Ideal Op-Amp

ECE 211 Circuits I

Lecture #14

Please visit Bison Academy for corresponding
lecture notes, homework sets, and solutions

Op-Amp Models

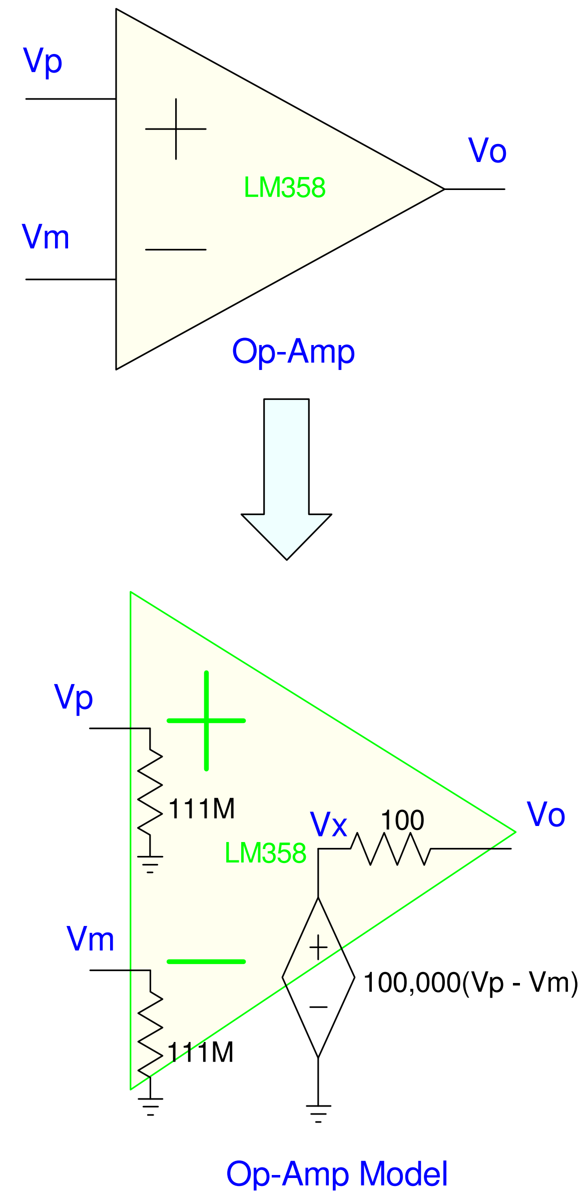
Last lecture looked at circuit models for an op-amp

- Replace it with it's circuit model
- Write the voltage node equations
- Solve

This resulted in somewhat painful analysis for simple circuits

- It gets worse with multiple op-amps

We need a better tool



Ideal Op-Amp

Engineering solution:

- If you have a difficult problem, change the problem
- Make it simpler while
- Keeping the flavor of the original problem

Assume

- The differential gain is infinity
  - *vs. 100,000*
- The input current is zero
  - *Input impedance = infinity*
  - *vs. 111M Ohms*

It may not seem like it, but this greatly simplifies op-amp circuit analysis

Term	LM358	Ideal
Input Bias Current	45nA	0nA
(Input Impedance @ 5V)	111M	infinity
Open-Loop Gain	100,000	infinity
Gain Bandwidth Product	1MHz	infinity
Slew Rate	250,000 V/s	infinity
Voltage swing from rail	1.5V	0V
Output Current	20mA	infinity
Output Resistance	100 Ohms	0 Ohms

Circuit Analysis with Ideal Op-Amps

- Two methods commonly used

Method #1	Method #2

Voltage Nodes

- Assume circuit has N voltage nodes
- Write N nodal equations
- Vp = Vm is usually one equation
  - *This is the equation at Vo*
  - *Usually true with negative feedback*

Solve N equations for N unknowns

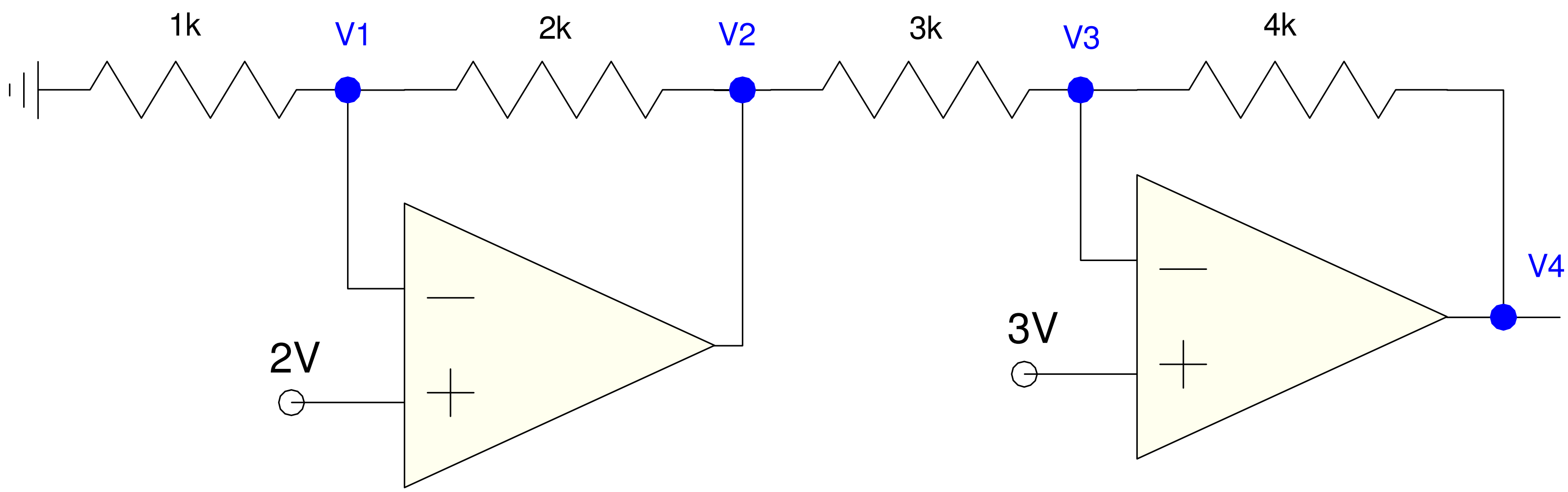
What voltages make the circuit work?

