Introduction to Operational Amplifiers

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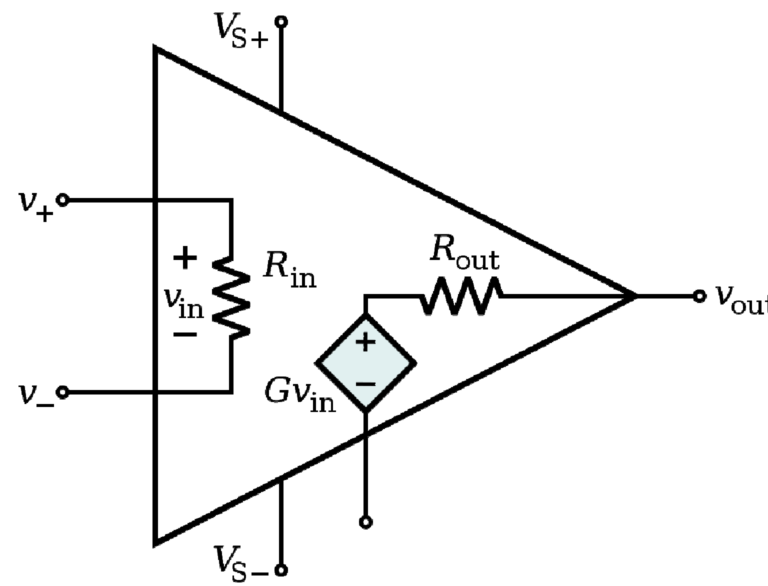
Thévenin's theorem

- Any linear electrical network with voltages, current sources, and resistances can be replaced with a single voltage source putting out V_{th} and a single series resistor of value R_{th}
- The equivalent resistance of a battery is why it doesn’t turn into a grenade when you short the terminals.
- R_{th} is also sometimes called impedance when we’re talking about circuit outputs.

The Ideal Operational Amplifier

- An operational amplifier is a three-terminal device with, ideally, the following properties:
  - Infinite open-loop gain $G = {}^{v_{out}}/_{v_{in}}$
  - Infinite input impedance R_{in}
  - Zero input offset voltage
  - Infinite voltage/current/bandwidth/slew rate at the output with zero time delay
  - Zero output impedance R_{out}
  - Infinite common mode & power supply rejection ration (CMRR & PSRR)



Real Op Amps

- Open loop gain is finite but very large – typically 100,000 or more at DC
- Input impedance is finite but very large; more important is the offset voltage and bias currents on the inputs, which are non-zero.
- Output impedance is non-zero – it is possible to load the output down so it won’t reach the full range.
- Input and output voltage are constrained by the power rails, often minus some offset.
- CMRR & PSRR are finite but large – typically 65-100 dB or higher
- Bandwidth and slew rate are not infinite

The Golden Rules

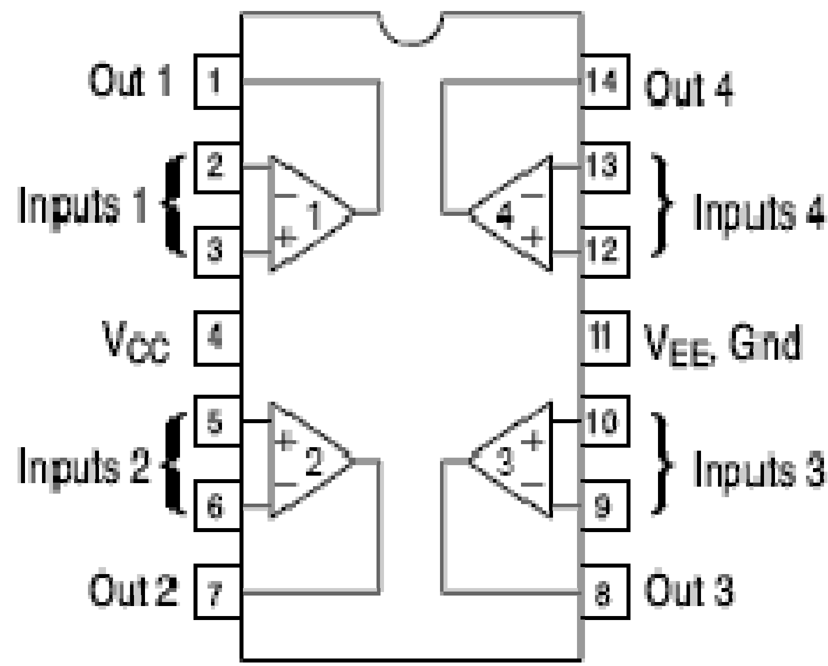
- In practice, those properties boil down to two rules of thumb.
- The output of the op-amp will change to keep the positive and negative inputs equal.
- The inputs draw no current.

