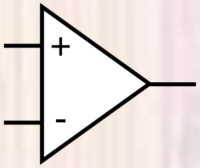
OpAmp Circuits

Last updated 1/11/24

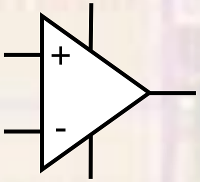
OpAmps

- Operational Amplifier (OpAmp)
  - High Gain difference amplifier

$$V_o = A_{od}\,(V_+ - V_-)$$



Implied power connections

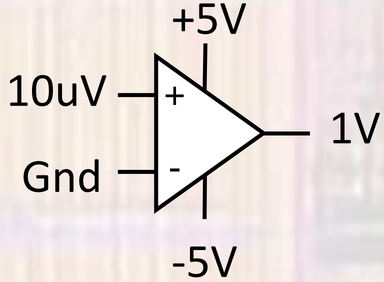


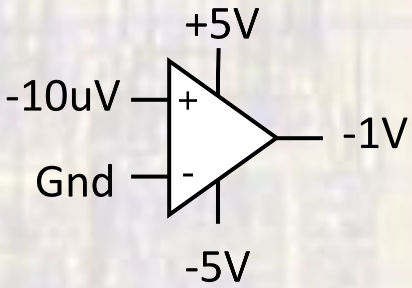
Explicit power connections

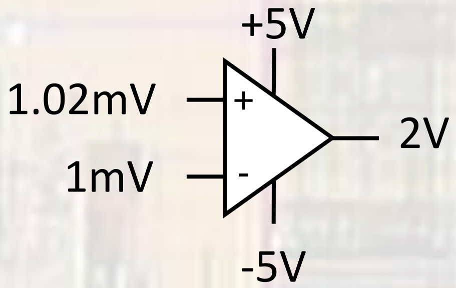
OpAmps

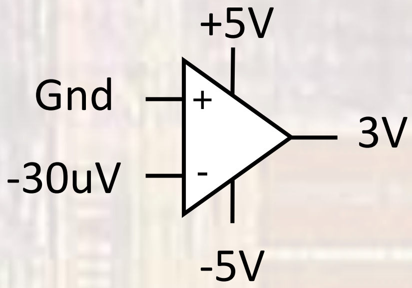
- Ideal OpAmp
  - High Gain difference amplifier

$$V_o = A_{od}(V_+ - V_-) \qquad\qquad A_{od} = 100{,}000$$





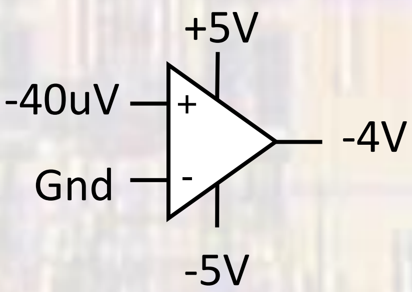


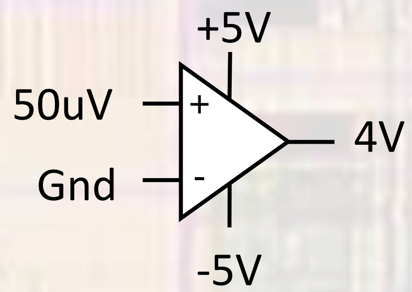


OpAmps

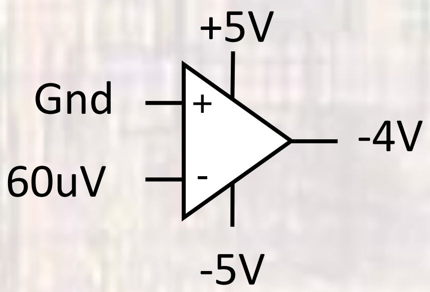
- OpAmp Limitations
  - Output Swing
    - Common opamps can only swing the output to about 1V from the positive or negative voltage rails
    - Rail-to-rail opamps can get to within 10s of mv of the rails

$$A_{od} = 100,000$$





Output Saturated
(clipped, limited)

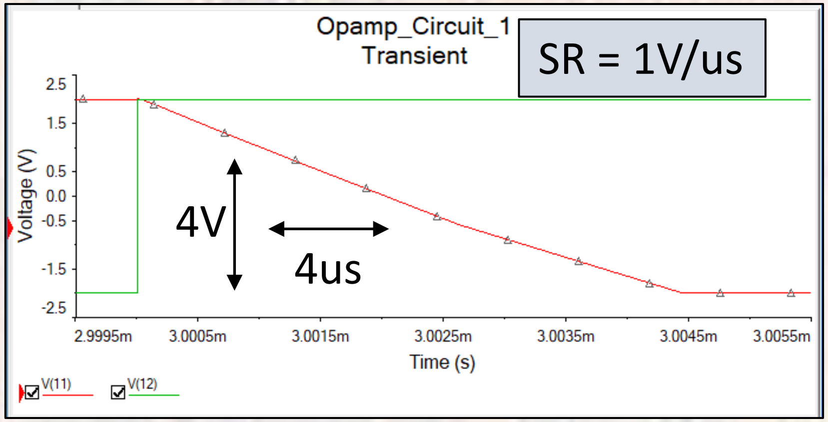


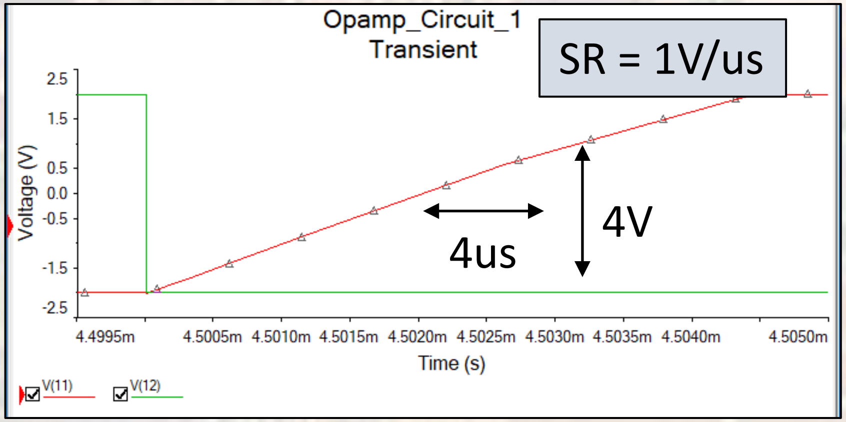
Output Saturated
(clipped, limited)

OpAmps

- OpAmp Limitations
  - Slew Rate
    - Limit on how fast the output can change
    - Limits large signal rise and fall times at the output
      - Typically between 1V/us and 100V/us

$$\left({}^{dV_o}/_{dt}\right)_{max} = SR$$



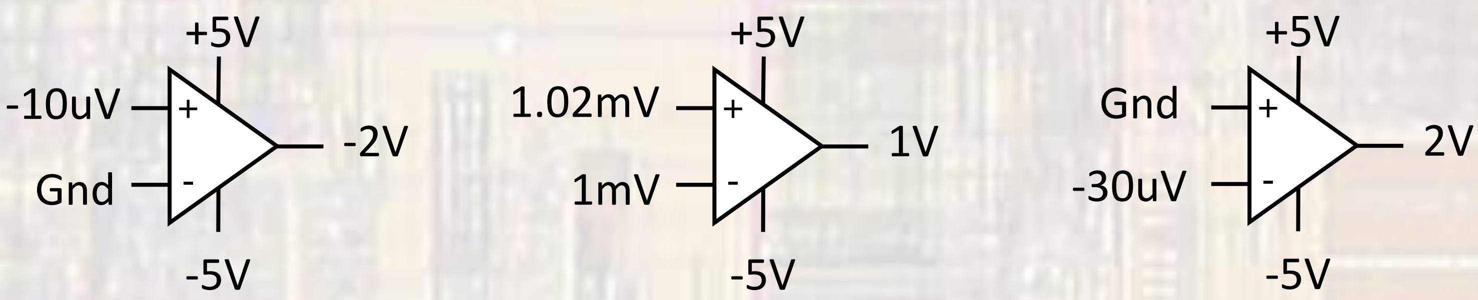


OpAmps

- OpAmp Limitations
  - Input Offset
    - This represents a built-in error between the + and – inputs
      - Bipolar: < 20mV
      - CMOS: < 1mV

$$V_o = A_{od}(V_+ - V_- - V_{offset})$$

A_{od}= 100,000
V_{os} = 10uV



OpAmps

- OpAmp Limitations
  - Input bias current / input bias current offset
    - The required input current to operate the opamp
    - The offset from + to – for the input bias currents
    - Bipolar inputs
      - Bias current, typically < 1uA
      - Offset, typically 20% - 50% of bias current
    - CMOS inputs, typically < 1nA

OpAmps

- OpAmp Limitations
  - Input Impedance
    - The impedance looking into the inputs
    - Bipolar input opamps typically between 1MΩ and 10MΩ
    - CMOS input opamps typically > 10GΩ
  - Output Impedance
    - The impedance looking into the output
    - Typically < 50Ω

