PURDUE UNIVERSITY DEPARTMENT OF PHYSICS

Physics 53600

Electronics Techniques for Research

Now in PowerPoint!

Spring 2020 Semester

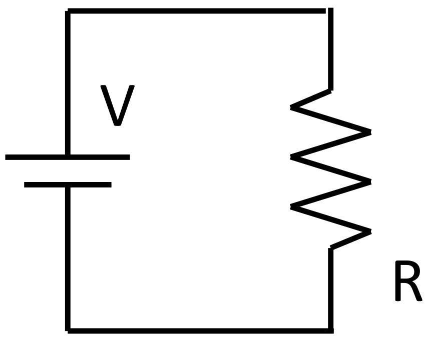
Prof. Matthew Jones

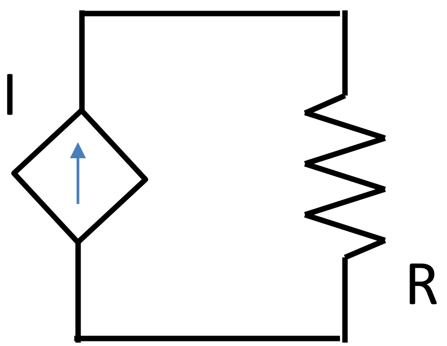
More Information

- Course web page, whereat can be found the syllabus: http://www.physics.purdue.edu/~mjones/phys53600_Spring2020
- Information about the lab will be posted before next Tuesday. Check the web page before you attend the lab.

Circuits

- In general, electrical circuits require
  - A source of energy (electric potential)
  - A path through which current will flow





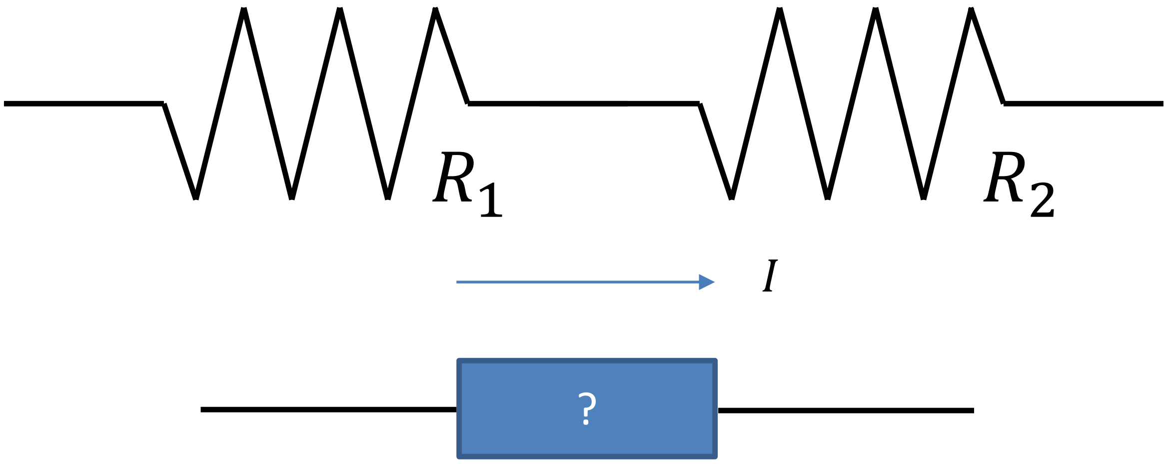
- What do we want to learn?
  - Current given voltage? Voltage given current?
  - Power dissipated by resistor?

Modeling Physical Systems

- Another common problem is to describe a physical system in terms of ideal circuit elements.
  - We construct a model of the electrical properties of the physical system
  - If the model is reasonably accurate, then we can use it to predict what the system will do under various conditions

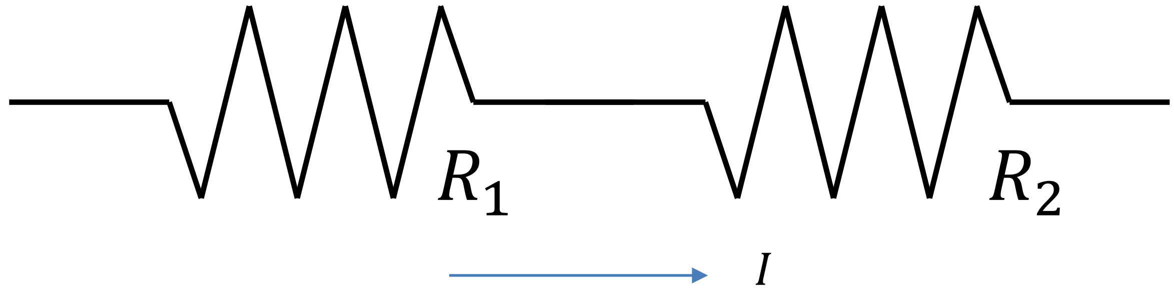
Example

- Construct a model for a system that consists of two resistors in series:



- The current through each system will be the same
- The potential difference across each system should be the same.

Example



- Potential difference across each resistor:

$$\Delta V_{R_1} = IR_1$$

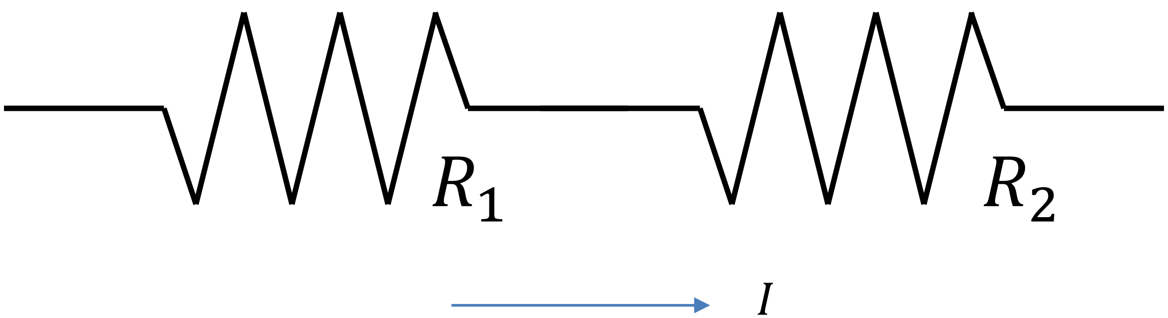
$$\Delta V_{R_2} = IR_2$$

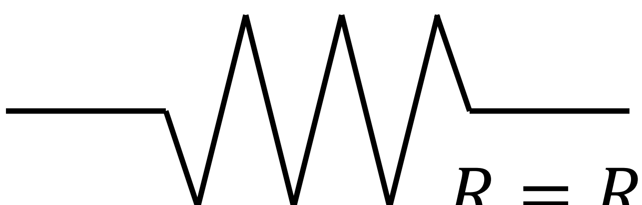
- Total potential difference:

$$\Delta V = I(R_1 + R_2)$$

Example

- The equivalent system can be described using one resistor:

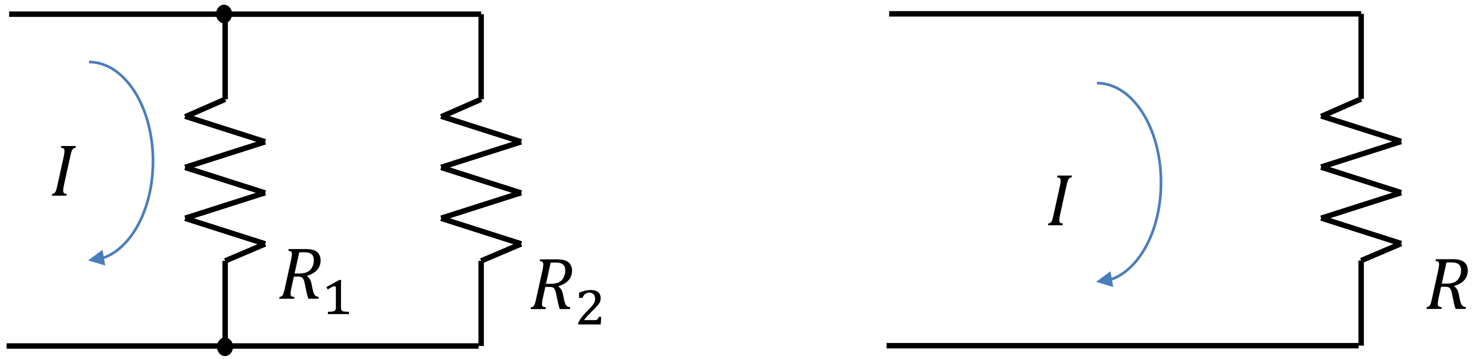




$$R = R_1 + R_2$$

- Both systems behave the same in a circuit.