Subject to...

- Vp = Vm
  - *Usually true with negative feedback*
- Currents must balance

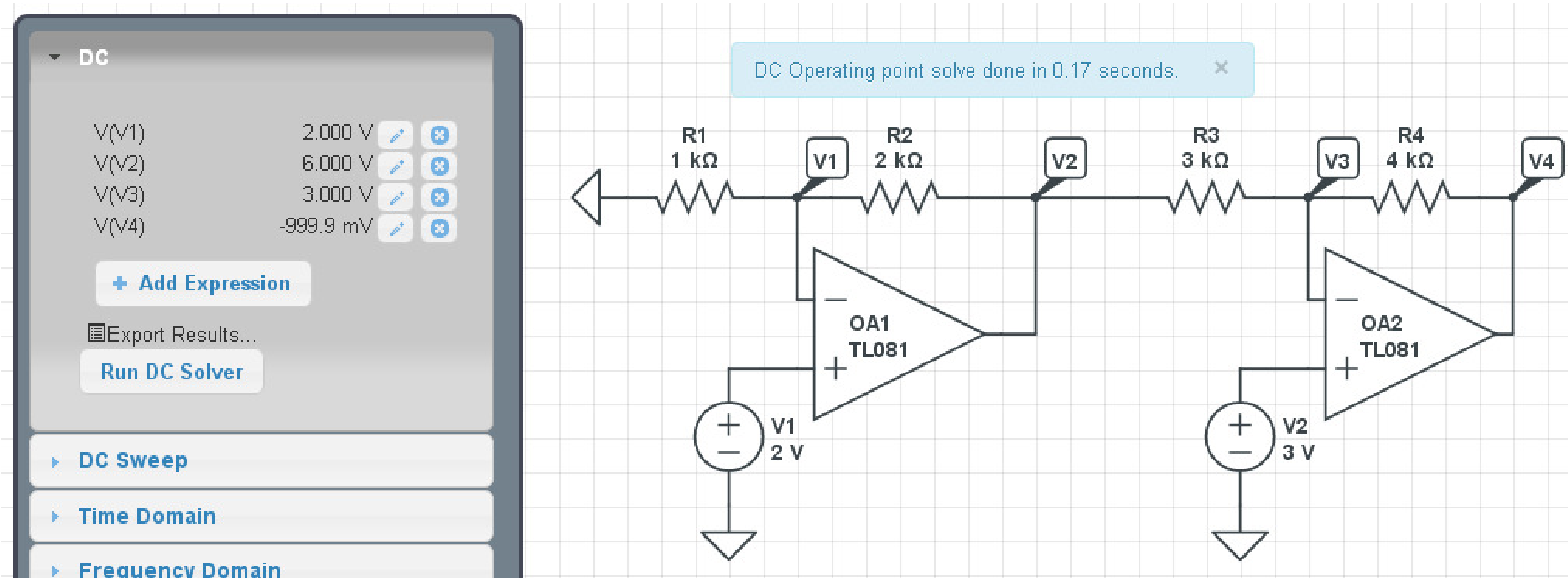
Example #1: Find the voltages

Find {V1, V2, V3, V4}



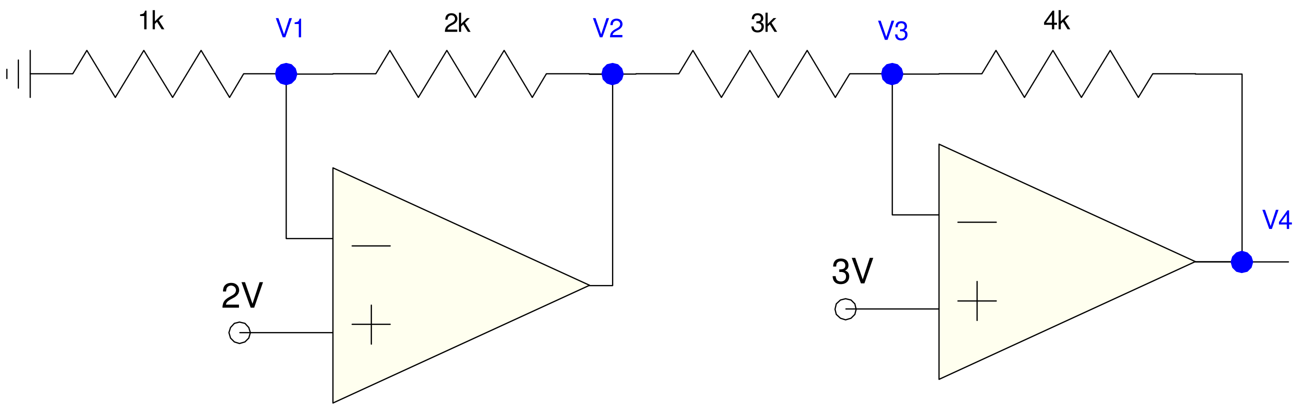
Example #1: CircuitLab

- note: All op-amps give about the same result
- All are differential amplifiers with high gain and high input impedance