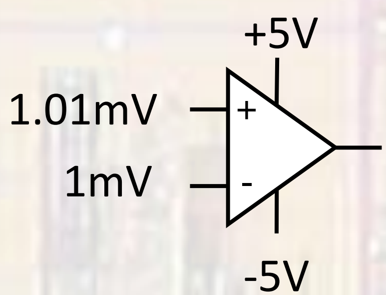
OpAmps

- OpAmp Limitations
  - Common Mode Rejection Ratio (CMMR)
    - This represents the opamps ability to reject signals that are present on both inputs (common)
    - CMRR is the ratio of the common-mode gain to differential-mode gain

$$V_o = A_{od}(V_+ - V_-) + A_{CM}\frac{(V_+ + V_-)}{2}$$

$$CMRR = \frac{A_{od}}{A_{CM}} \qquad CMRR_{dB} = 20\log\frac{A_{od}}{A_{CM}}$$

A_{od} = 100,000
A_{CM} = 80dB
(10,000)

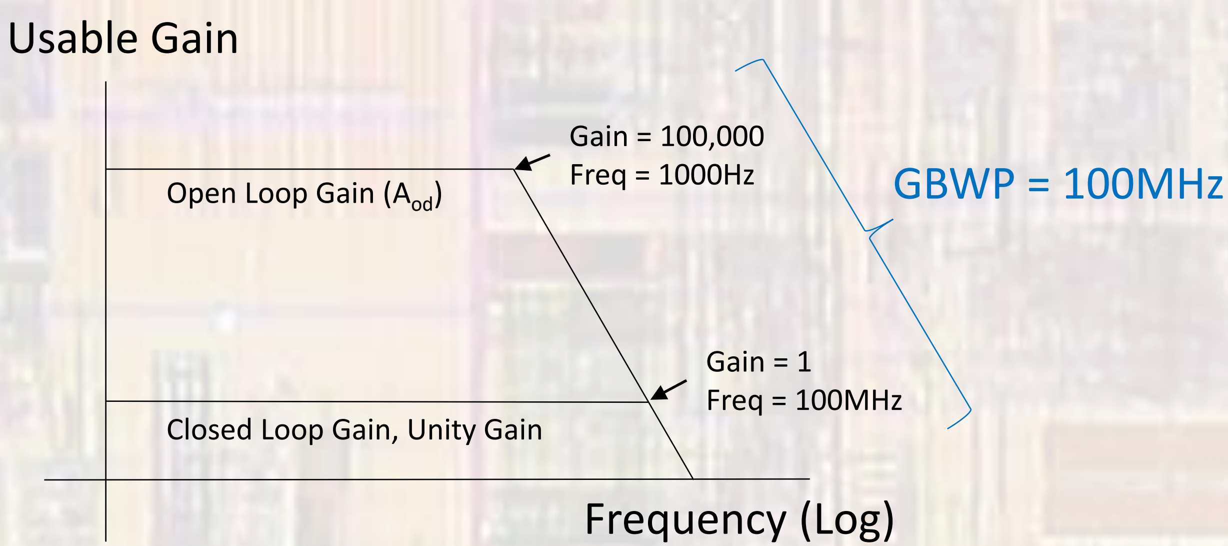


$$1V + \frac{100{,}000}{10{,}000}\frac{(1.01mV + 1mV)}{2}$$

1V + 10.05mV = 1.01V

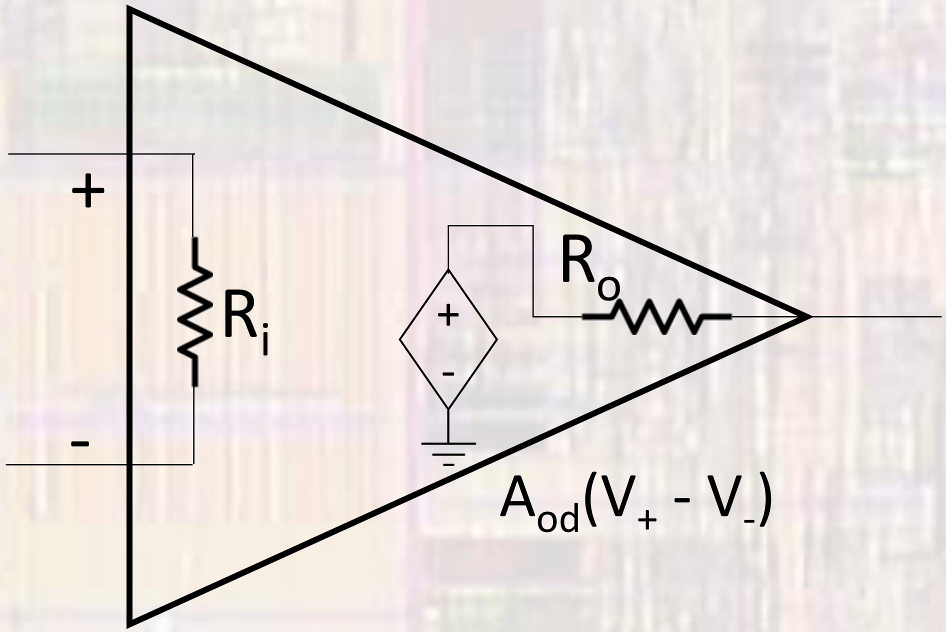
OpAmps

- OpAmp Limitations
  - Gain Bandwidth Product
    - Product of the Gain at a specific frequency and the frequency
    - For most negative feedback configurations this is constant
    - Sometimes called the Unity Gain Bandwidth



OpAmps

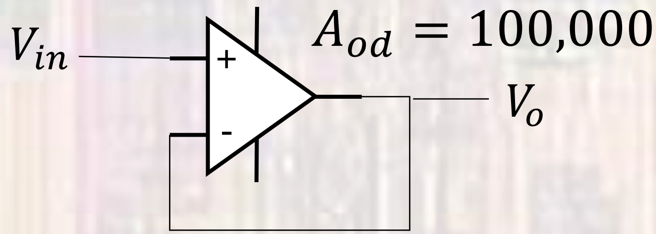
- OpAmp Models



OpAmp Circuits

- Most opamps are operated in negative feedback configurations
  - Output feeds back to the - input

- Voltage Follower



$$V_o = A_{od}(V_+ - V_-)$$

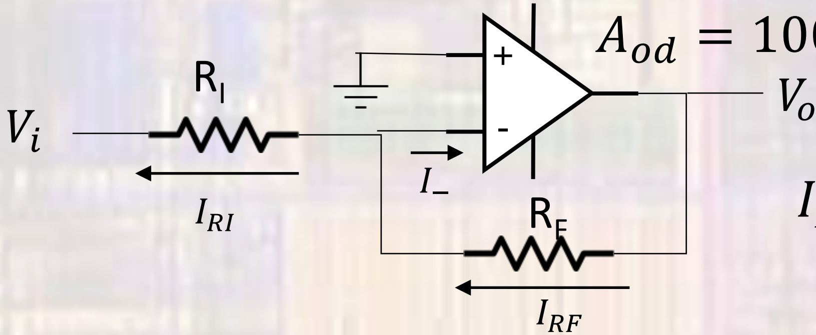
$$V_o = A_{od}(V_{in} - V_o)$$

$$V_o = \frac{A_{od}}{1 + A_{od}} V_{in} = V_{in}\big|_{A_{od} \gg 1}$$

$$\boxed{A_v = \frac{V_o}{V_{in}} = \frac{A_{od}}{1 + A_{od}} = 1}$$

OpAmp Circuits

- Fixed Gain Inverting Amplifier
  - Gnd ref



$$A_{od} = 100{,}000$$

$$I_{RF} = I_{RI} + I_{-} = I_{RI}$$

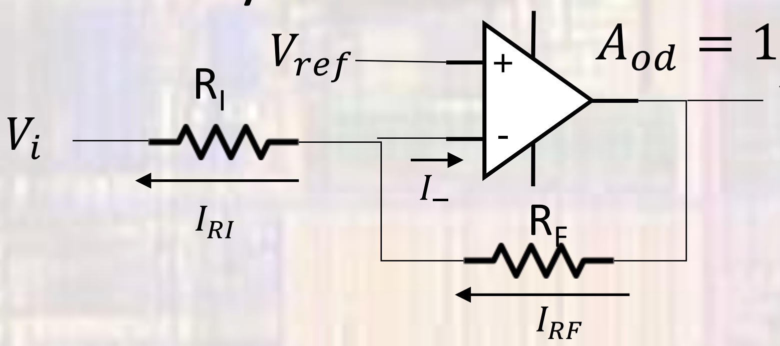
$$I_{RF} = \frac{V_o - V_-}{R_F} = \frac{V_o - \left(V_+ - \frac{V_0}{A_{od}}\right)}{R_F} \qquad I_{RI} = -\frac{V_i - V_-}{R_I} = -\frac{V_i - \left(V_+ - \frac{V_0}{A_{od}}\right)}{R_I}$$

$$\frac{V_o - \left(\cancelto{0}{V_+} - \cancelto{0}{\frac{V_0}{A_{od}}}\right)}{R_F} = -\frac{V_i - \left(\cancelto{0}{V_+} - \cancelto{0}{\frac{V_0}{A_{od}}}\right)}{R_I}$$