Another Example

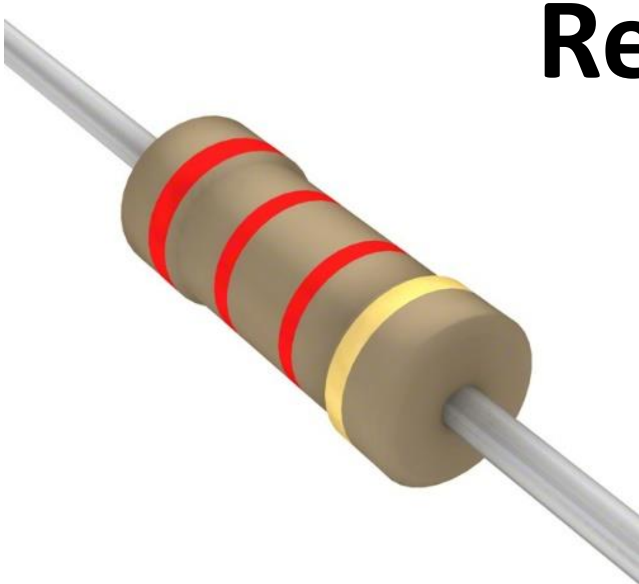


- Equivalent resistance:

$$R = \left(\frac{1}{R_1} + \frac{1}{R_2}\right)^{-1} = \frac{R_1 R_2}{R_1 + R_2}$$

- Both systems behave the same in a circuit.

Real Resistors

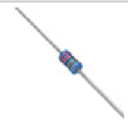
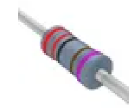


PRICE BREAK	UNIT PRICE	EXTENDED PRICE
1	0.10000	$0.10
10	0.04000	$0.40
25	0.02880	$0.72
50	0.02200	$1.10
100	0.01620	$1.62
250	0.01236	$3.09
500	0.00990	$4.95
1,000	0.00729	$7.29

Product Attributes

TYPE	DESCRIPTION
Categories	Resistors Through Hole Resistors
Manufacturer	Stackpole Electronics Inc
Series	CF
Packaging	Cut Tape (CT) ?
Part Status	Active
Resistance	2.2 kOhms
Tolerance	±5%
Power (Watts)	0.25W, 1/4W
Composition	Carbon Film
Features	Flame Retardant Coating, Safety
Temperature Coefficient	0/ -400ppm/°C
Operating Temperature	-55°C ~ 155°C
Package / Case	Axial
Supplier Device Package	Axial
Size / Dimension	0.091" Dia x 0.236" L (2.30mm x 6.00mm)

Real Resistors

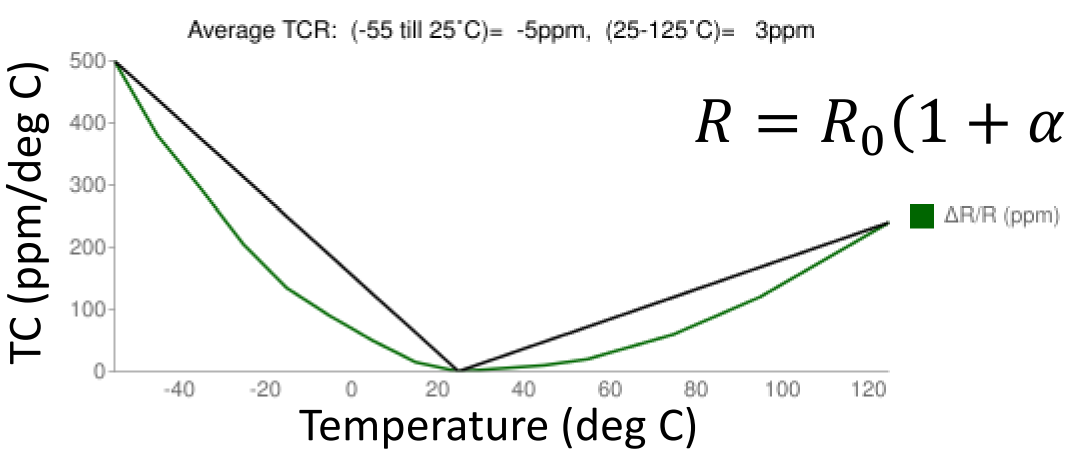
Digi-Key Part Number	CF14JT2K20CT-ND	S2.2KCACT-ND	2.2KADCT-ND
Manufacturer Part Number	CF14JT2K20	RNMF14FTC2K20	MFP-25BRD52-2K2
Manufacturer	Stackpole Electronics Inc	Stackpole Electronics Inc	Yageo
Image			
Description	RES 2.2K OHM 1/4W 5% AXIAL	RES 2.2K OHM 1/4W 1% AXIAL	RES 2.2K OHM 1/4W 0.1% AXIAL
Quantity Available	46,521 - Immediate	83,615 - Immediate	3,122 - Immediate
Unit Price USD	$0.10000	$0.10000	$0.64000
Minimum Quantity	1	1	1
Series	CF	RNMF (Mini)	MFP
Packaging	Cut Tape (CT) Alternate Packaging	Cut Tape (CT) Alternate Packaging	Cut Tape (CT) Alternate Packaging
Part Status	Active	Active	Active
Resistance	2.2 kOhms	2.2 kOhms	2.2 kOhms
Tolerance	±5%	±1%	±0.1%
Power (Watts)	0.25W, 1/4W	0.25W, 1/4W	0.25W, 1/4W
Composition	Carbon Film	Metal Film	Metal Film
Features	Flame Retardant Coating, Safety	Flame Retardant Coating, Safety	-
Temperature Coefficient	0/ -400ppm/°C	±50ppm/°C	±25ppm/°C
Operating Temperature	-55°C ~ 155°C	-55°C ~ 155°C	-55°C ~ 155°C
Package / Case	Axial	Axial	Axial
Supplier Device Package	Axial	Axial	Axial
Size / Dimension	0.091" Dia x 0.236" L (2.30mm x 6.00mm)	0.070" Dia x 0.130" L (1.78mm x 3.30mm)	0.094" Dia x 0.248" L (2.40mm x 6.30mm)

Real Resistors

Electrical Specifications - CF							
Type/Code	Power Rating (Watts) @ 70ºC	Maximum Working Voltage [1]	Maximum Overload Voltage	Dielectric Withstanding Voltage	Resistance Temperature Coefficient per Ohmic Range	Ohmic Range (Ω) and Tolerance	
						2%	5%
CF18	0.125 W	250 V	500 V	350 V	< 10 Ω = ±400 ppm/ºC	10 - 1 M	1 - 22 M
CF14	0.25 W	350 V	600 V	350 V	10 Ω to 9.99 K Ω = 0 ~ -400 ppm/ºC	1 - 1 M	1 - 22 M
CF12	0.5 W	350 V	700 V	600 V	10 K Ω to 99 K Ω = 0 ~ -500 ppm/ºC	10 - 1 M	1 - 22 M
CF1	1 W	500 V	1,000 V	600 V	100 K Ω to 999 K Ω = 0 ~ -850 ppm/ºC	1 - 1 M	1 - 10 M
CF2	2 W	500 V	1,000 V	600 V	1 M Ω and above = 0 ~ -1500 ppm/ºC	1 - 1 M	1 - 10 M

- Temperature coefficient:

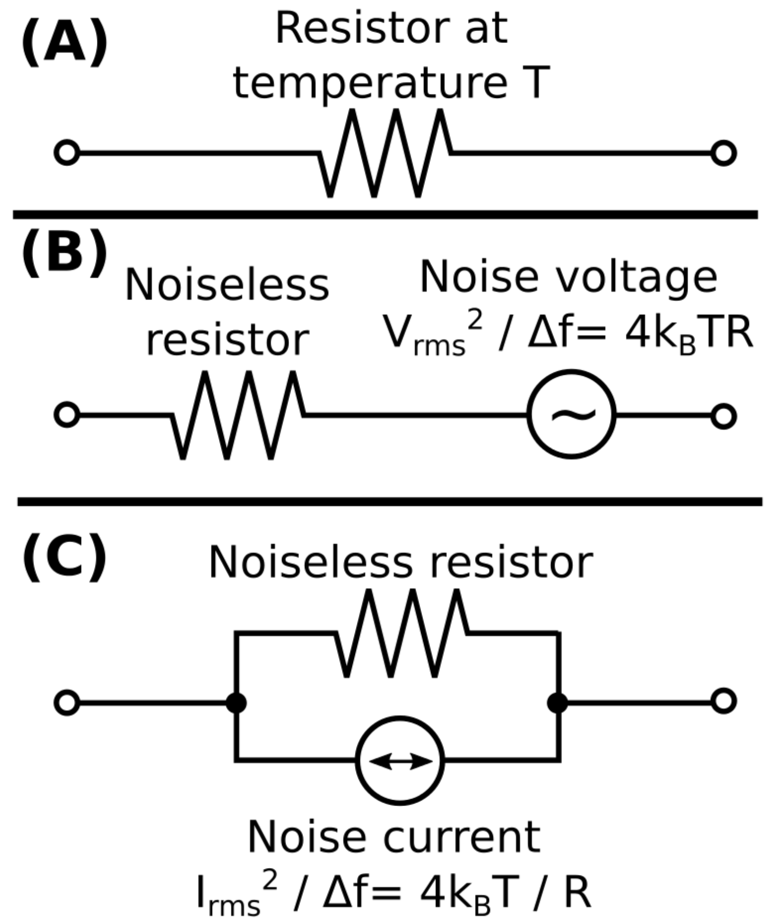
$$TC = \frac{1}{R}\frac{\Delta R}{\Delta T}$$



$$R = R_0(1 + \alpha(T - T_0) + \beta(T - T_0)^2)$$

Real Resistors

- Real resistors are (small) sources of random noise
- Random thermal motion of charge carriers produces (small) voltage/current fluctuations
- Approximately white noise – power spectral density is approximately constant over a wide frequency range