Feedback

- Feedback is key to doing useful things with op amps.
- Positive feedback is where we connect the output back to the positive input through some circuit.
- Negative feedback is where we connect the output back to the negative input through some circuit, and is by far the more common and useful mode.

Our Op-Amps

- We're using the LM324N, which has four op-amps in a single 14 pin DIP package.
- Most quad op-amps share the same pinout.
- It's a common, cheap part with a power supply range as high as 32V (or ±16V)

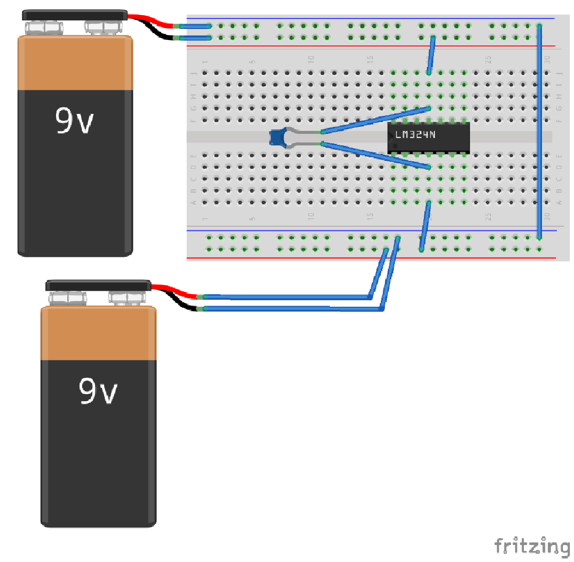


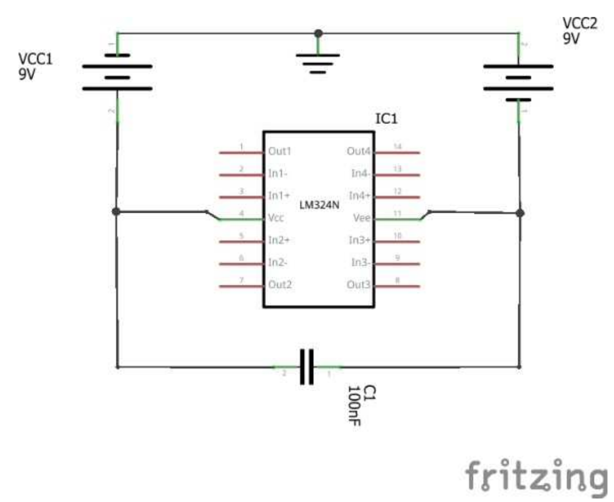
Key Datasheet Values

- Common mode voltage range includes ground/V_{EE}
- Input offset voltage 3 mV
- Input offset current 2 nA
- Input bias current 20 nA
- Open loop gain 100,000
- CMRR 65 – 80 dB
- PSRR 65 – 100 dB
- Max $V_{out} = V_{cc} - 1.5V$
- Output current -30 mA – 20 mA
- Gain-Bandwidth Product 1.2 MHz
- Slew Rate 0.5 $V/\mu s$

Power Supply Hookup

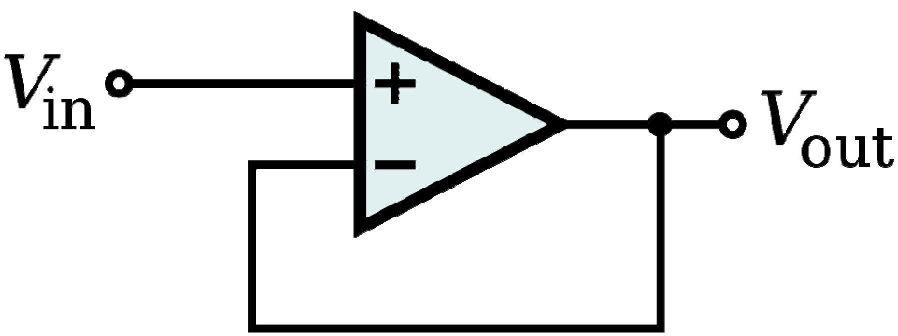
- We need a bipolar power supply for this class
- You can use a unipolar supply, with some limitations, for general projects.