$$\boxed{V_o = -\frac{R_F}{R_I} V_i} \qquad \boxed{A_v = -\frac{R_F}{R_I}}$$

OpAmp Circuits

- Fixed Gain Inverting Amplifier
  - Arbitrary ref



$A_{od} = 100{,}000$

$I_{RF} = I_{RI} + I_- = I_{RI}$

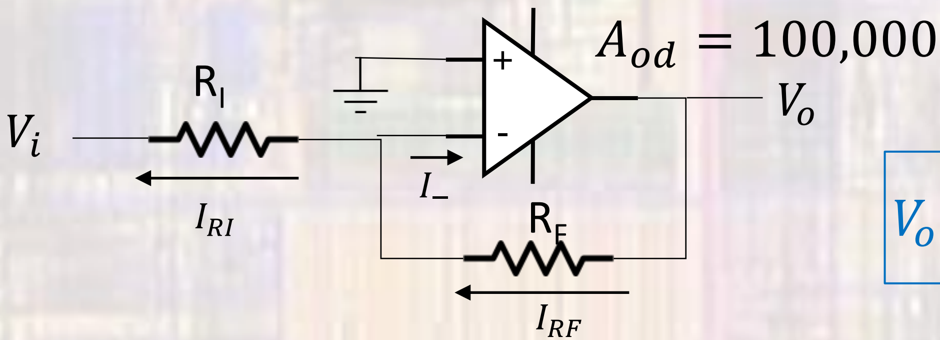
$$I_{RF} = \frac{V_o - V_-}{R_F} = \frac{V_o - \left(V_{ref} - \frac{V_0}{A_{od}}\right)}{R_F} \qquad I_{RI} = -\frac{V_i - V_-}{R_I} = -\frac{V_i - \left(V_{ref} - \frac{V_0}{A_{od}}\right)}{R_I}$$

$$\frac{V_o - \left(V_{ref} - \cancelto{0}{\frac{V_0}{A_{od}}}\right)}{R_F} = -\frac{V_i - \left(V_{ref} - \cancelto{0}{\frac{V_0}{A_{od}}}\right)}{R_I}$$

$$\boxed{V_o = -\frac{R_F}{R_I}V_i + \left(1 + \frac{R_F}{R_I}\right)V_{ref}}$$

OpAmp Circuits

- Inverting Amplifier
  - Second look



$$V_o = -\frac{R_F}{R_I}V_i$$

$$V_- = V_i + V_{R_I} = V_i + (V_o - V_i)\frac{R_I}{R_I + R_F}$$

$$V_- = \frac{V_iR_I + V_iR_F + V_oR_I - V_iR_I}{R_I + R_F} = \frac{V_iR_F + V_oR_I}{R_I + R_F} = \frac{V_iR_F - \frac{R_F}{R_I}V_iR_I}{R_I + R_F}$$

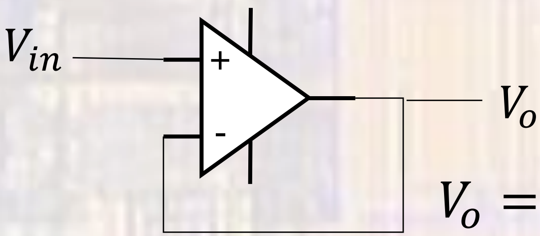
$$V_- = \frac{V_iR_F - R_FV_i}{R_I + R_F} = 0$$

V_ is called a virtual ground

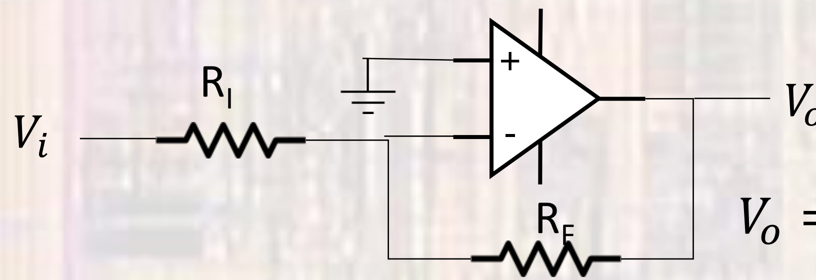
OpAmp Circuits

- Inverting Amplifier

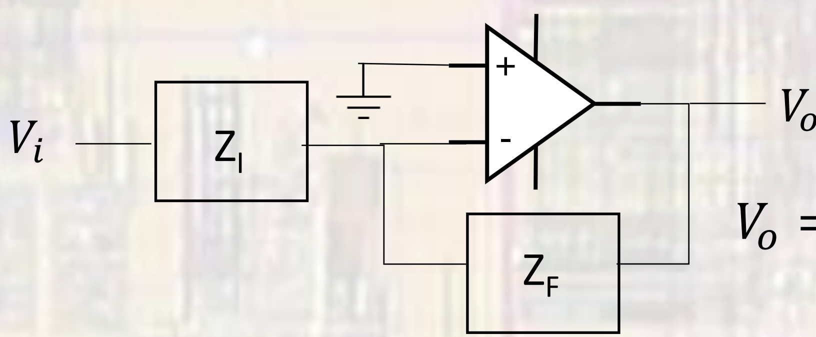
An opamp in a negative feedback configuration will drive its output to force the V+ and V- inputs to be equal



$$V_o = V_{in}$$



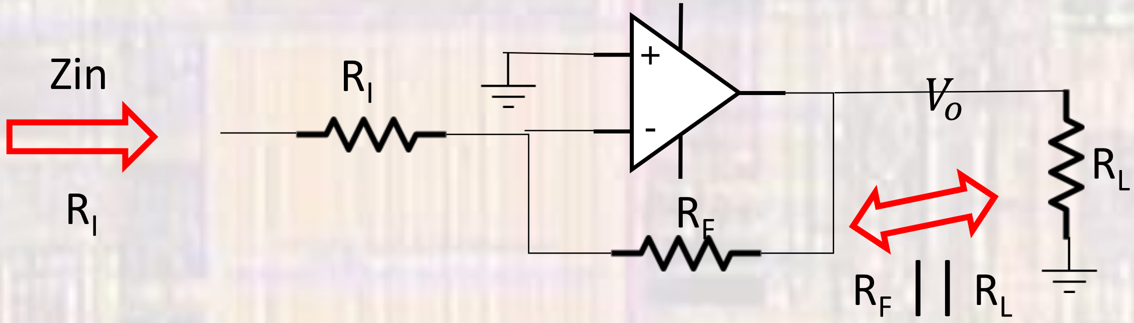
$$V_o = -\frac{R_F}{R_I} V_i$$



$$V_o = -\frac{Z_F}{Z_I} V_i$$

OpAmp Circuits

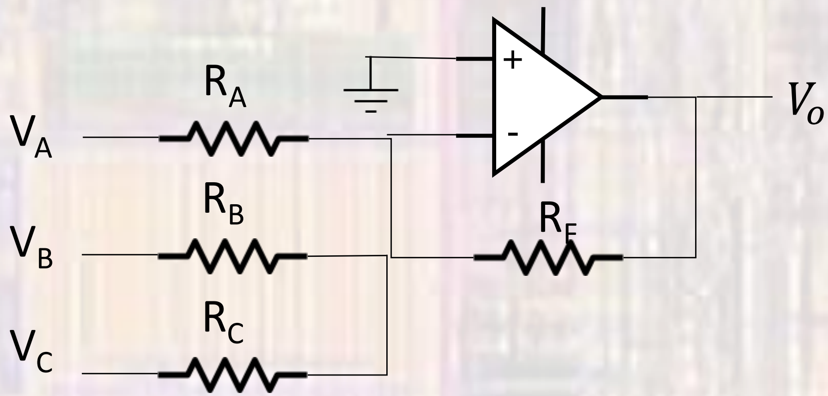
- Fixed Gain Inverting Amplifier



Input impedance concerns
Input current and input offset current concerns
Output impedance concerns

OpAmp Circuits

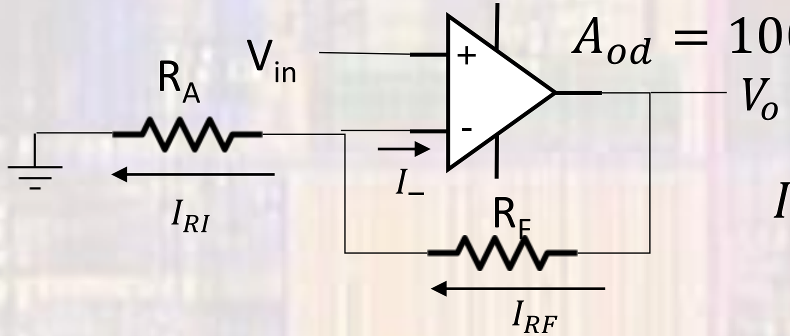
- Fixed Gain Inverting Summing Amplifier
  - By superposition



$$V_o = -\frac{R_F}{R_A} V_A - \frac{R_F}{R_B} V_B - \frac{R_F}{R_C} V_C$$

OpAmp Circuits

- Fixed Gain Non-Inverting Summing Amplifier
  - Full Analysis



$A_{od} = 100{,}000$

$$I_{RF} = I_{RA} + I_{-} = I_{RA}$$

$$I_{RF} = \frac{V_o - V_{-}}{R_F} = \frac{V_o - \left(V_{in} - \frac{V_0}{A_{od}}\right)}{R_F}$$

$$I_{RA} = \frac{V_{-} - 0}{R_A} = \frac{V_{in} - \frac{V_0}{A_{od}}}{R_A}$$

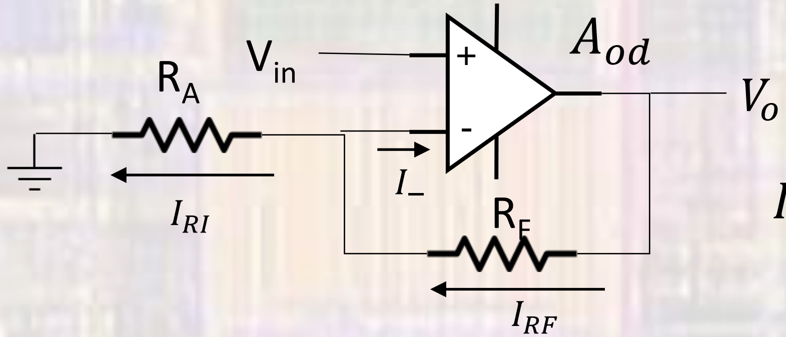
$$\frac{V_o - V_{in} + \overset{0}{\cancel{\frac{V_0}{A_{od}}}}}{R_F} = \frac{V_{in} - \overset{0}{\cancel{\frac{V_0}{A_{od}}}}}{R_A}$$