Example #1: Voltage Nodes

Write 4 equations for 4 unknowns

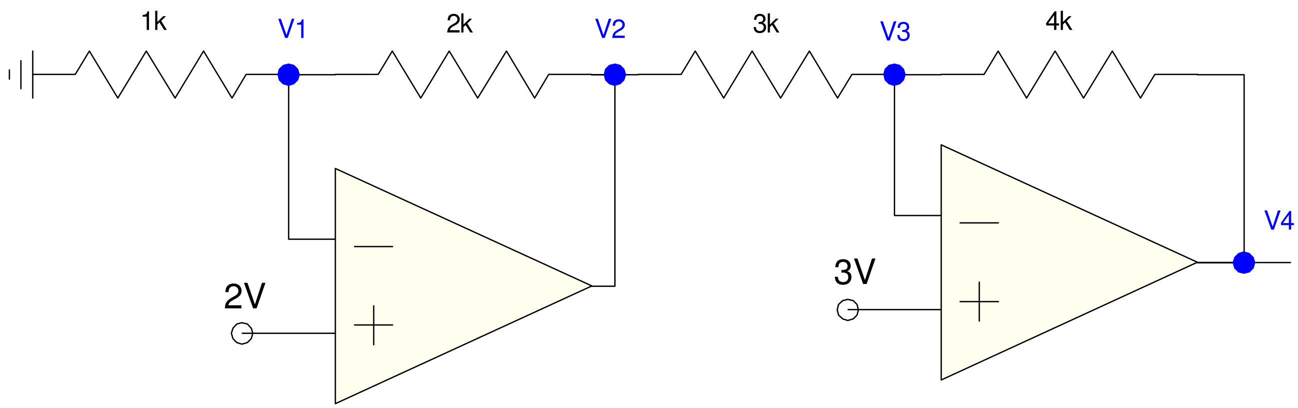


Example #1: Voltage Nodes

Easy ones: Vp = Vm

$$V_1 = 2$$

$$V_3 = 3$$



Two mode equations

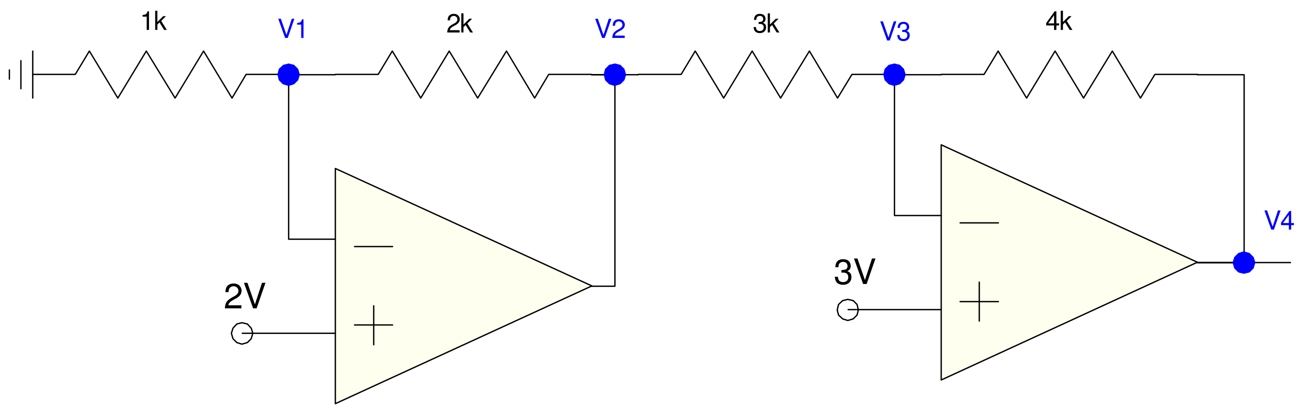
$$\left(\frac{V_1}{1k}\right) + \left(\frac{V_1 - V_2}{2k}\right) = 0$$

