In}$$

$$G_v = V_{out}/V_{in}$$



https://en.wikipedia.org/wiki/Amplifier

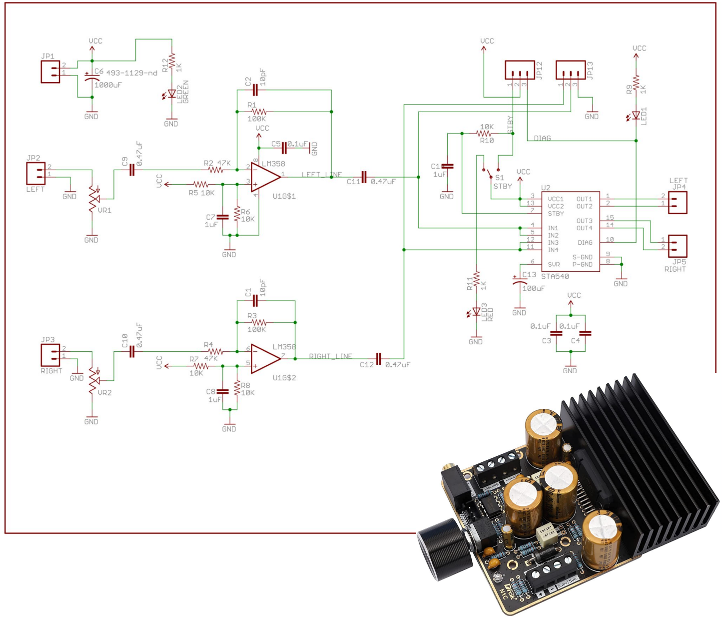
How is an Amplifier Used?



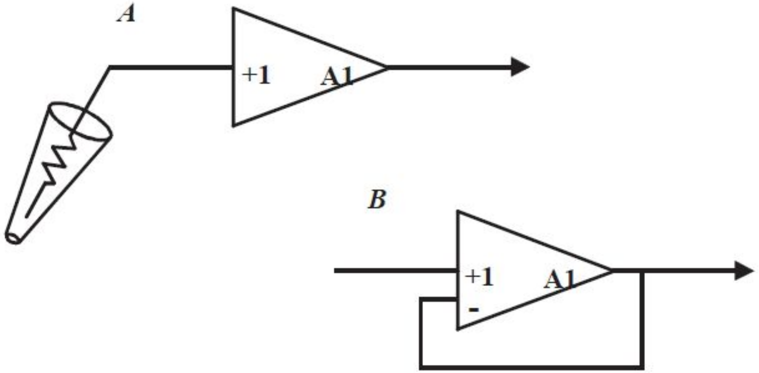
- Signal conditioning
  - Correct mismatched source and load impedance (e.g. micropipette electrode)
  - Reduce noise susceptibility (e.g. high impedance signal over long cable)
  - Increase voltage signal amplitude
  - Convert units (e.g. current to voltage)
- Power amplification
  - Drive a speaker
  - Step-up voltage (e.g. piezo transducer)
  - Radio Frequency (cell towers, radio broadcast, deep space communication)

What is All This?

Speaker demo

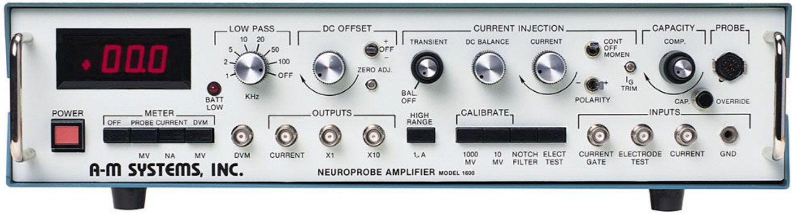


What are the knobs
and symbols?



Ideal Amplifier Characteristics

- Linearity (signal shape is not distorted)
- High input impedance and Low output impedance
- Power
- Bandwidth (amplifier must be ‘faster’ than the fastest signal)

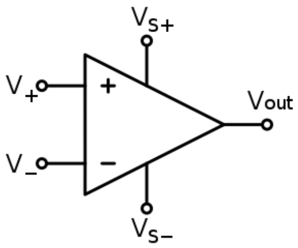


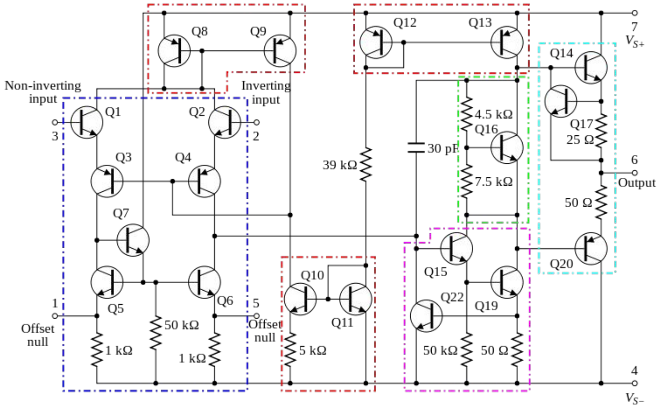
Amplifier must be appropriately suited to the signal it’s amplifying. Multiple amplifier designs exist. Op Amps – a common building block.

Op Amps - Intro

- Analog, general-purpose integrated circuits (ICs)
- 2 input terminals, 1 output (some also have additional adjustment pins)
    - Differential input, single ended output
- Require power and a few external components
- Analog engineer’s building block

	Transistor Count
Op Amp	<100
Arduino	~10^6
CPU	~10^9



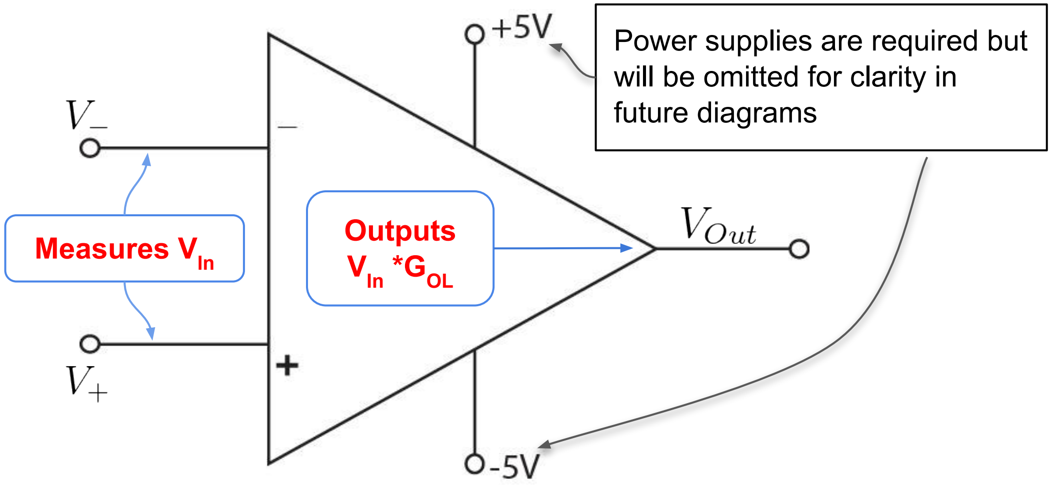


Op Amps - Ports and Transfer Function

Inverting Input: V_-

Non-inverting Input: V_+

Open-loop Gain: G_{OL}



$$V_{Out} = G_{OL} * (V_+ - V_-)$$

Open-loop gain is a large number (10^5-10^7) which is not precisely known. Circuit designs do not rely on exact open-loop gain value.

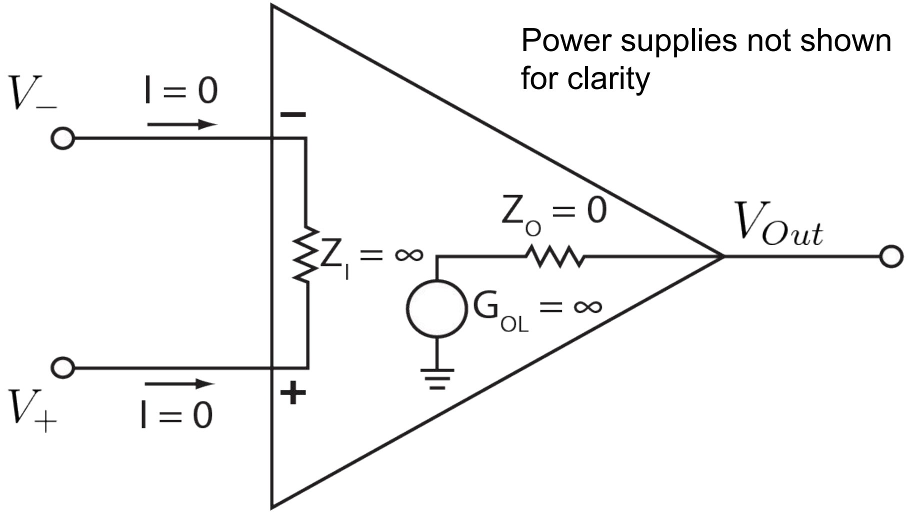
Idealized Op Amp Model

Infinite input impedance Z_I

Zero output impedance Z_O

Infinite open-loop gain

Infinite bandwidth



Power supplies not shown for clarity

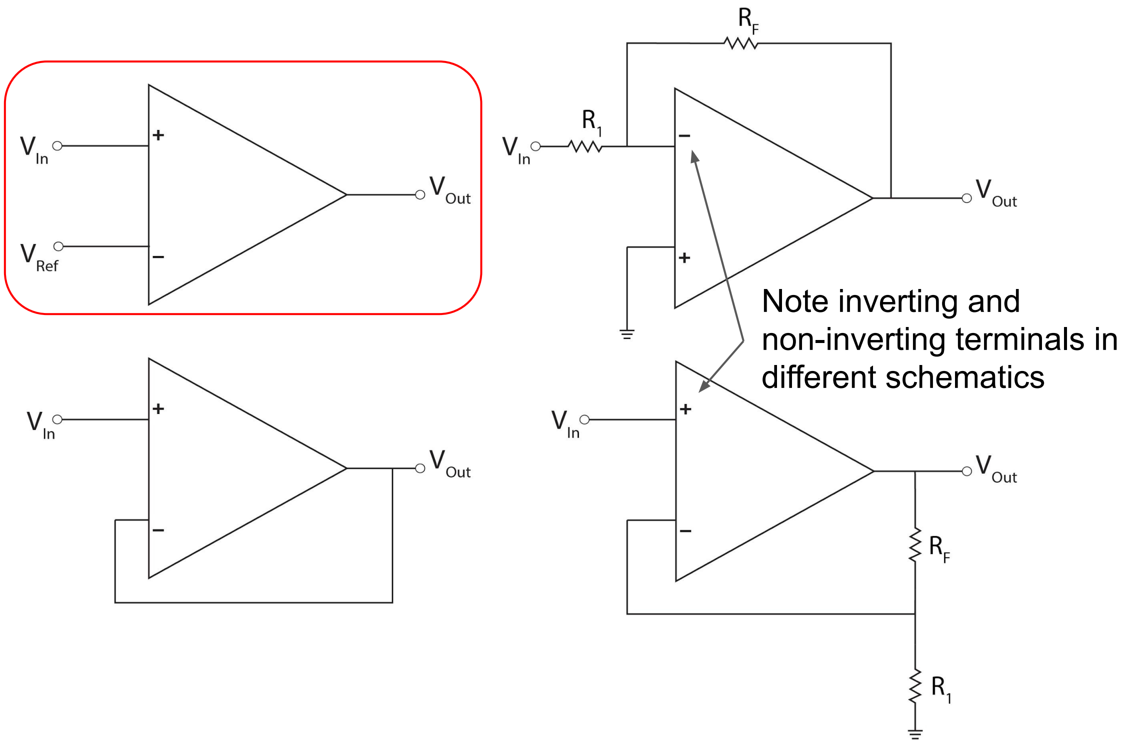
$$V_{Out} = G_{OL} * (V_+ - V_-)$$

Op Amp Circuits

Key concept: Most Op Amp circuits require external components to build a feedback network. The full circuit behavior is dependent on the specific Op Amp and the external feedback network.