$$\boxed{V_o = \left(1 + \frac{R_F}{R_A}\right) V_{in}}$$

$$\boxed{A_v = 1 + \frac{R_F}{R_A}}$$

OpAmp Circuits

- Fixed Gain Non-Inverting Summing Amplifier
  - Simplified analysis
    - Output moves to make the + and – inputs equal



$$I_{RF} = I_{RA} + I_- = I_{RA}$$

$$I_{RF} = \frac{V_o - V_-}{R_F} = \frac{V_o - V_{in}}{R_F}$$

$$I_{RA} = \frac{V_- - 0}{R_A} = \frac{V_{in}}{R_A}$$

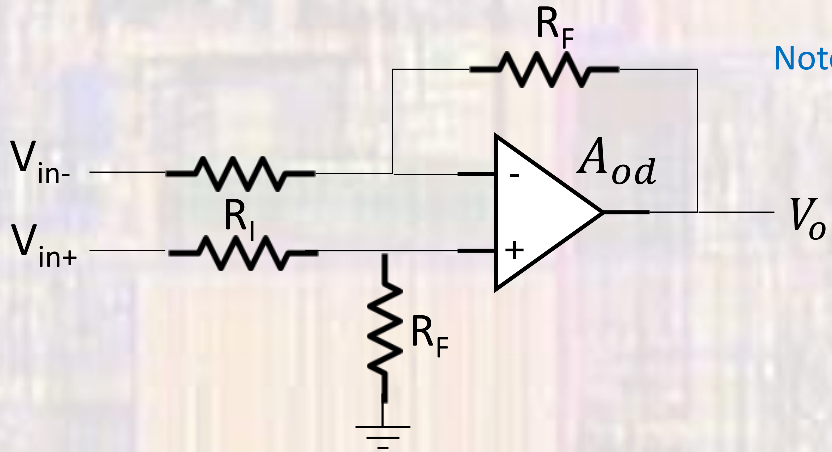
$$\frac{V_o - V_{in}}{R_F} = \frac{V_{in}}{R_A}$$

$$\boxed{V_o = \left(1 + \frac{R_F}{R_A}\right) V_{in}}$$

$$\boxed{A_v = 1 + \frac{R_F}{R_A}}$$

OpAmp Circuits

- Difference Amplifier



Note: no power pins
Amplifier flipped upside down

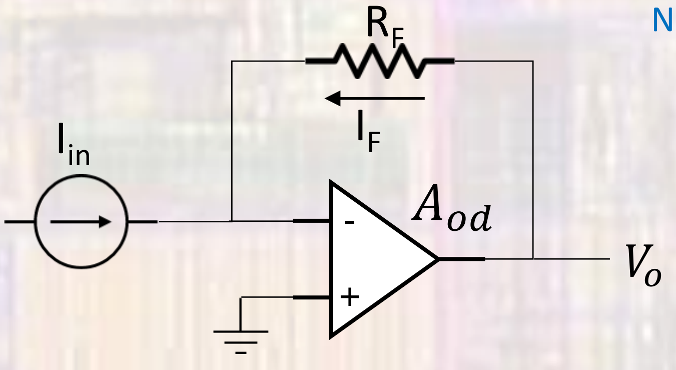
$$V_+ = V_{in+}\frac{R_F}{R_I + R_F} = V_-$$

$$\frac{V_{in-} - V_-}{R_I} = -\frac{V_o - V_-}{R_F}$$

$$\boxed{V_o = \frac{R_F}{R_I}(V_{in+} - V_{in-})}$$

OpAmp Circuits

- Current to Voltage Converter



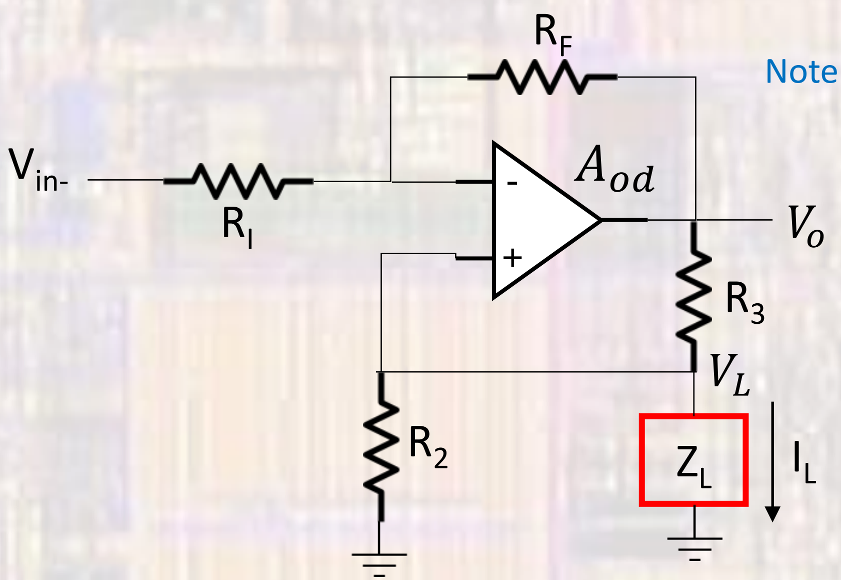
Note: no power pins
Amplifier flipped upside down

$$I_F = \frac{V_o - \cancel{V_-}^{\,0}}{R_F} = -I_{in}$$

$$\boxed{V_o = -I_{in} R_F}$$

OpAmp Circuits

- Voltage to Current Converter

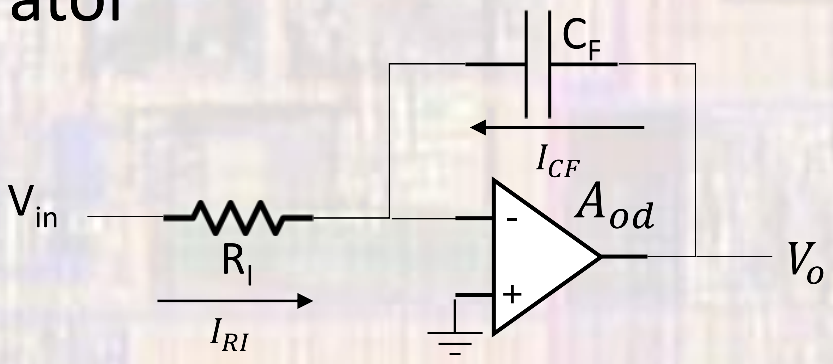


Note: no power pins
Amplifier flipped upside down

$$I_L = \left.\frac{-V_{in}}{R_2}\right|_{\frac{R_F}{R_2 R_3} = \frac{1}{R_2}}$$

OpAmp Circuits

- Integrator



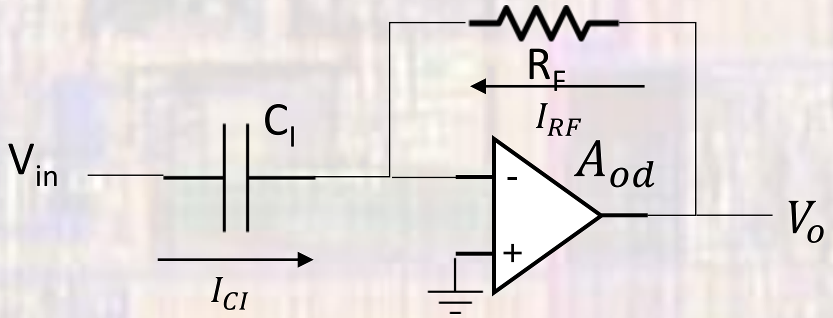
$$I_{CF} = C_F \frac{d_{vo}}{d_t} = -\frac{V_{in}}{R_I}$$

