18-100 Introduction to Electrical and Computer Engineering

Lecture 02
Circuits

Schedule (Subject to Change)

Week	Date	Day	Lecture Topic
1	13-Jan	M	L01: Intro, Physics, EM, Leveling Students
	15-Jan	W	L02: Circuits Basics
2	20-Jan	M	Martin Luther King Celebration (No Lecture)
	22-Jan	W	L03: Equivalent Circuits
3	27-Jan	M	L04: Semiconductors, Diodes, LEDs
	29-Jan	W	L05: MOSFETs to Simple Gates
4	3-Feb	M	L06: Professional Identity, Professional Responsibility, and Ethics
	5-Feb	**W**	**Exam 1**
5	10-Feb	M	L07: Capacitors, RC Time Constants, RC Circuits
	12-Feb	W	L08: Inductors, RL Time Constants, 555
6	17-Feb	M	L09: Binary, Logic Gates, Boolean Logic
	19-Feb	W	L10: Latches, Registers, RAM, Flip-Flops
7	24-Feb	M	L11: Computers
	26-Feb	W	L12: Op Amps
	3-Mar	M	SPRING BREAK
	5-Mar	W	SPRING BREAK

Schedule (Subject to Change)

	3-Mar	M	SPRING BREAK
	5-Mar	W	SPRING BREAK
8	10-Mar	M	L13: Arduino Programming Case Study
	12-Mar	W	L14: Serial Communication Protocols
9	17-Mar	M	L15: Analog-to-Digital (ADC) and Digital-to-Analog (DAC) Conversion
	19-Mar	W	L16: Time Varying Signals and Spectra (Trig)
10	24-Mar	M	L17: Wireless Communication: Modulation to Protocols
	26-Mar	W	L18: Review/Exam Preview
11	**31-Mar**	**M**	**Exam 2**
	2-Apr	W	L19: Complex Numbers, Phasors, and Impedence
12	7-Apr	M	L20: Analog Filters, LC Circuits , Resonance
	9-Apr	W	L21: Crypto
13	14-Apr	M	L22: IoT and Cloud
	16-Apr	W	L23: Information Theory and Data Compression
14	21-Apr	M	L24: AI and ML
	23-Apr	W	L25: Course wrap up
Final	**Exams**	**Period**	**Exam 3 (Scheduled by Registrar during the Final Exams Period)**

Objectives of this Lecture

- Ideal voltage sources and current sources each have one job
- Circuit nodes
- Conductors and resistors
- Ohm's Law

- Kirchhoff's Current Law (KCL)
- Kirchhoff's Voltage Law (KVL)

Electrical and Computer Engineering Models

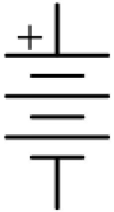
$$\Delta V = IR$$

$$\sum i_{IN} = \sum i_{OUT}$$

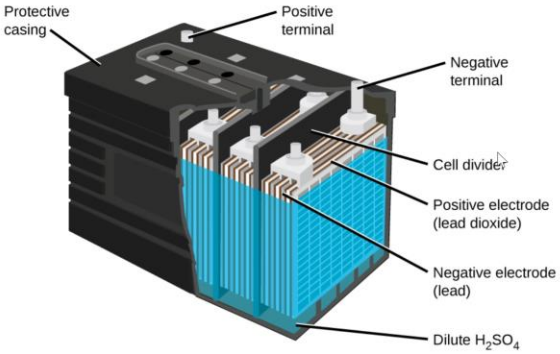
$$\sum v_{UP} = \sum v_{DOWN}$$

Alessandro Volta (1745 – 1827)

- Professor of Chemistry
- Discovered methane (CH_4)
- Friend of Luigi Galvani
- Believed electrical flow was due to dissimilar metals, not "animal electricity

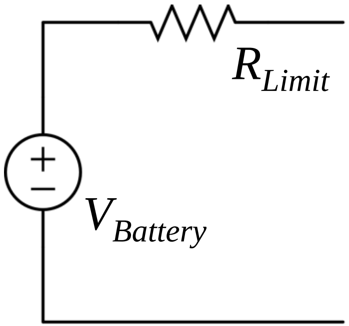


- Created a "pile" of stacked silver and zinc plates separated by an electrolyte (soaked cloth or paper)
- Each stacked pile could generate 1V to 2V (1799)
- Stacks could be connected in series or parallel