$$\left(\frac{V_3 - V_2}{3k}\right) + \left(\frac{V_3 - V_4}{4k}\right) = 0$$

Solve

Example #1: Figure out voltages

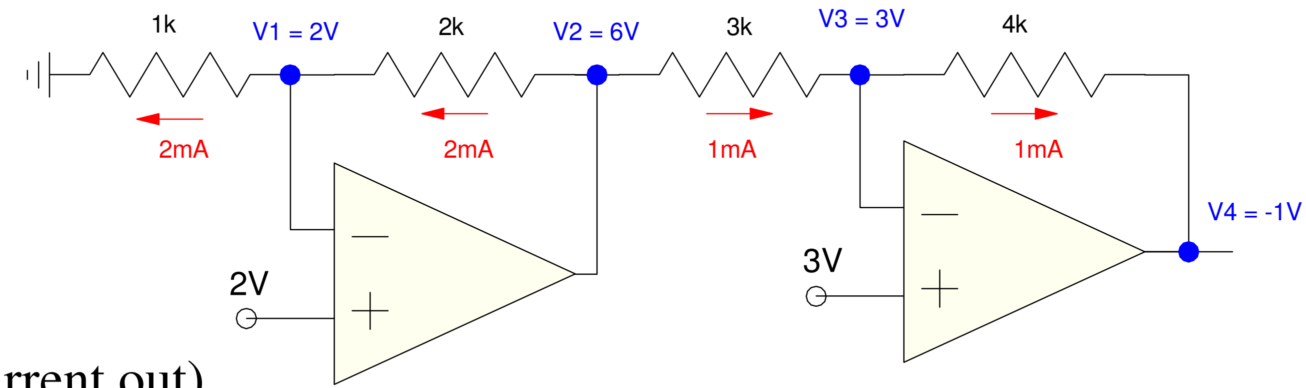
- Vp = Vm
- Currents balance



Example #1: Figure out voltages

Start with

- V1 = 2V
- V3 = 3V



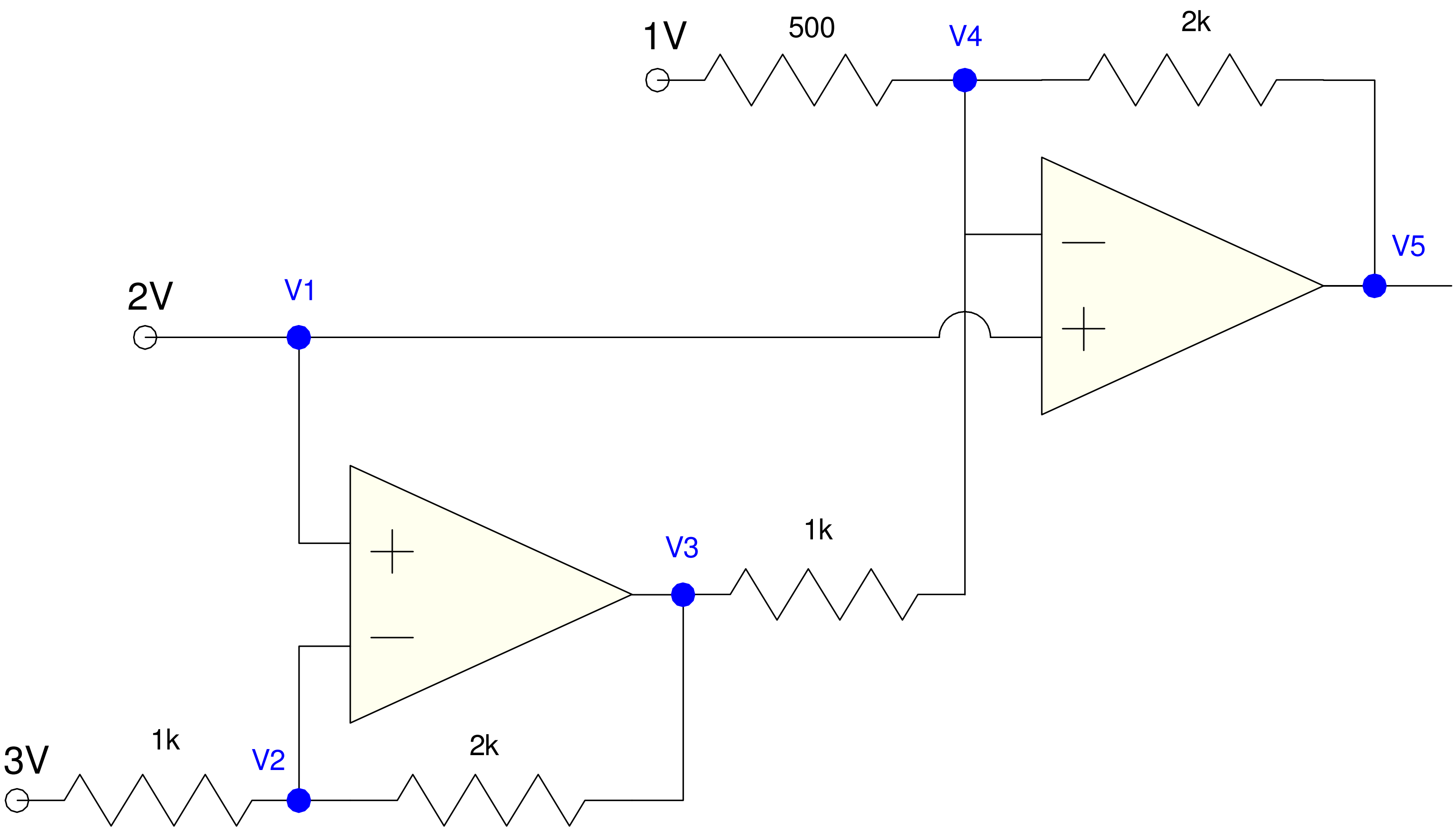
First op-amp

- I(1k) = 2mA (2V @ 1k)
- I(2k) = 2mA (current in = current out)
- V2 = 6V   (V1 + 2k * 2mA)

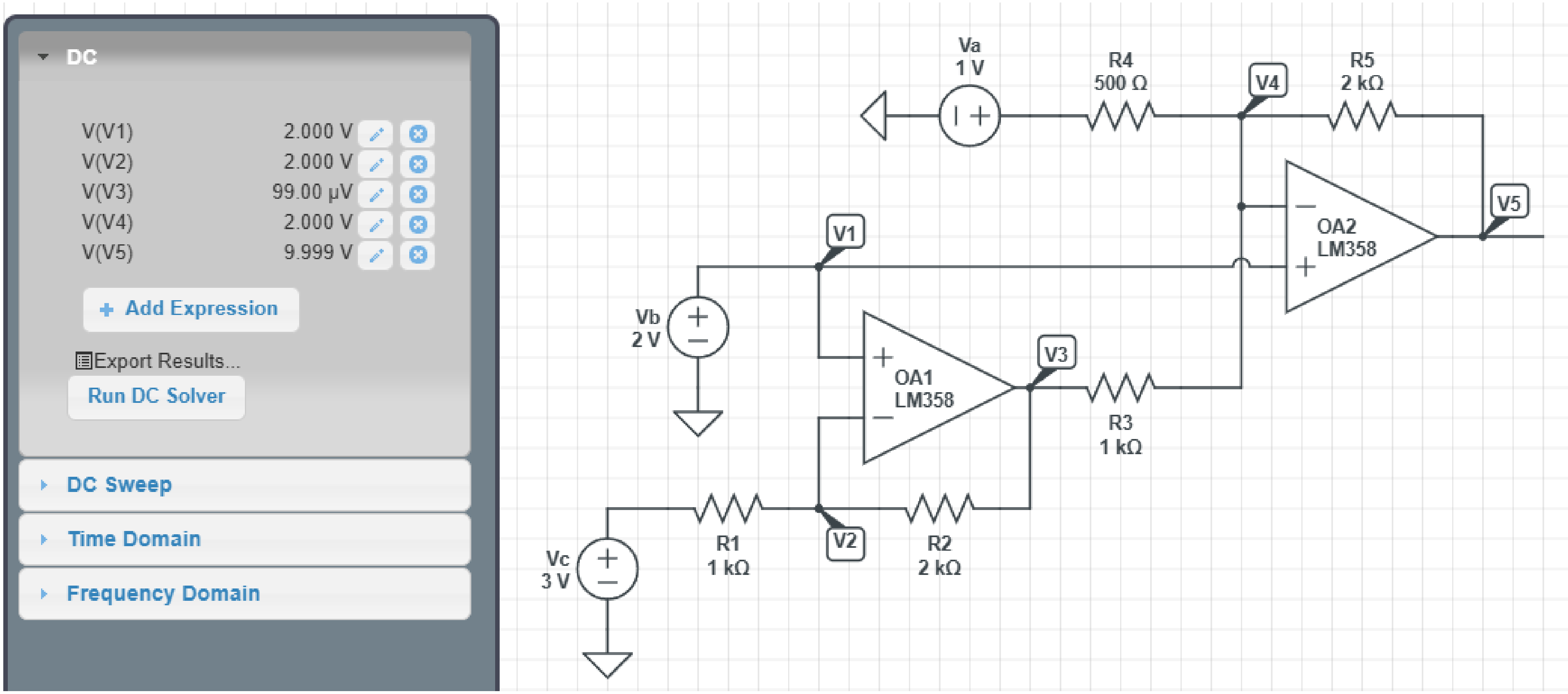
Second op-amp

- I(3k) = 1mA   (3V @ 3k)
- I(4k) = 1mA   (current in = current out)
- V4 = -1V   (V3 - 4k * 1mA)