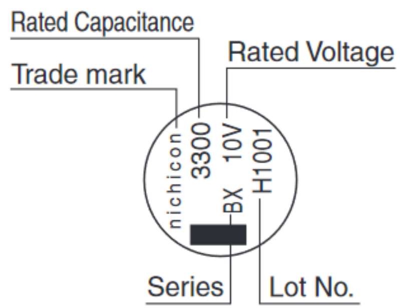
Example: $R = 50\ \Omega, \Delta f = 1\ \mathrm{Hz}, T = 300\ \mathrm{K} \Rightarrow v_{\mathrm{rms}} = 1\ \mathrm{nV}$

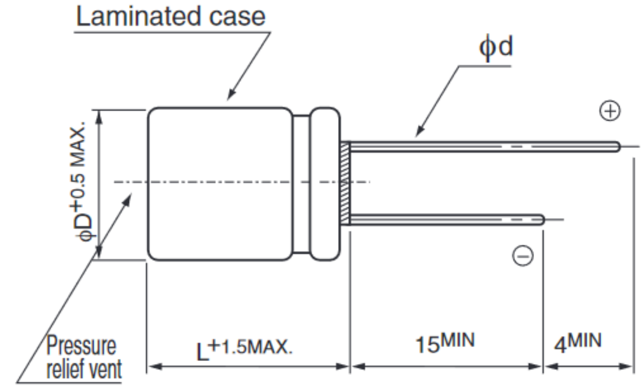
Real Capacitors

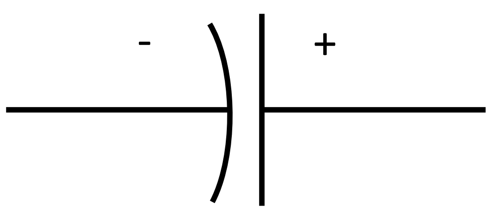
- There are many different types of capacitors constructed using various technologies
- Primary considerations:
  - Voltage rating
  - Capacitance range
  - Polarity (!)
  - Frequency response
  - Operating temperature range
  - Temperature coefficient
  - Size
  - Cost

Real Capacitors

Example: *Aluminum electrolytic capacitor*



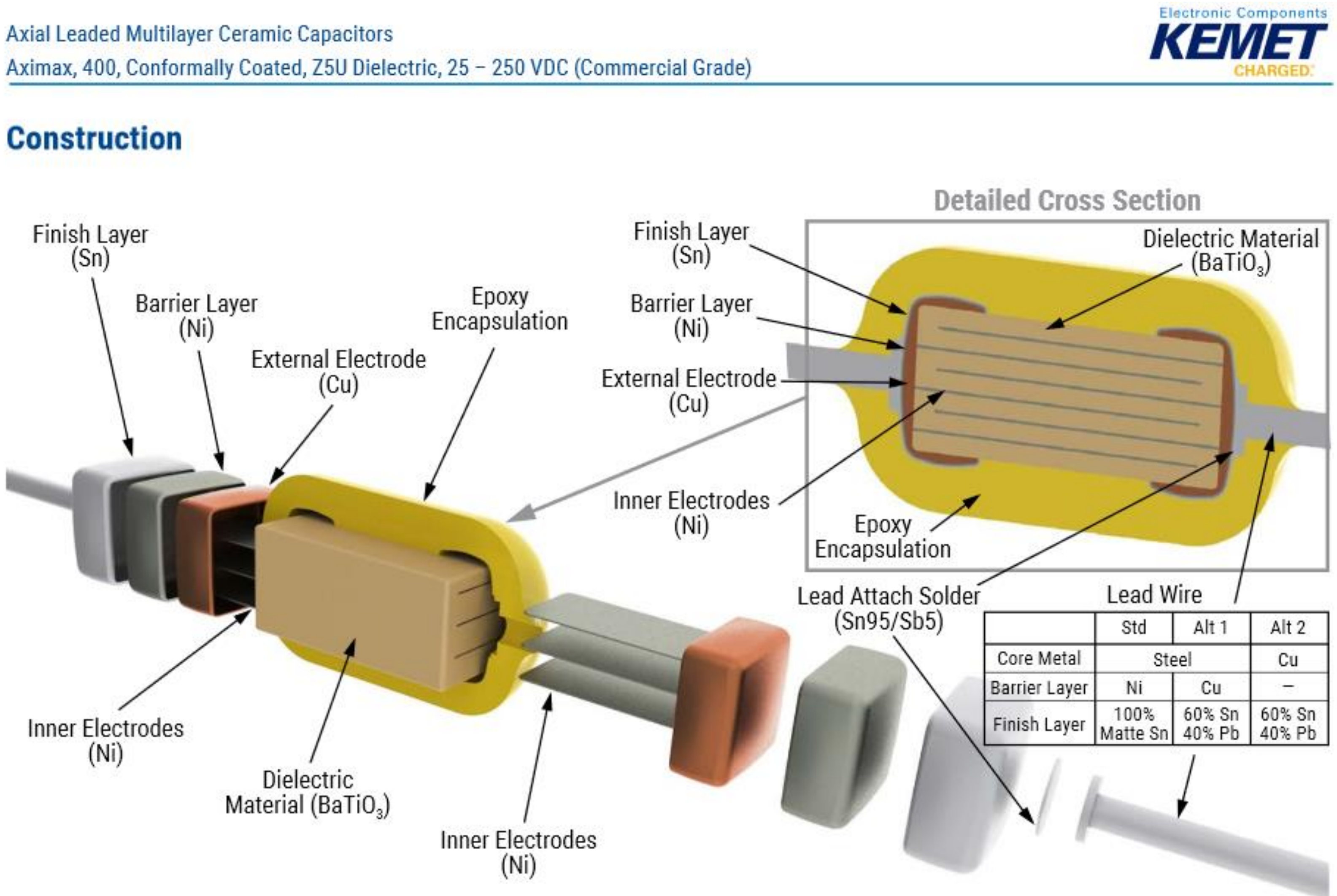




Short lead/black mark indicates the cathode (more negative terminal). *But be careful*: Sometimes the mark indicates the anode!

Tantalum capacitor with mark labeling the anode.

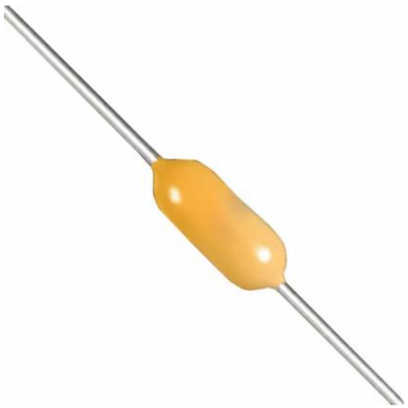
Real Capacitors



	Std	Alt 1	Alt 2
Core Metal	Steel		Cu
Barrier Layer	Ni	Cu	–
Finish Layer	100% Matte Sn	60% Sn 40% Pb	60% Sn 40% Pb