Real Batteries

- Cannot provide infinite current
- Essentially, they have a built-in resistance that limits their maximum current



battery type: Alkaline Manganese (Mercury free)
battery size: IEC: LR6; JIS: AM-3; ANSI: 15A; MN1500; Mignon
chemical system: Zn / KOH-H_2O / MnO_2

		Conditions
nominal voltage:	1.5 V	
open circuit voltage:	1.57...1.65 V	new battery
	1.55...1.65 V	after 1 year storage at 20°C
capacity		all measurements at 20°C ambient
rated:	2800 mAh	discharge at 10mA load; 24hours/day
		End Voltage (EV): 0.8V

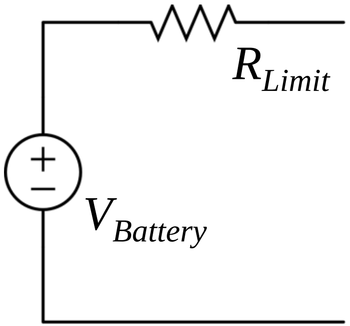
typical service output

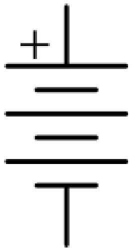
Load		10Ω	1000mA	1.5w/ 0.65w	1000 mA	3.3Ω	250mA	3.9Ω	100mA	24Ω	43Ω
Test mode		24h/d	24h/d	2s/28s 5min/h	10s/m 1h/d	4m/h 8h/d	1h/d	1h/d	1h/d	15s/m 8h/d	4h/d
End voltage		0.9V	0.9V	1.05V	0.9V	0.9V	0.9V	0.8V	0.9V	1.0V	0.9V
Unit		h	m	pulse	pulse	m	h	h	h	h	h
Applications		Reference	Reference	Digital still camera	Photo flash	Portable lighting	CD/ Electronic games	Motor/ toy	Digital audio	Remote control	Radio/ Clock
Initial	MAD	18.5	38.0	55	380	300	7.0	7.0	21.0	42.0	89.0
	Normal	19.5	50.0	70	450	320	7.8	7.5	22.5	45.0	91.5
Stored 1 year	MAD	18.2	30.0	45	300	280	6.7	6.7	20.5	41.0	87.0
	Normal	18.8	40.0	60	360	300	7.2	7.2	21.5	43.0	89.0

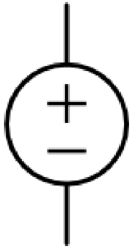
internal resistance: (new battery) $\leq 0.25\ \Omega$ at 1kHz, sine wave measurement according to IEC 896-2

Real Batteries **Are Modeled as Ideal Voltage Sources**

- Cannot provide infinite current
- Essentially, they have a built-in resistance that limits their maximum current

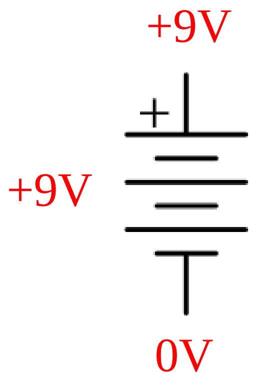


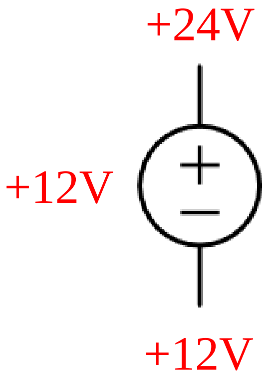


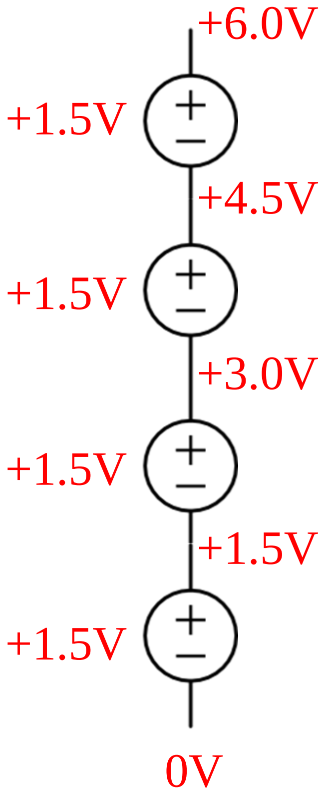


- One job:
  $V_{positive} = V_{negative} + V_{supply}$
- Can do this for **any** current (1A, 1mA, 0A, +∞A, –∞A…)