Example #2: Determine the voltages

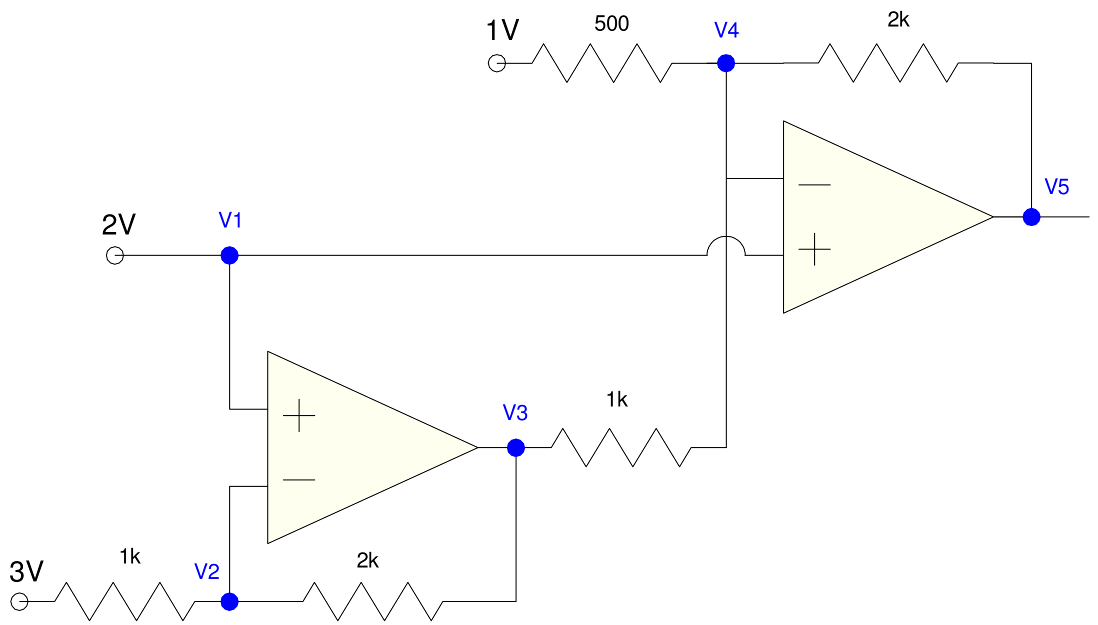


Example #2: CircuitLab



Example #2: Nodal Equations

Write 5 equations for 5 unknowns



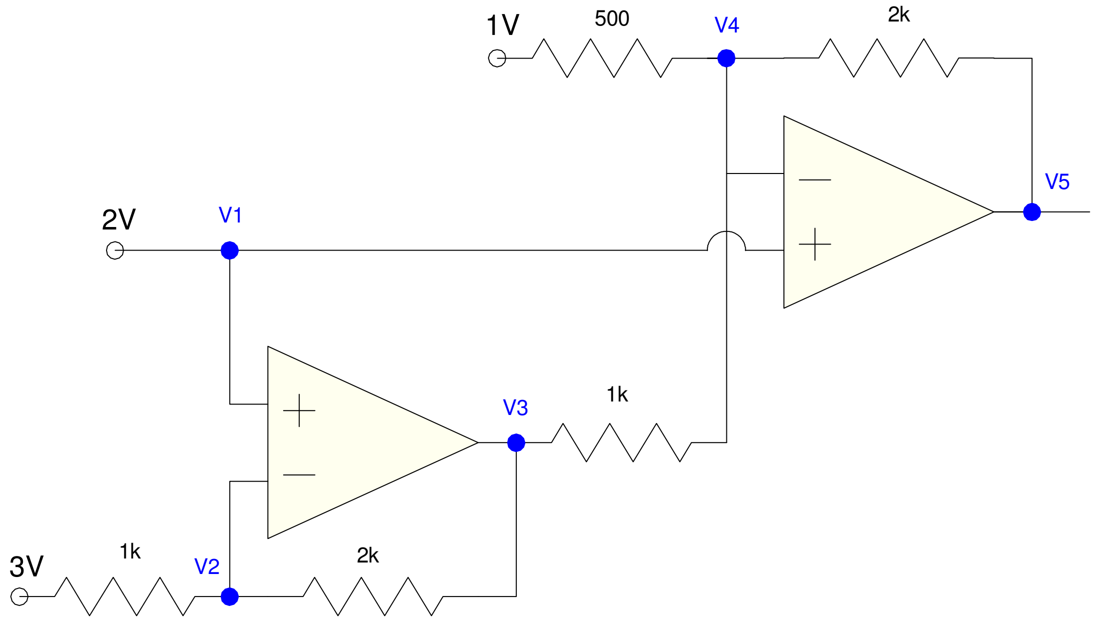
Example #2: Nodal Equations

Easy ones (Vp = Vm)

$$V_1 = 2$$

$$V_2 = V_1$$

$$V_4 = V_1$$



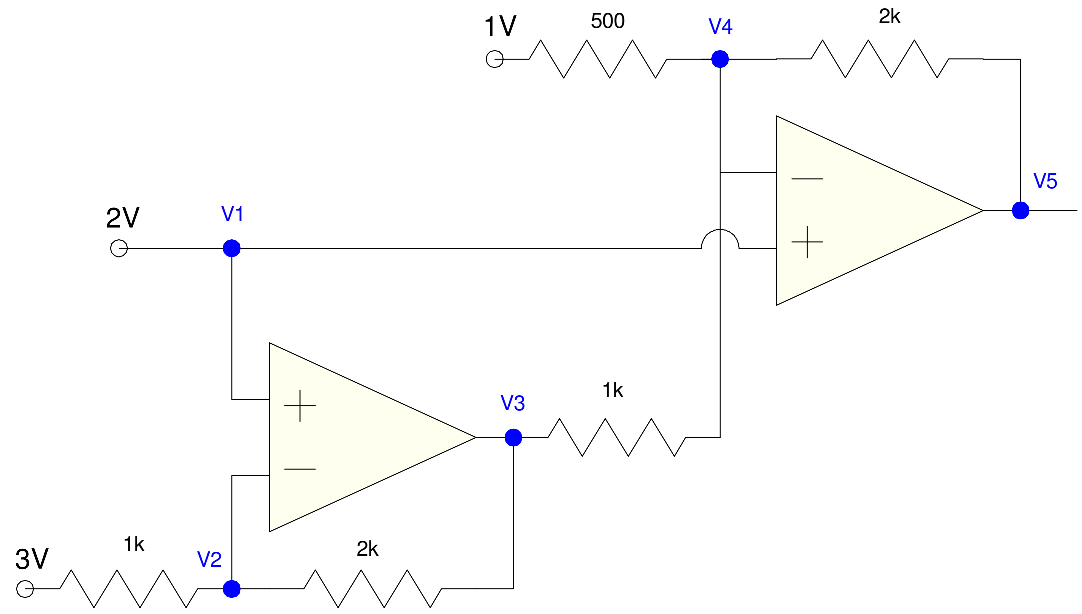
Write two more node equations:

$$\left(\frac{V_2-3}{1k}\right) + \left(\frac{V_2-V_3}{2k}\right) = 0$$

$$\left(\frac{V_4-1}{500}\right) + \left(\frac{V_4-V_5}{2k}\right) + \left(\frac{V_4-V_3}{1k}\right) = 0$$