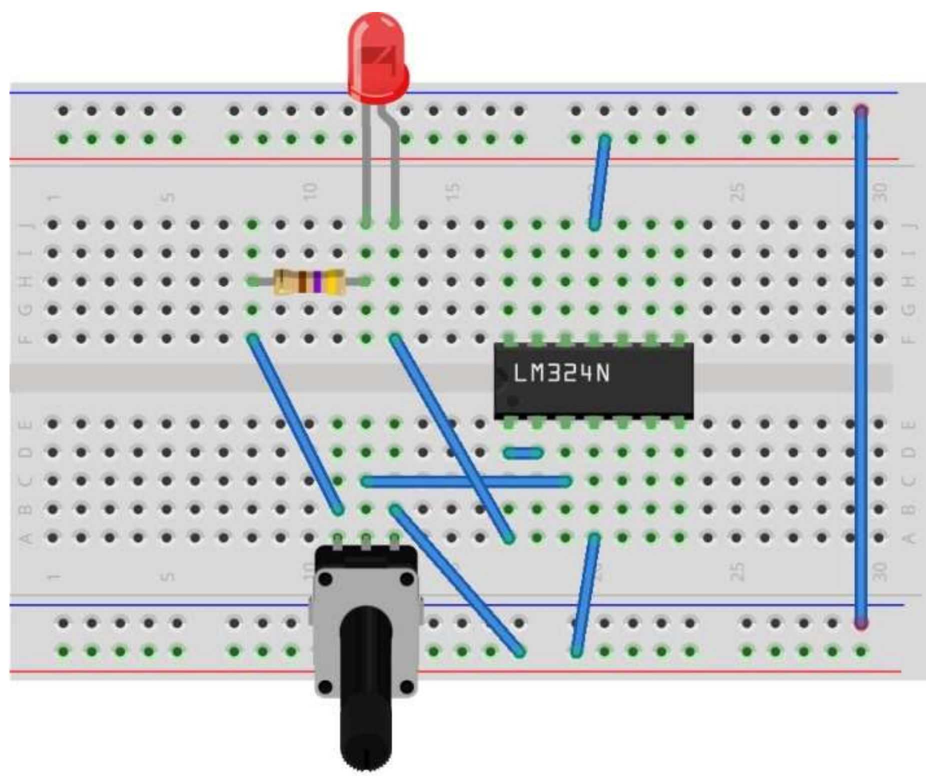




The Voltage Follower

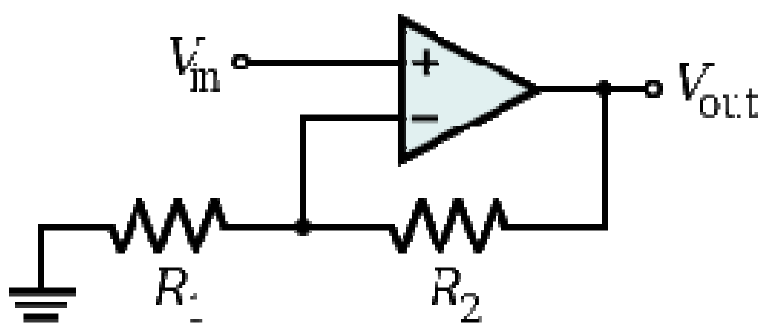
- Simple negative feedback
- $V_{out} = V_{in}$