Real Capacitors

- Ceramic capacitors are not polarized



Detailed Description

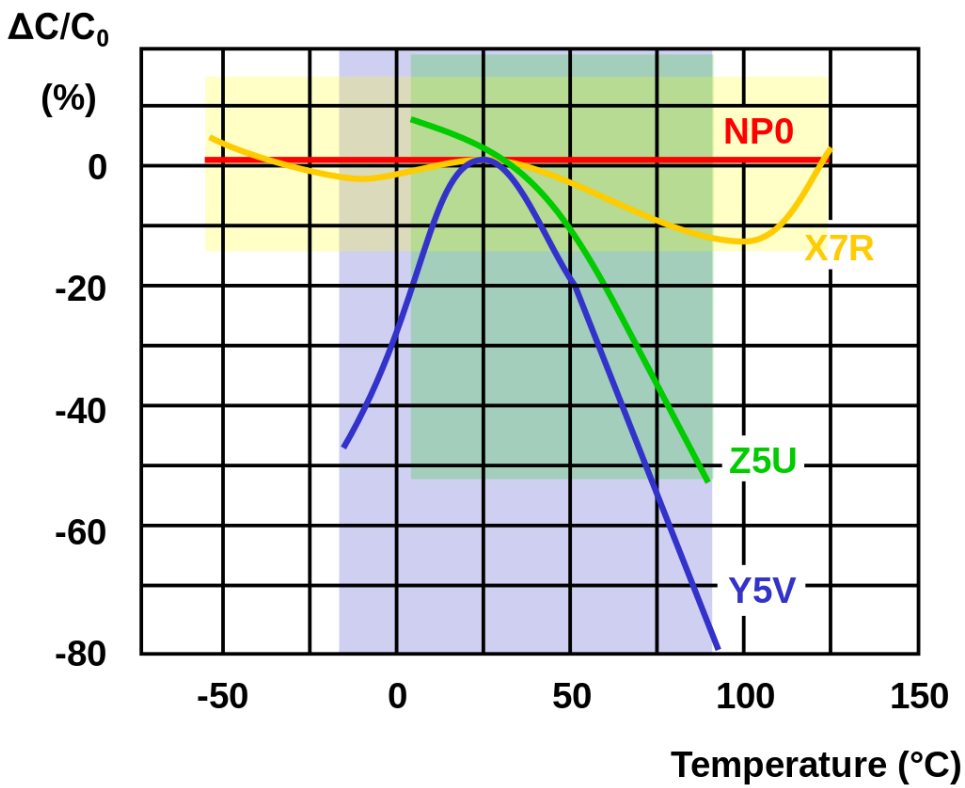
0.22µF ±20% 50V Ceramic Capacitor Z5U Axial

Tolerance

Maximum operating voltage

Dielectric material

Real Capacitors



Cost:

Z5U: $0.31 each

X7R: $0.51 each

Model for a real capacitor:

$$C = C_0 \cdot (1 + a\,V + b\,V^2) \cdot (1 + \alpha(T - T_0) + \beta(T - T_0)^2)$$

Real Voltage Sources

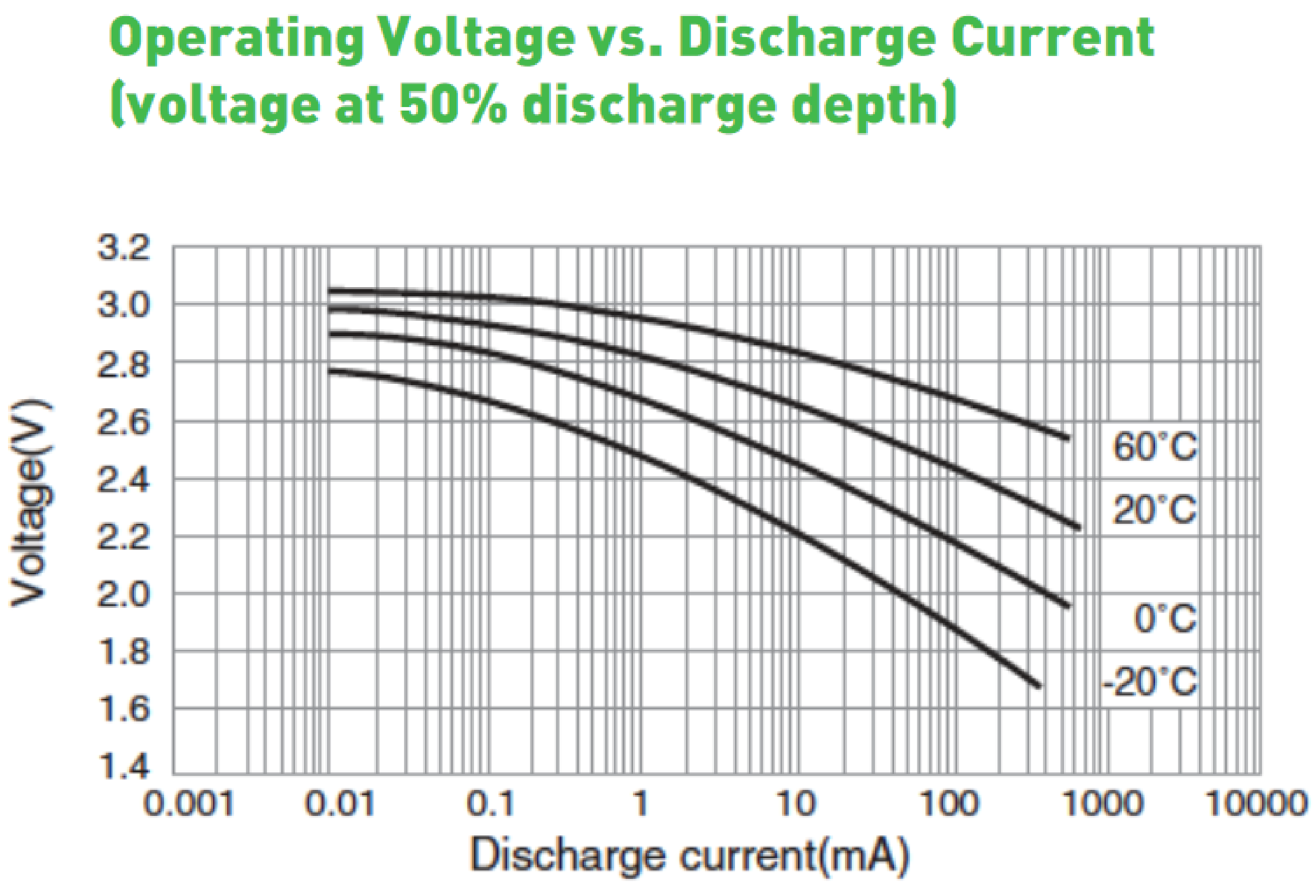
- An ideal voltage source produces a constant potential difference, independent of the current through it
- A chemical battery is not an ideal voltage source

Specifications

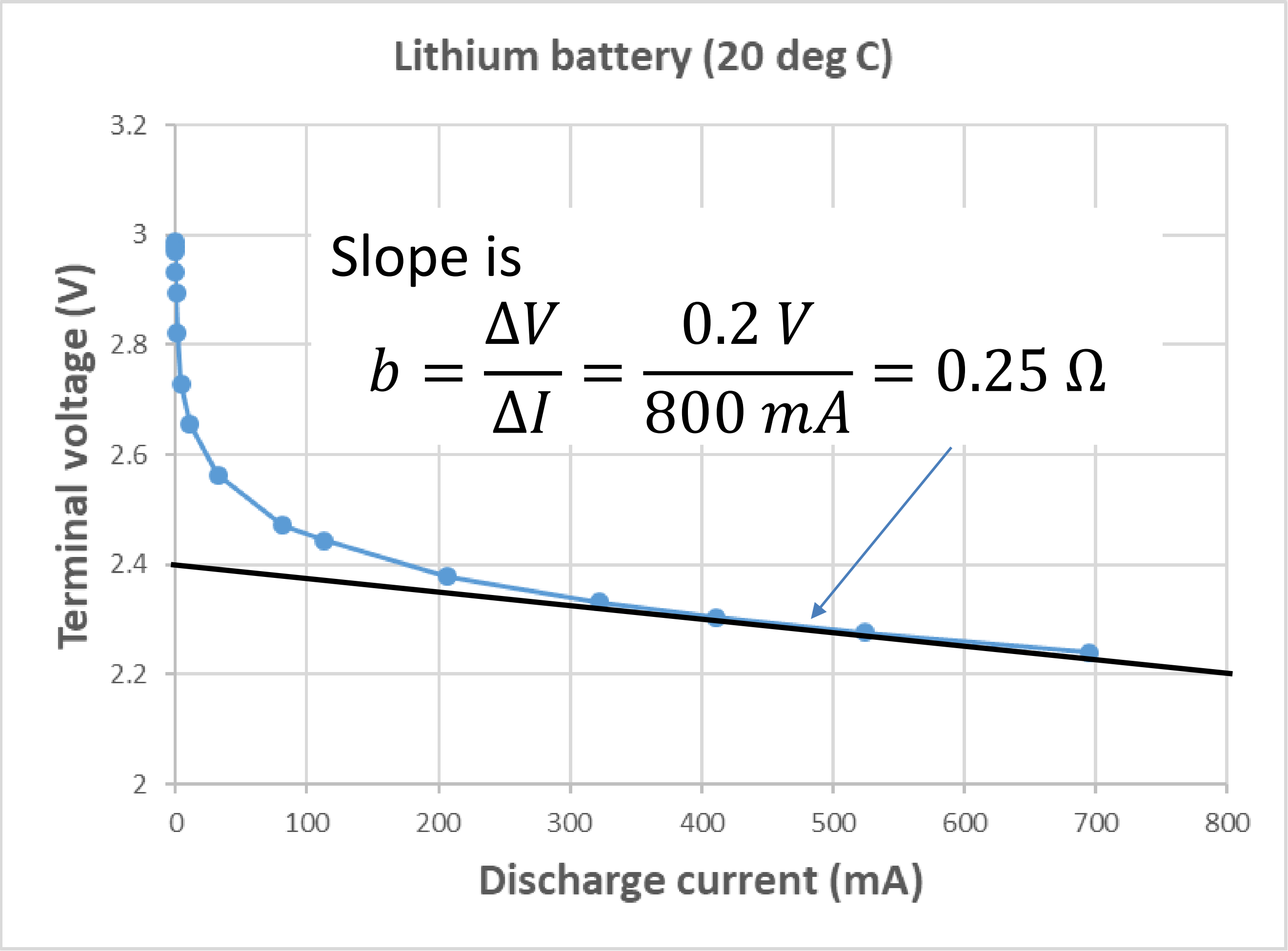
Nominal Capacity:	1800 mAh
Nominal Voltage:	3V
Weight:	Approximately 18g
Operating Temperature:	-40°C - +85°C