Solve

Example #2: Figure it out



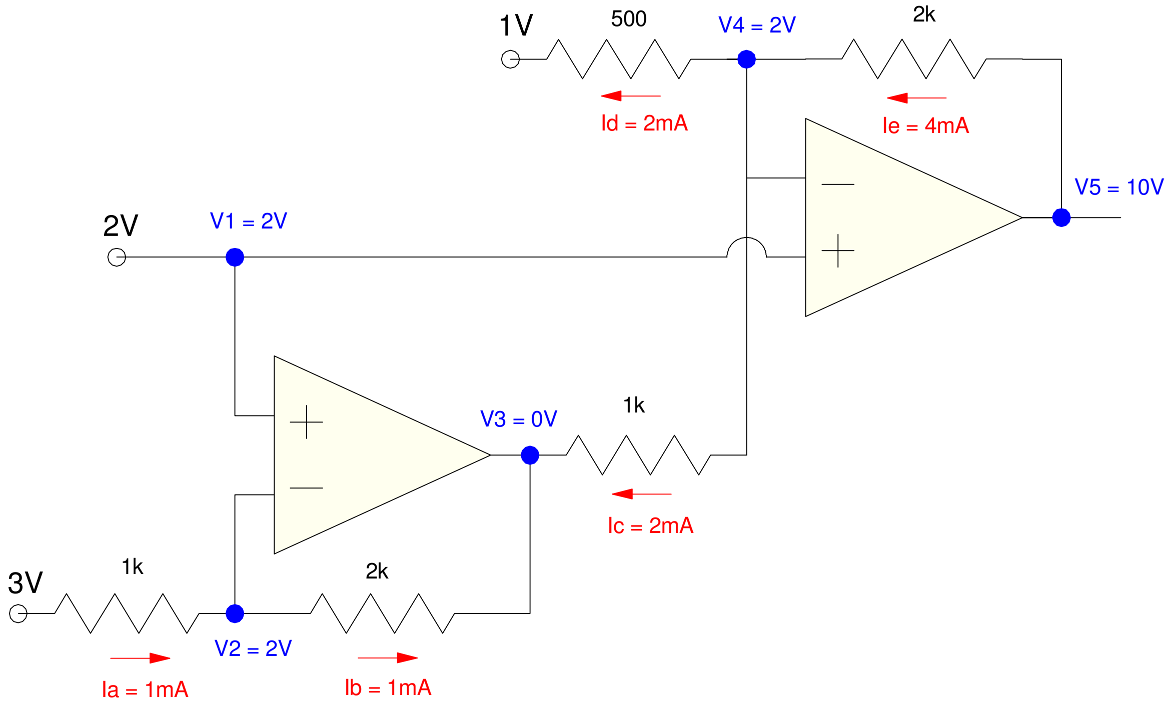
Example #2: Figure it Out

Easy Ones

- V1 = 2V
- V2 = V1 = 2V
- V4 = V1 = 2V

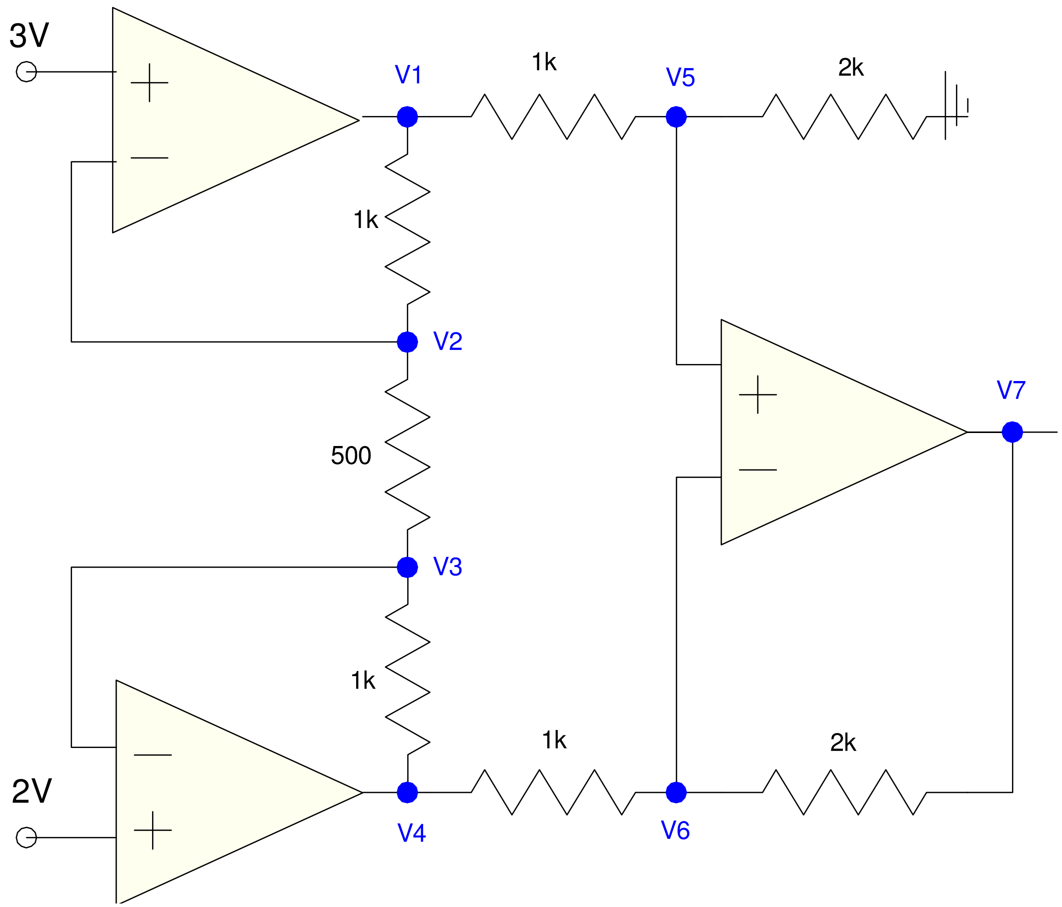
Make the currents balance

- Ia = 1mA
- Ib = Ia = 1mA
- V3 = V2 - Ib*2k = 0V
- Ic = 2mA
- Id = 2mA
- Ie = Ic + Id = 4mA
- V5 = V4 + 2k*Ie = 10V