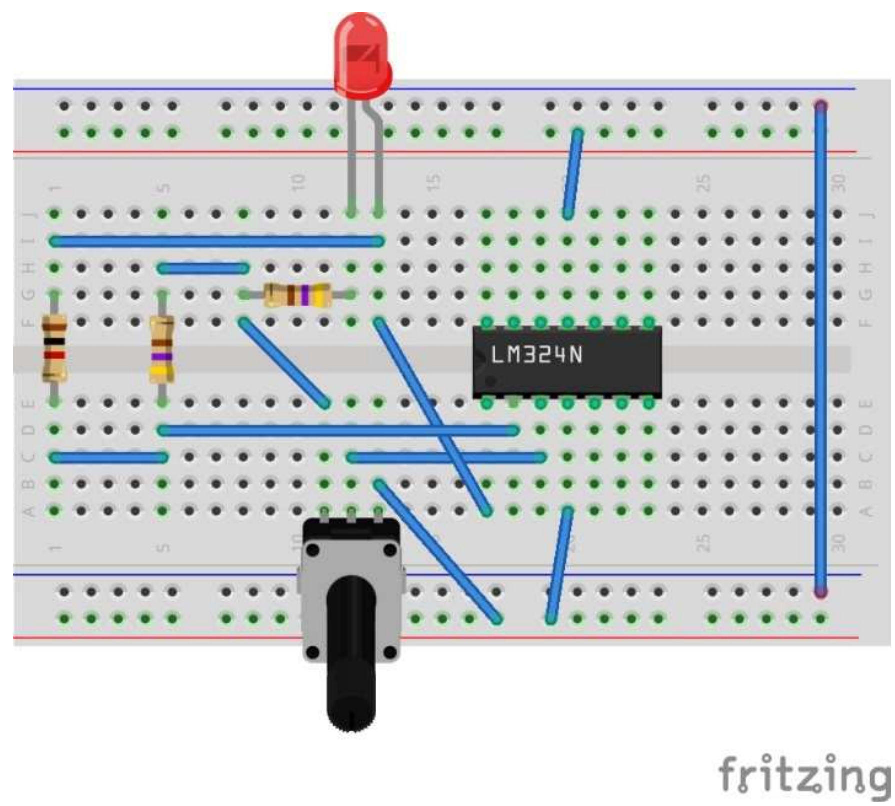




Non-Inverting Amplifier

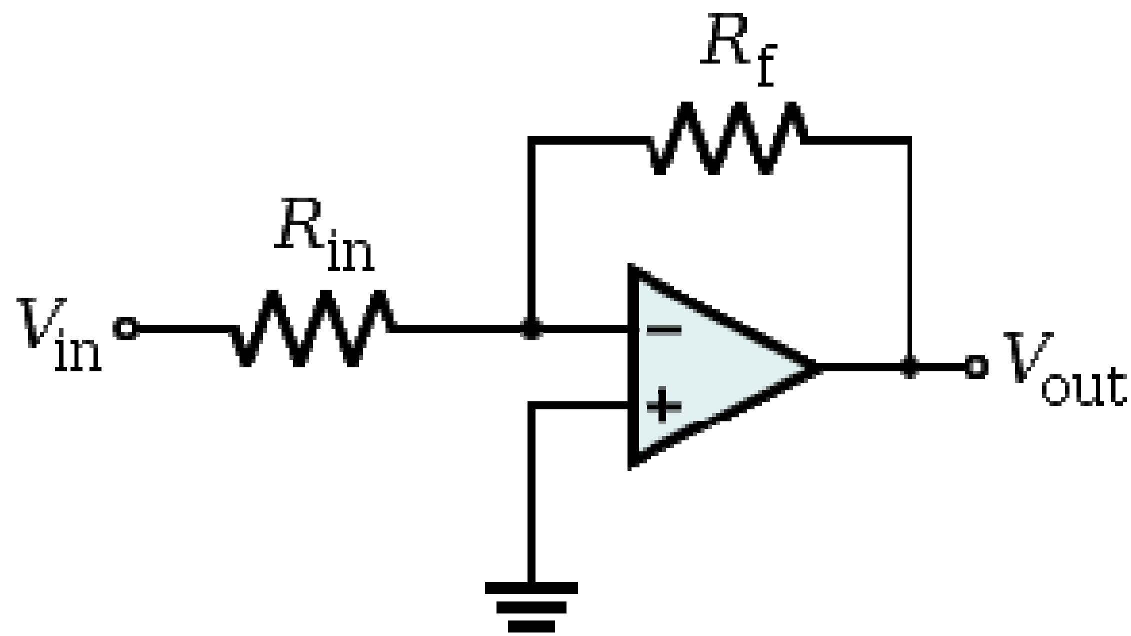
- Let's add a voltage divider to the feedback…
- $V_{out} = \left(1 + \frac{R_1}{R_2}\right) V_{in}$
- $Z_{in} = R_{in} \times G_{OL} \approx \infty$