Real Voltage Sources

- The operating voltage is not constant:



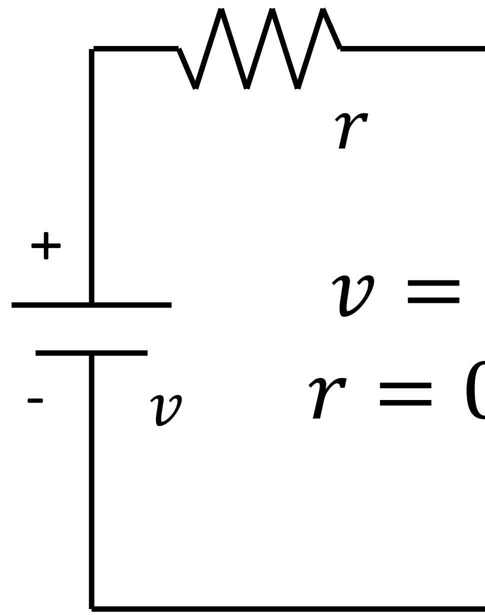
Real Voltage Sources



$$b = \frac{\Delta V}{\Delta I} = \frac{0.2\ V}{800\ mA} = 0.25\ \Omega$$

https://apps.automeris.io/wpd/

Model for a Real Voltage Source



$$v = 2.4\ V$$
$$r = 0.25\ \Omega$$

The model is only valid for a specific range of discharge currents, in this case maybe between 300 and 700 mA, and only when the temperature is 20 °C.

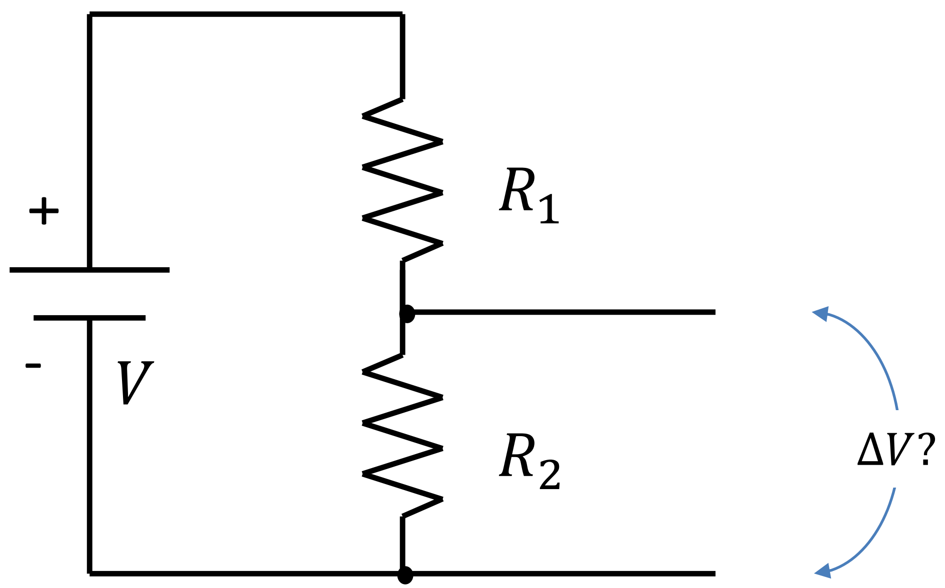
Common DC Voltage Sources

- Frequently, only a limited number of DC voltage sources are present in a circuit:

Voltage (V)	Application
1.2 V	Integrated circuit core voltage
1.8 V	Low voltage digital circuits
2.5 V	Digital I/O logic
3.3 V	Digital logic
5 V	Analog/digital logic
12 V	Power distribution, industrial applications
24 V	Avionics and defense applications
48 V	Power distribution
> 50 V	Safety precautions required!

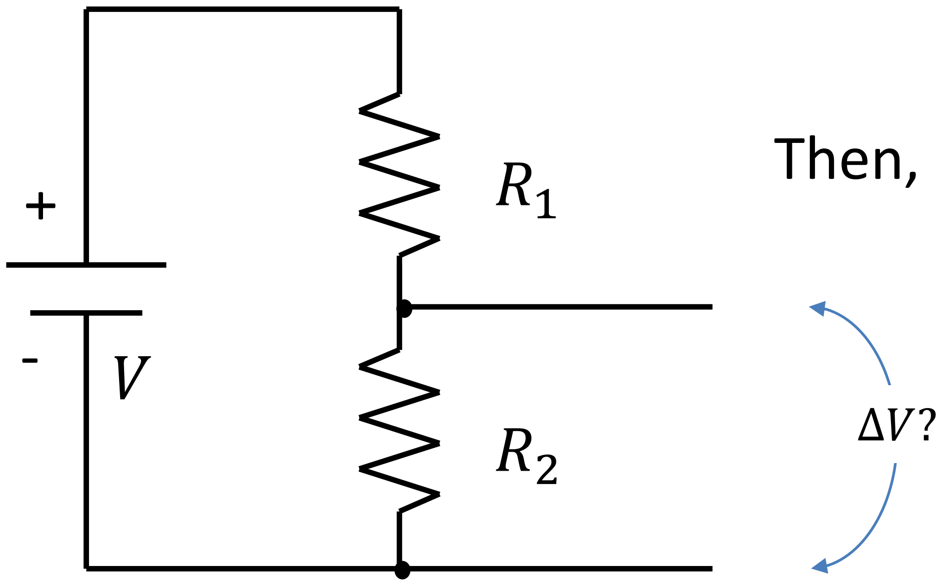
Voltage Divider Circuit

- A common technique for generating other voltages is with a voltage divider:



Voltage Divider Circuit

- A common technique for generating other voltages is with a voltage divider:



With no load applied, the current through R_1 and R_2 will be

$$I = \frac{V}{R_1 + R_2}$$

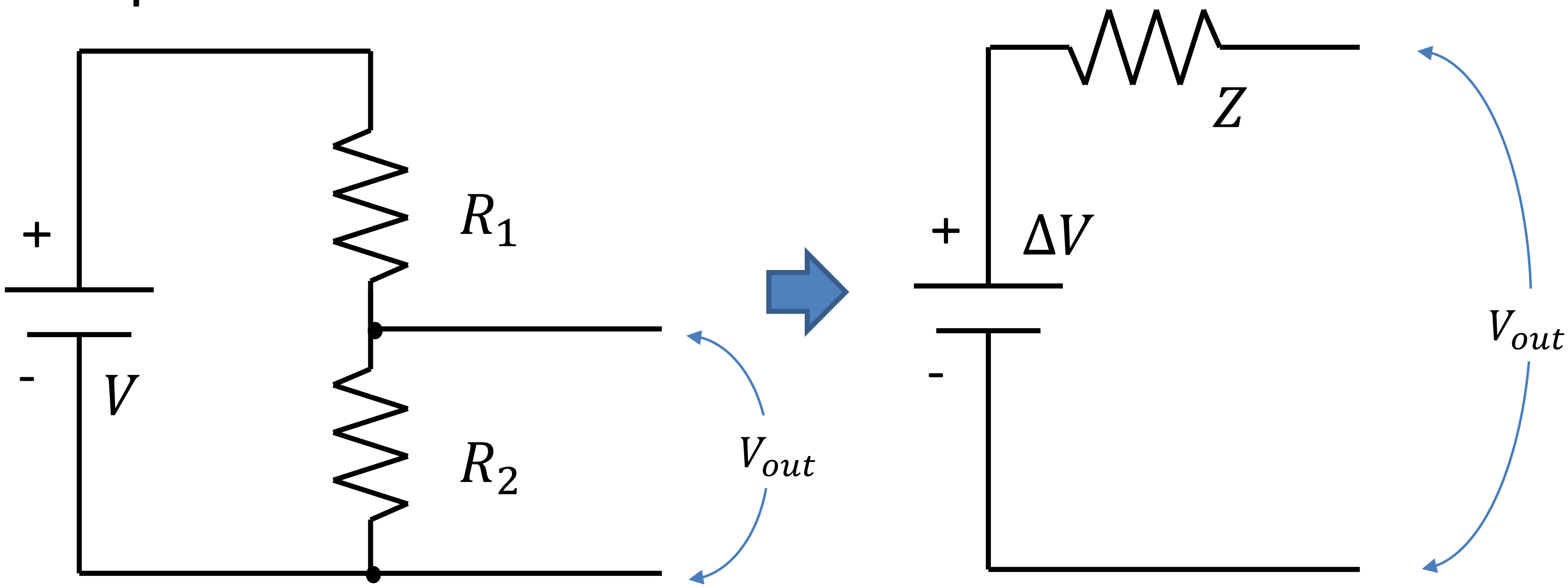
Then,

$$\Delta V = IR_2 = \frac{VR_2}{R_1 + R_2}$$

But this is not enough information to solve for R_1 and R_2 uniquely.