Example #3: Determine the Voltages

- Write 5 equations for 5 unknowns



Example #3: Nodal Equations

Easy Ones (Vp = Vp)

$$V_2 = 3V$$

$$V_3 = 2V$$

$$V_5 = V_6$$

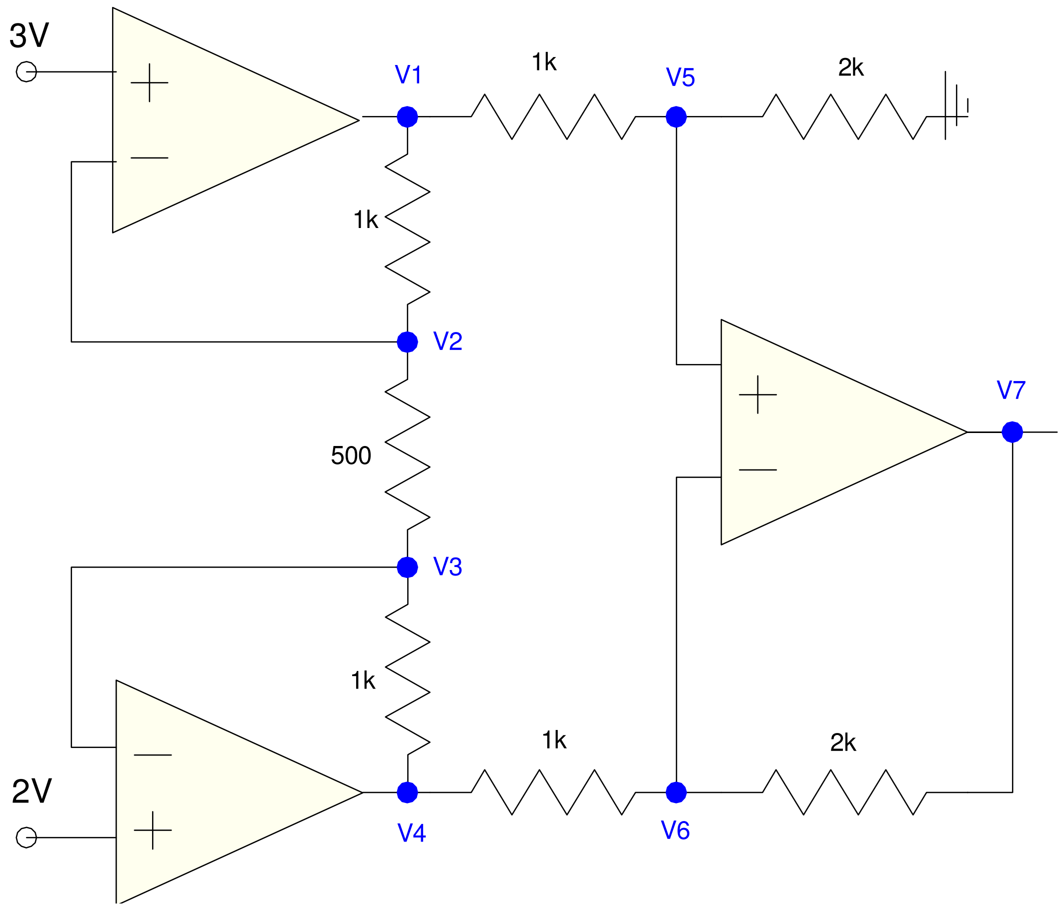
Node equtions

$$\left(\frac{V_2 - V_1}{1k}\right) + \left(\frac{V_2 - V_3}{500}\right) = 0$$

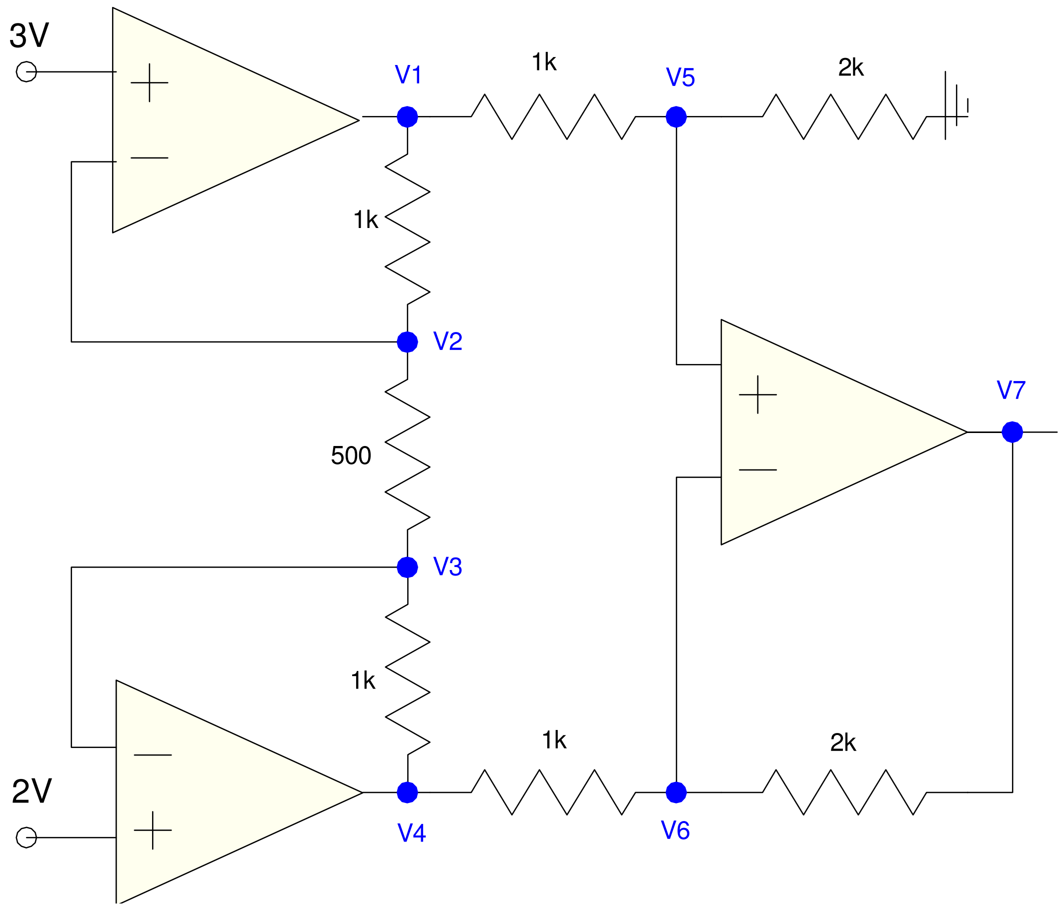
$$\left(\frac{V_3 - V_2}{500}\right) + \left(\frac{V_3 - V_4}{1k}\right) = 0$$