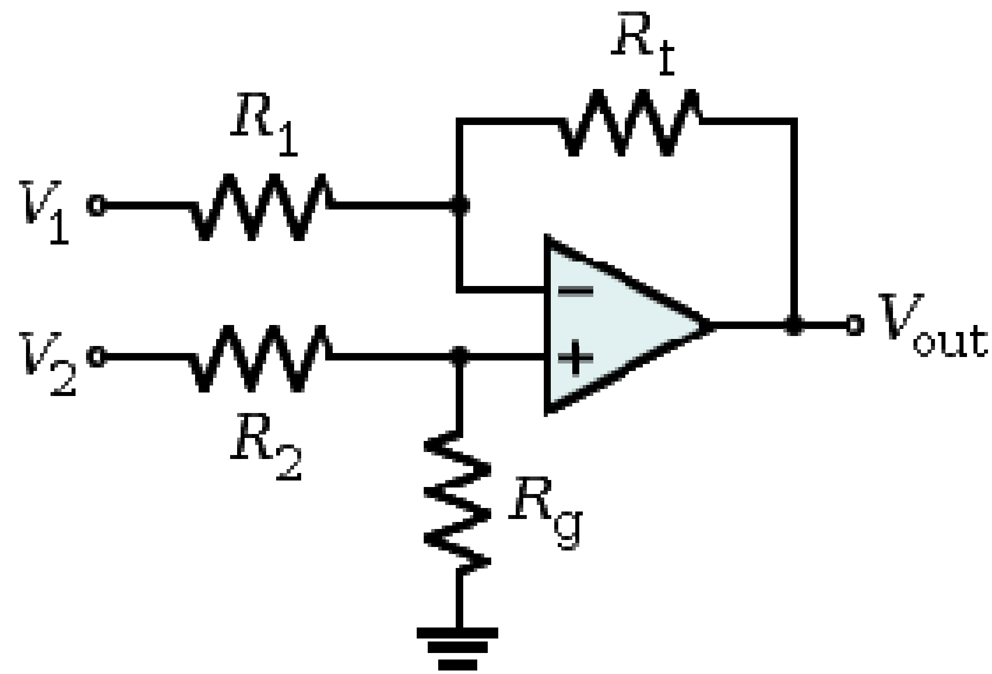
Inverting Amplifier

- $V_{out} = -\frac{R_f}{R_{in}} V_{in}$
- $Z_{in} = R_{in}$
- Negative input terminal must always be at ground, so output falls or rises such that the voltage divider balances.