Voltage Divider Circuit

- Equivalent circuit:



$$\Delta V = \frac{V R_2}{R_1 + R_2} \qquad Z = \frac{R_1 R_2}{R_1 + R_2}$$

This is a very good assignment question!

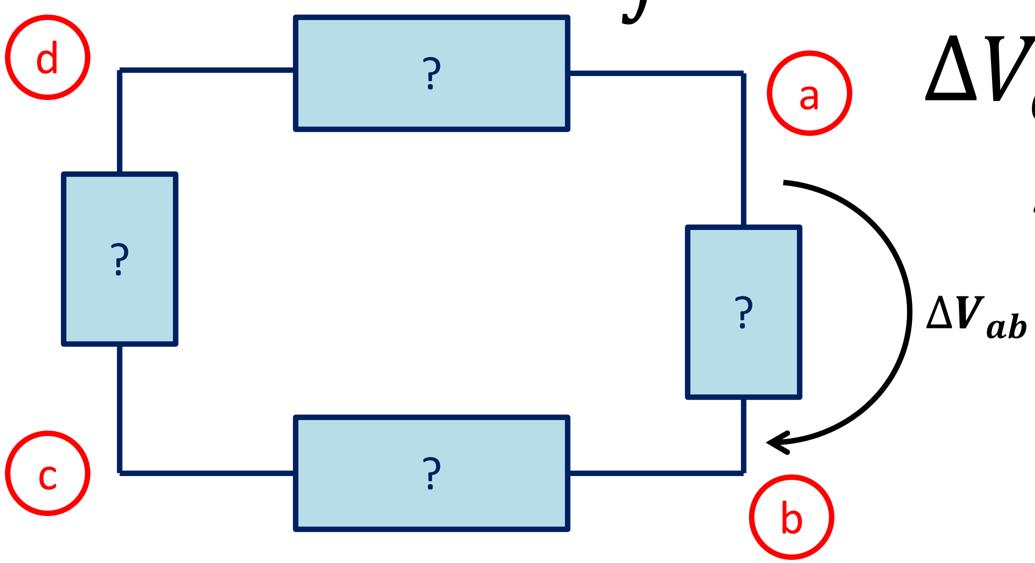
What about more Complicated Circuits?

- We need a systematic way of analyzing arbitrarily complex circuits
- Calculate the currents that flow in an electric circuit composed of various circuit elements connected by wires.
- The currents will be solutions to a system of (differential) equations
- If the problem is too complicated to solve algebraically, get a computer to solve it numerically

Kirchhoff Loop Rule

- Recall that work done to move a charge q from point a to point b is $W = -q\int_a^b \vec{E}\cdot d\vec{\ell}$
- If a and b are the same point then $W = 0$

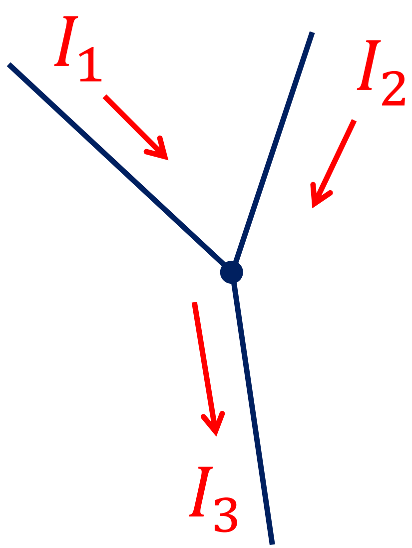
$$\oint \vec{\mathrm{E}}\cdot \mathrm{d}\vec{\ell} = 0$$



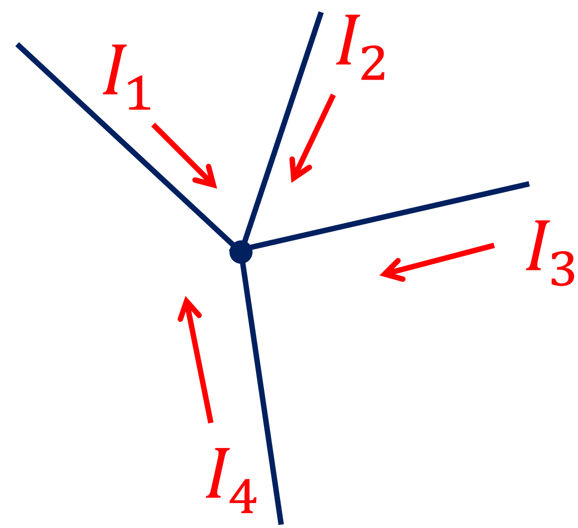
$$\Delta V_{ab} + \Delta V_{bc} + \Delta V_{cd} + \Delta V_{da} = 0$$

Kirchhoff's Node Rule

- The sum of the currents entering a node must equal the sum of the currents leaving.



$$I_1 + I_2 = I_3$$

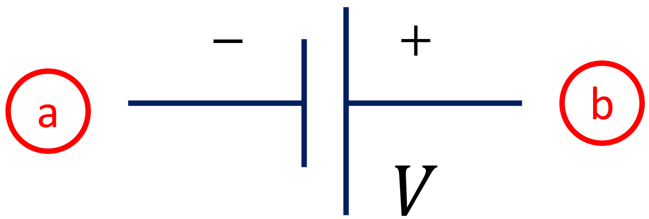


$$I_1 + I_2 + I_3 + I_4 = 0$$

(at least one of these must be negative)

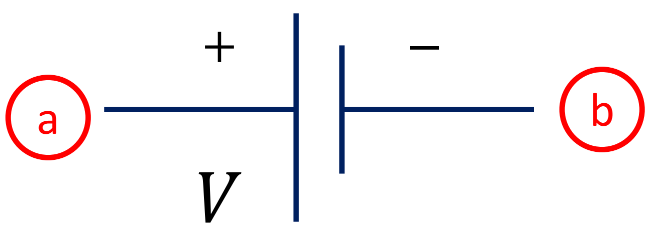
Circuit Elements

- Voltage sources (like batteries):



$$V_b = V_a + V$$

- Make sure you get the sign right!

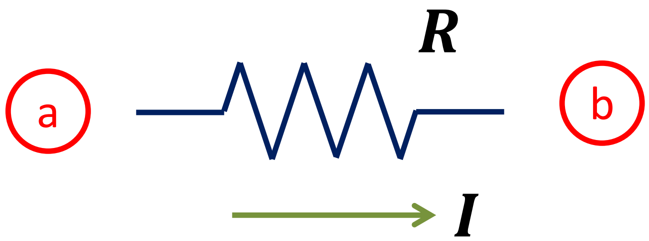


$$V_b = V_a - V$$

Circuit Elements

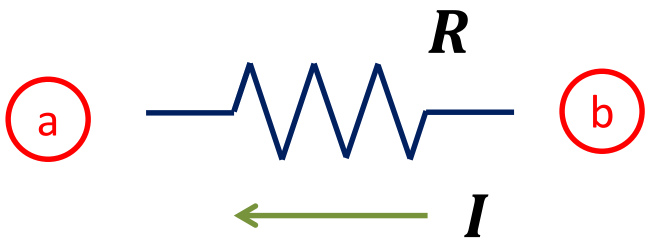
- Resistors:

The charges lose energy as they are pushed through the resistor.