Design Goal: When appropriately designed, system behavior is invariant to specific Op Amp details and is fully specified by the external feedback components.

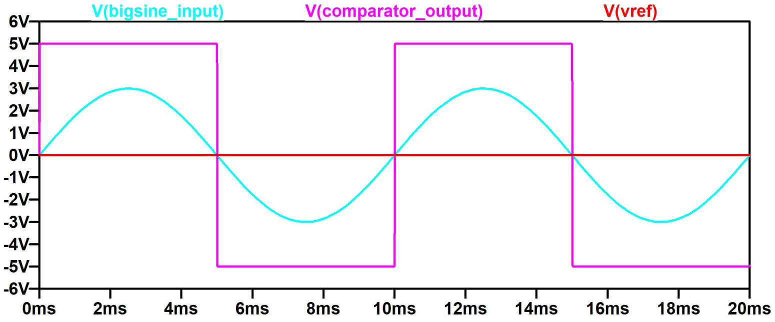
Golden Rule: With proper feedback, Op Amp "tries" to bring both inputs to same voltage

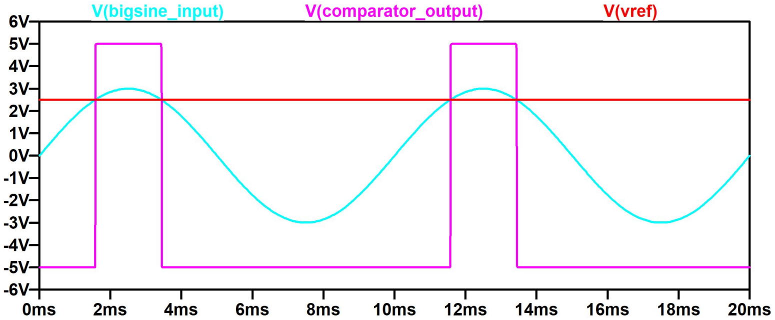


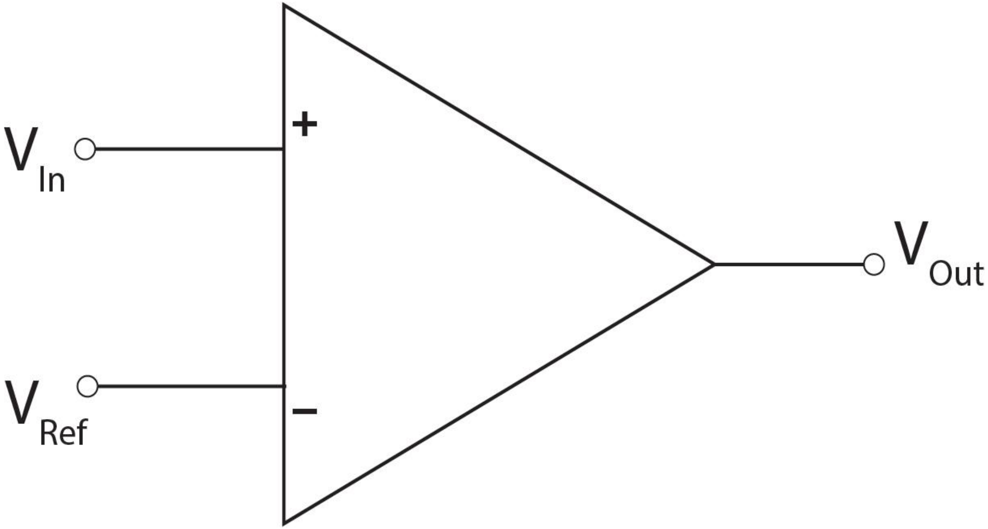
A given Op Amp can be configured with external components to build different amplifiers/circuits

Op Amp Circuit Topology: Comparator

Op Amps are (almost) never used in open loop (i.e. without feedback). Circuit behaves as a comparator (threshold detector).







Supply	$\pm 5V$
Input Z	$500 M\Omega^*$

* Dependent on specific Op Amp

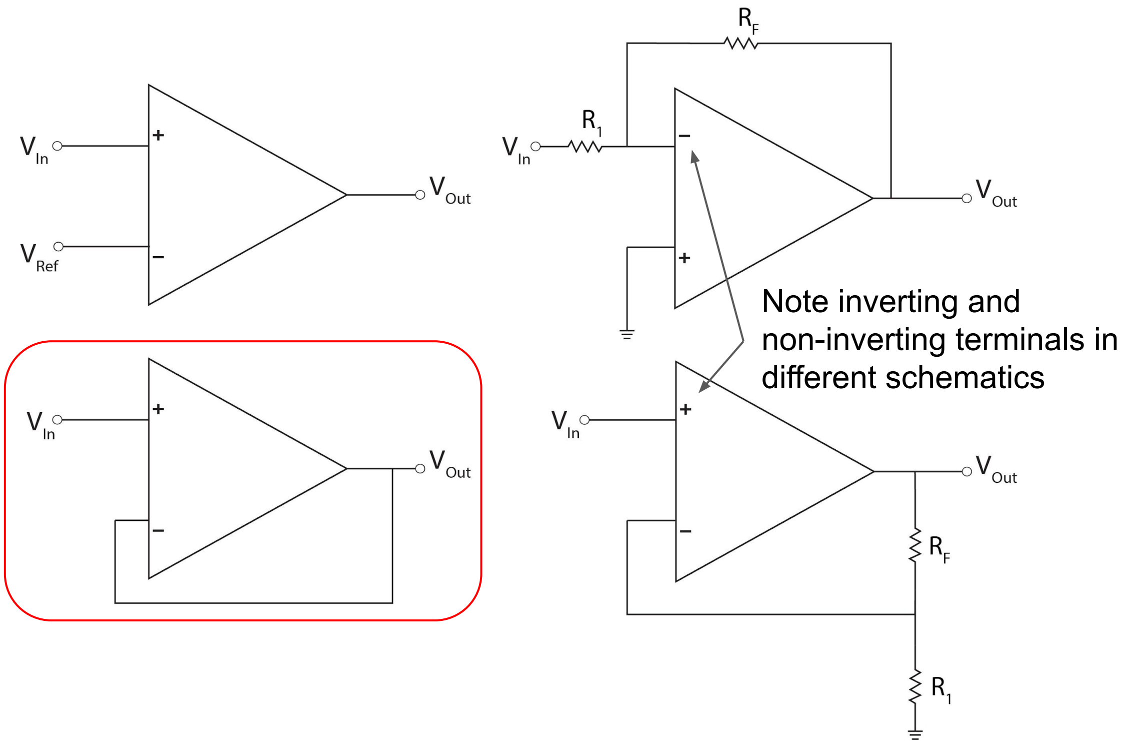
http://falstad.com/circuit/e-opamp.html

Op Amp Circuits

Key concept: Most Op Amp circuits require external components to build a feedback network. The full circuit behavior is dependent on the specific Op Amp and the external feedback network.

Design Goal: When appropriately designed, system behavior is invariant to specific Op Amp details and is fully specified by the external feedback components.

Golden Rule: With proper feedback, Op Amp “tries” to bring both inputs to same voltage



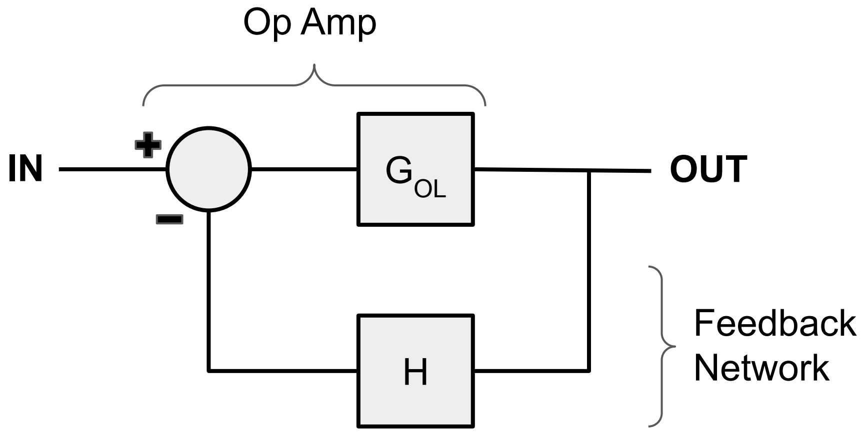
Flexibility and utility of Op Amp circuits comes from incorporating feedback

Negative Feedback

Why Feedback?