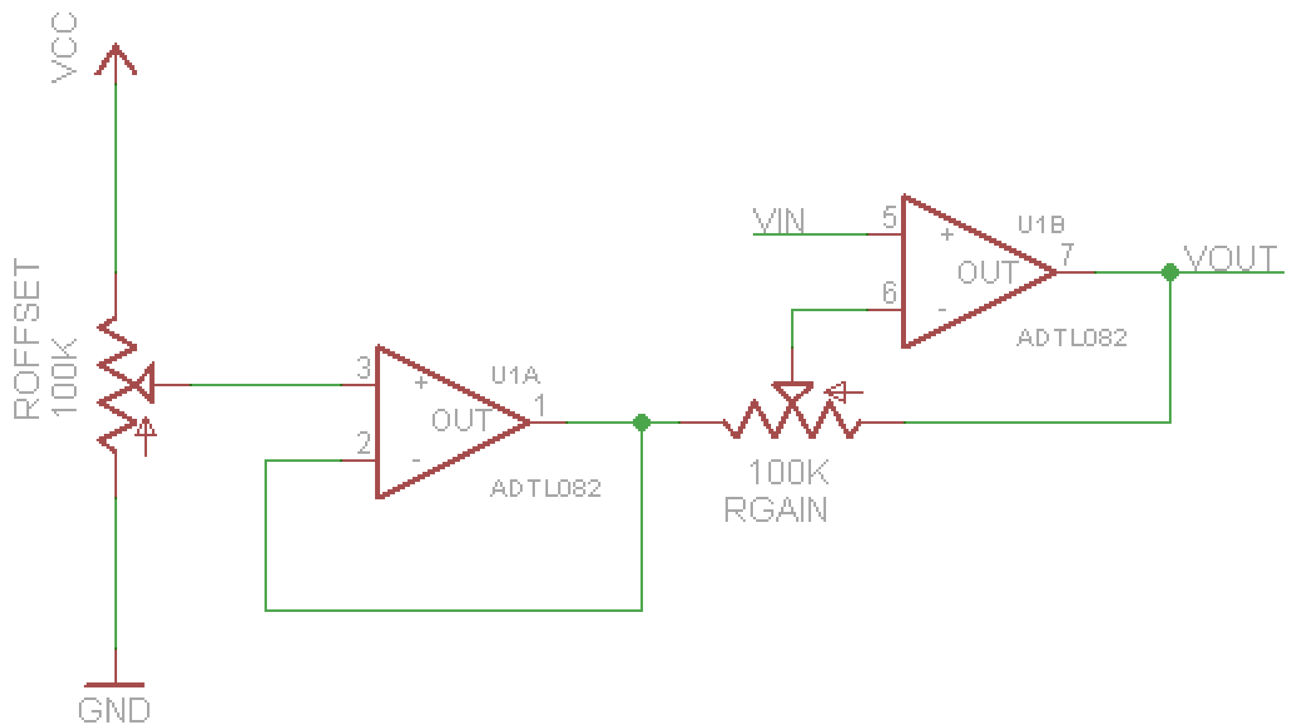
Differential Amplifier

- Let's combine these two…
- Assuming ${}^{R_1}/_{R_f} = {}^{R_2}/_{R_g}$
- $V_{out} = \frac{R_f}{R_1}(V_2 - V_1)$
- If the above assumption is not true, then the CMRR is low
- $Z_1 = R_1; Z_2 = R_2$



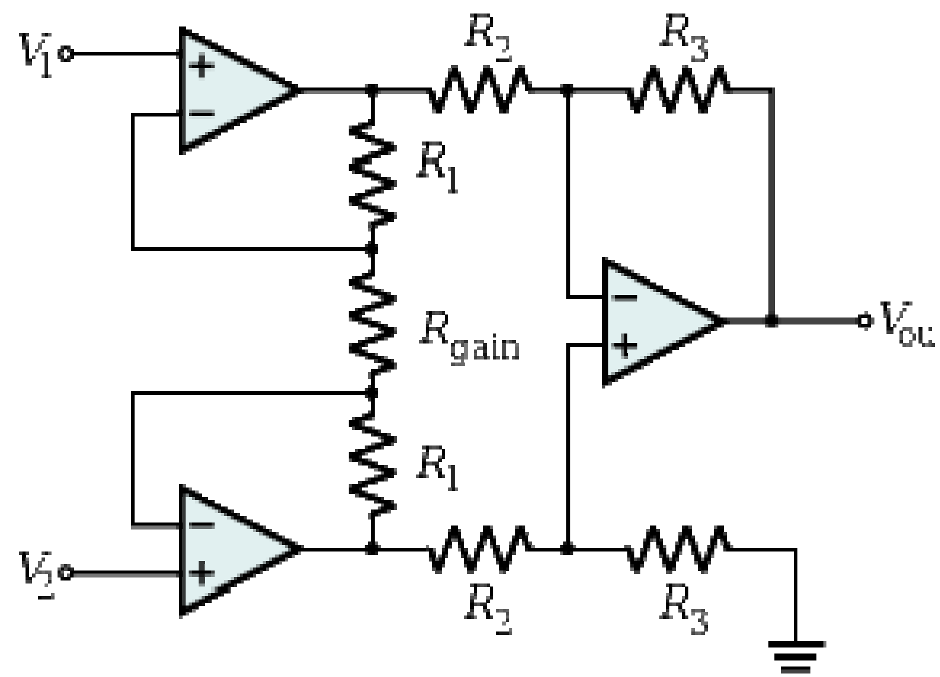
A quick word about ground

- Ground in all these circuits is where you choose to put it.
- Therefore, we can use it to introduce output offset