$$V_b = V_a - IR$$

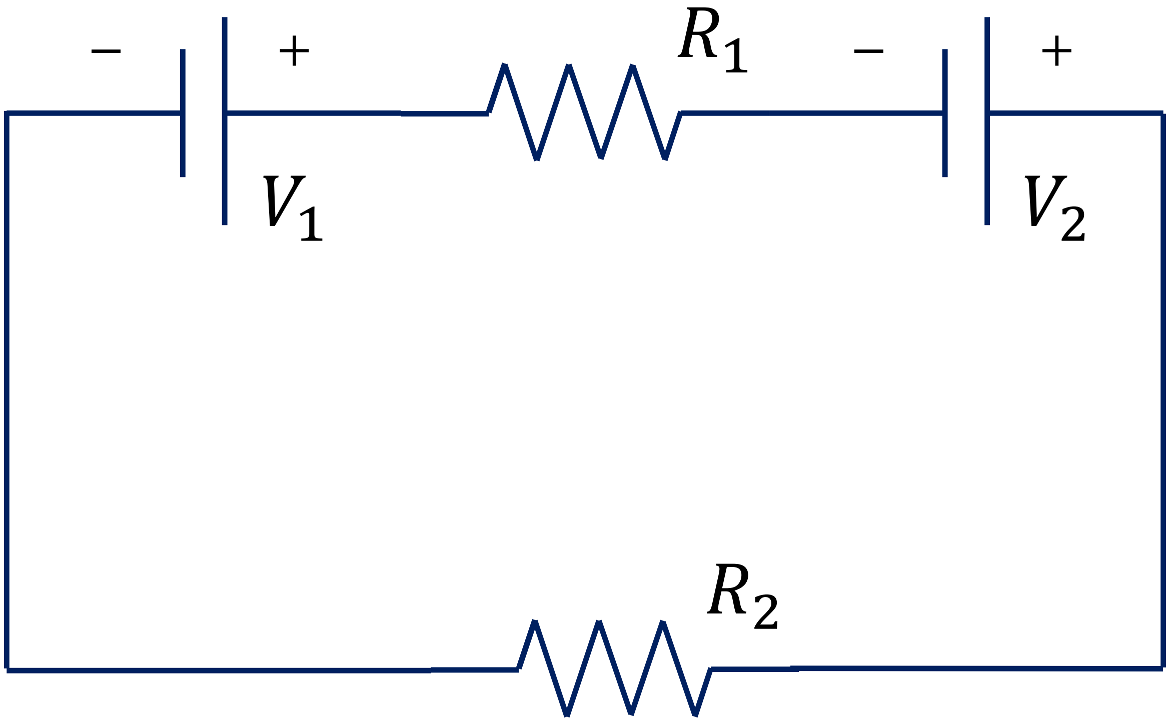
- Make sure you get the sign right!



$$V_b = V_a + IR$$

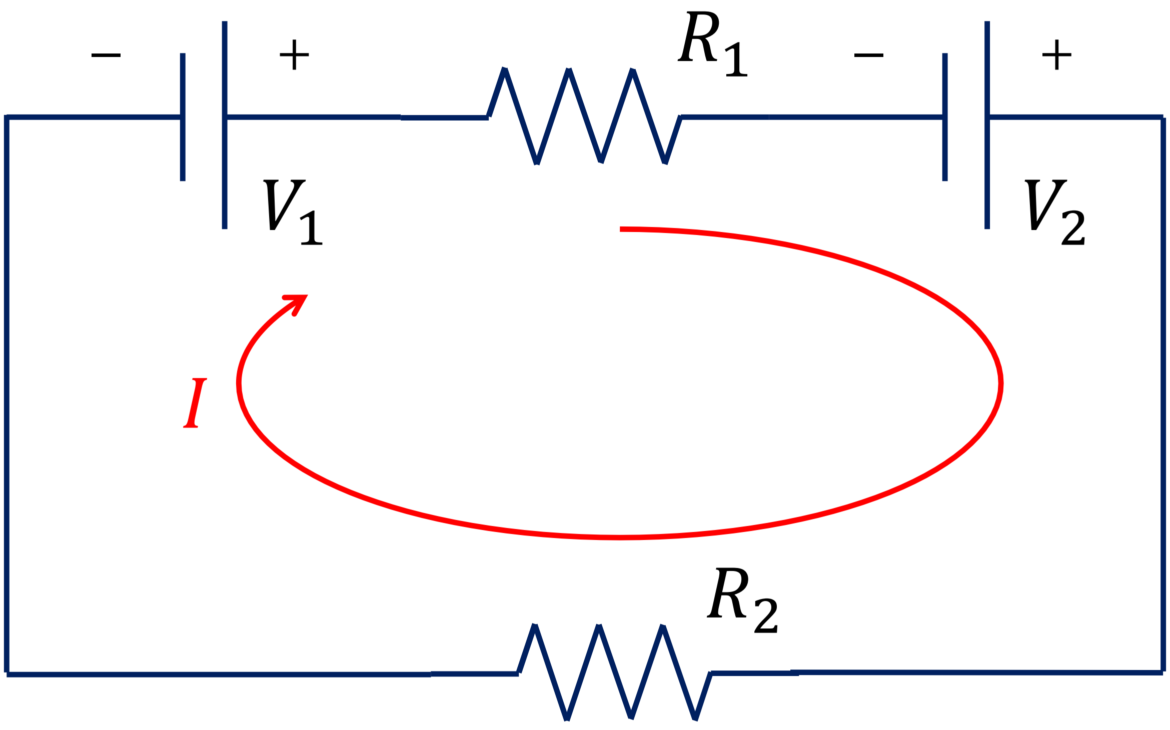
Circuit Analysis

- Find the current in the following circuit:



Circuit Analysis

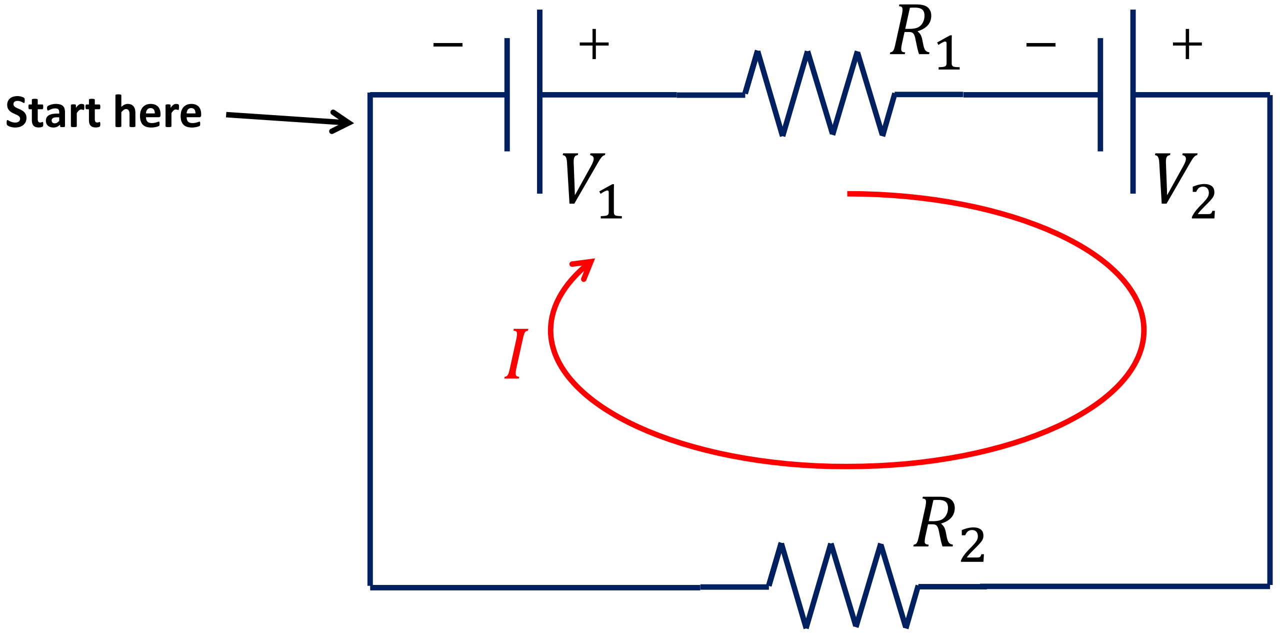
- Step 1: Draw a loop to represent the current.



Which direction? It doesn't matter, but let's ALWAYS pick clockwise to avoid confusion.