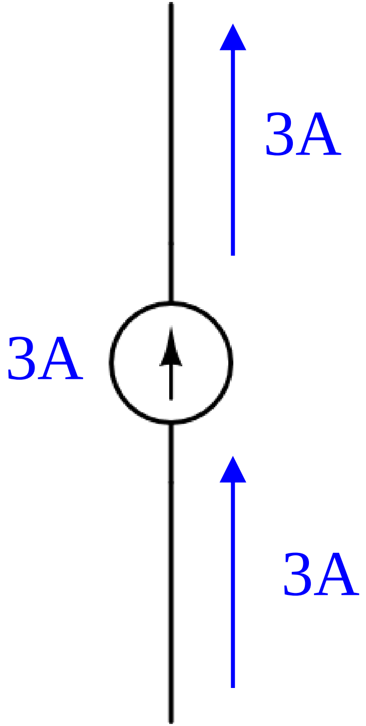
Ideal Voltage Sources ($V_{positive} = V_{negative} + V_{supply}$)







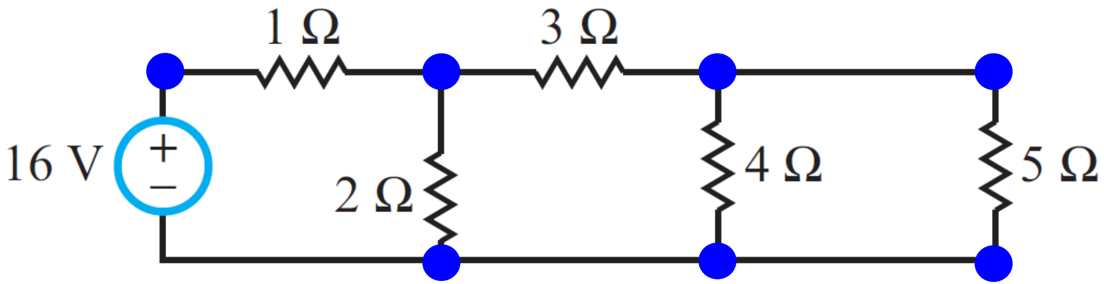
Ideal Current Sources



- One job:
  $I_{IN} = I_{SUPPLY} = I_{OUT}$
- Can do this for **any** voltage
  (1V, 1mV, 0V, +∞V, –∞V…)

Always

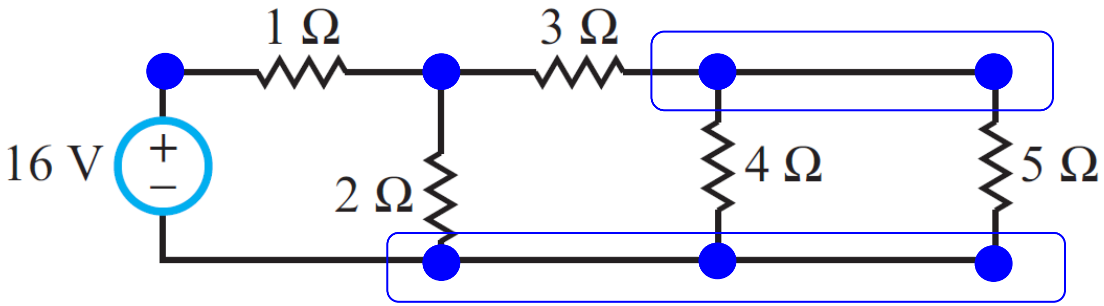
Nodes:



- A point where two or more elements have a common connection
- The voltage or potential at any node is constant across the node

How to find the nodes: 1) Put down dots on any wires that don't have dots

Nodes:



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2) Find out if any dots can be connected just by wires, if they are, one is a duplicate and erase it