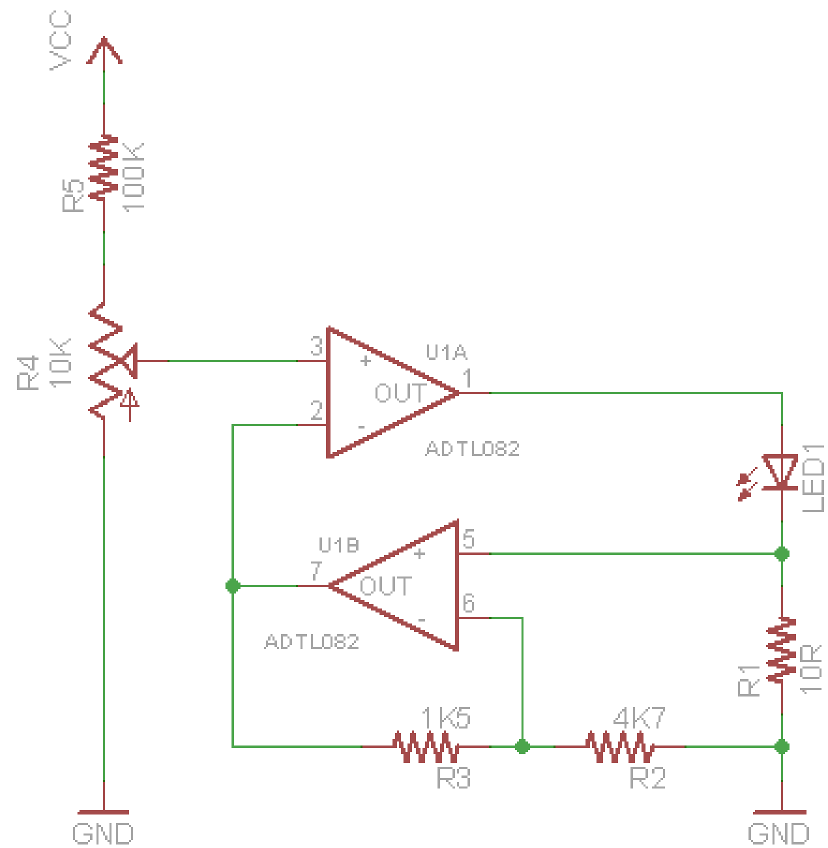
Instrumentation Amplifier

- Let's get a differential amplifier with really large input impedance…
- $V_{out} = \left(1 + \frac{2R_1}{R_{gain}}\right)\frac{R_3}{R_2}(V_2 - V_1)$
- Without R_{gain}, it's just two voltage followers feeding a differential amplifier.
- Works best when R_{gain} is present and can be used to set the gain of the whole circuit