Op Amp gain is not precisely known, is variable, and is outside of our control

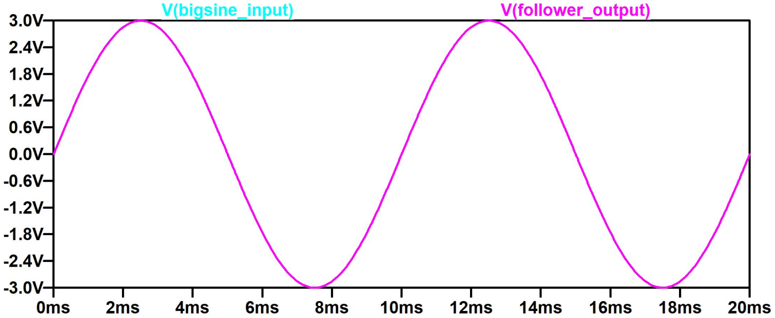
- Fraction of the output is **subtracted** from the input
- G_{OL} and H are complex-valued functions
- G_{OL} is the Op Amp open-loop gain
- If $G_{OL}H \gg 1$, the system behavior will be governed solely by the feedback network H

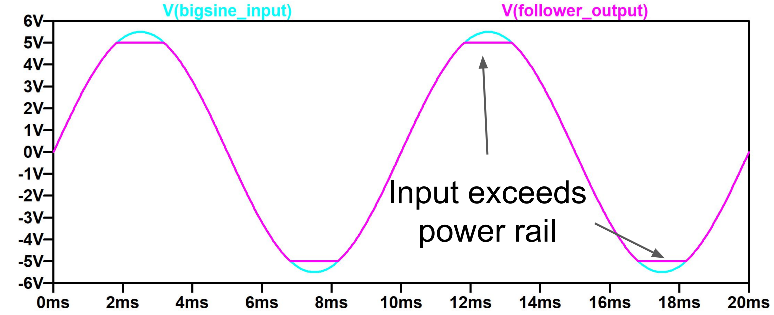


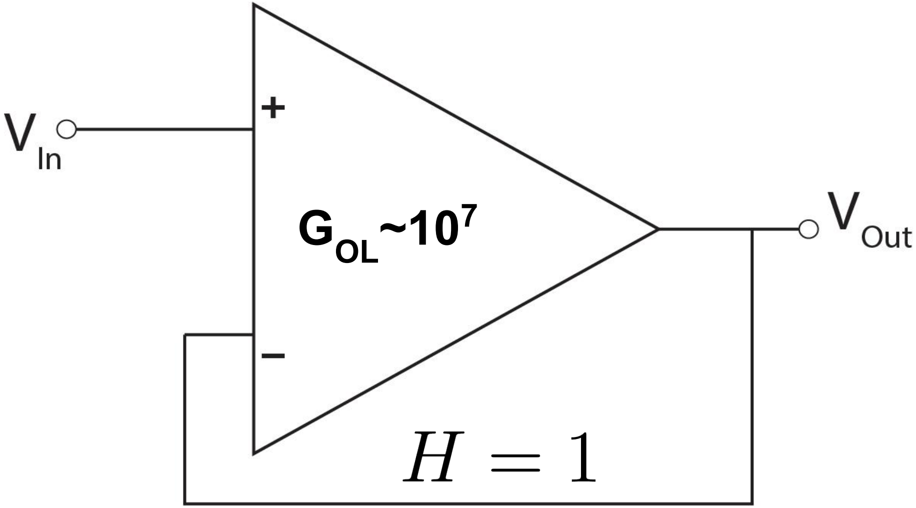
Circuit Gain: $$\frac{OUT}{IN} = \frac{G_{OL}}{1 + G_{OL}H} \approx \frac{1}{H}$$

Op Amp Circuit Topology: Buffer

Output is “fed back” to the inverting input. Output “follows” input with voltage gain = 1. This topology can provide current gain and low output impedance. Input impedance is high. Useful as preamplifier.







$$\frac{V_O}{V_I} = \frac{G_{OL}}{1 + G_{OL}H}$$

$$\frac{V_O}{V_I} = \frac{G_{OL}}{1 + G_{OL}} \approx 1$$

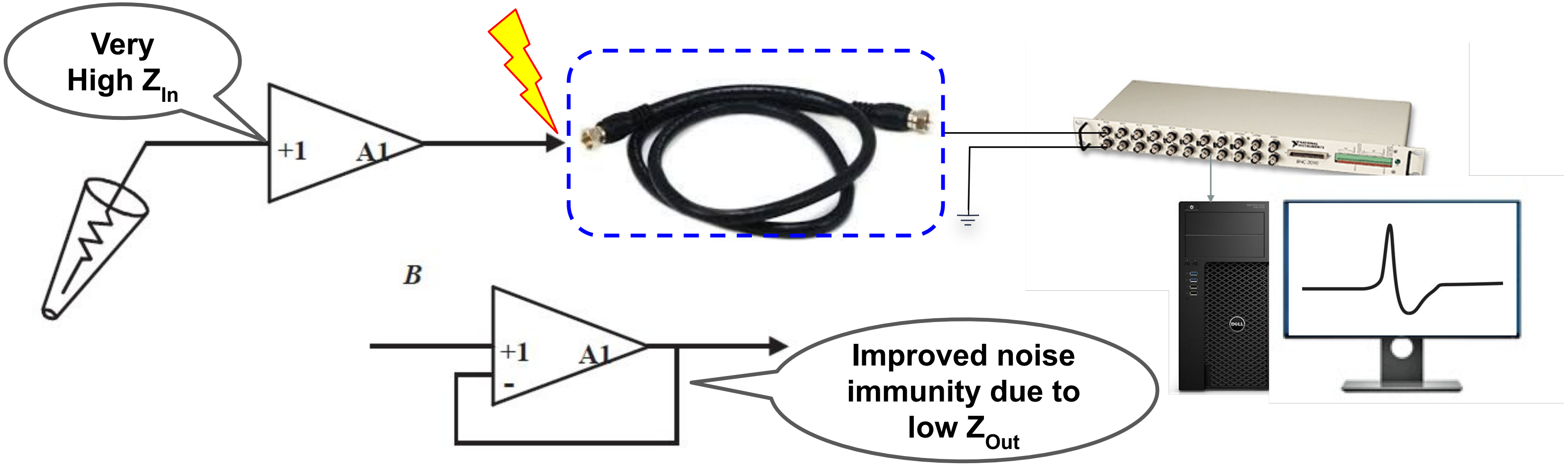
$$V_{Out} = V_{In}$$

https://tinyurl.com/y52lcy2p

Buffer Examples

What's the use of replicating a voltage signal?

- Amplifies power of signal
- Signal conditioning: "fixes" impedance, reduces noise susceptibility
- Used as 1x pre-amplifier in a headstage. Front end for intracellular recording amplifier. Can be combined with current source to make current clamp amp.

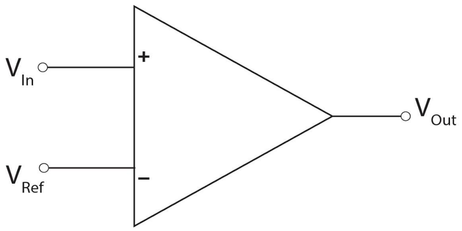


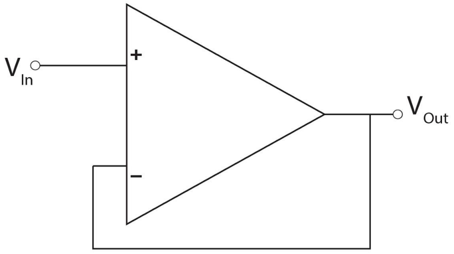
Op Amp Circuits

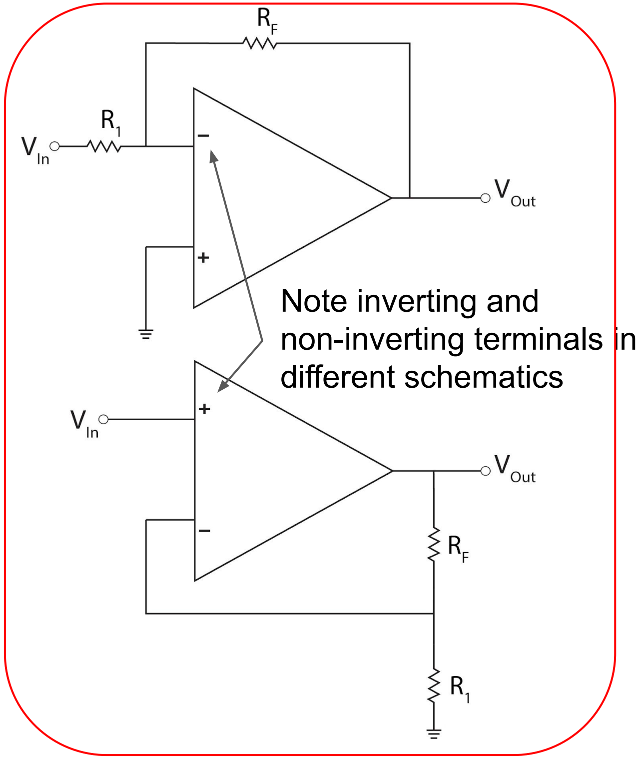
Key concept: Most Op Amp circuits require external components to build a feedback network. The full circuit behavior is dependent on the specific Op Amp and the external feedback network.

Design Goal: When appropriately designed, system behavior is invariant to specific Op Amp details and is fully specified by the external feedback components.

Golden Rule: With proper feedback, Op Amp "tries" to bring both inputs to same voltage