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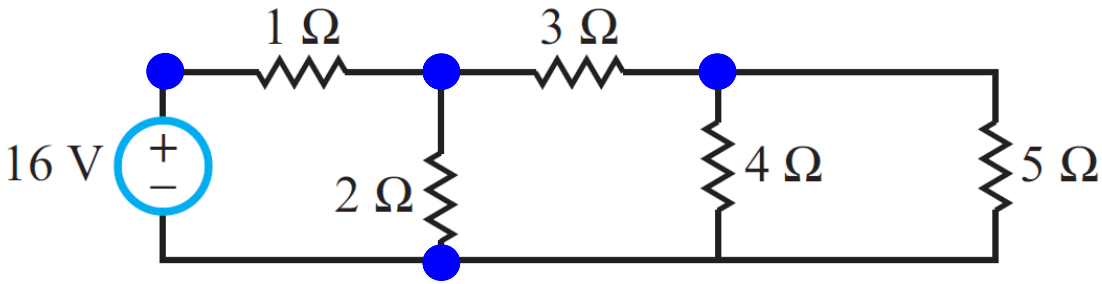

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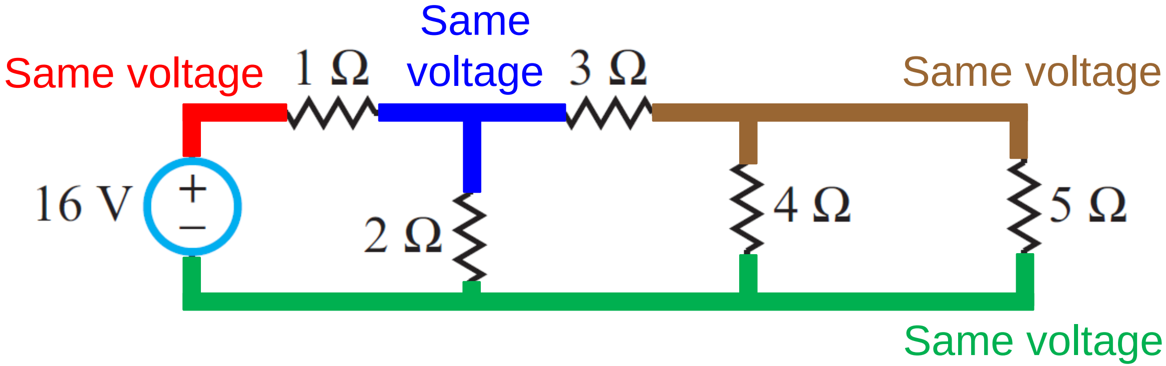
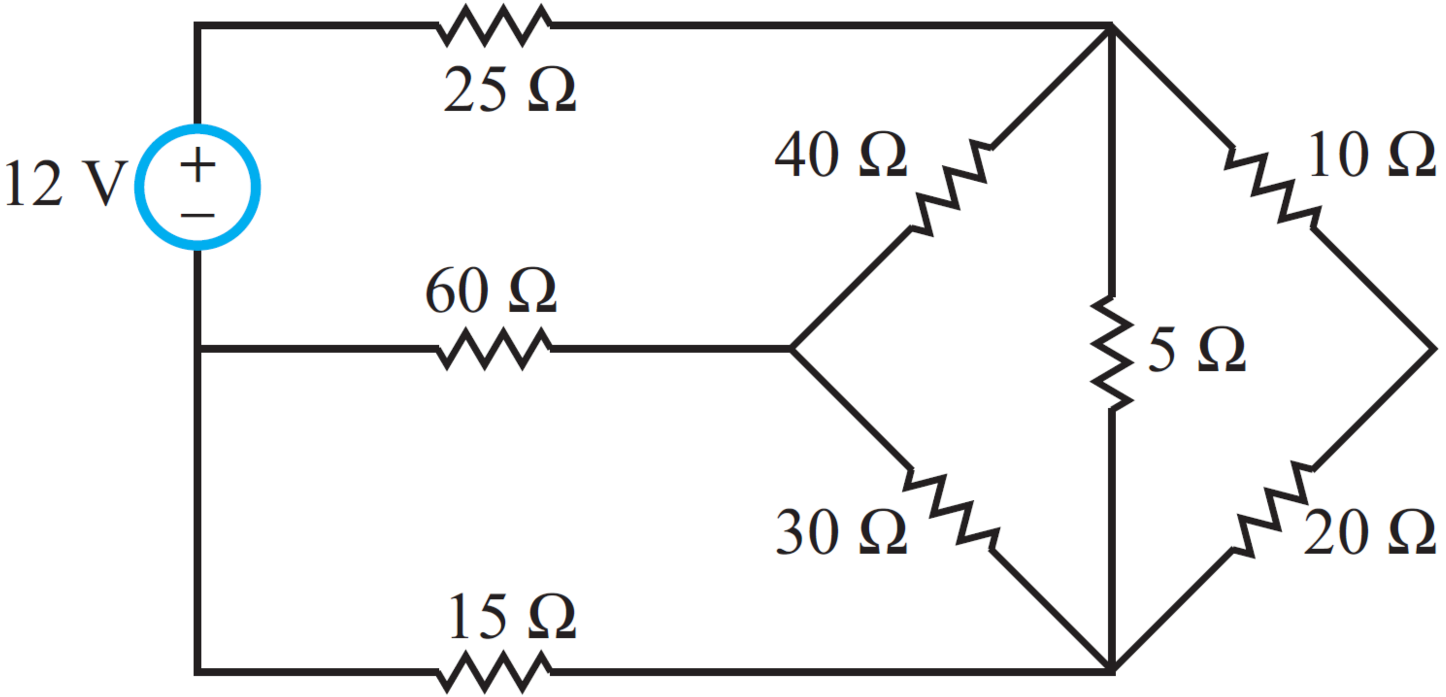