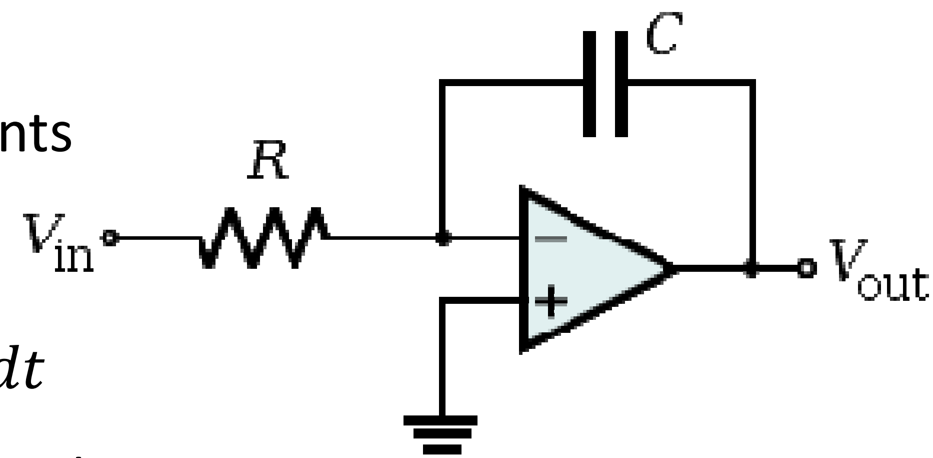
Controllable Current Source

- Voltage across R1 is proportional to current. i1 = 20 mA max, for a max voltage of 200 mV
- U1B, R2, & R3 form a non-inverting amplifier with a gain of 4.13, giving a max feedback voltage of 826 mV
- R4 & R5 give a variable signal from 0 – 818 mV
- U1A varies output voltage so the feedback and signal voltages are equal.



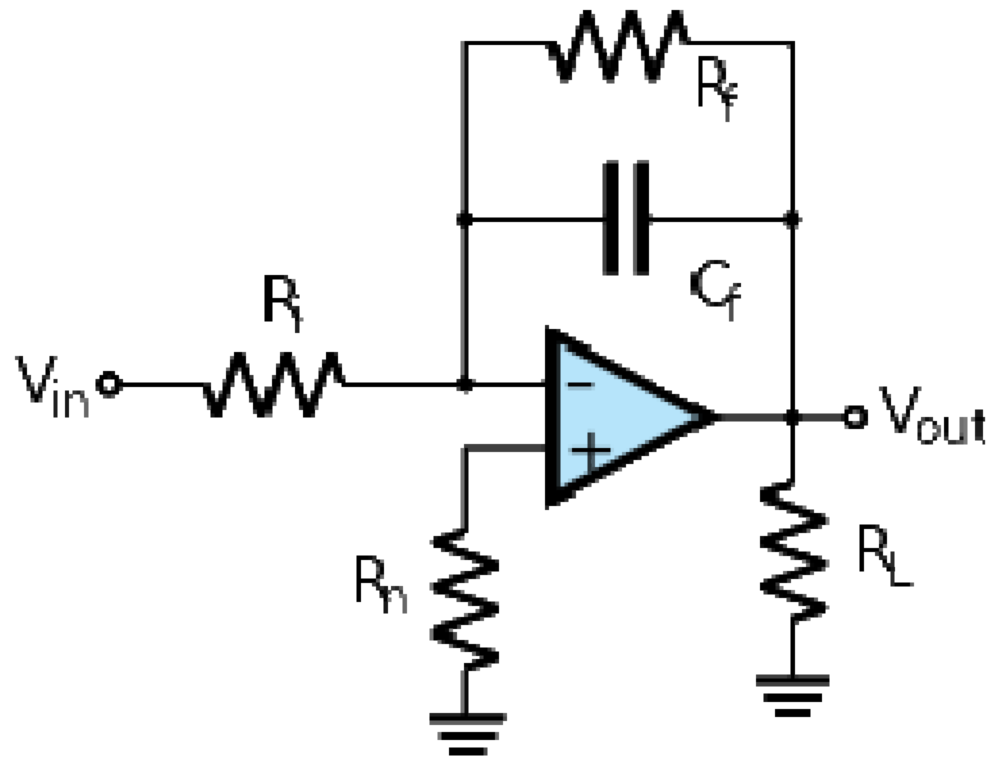
Integrator (simple)

- It's possible to use feedback elements other than resistors to get other functions.
- $V_{out}(t_1) = V_{in}(t_1) - \frac{1}{RC}\int_{t_0}^{t_1} V_{in}(t)dt$
- However… this will eventually drift out of the operating range due to:
  - The input V_{in} has a non-zero DC component
  - Input bias current and offset voltage is non-zero



Integrator (robust)

- Adding some resistors allows us to make the integrator robust.
- If $R_n = \frac{1}{\frac{1}{R_i}+\frac{1}{R_f}} = R_i||R_f$
- Then our bias problems go away, along with small DC inputs.



Log & Exponential Amplifiers

- We can also take advantage of the exponential behavior of a diode…
- $V_{out} = -V_T ln\left(\frac{V_{in}}{I_S R}\right)$
- $V_{out} = -RI_D = -RI_s e^{\frac{V_{in}}{V_T}}$