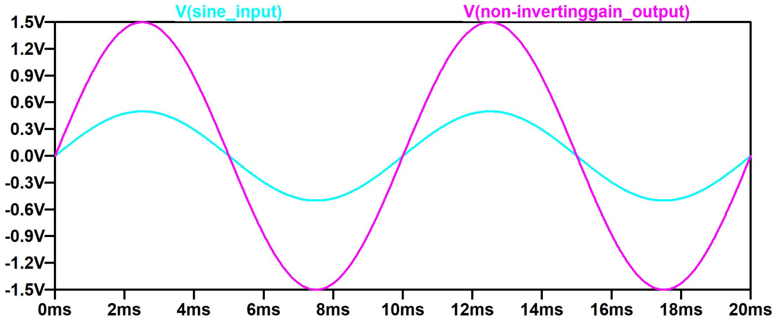




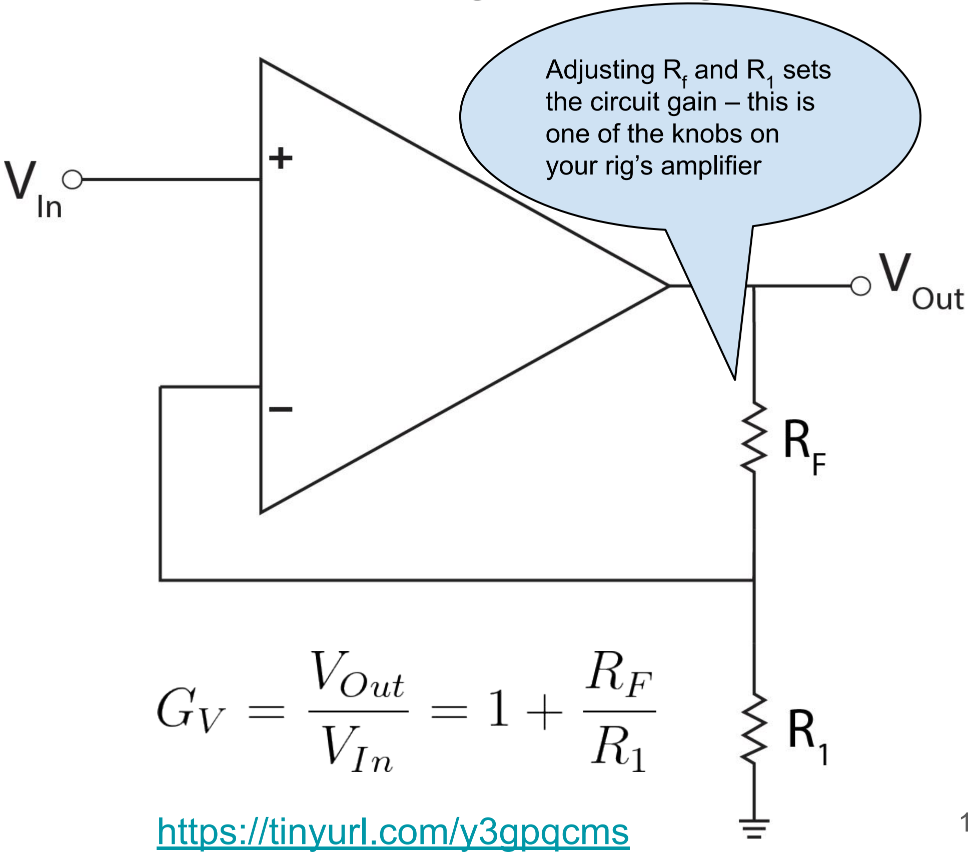
A given Op Amp can be configured with external components to build different amplifiers/circuits

Op Amp Circuit Topology: Non-inverting Voltage Gain

- Fraction of V_{Out} is fed back to inverting input
- Gain determined by external resistor network
- Input impedance determined by Op Amp (high)



V_{In}	$\pm .5V$
R_F, R_1	20K, 10K
G_V	3

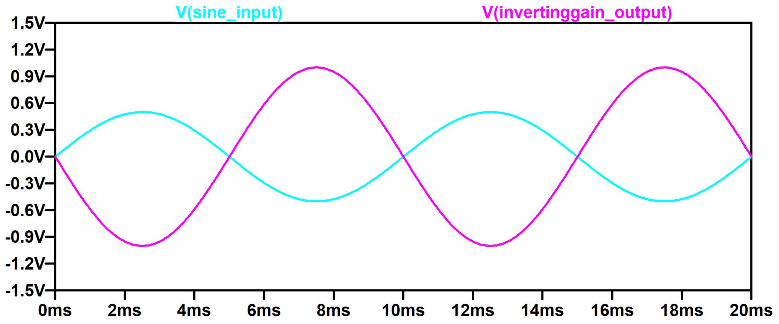


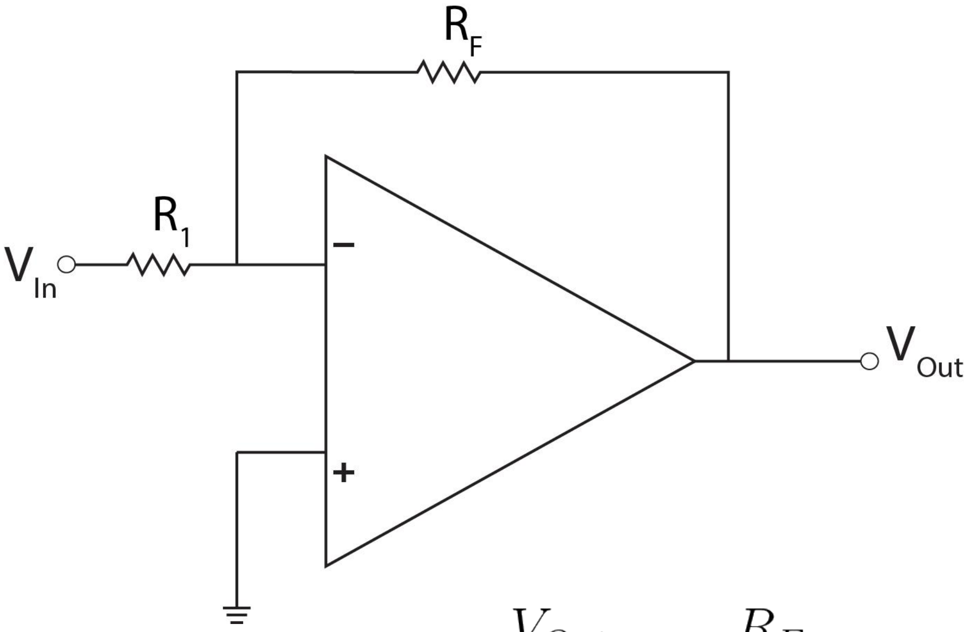
$$G_V = \frac{V_{Out}}{V_{In}} = 1 + \frac{R_F}{R_1}$$

https://tinyurl.com/y3gpqcms

Op Amp Circuit Topology: Inverting Voltage Gain

- Gain determined by external components
- Negative feedback
- Inverting terminal held at “virtual ground”
- Output is opposite polarity
- Input impedance is R_1





V_{In}	$\pm .5V$
R_F, R_1	10K, 5K
G_V	-2

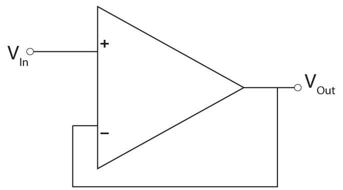
$$G_V = \frac{V_{Out}}{V_{In}} = -\frac{R_F}{R_1}$$

https://tinyurl.com/y3uyu5jc

Comparison of Basic Op Amp Topologies

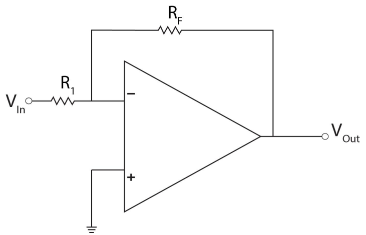
Buffer

- High input impedance
- Voltage Gain: $G_V = 1$
- Can provide current gain and "fixes" impedance



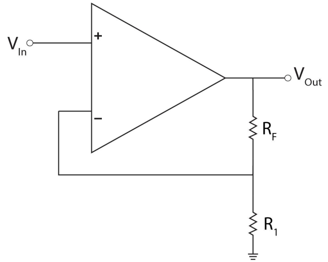
Inverting Amp

- Modest input impedance: R_1
- Voltage Gain: $G_V = -\frac{R_F}{R_1}$
- Gain can be less than unity
- Can be used to sum several voltages
- Can provide voltage offset



Non-inverting Amp

- High input impedance
- Voltage Gain: $G_V = 1 + \frac{R_F}{R_1}$
- Not suitable for Gain < 1
- Potentially lower noise (due to absence of input resistor



Historical Interlude 1 – Feedback and Op Amps

Negative Feedback – Harry Black, Bell Labs 1934

- Worked to improve telephone line transmission. Variable and unpredictable amplifier gain caused poor signal
- Notion of using high-gain amplifier and **negative feedback** network of passive components.
- Stability a problem

Classical Control Theory – Hendrik Bode, 1945

- Major contributor to the development of anti-aircraft/missile artillery during WWII
- Graphical methods for stability analysis of feedback networks
- Made design accessible to the average engineer of the time

Op Amp history and applications

- Early Op Amps utilized vacuum tubes and were primarily used for analog computers.
- Analog computers disappeared. Op Amps firmly established in signal-conditioning applications.
- Miniaturized to the size of a brick (1950s). First commercially viable transistor Op Amps emerge (1960s)
- Modern IC Op Amps are ubiquitous but out of sight.

www.newnesspress.com Texas Instruments, *Op Amps for Everyone*

Historical Interlude 2 – Characterizing the Axon Membrane

Voltage Clamp Technique – invented by George Marmont in 1947 (published 1949)

- Measure current through cell membrane while controlling the voltage across it
- Uses negative feedback design, which was a key technological innovation
- The paper includes circuit diagrams and has 4 references, one of which is Bode ’45 "Network Analysis and Feedback Amplifier Design"

Hodgkin and Huxley develop an accurate model of the membrane

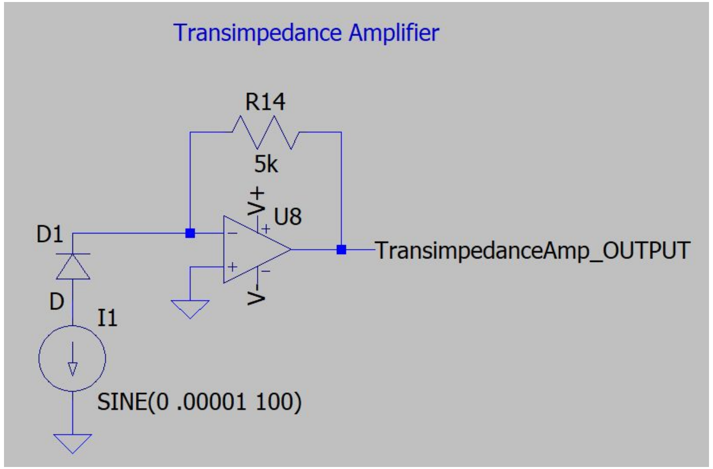
- Hodgkin initially uses Marmont’s voltage clamp apparatus
- Conduct experiments that isolate membrane currents due to different ions
- Publish 5 seminal papers 1949-1952 that describe the ion channel model in squid giant axon

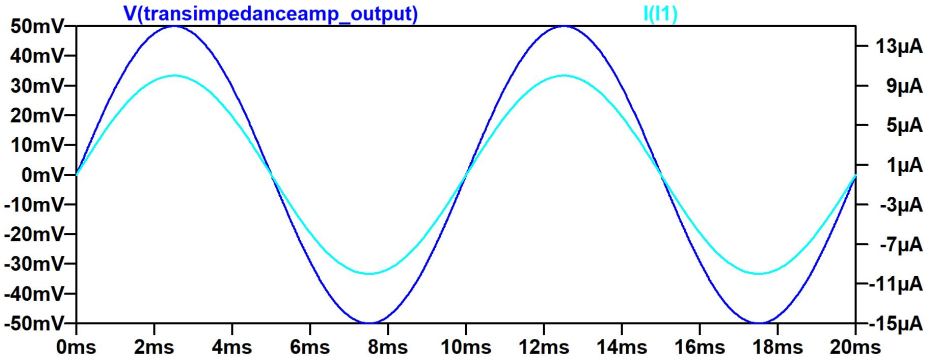
> "Hodgkin, with his wartime expertise in radar, could easily design his own system, and proceeded to do so. No sooner had Hodgkin returned to Cambridge than he put the departmental instrument maker onto building a feedback amplifier.”