Circuit Analysis

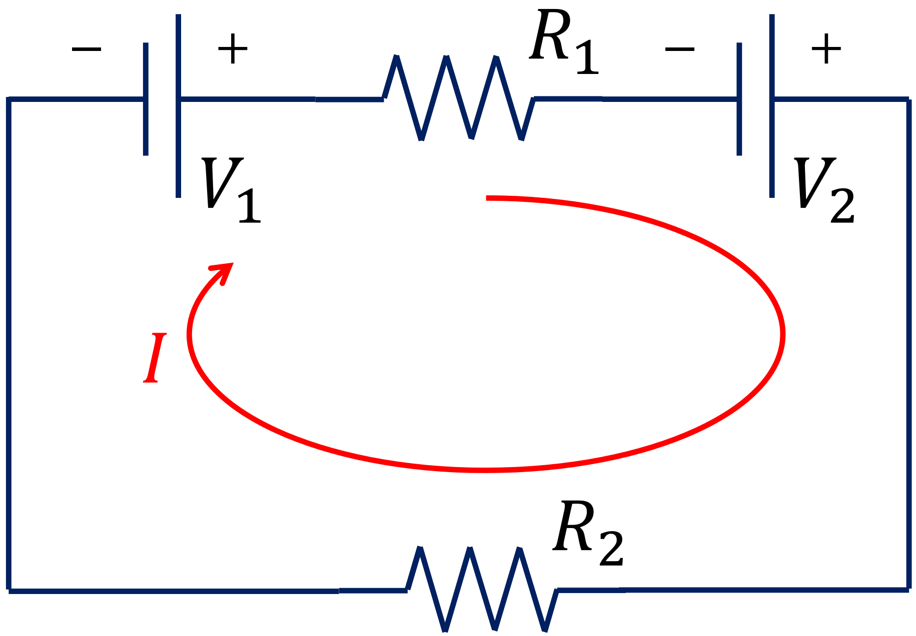
- Step 2: Apply Kirchhoff's Loop Rule…



$$V_1$$

Circuit Analysis

- Step 3: Solve for I…

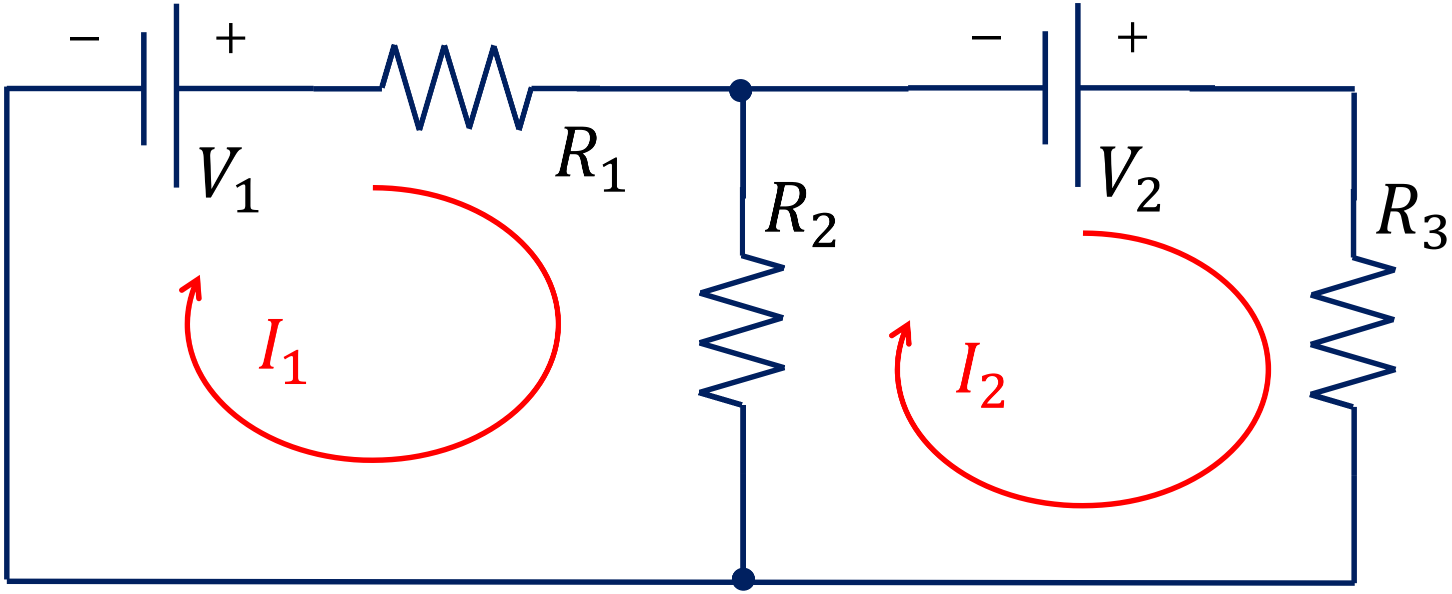


$$I = \frac{V_1 + V_2}{R_1 + R_2}$$

What if I is negative? Then it means the current flows in the opposite direction.

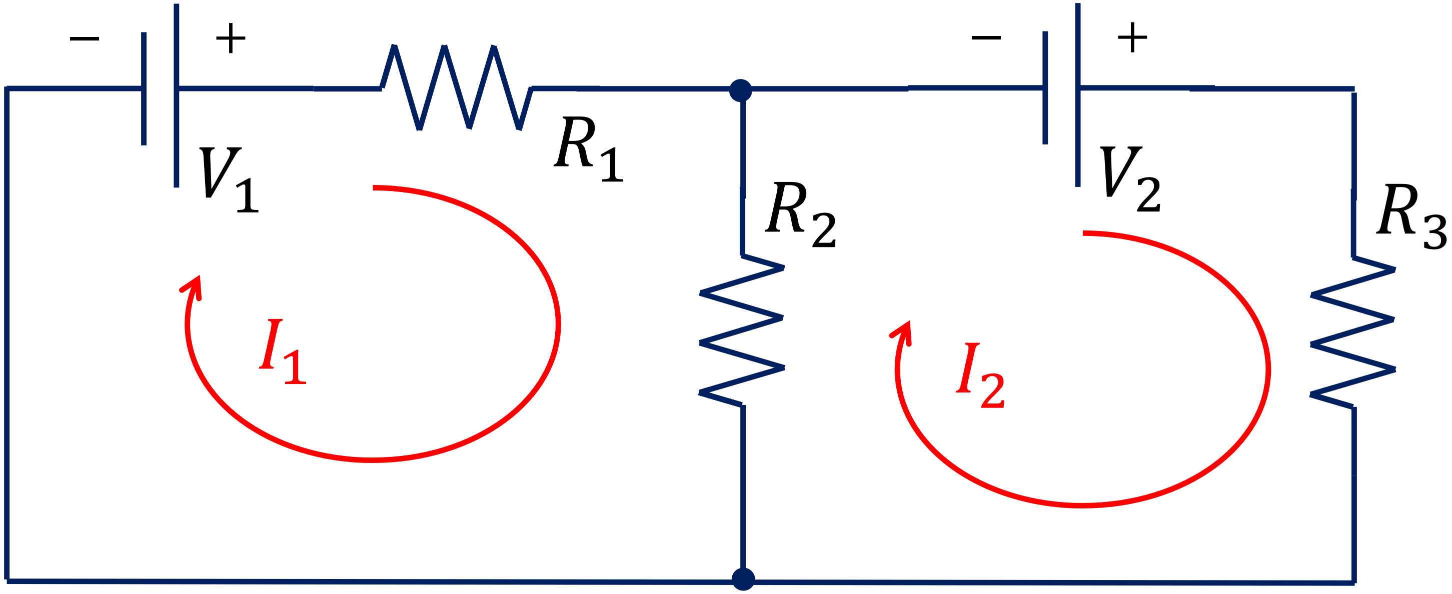
Two Loops

- Step 1: Assign currents to each loop



Two Loops

- Step 2: Apply Kirchhoff's Loop rule



$$V_1 - I_1 R_1 - (I_1 - I_2) R_2 = 0$$
$$V_2 - I_2 R_3 - (I_2 - I_1) R_2 = 0$$

Two Loops

$$V_1 - I_1 R_1 - (I_1 - I_2) R_2 = 0$$
$$V_2 - I_2 R_3 - (I_2 - I_1) R_2 = 0$$

This is a system of linear equations… write them as a matrix equation:

$$\begin{pmatrix} R_1 + R_2 & -R_2 \\ -R_2 & R_2 + R_3 \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \end{pmatrix} = \begin{pmatrix} V_1 \\ V_2 \end{pmatrix}$$

This should *always* be a symmetric matrix.

Kramer's Rule

- This is the "formula" that gives you the solution to a system of linear equations:

$$a_1x + b_1y = c_1$$
$$a_2x + b_2y = c_2$$

$$x = \frac{\begin{vmatrix} c_1 & b_1 \\ c_2 & b_2 \end{vmatrix}}{\begin{vmatrix} a_1 & b_1 \\ a_2 & b_2 \end{vmatrix}} = \frac{c_1b_2 - c_2b_1}{a_1b_2 - a_2b_1}$$

$$y = \frac{\begin{vmatrix} a_1 & c_1 \\ a_2 & c_2 \end{vmatrix}}{\begin{vmatrix} a_1 & b_1 \\ a_2 & b_2 \end{vmatrix}} = \frac{a_1c_2 - a_2c_1}{a_1b_2 - a_2b_1}$$

Two Loops

$$\begin{pmatrix} R_1 + R_2 & -R_2 \\ -R_2 & R_2 + R_3 \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \end{pmatrix} = \begin{pmatrix} V_1 \\ V_2 \end{pmatrix}$$

$$I_1 = \frac{\begin{vmatrix} V_1 & -R_2 \\ V_2 & R_2 + R_3 \end{vmatrix}}{\begin{vmatrix} R_1 + R_2 & -R_2 \\ -R_2 & R_2 + R_3 \end{vmatrix}} = \frac{V_1(R_2 + R_3) + V_2 R_2}{(R_1 + R_2)(R_2 + R_3) - (R_2\ )^2}$$

$$I_2 = \frac{\begin{vmatrix} R_1 + R_2 & V_1 \\ -R_2 & V_2 \end{vmatrix}}{\begin{vmatrix} R_1 + R_2 & -R_2 \\ -R_2 & R_2 + R_3 \end{vmatrix}} = \frac{V_2(R_1 + R_2) + V_1 R_2}{(R_1 + R_2)(R_2 + R_3) - (R_2\ )^2}$$