$$d_{vo} = -\frac{V_{in}}{C_F R_I} d_t$$

$$\boxed{V_o = V_{CF_0} - \frac{1}{C_F R_I} \int_0^t V_{in}(t')\, d_{t'}}$$

OpAmp Circuits

- Differentiator

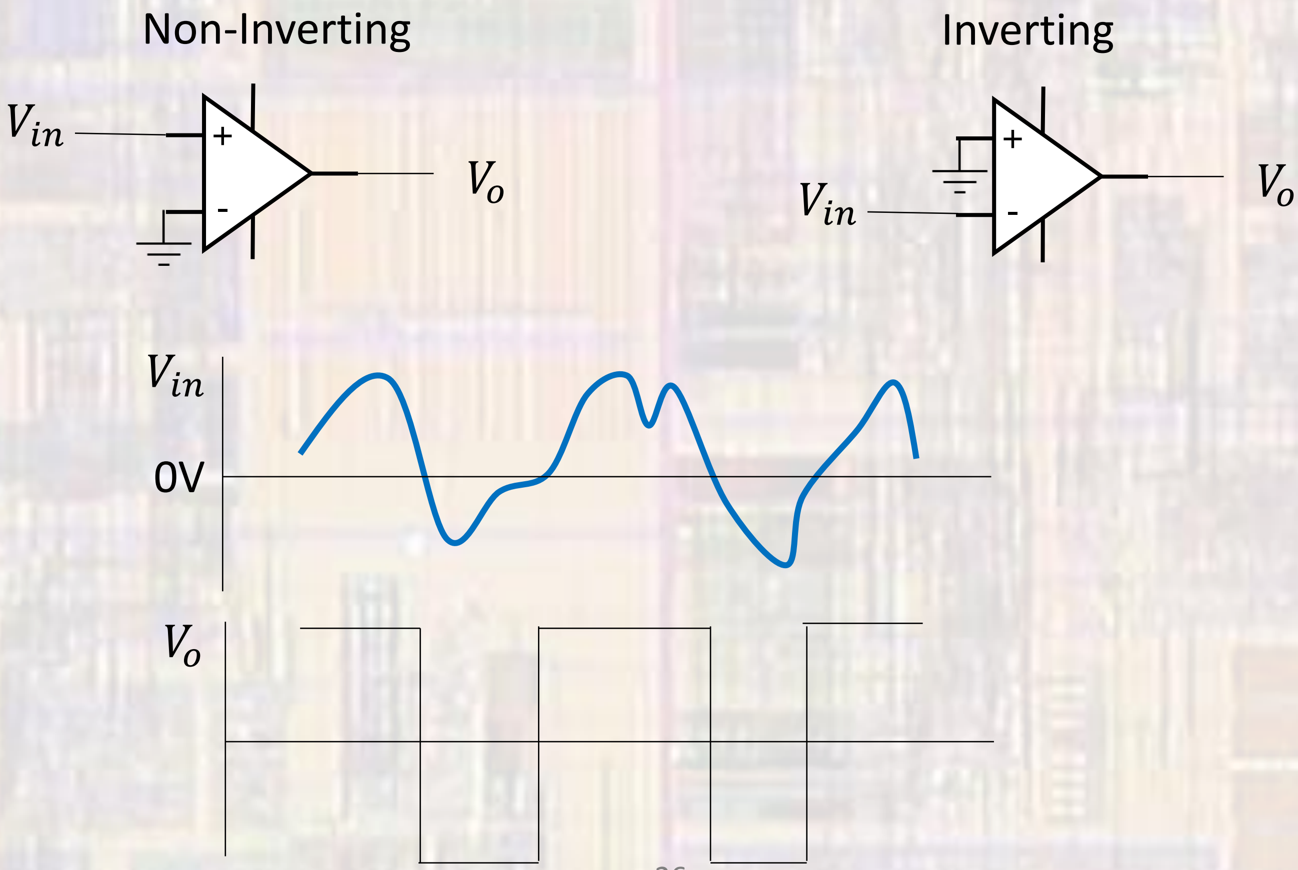


$$I_{CI} = C_I \frac{d_{vin}}{d_t} = -\frac{V_o}{R_F}$$

$$\boxed{V_o = -R_F C_I \frac{d_{vin}}{d_t}}$$

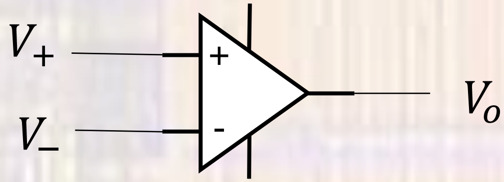
OpAmp Circuit

- Zero Crossing Detector
  - Open Loop opamp



OpAmp Circuit

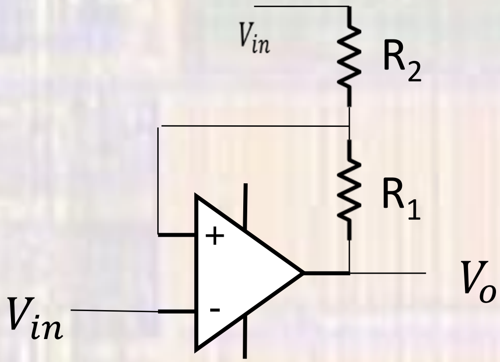
- Comparator
  - Special opamp with non-saturating outputs
    - Reduced delay in switching rail-to-rail



$V_o = vdd\ or\ vss$

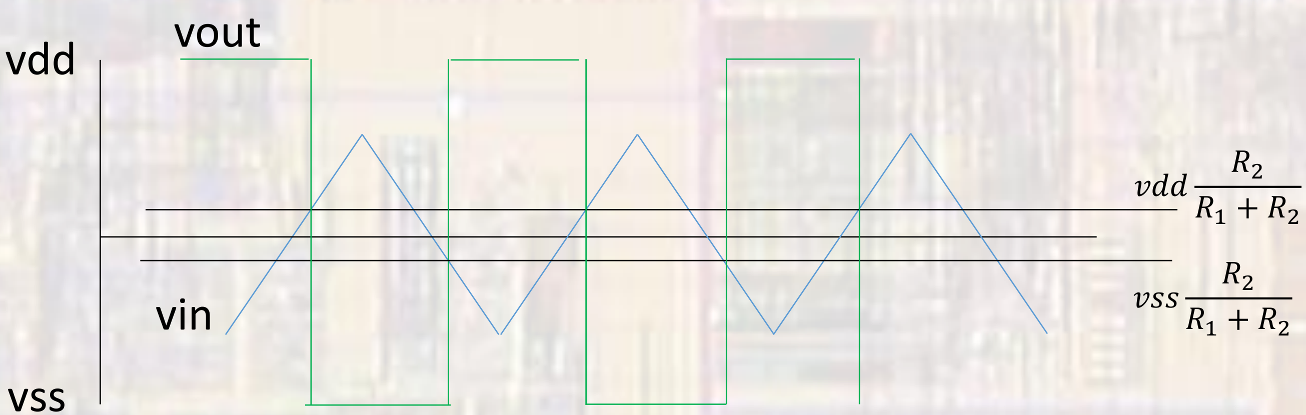
OpAmp Circuit

- Schmitt Trigger
  - Positive feedback
  - Non-overlapping switching points



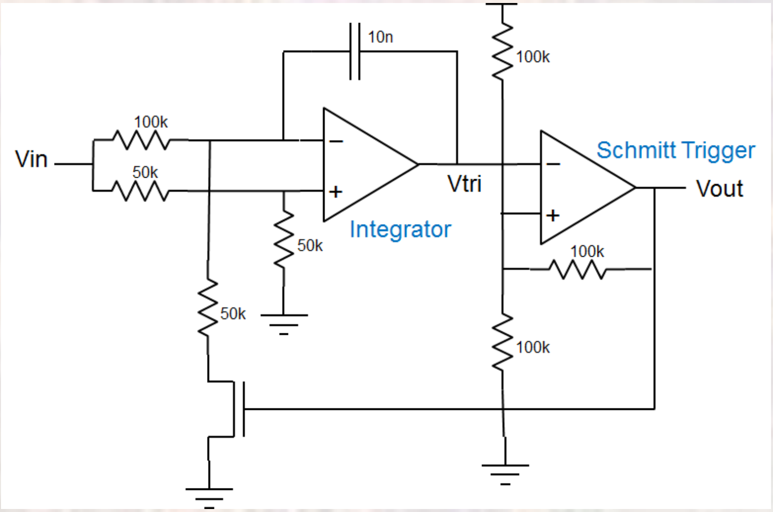
$$when\ V_o = vdd, then\ v_+ = vdd\frac{R_2}{R_1 + R_2}$$

$$when\ V_o = vss, then\ v_+ = vss\frac{R_2}{R_1 + R_2}$$

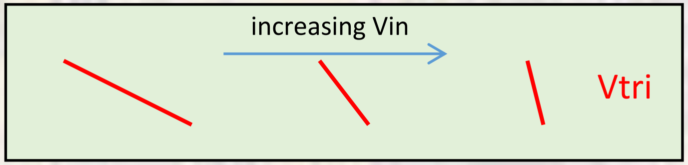


OpAmp Circuit

- Voltage Controlled Oscillator (VCO)

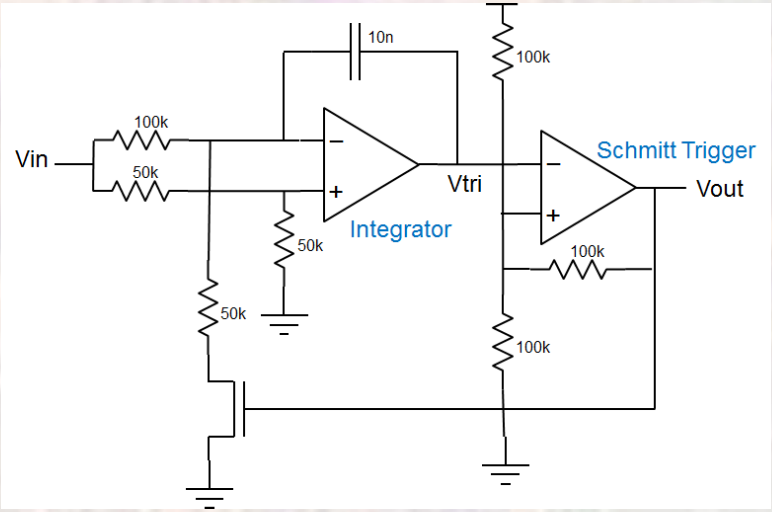


  - Integrator
    - Opamp wants v+input = v-input
    - When the MOSFET is off
      - + input is Vin/2 (minus input wants to be Vin/2)
      - current through 100K resistor must go through C
      - current through C   Ic = -Cdv/dt
      - -dv/dt is proportional to Vin → the opamp slews down