$$\left(\frac{V_5 - V_1}{1k}\right) + \left(\frac{V_5}{2k}\right) = 0$$

$$\left(\frac{V_6 - V_4}{1k}\right) + \left(\frac{V_6 - V_7}{2k}\right) = 0$$



Example #3: Figure out the voltages



Example #3: Figure out the voltages

Start with

$V2 = 3V$

$V3 = 2V$

$Ia = (V2-V3)/500 = 2mA$

$Ib = Ic = Ia = 2mA$

$V1 = V2 + Ib*1k$

$V4 = V3 - Ic*1k$

$Id = V1 / 3k = 1.67mA$

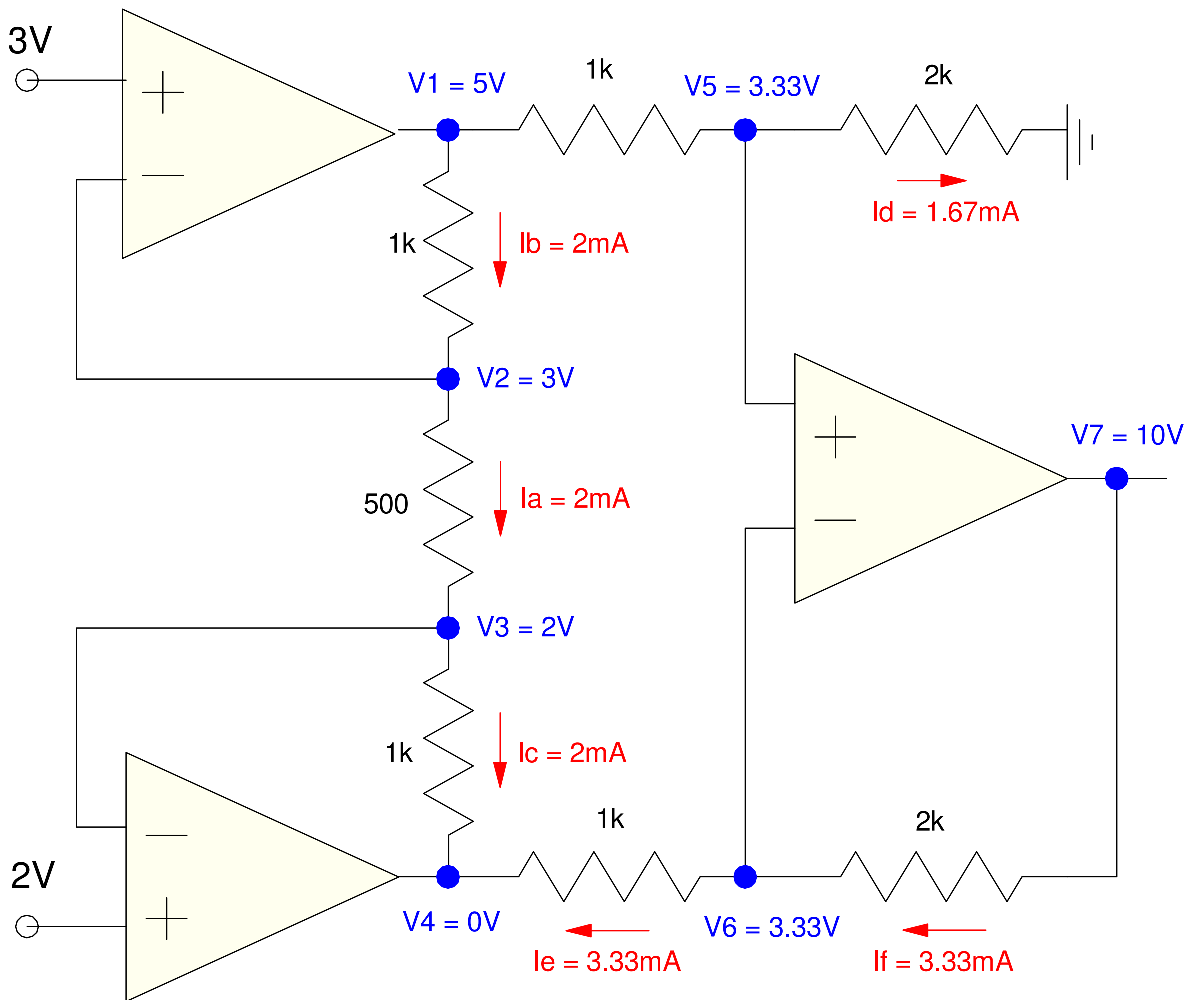
$V5 = 2k * Id = 3.33V$

$V6 = V5 = 3.33V$

$Ie = (V6-V4)/1k = 3.33mA$

$If = Ie = 3.33mA$

$V7 = V6 + 2k*If$



Summary

There are two main methods for analyzing op-amp circuits

- Assume ideal op-amps
- Assume Vp = Vp
  - *Usually the case when there's negative feedback*

a) Voltage nodes

- Start with Vp = Vm
- Write remaining N equations for N unknowns

b) Figure it out

- Currents have to balance
- Vp = Vm *usually* holds