- A point where two or more elements have a common connection
- The voltage or potential at any node is constant across the node

How to find the nodes:

1) Put down dots on any wires that don’t have dots
2) Find out if any dots can be connected just by wires, if they are, one is a duplicate and erase it
3) Check for any wires that don’t have dots and repeat

How Many Nodes in This Circuit?



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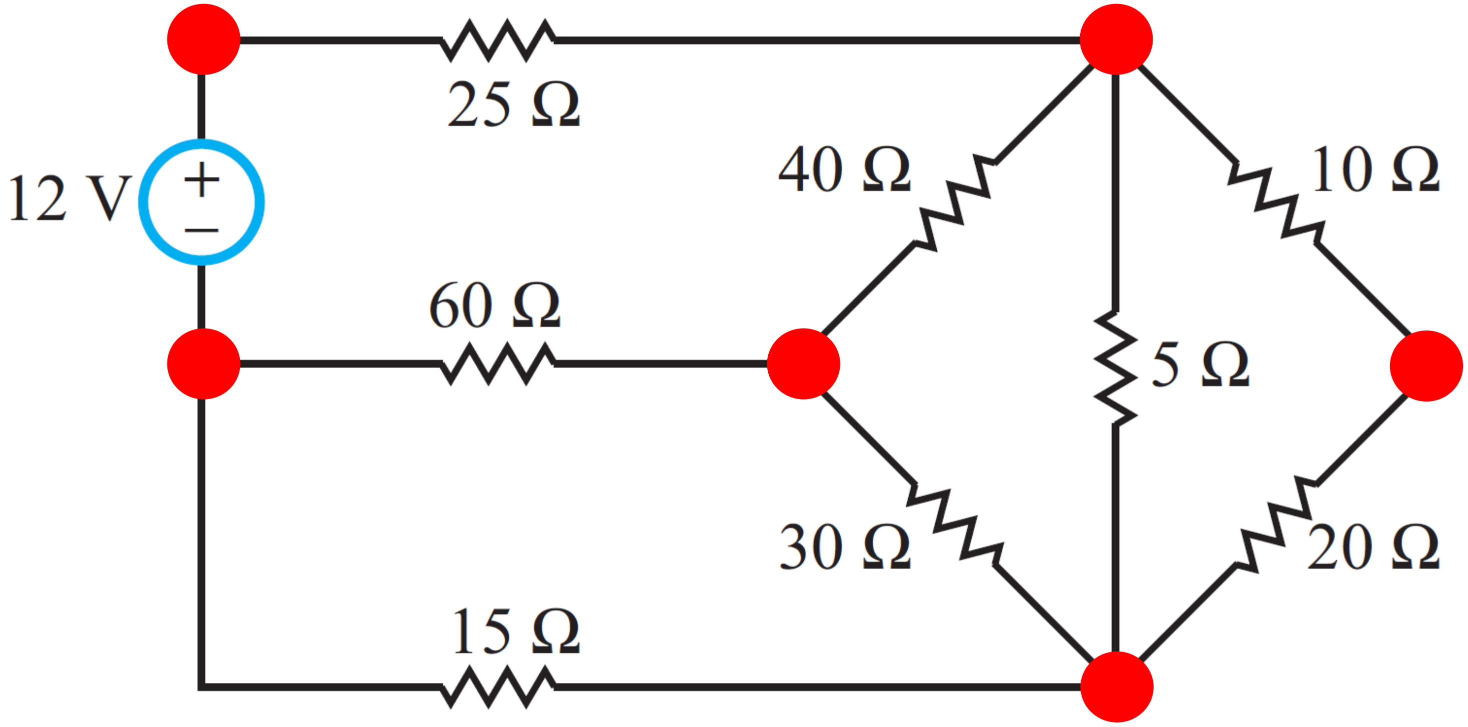
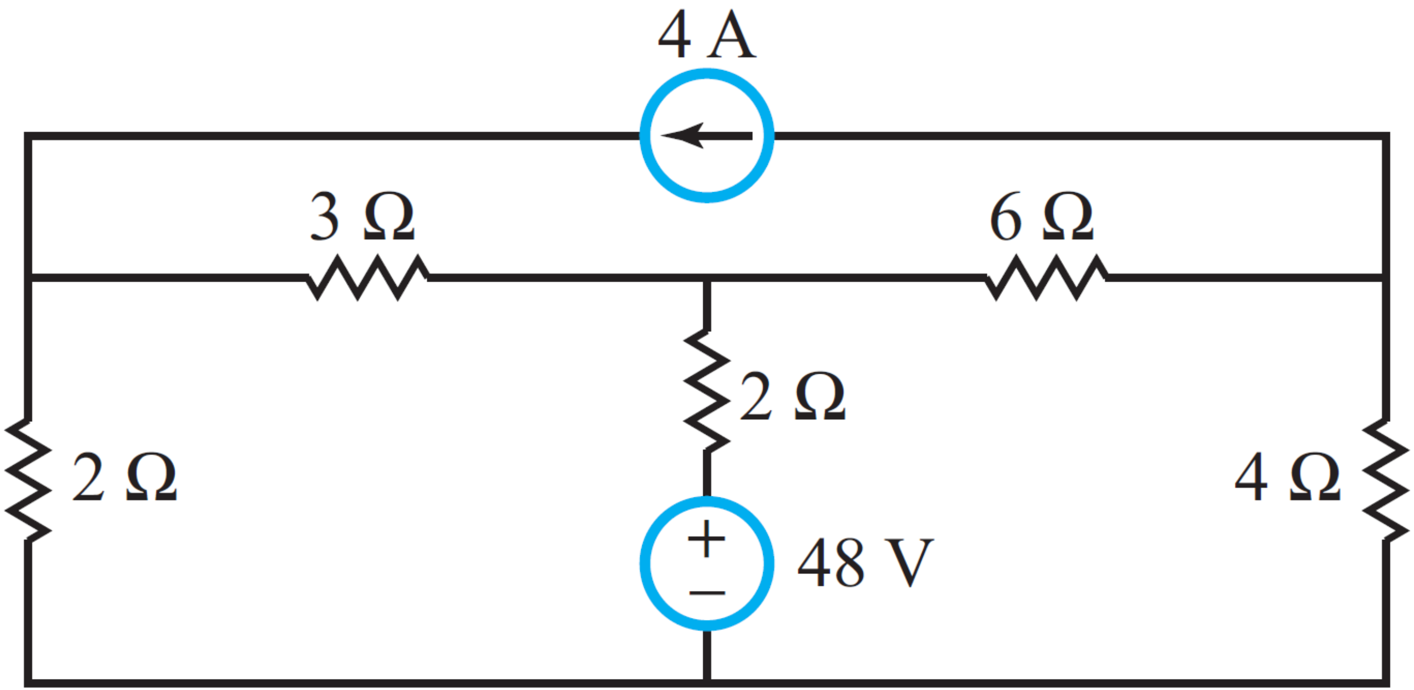
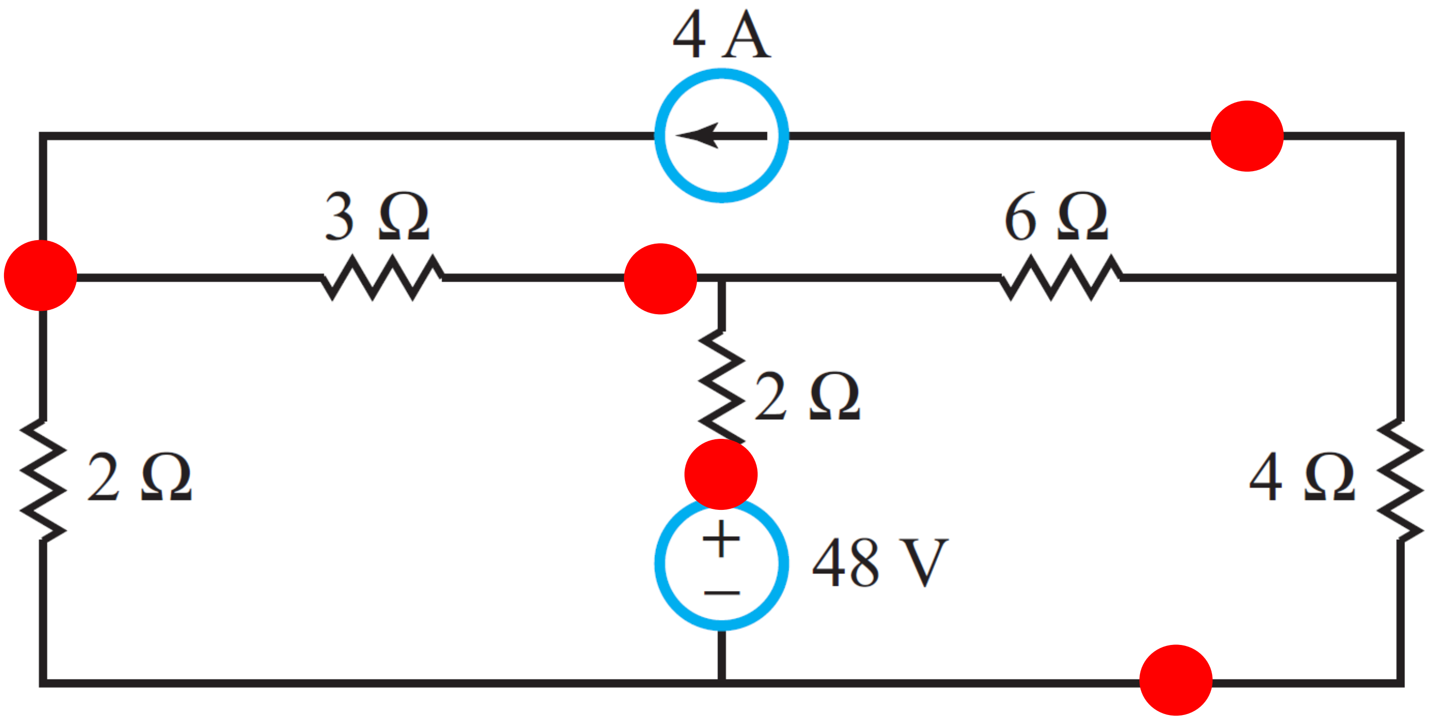