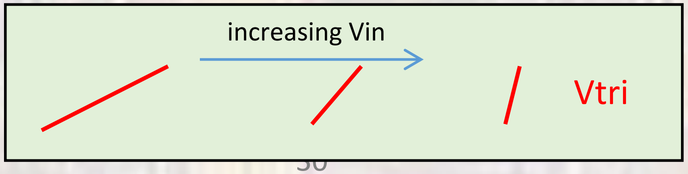


OpAmp Circuit

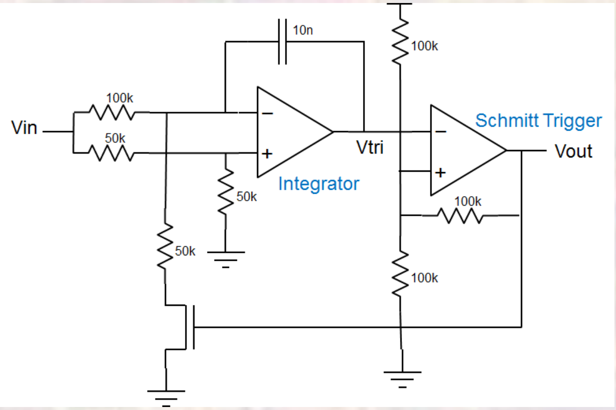
- Voltage Controlled Oscillator (VCO)



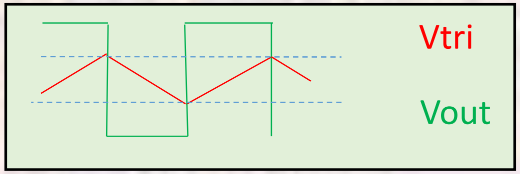
  - Integrator
    - Opamp wants v+input = v-input
    - When the MOSFET is on
      - + input is Vin/2 (minus input wants to be Vin/2)
      - current through the 100K resistor is ½ the current through 50K and MOSFET
      - the other half the current through the MOSFET must come from the C
      - current through C   Ic = Cdv/dt
      - dv/dt is proportional to Vin → the opamp slews up

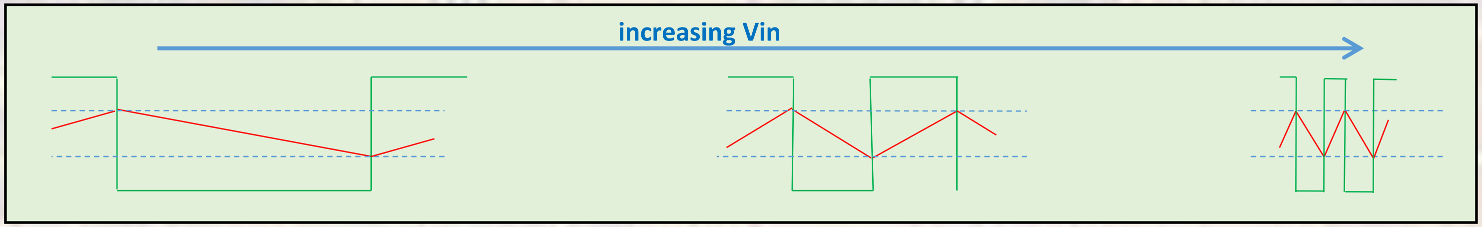


OpAmp Circuit



- Voltage Controlled Oscillator (VCO)
  - Schmitt Trigger
    - When Vout is high
      - Mosfet is on → Vtri is slewing up
      - + input is Vdd*2/3
      - When Vtri goes above Vdd*2/3 the opamp switches to Vout = 0
      - mosfet turns off → Vtri slews down
    - When Vout is low
      - Mosfet is off → Vtri is slewing down
      - + input is Vdd*1/3
      - When Vtri goes below Vdd*1/3 the opamp switches to Vout = high
      - mosfet turns on → Vtri slews up