Development of classical control theory and early electronics were necessary to achieve voltage clamp techniques that enabled key discoveries in neuroscience.

“Advanced” Op Amp Circuit Topologies
Transimpedance Amp

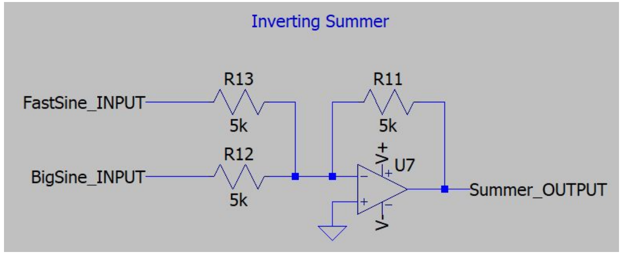
- Current controlled voltage source.
- Converts current input into voltage output
- Gain has units of V/A = Ohms
- Photodiodes, PMTs

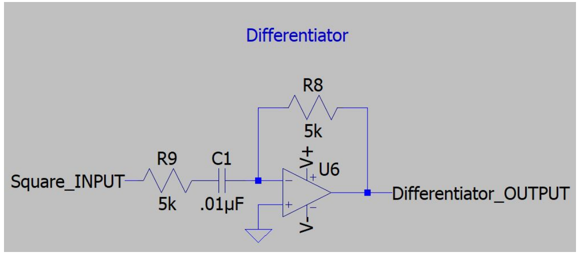


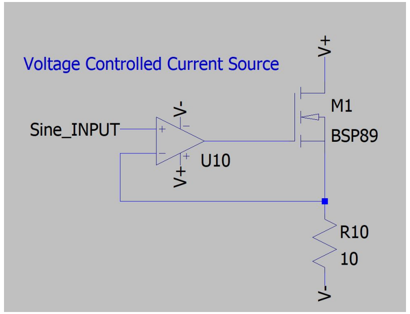


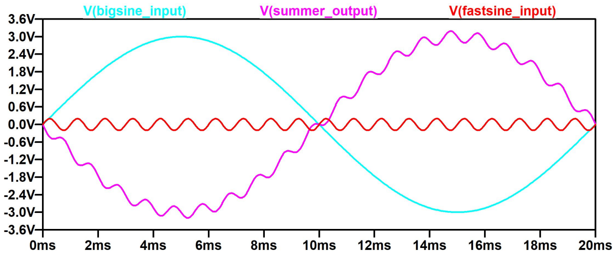
“Advanced” Op Amp Circuit Topologies

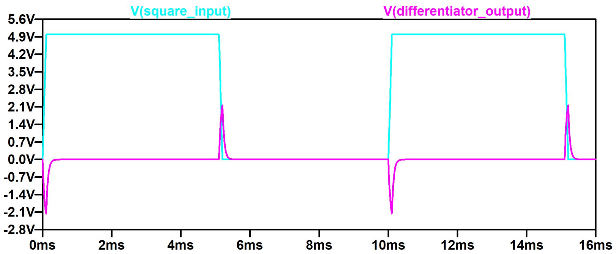
Differentiator, Integrator, Summer, Current Source, Ideal Diode, Instrumentation Amplifier, and other topologies are possible.

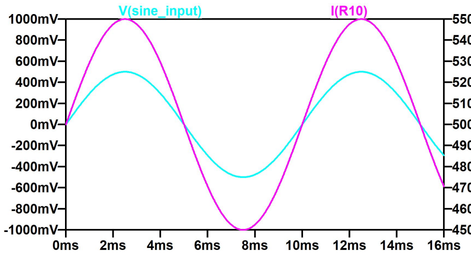






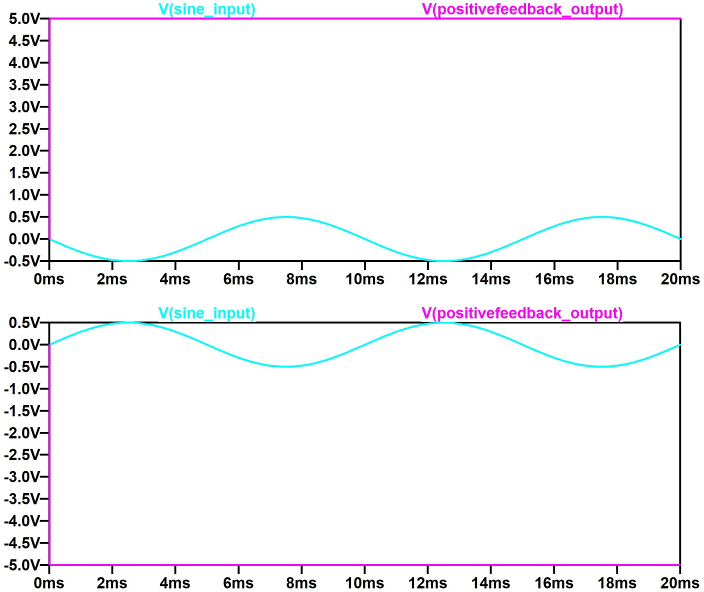


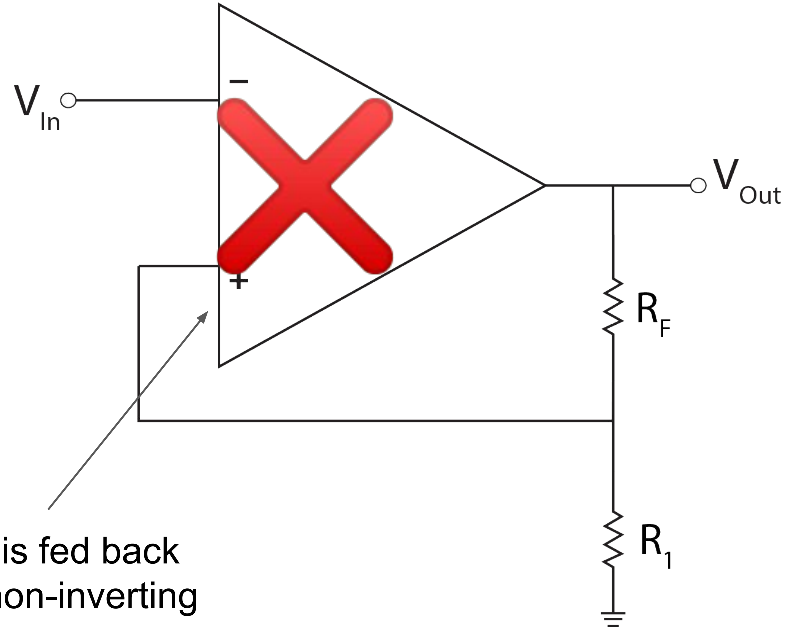




What About Positive Feedback?

- Topology **appears** similar to non-inverting amplifier
- Unstable behavior
  - Amplifies error signal
- Rarely used (though there are exceptions e.g. hysteresis circuits)





Output is fed back to the non-inverting input.

Stability

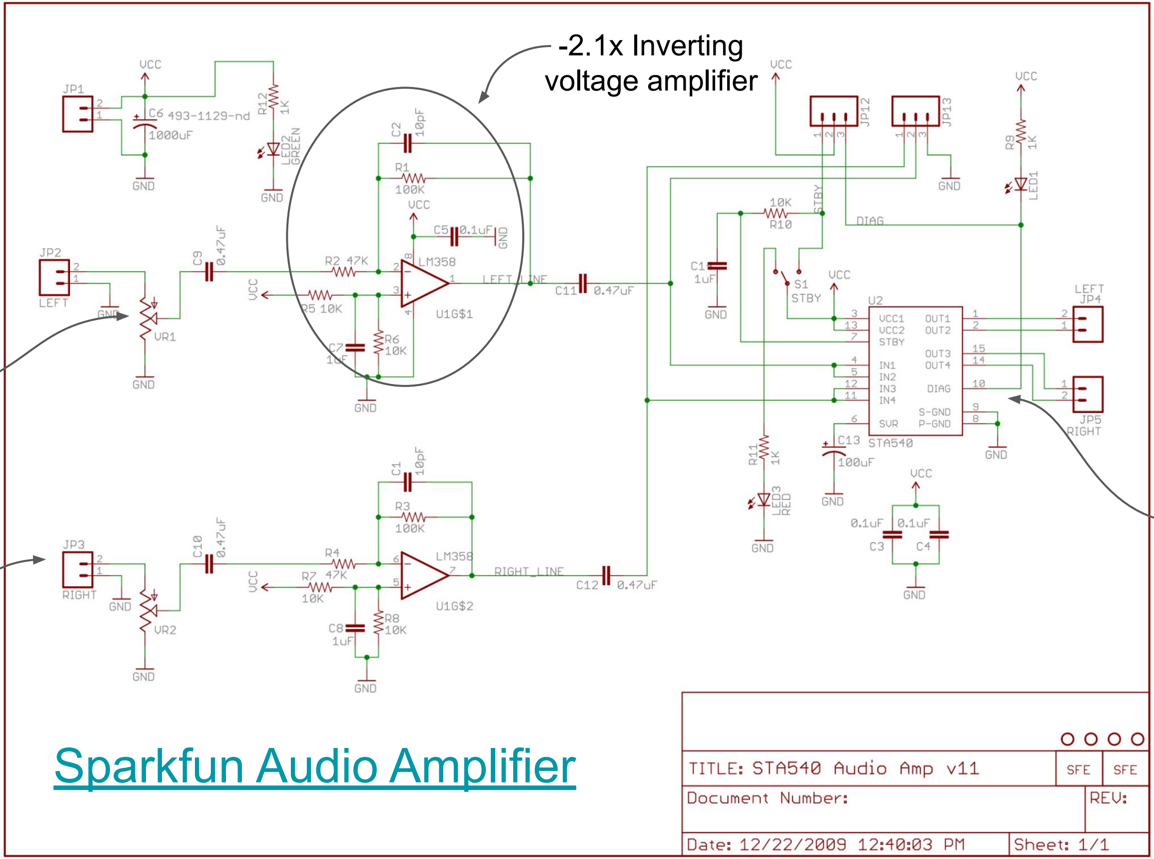
- General purpose Op Amps are designed to be stable under “normal” conditions
  - “internally compensated” is a term that indicates this in a datasheet
- Some Op Amp circuit topologies delay the output signal
  - E.g. Capacitor (also problematic for very fast signals, and high-gain amps),
  - Introduces a phase-shift (as you saw in RC filter assignment)
- With sufficient output phase-shift, negative feedback begins to “look” like positive feedback
  - The circuit starts to exhibit overshoot and ringing, and eventually becomes unstable
- Analytical and numerical tools exist to evaluate stability
- Circuit techniques can compensate for otherwise unstable behavior