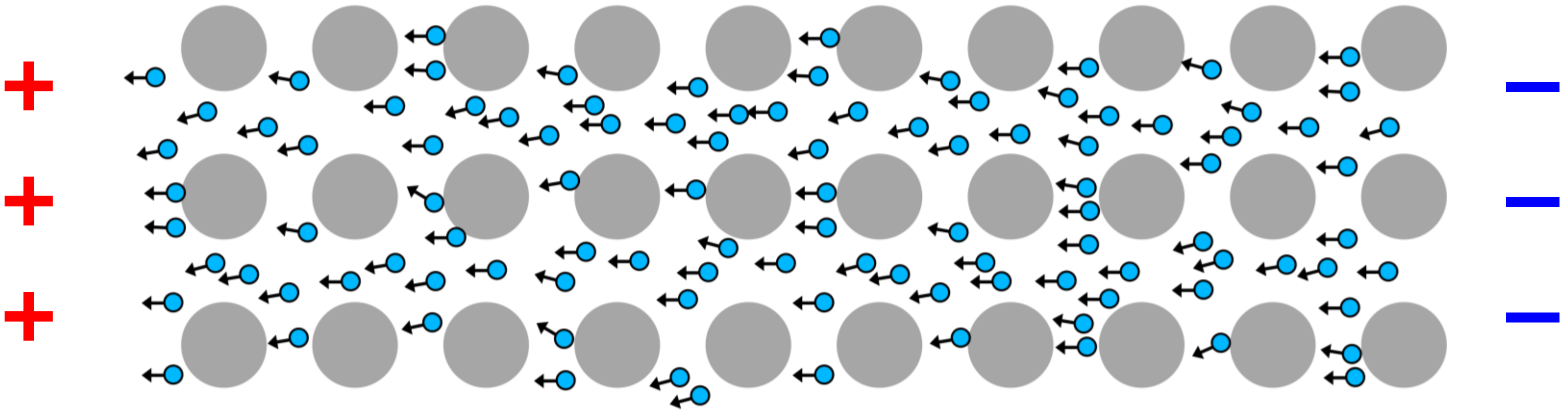
How Many Nodes in This Circuit?