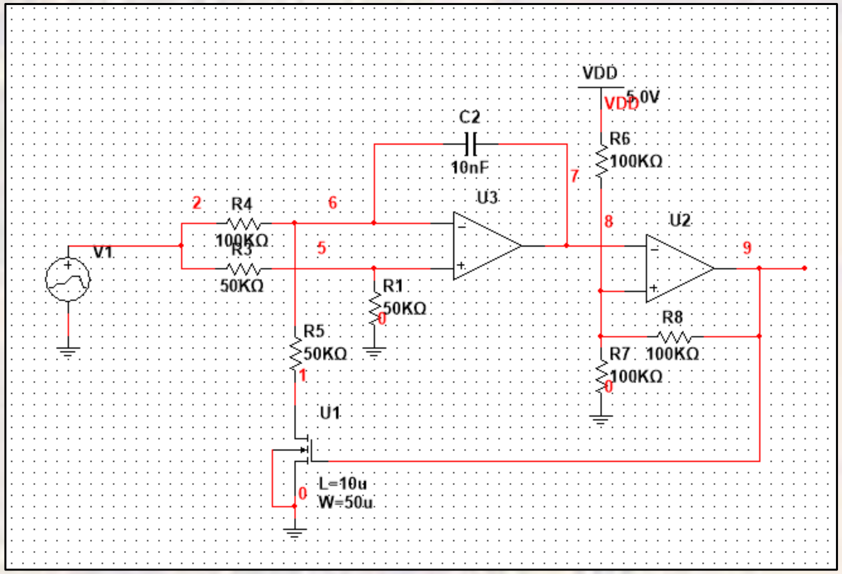


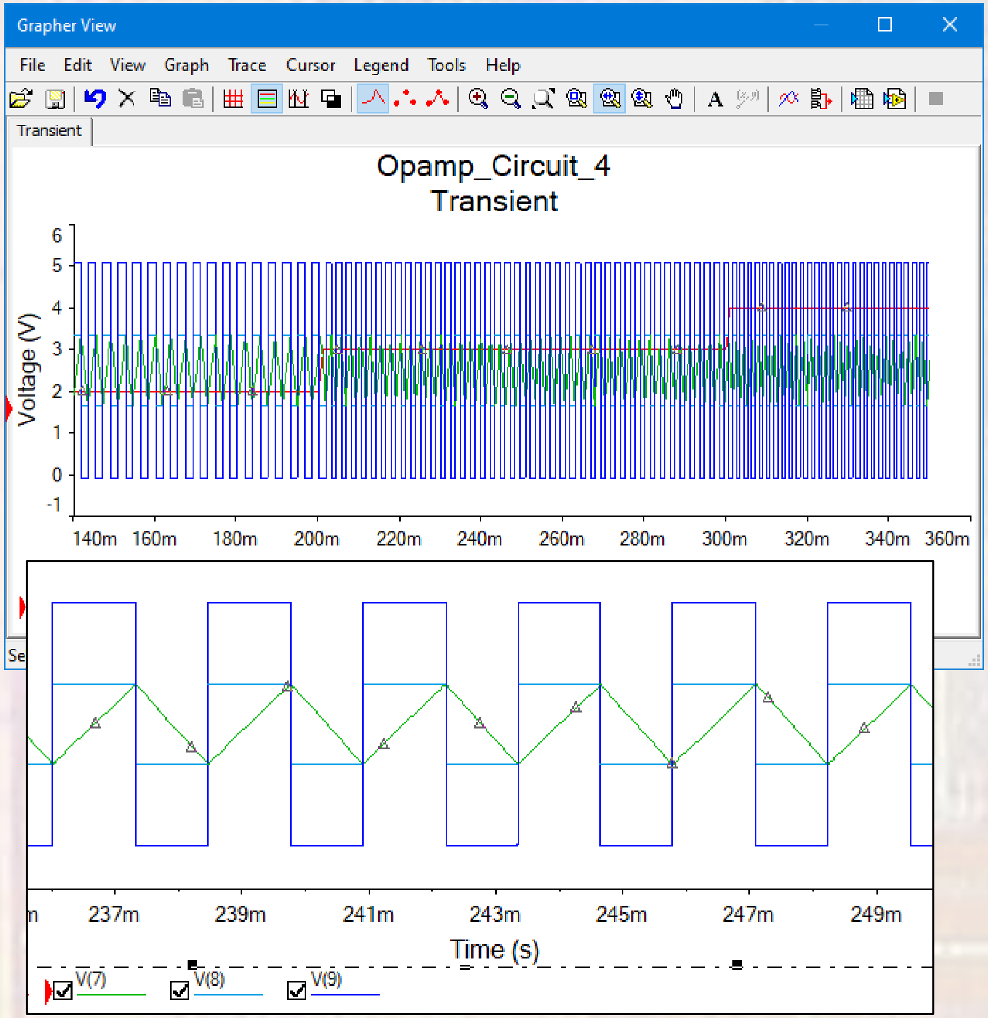


VCO

OpAmp Circuit

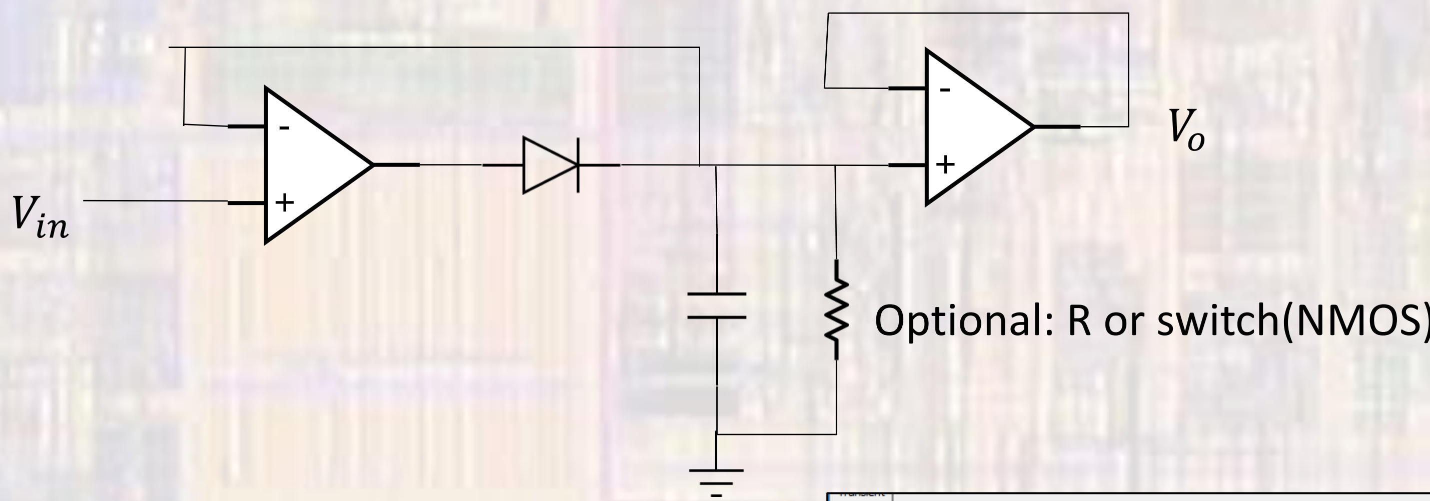
- Voltage Controlled Oscillator (VCO)

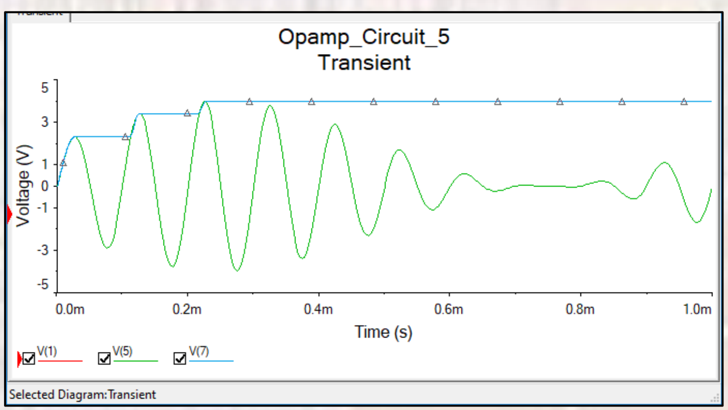




OpAmp Circuit

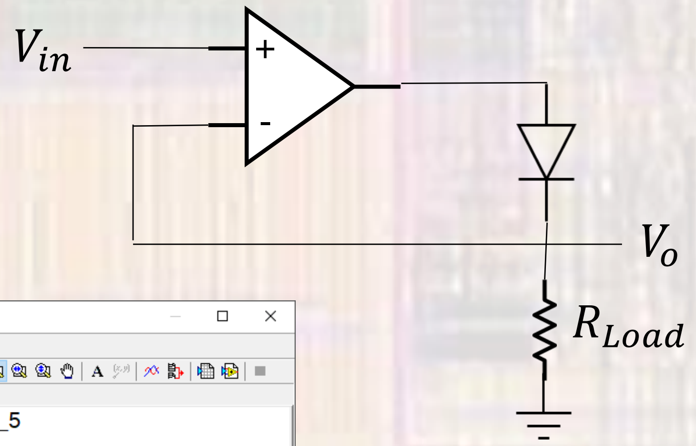
- Peak Detector

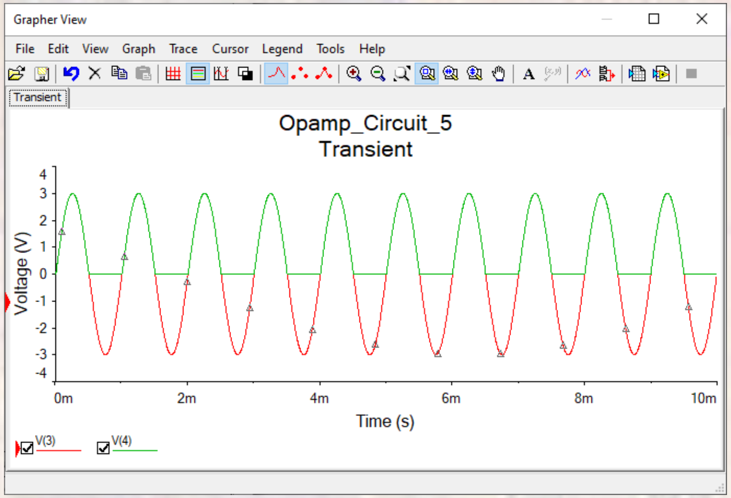




OpAmp Circuit

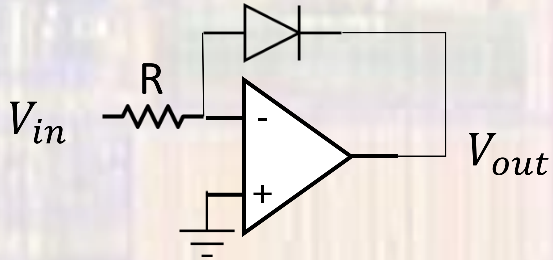
- Half-Wave Precision Rectifier
  - Removes the Diode voltage drop from the output





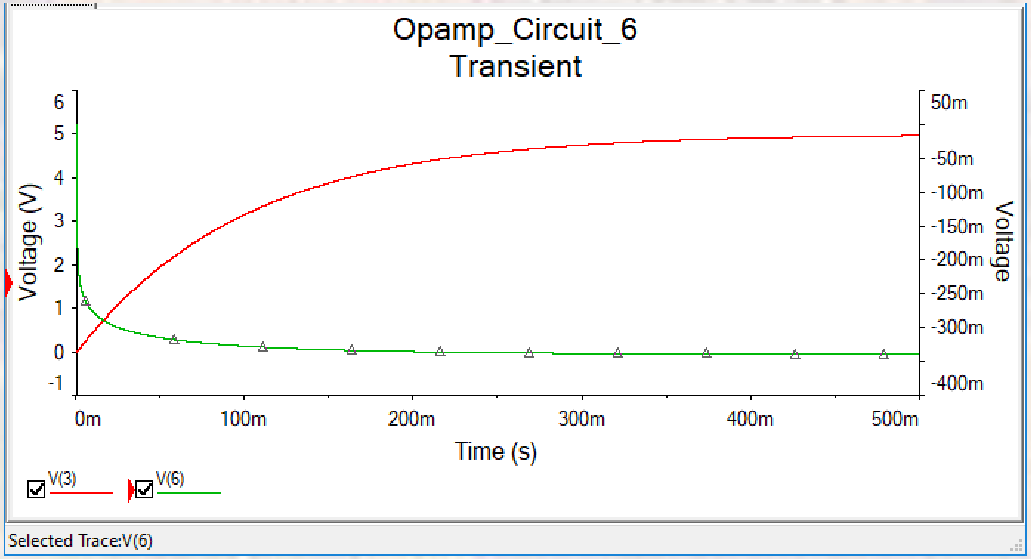
OpAmp Circuit

- Log Amplifier



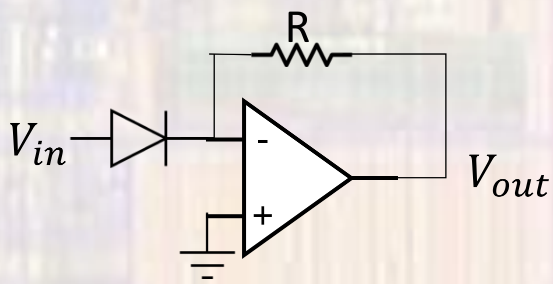
$$V_{in}/_R = I_D = I_S e^{\frac{V_D}{nV_T}} = I_S e^{\frac{-V_{out}}{nV_T}}$$