Speaker Demo Schematic

Voltage divider volume control

Input Jack

-2.1x Inverting voltage amplifier



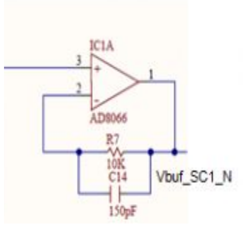
[Sparkfun Audio Amplifier]

To Speaker

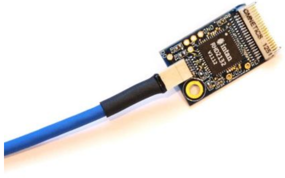
10x voltage gain power amplifier (Op Amps inside)

Practical Recap

- Op Amps are a common building block used by engineers
- Different circuits can be made by designing the appropriate feedback network
- Op Amps in commercial Rig Electronics
  - Headstage (unity-gain voltage buffer, current amplifier)
  - Gain stages inside a commercial amp (inverting or non-inverting, implement voltage/current clamp)
  - Filters (more sophisticated versions of the simple RC filter)
  - Piezo amplifiers (high voltage)
  - PMT amplifiers (transimpedance - i.e. current to voltage)
- When to build a home-made circuit?
  - Check if a commercial product exists
  - Glueware, signal conditioning, level shifting
    - Scale voltage to match full range of acquisition card
    - Summing multiple voltages, e.g. tunable offset.
  - Voltage controlled current source



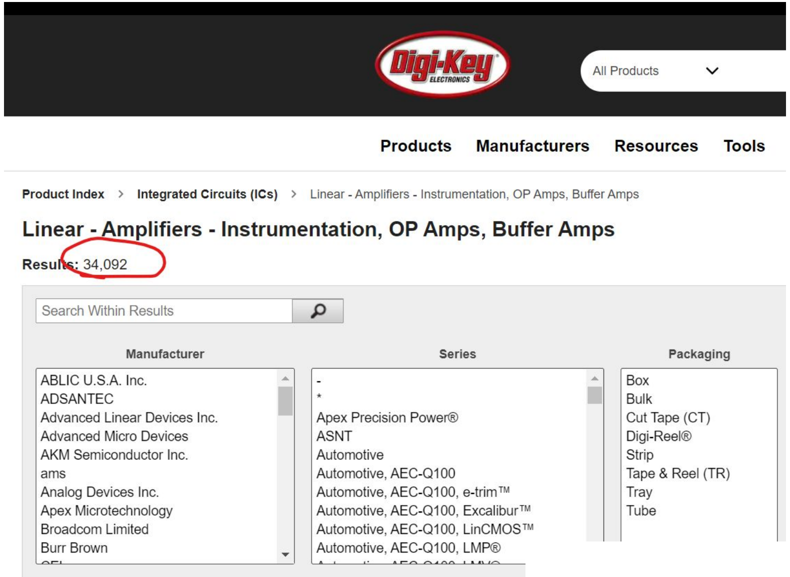
Analog Discovery input stage



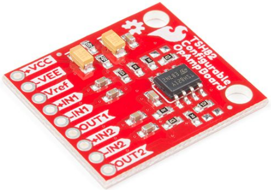
Axon Instruments Patch-Clamp Amplifiers

Selecting an Op Amp

- Power supply voltage
  - Min and Max voltage needed for operation
  - Single supply or positive and negative
- Max output current
- Gain-Bandwidth Product
- Package (surface mount or through-hole)



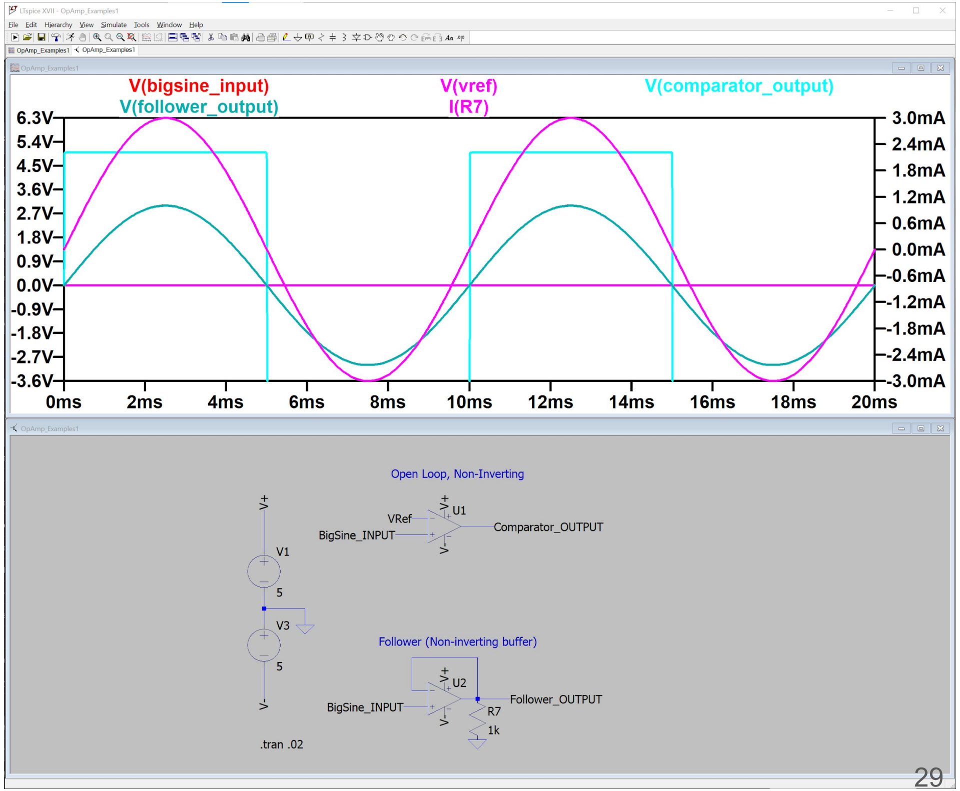
1000s of Op Amps from 10s of manufacturers optimize certain characteristics (e.g. general purpose, low-noise, high slew rate, instrumentation, rail-to-rail, high-voltage, etc.)



Sparkfun configurable Op Amp board

Design Tools and Recommended Resources

- LT SPICE (**S**imulation **P**rogram with **I**ntegrated **C**ircuit **E**mphasis)
- *The Art of Electronics* (Horowitz and Hill)
- TI design docs
  - *The Signal* e-book (Bruce Trump)
  - TI Precision Labs (video tutorials)
- Analog Devices University Program materials
  - Analog Electronics
  - Electronics I and II
- Allaboutcircuits.com
- Falstad Demos
- https://en.wikipedia.org/wiki/Operational_amplifier_applications

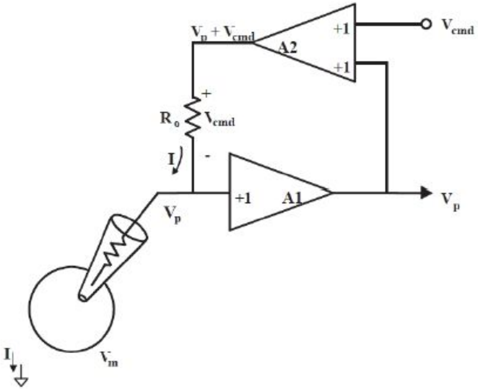


Axon Guide

- The axon guide provides an overview of e-phys techniques
- Circuit-level implementations
- Describes current/voltage clamp

The Axon Guide

Electrophysiology and Biophysics Laboratory Techniques
Fifth Edition



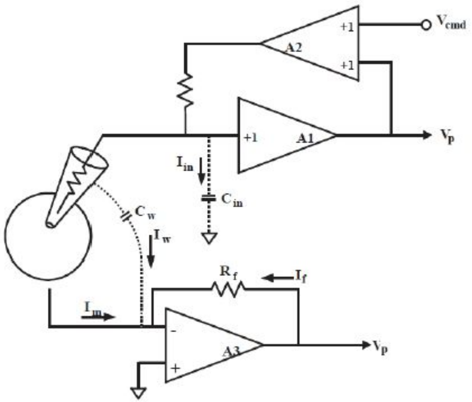


Figure 3-6: Virtual-ground current measurement.

Assignment and Next Lecture

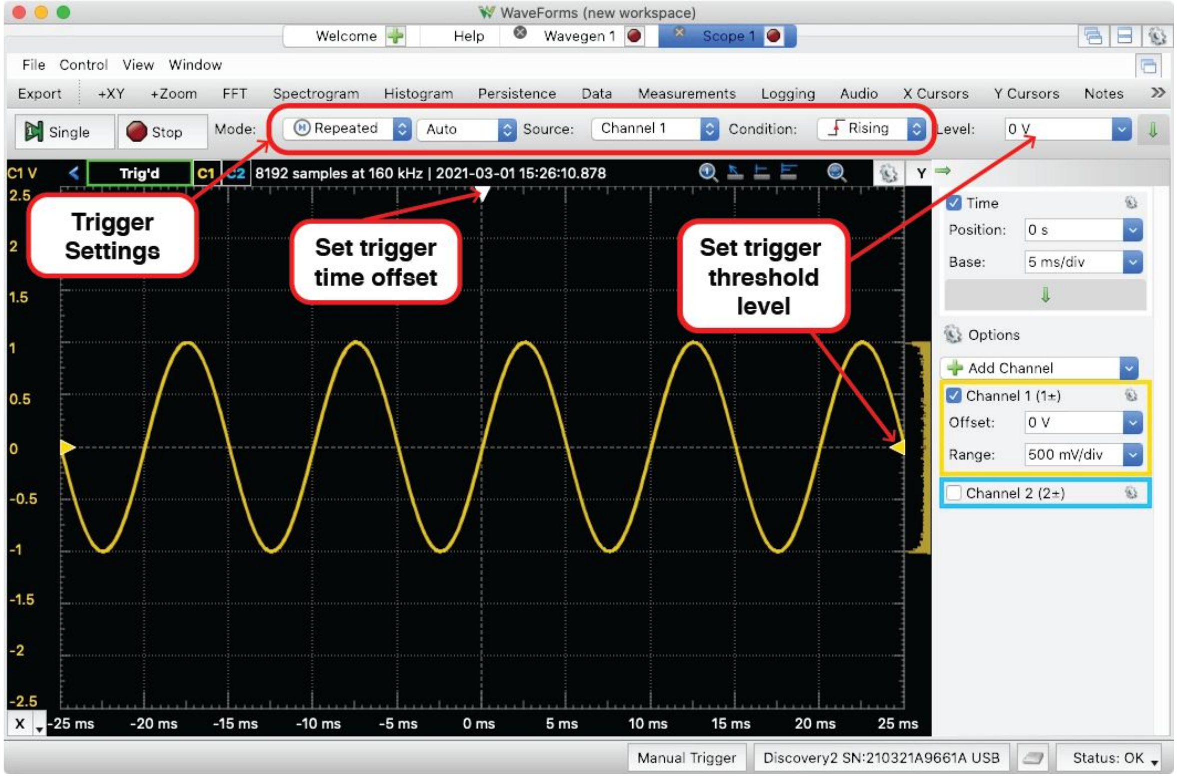
Lecture 3

- Data acquisition (sampling, aliasing)
- Triggering
- Advanced topics

Assignments

- Continue working on assignment 1 if you're not done
- Assignment 2 explores topics on noise and amplifiers
  - https://hms-ric.github.io/rig-nanocourse/Assignments/Assignment2.html
  - Builds on the first assignment. Questions are slightly less straightforward, but we are here to help
- Plan to spend ~1 hr on the homework