$$V_{out} = -nV_T ln\left(\frac{V_{in}}{I_S R}\right)$$



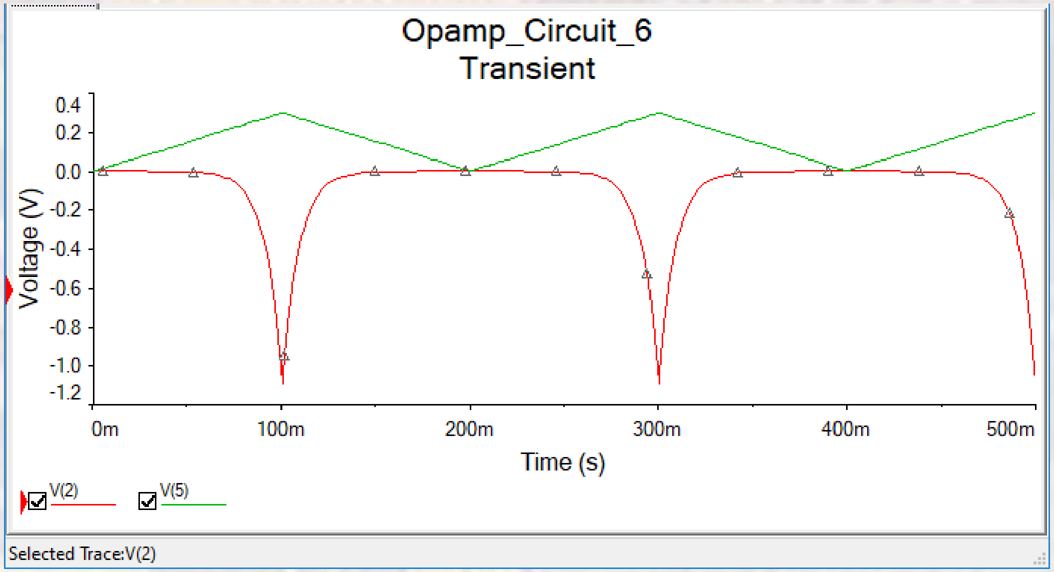
OpAmp Circuit

- Exponential Amplifier



$$V_{out}/_R = I_D = I_S e^{\frac{V_D}{nV_T}} = I_S e^{\frac{V_{in}}{nV_T}}$$

$$V_{out} = -RI_S e^{\frac{V_{in}}{nV_T}}$$

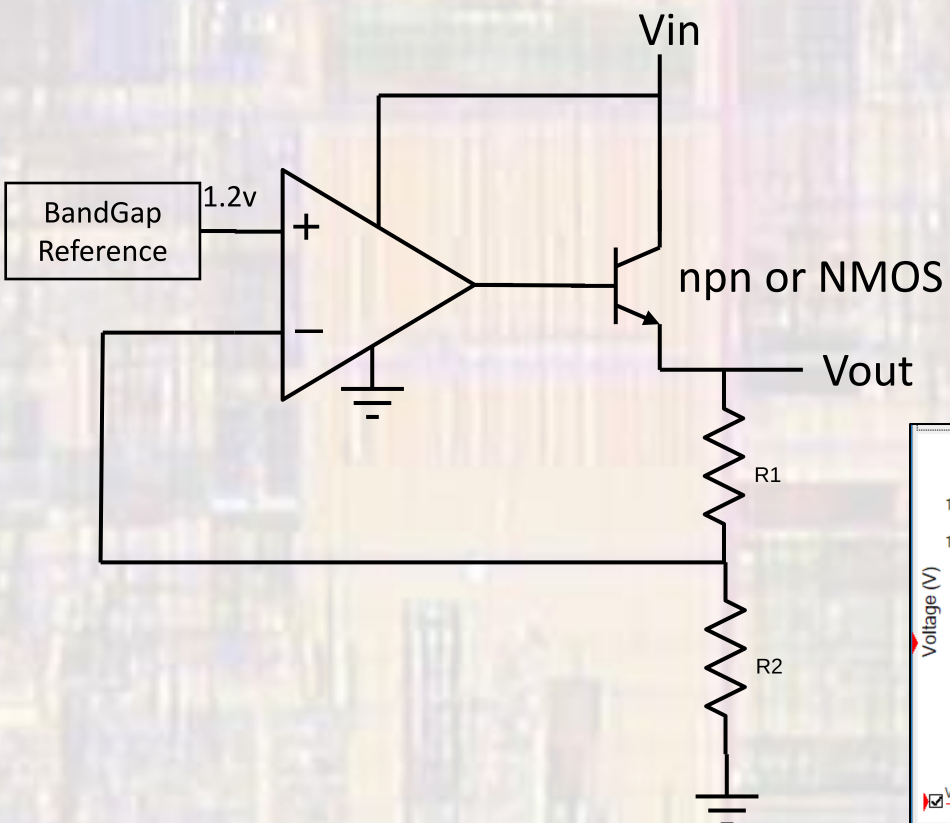


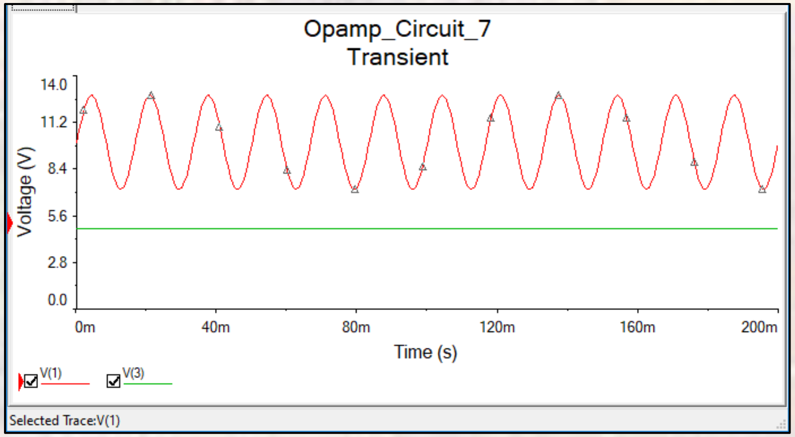
OpAmp Circuit

- Regulated Supply
  - Super Simple Regulator

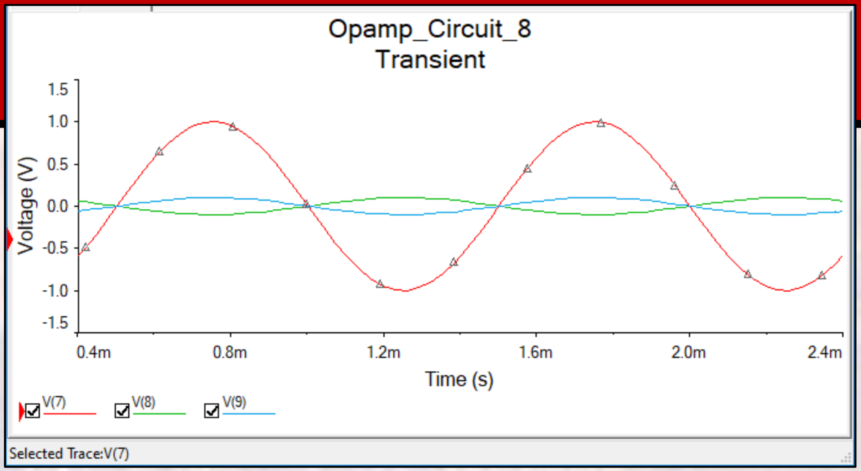
$$\frac{R2}{R1 + R2} Vout = Vbg$$

$$Vout = Vbg \frac{R1 + R2}{R2}$$

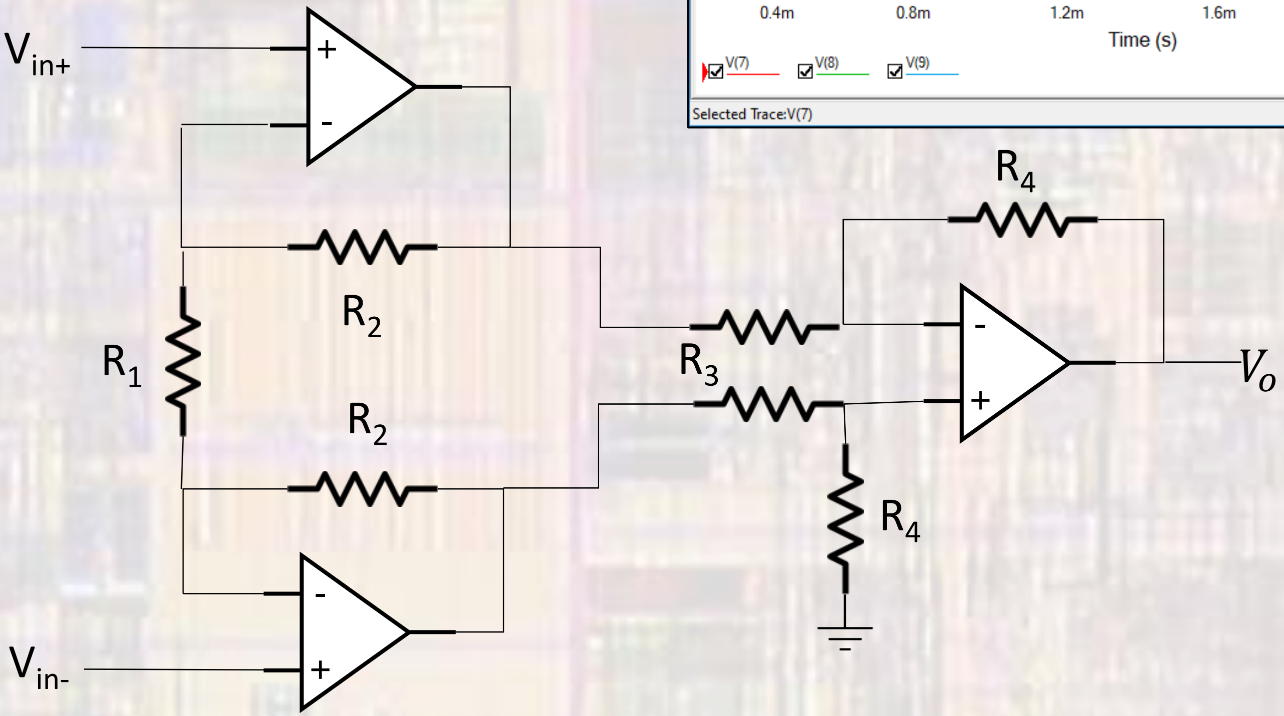




OpAmp Circuit



- Instrumentation Amplifier



$$V_o = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)(V_{in+} - V_{in-})$$