Triggering

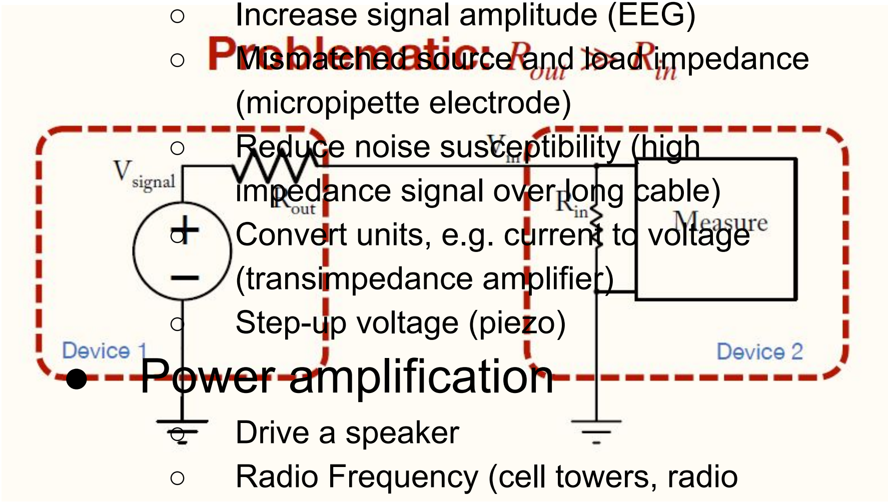


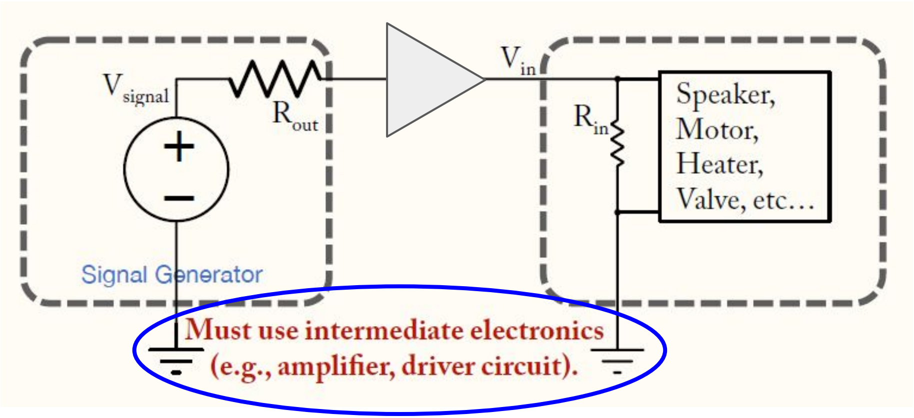
WaveForms (new workspace)
Welcome
Help
Wavegen 1
Scope 1
File Control View Window
Export +XY +Zoom FFT Spectrogram Histogram Persistence Data Measurements Logging Audio X Cursors Y Cursors Notes
Single
Stop
Mode: Repeated Auto Source: Channel 1 Condition: Rising Level: 0 V
Trig'd
8192 samples at 160 kHz | 2021-03-01 15:26:10.878
Trigger Settings
Set trigger time offset
Set trigger threshold level
Time
Position: 0 s
Base: 5 ms/div
Options
Add Channel
Channel 1 (1+)
Offset: 0 V
Range: 500 mV/div
Channel 2 (2+)
-25 ms -20 ms -15 ms -10 ms -5 ms 0 ms 5 ms 10 ms 15 ms 20 ms 25 ms
Manual Trigger
Discovery2 SN:210321A9661A USB
Status: OK

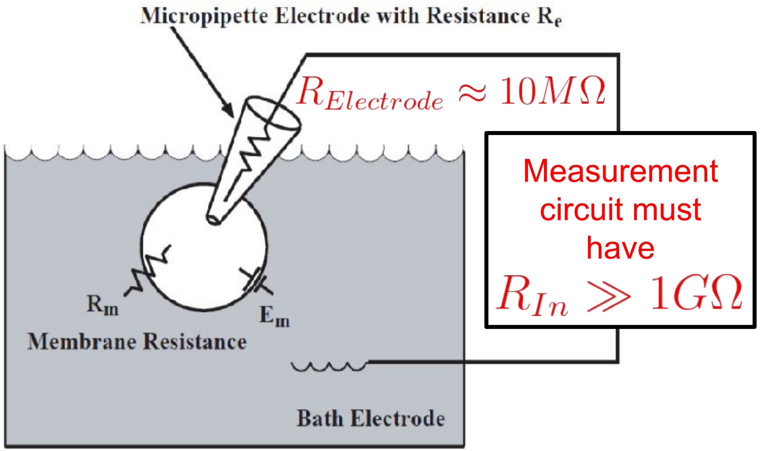
Backups

Why Amplifiers?

- Signal conditioning
  - Increase signal amplitude (EEG)
  - Mismatched source and load impedance (micropipette electrode)
  - Reduce noise susceptibility (high impedance signal over long cable)
  - Convert units, e.g. current to voltage (transimpedance amplifier)
  - Step-up voltage (piezo)
- Power amplification
  - Drive a speaker
  - Radio Frequency (cell towers, radio broadcast, deep space comms)



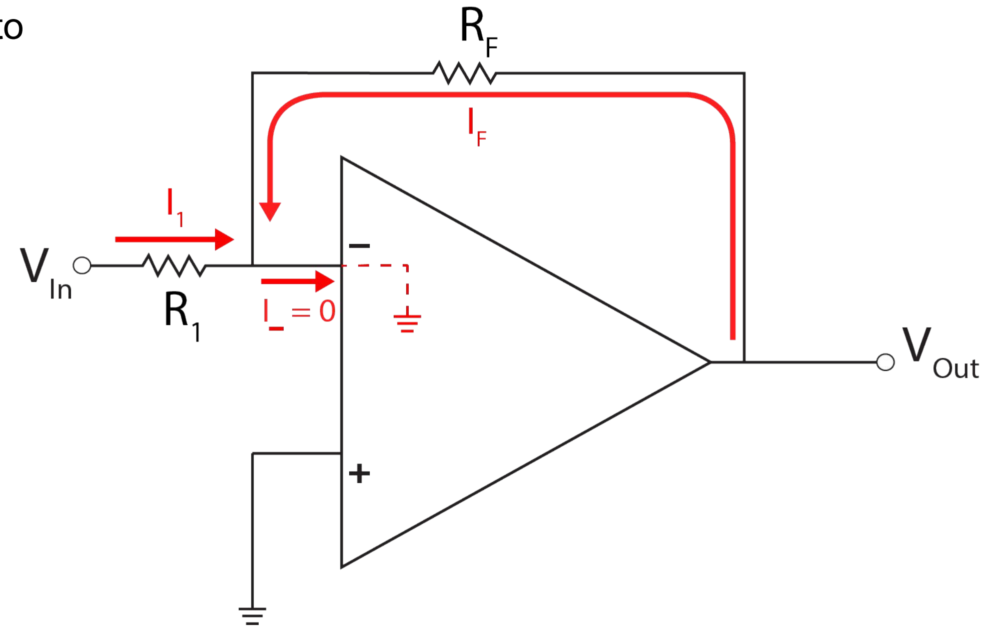




(From: The Axon Guide, Third Edition, Molecular Devices, LLC, 2012)

Techniques for Op Amp Circuit Analysis

- Op Amp adjusts output to drive both inputs to same potential
- Zero current into the device
- Virtual ground
- Agnostic to ground



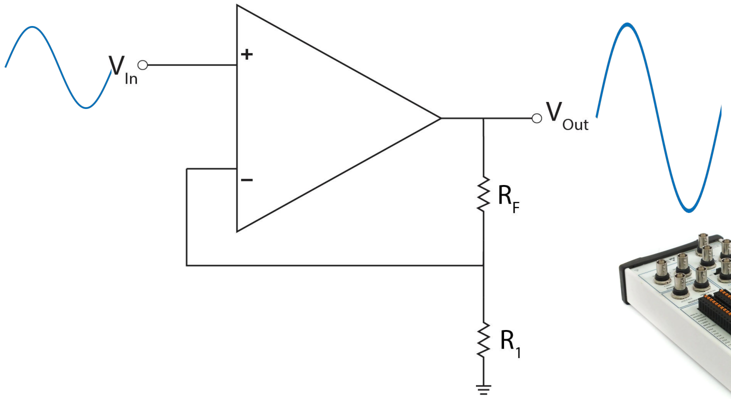
$$I_1 = -I_F$$

$$\frac{V_{In}}{R_1} = -\frac{V_{Out}}{R_F}$$

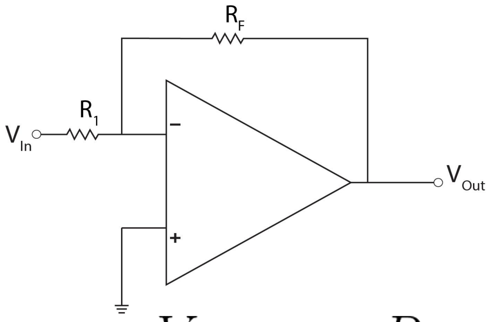
$$G_V = \frac{V_{Out}}{V_{In}} = -\frac{R_F}{R_1}$$

Non-Inverting Voltage Gain Examples

- Gain can be adjusted by varying R (volume control)
- Voltage scale on oscilloscope
- Amplify the signal to fill the full dynamic range of digitizer and thereby minimize quantization noise. More in lecture 3
- Gain is always greater than unity



Inverting Voltage Gain Examples



$$G_V = \frac{V_{Out}}{V_{In}} = -\frac{R_F}{R_1}$$

Unlike the non-inverting amplifier, inverting amp allows for gain < 1. Can attenuate signal while maintaining low output impedance.

- Scale down analog voltage to make compatible with low-voltage acquisition system (e.g. Intan)
- Input node can be used to sum multiple signals
- Non-inverting terminal can be held at a reference potential to add an offset to the input signal
- Provide virtual ground to measure current through bath electrode

Historical Interlude 1 – Feedback and Op Amps

- 1934, Harry Black, Bell Labs - worked to improve telephone line transmission
  - Variable and unpredictable amplifier gain caused poor signal
  - Notion of using high-gain amplifier and **negative feedback** network of passive components.
  - Stability a problem
- 1945, Hendrik Bode - pioneer of classical control theory and major contributor to development of anti-aircraft/missile artillery during WWII.
  - Graphical methods for stability analysis of feedback networks.
  - Made design accessible to the average engineer of the time
- Early *Operational Amplifiers* used mainly in analog computers. High-gain vacuum tube amplifier and passive feedback network. Performed real-time calculations (addition, multiplication, integration, etc.)
- Analog computers disappeared. Op Amps firmly established in signal-conditioning applications.
- 1950s: vacuum tube Op Amps miniaturized to the size of a brick. 1960s: first commercially viable transistor Op Amps. ~~New and improved models have been introduced continually since.~~
- Modern IC Op Amps are ubiquitous but out of sight. ~~Universal analog IC that can be configured to serve many analog tasks.~~

www.newnesspress.com Texas Instruments, *Op Amps for Everyone*

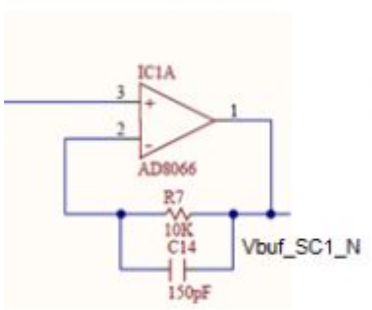
Op Amps in Commercial Products

Buffers, filters, amplifiers

1X Buffer

Axon Instruments Patch-Clamp Amplifiers

Op Amps are used to implement voltage clamp, current sources, active filters, piezo drivers, strain gauge amplifiers, thermocouple amps, transimpedance amps, etc.

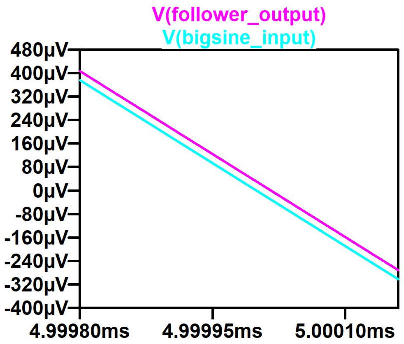


Analog Discovery input stage

Summary

- Signal quality, noise sources. EM pickup, C coupling, voltage divider attenuation. Passive solutions to mitigate noise sources
- Signal conditioning via active means
  - Negative Feedback
  - Several Op Amp topologies
    - Buffers
      - Less susceptible to noise pickup
      - Current gain
    - Voltage Amps

Deviations from Ideal Circuit Model



Nonzero input current (Input impedance not infinite)

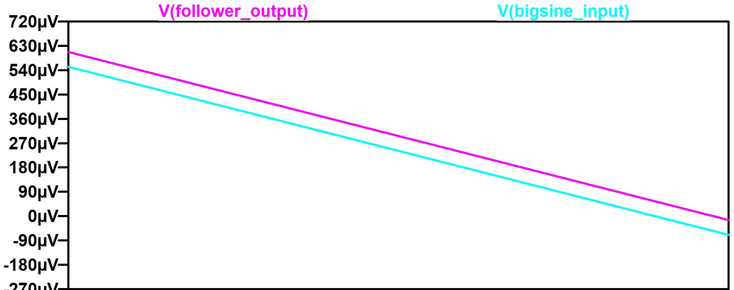
Limited output current (Output impedance not zero)

Input offset voltage

Slew Rate

Gain-Bandwidth Product

Be careful when designing for G > 100. Check datasheet for GBW

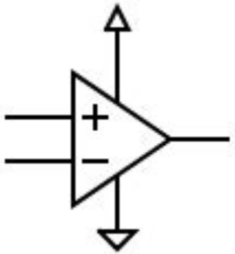


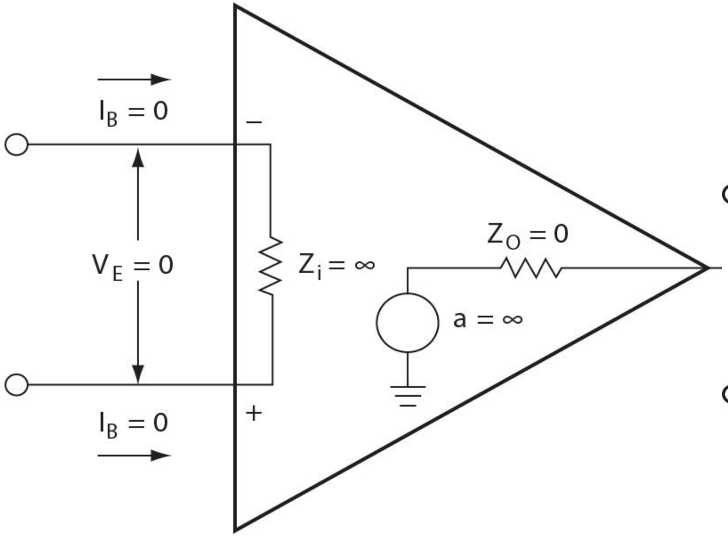
Embedding Falstad Demos in Slides

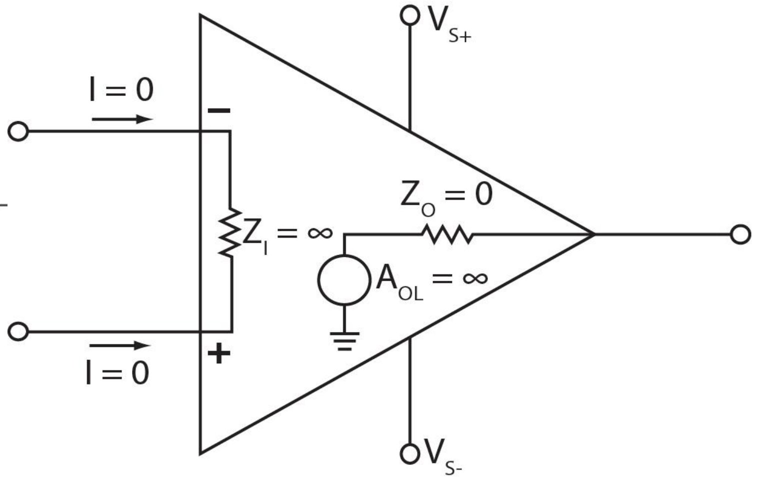
Haven't been successful yet. Tried with Keynote, PowerPoint, and Google Slides. It appears this functionality used to exist in earlier versions of software but some of it was taken out due security concerns?

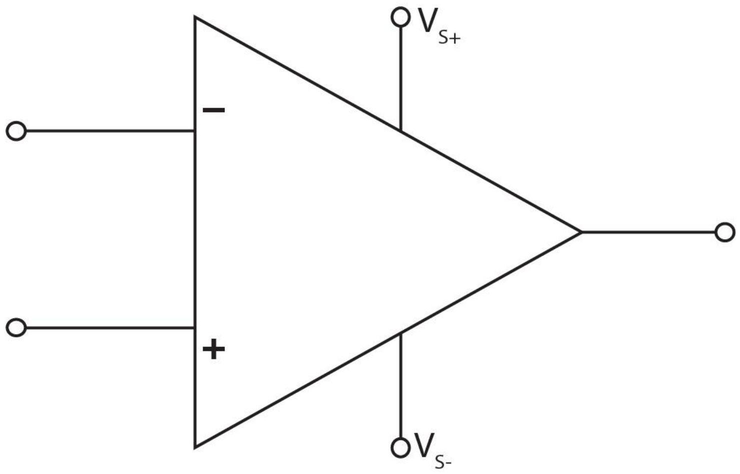
- LiveWeb How-to
  - Requires a registry hack (and another) on PPT, not clear if it'll work with Office 365)
- Pear Deck for Google Slides
  - shows a working preview of the Falstad demos, but I haven't gotten it to work yet in presentation mode
  - The free registration process requires connecting with an affiliated school (?)
- Site Sucker for MacOS. Makes a local copy of a website. Can maybe embed in Keynote?
- Presentation Point
  - Paid add-on but with free trial

Junk slide

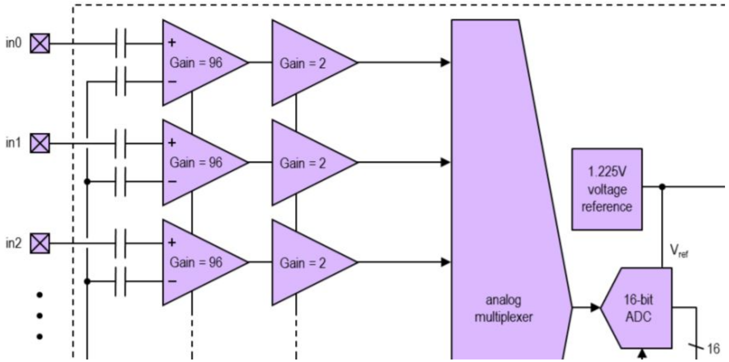

+
–


$I_B = 0$
–
$V_E = 0$
$Z_i = \infty$
$Z_O = 0$
$a = \infty$
+
$I_B = 0$


V_{S+}
$I = 0$
–
$Z_I = \infty$
$Z_O = 0$
$A_{OL} = \infty$
+
$I = 0$
V_{S-}



V_S+
V_S-



in0
in1
in2
Gain = 96
Gain = 2
1.225V voltage reference
V_ref
analog multiplexer
16-bit ADC
16