How Many Nodes in This Circuit?



Current Flowing through **Nearly** Ideal Conductors



- When a voltage differential is applied, electrons flow freely and uniformly
- No voltage or potential drop across the ideal conductor
- Electrons don't lose any energy as they flow
- 10Ω / 1000feet = 0.005Ω over 6 inches

Système international (SI) Units

Table 1-1: Fundamental and electrical SI units.

Dimension	Unit	Symbol
Fundamental:		
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric charge	coulomb	C
Temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd
Electrical:		
Current	ampere	A
Voltage	volt	V
Resistance	ohm	Ω
Capacitance	farad	F
Inductance	henry	H
Power	watt	W
Frequency	hertz	Hz

Always

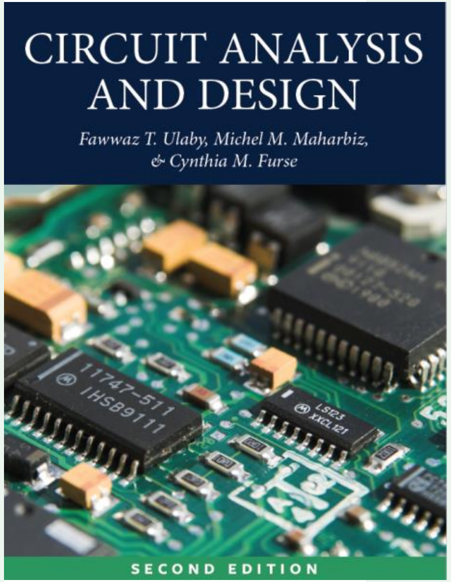
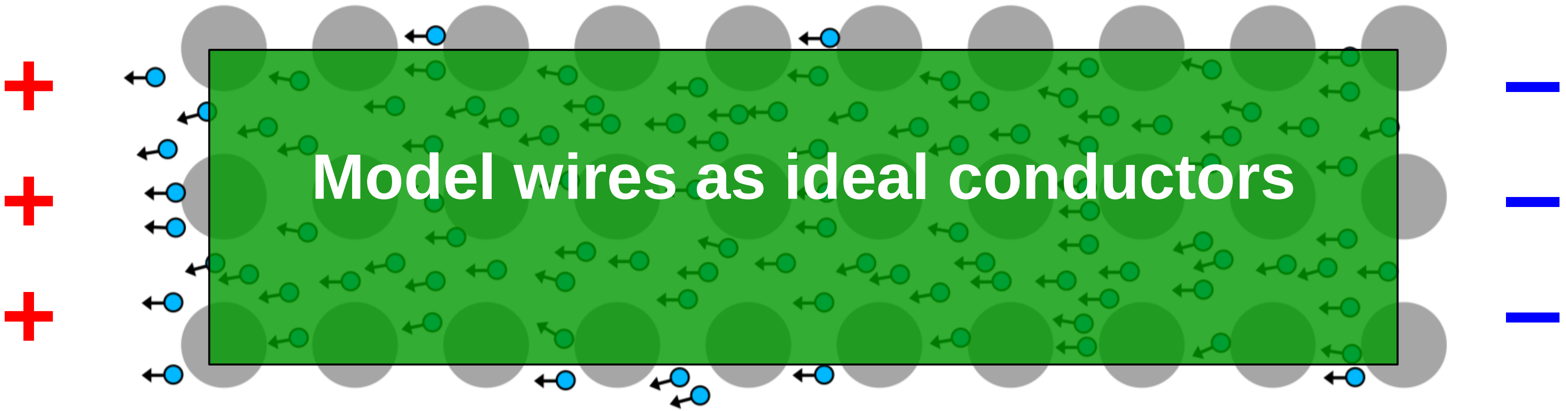


Table 1-2: Multiple and submultiple prefixes.

Prefix	Symbol	Magnitude
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}

https://services.publishing.umich.edu/Books/C/Circuit-Analysis-and-Design2

Current Flowing through **Nearly** Ideal Conductors

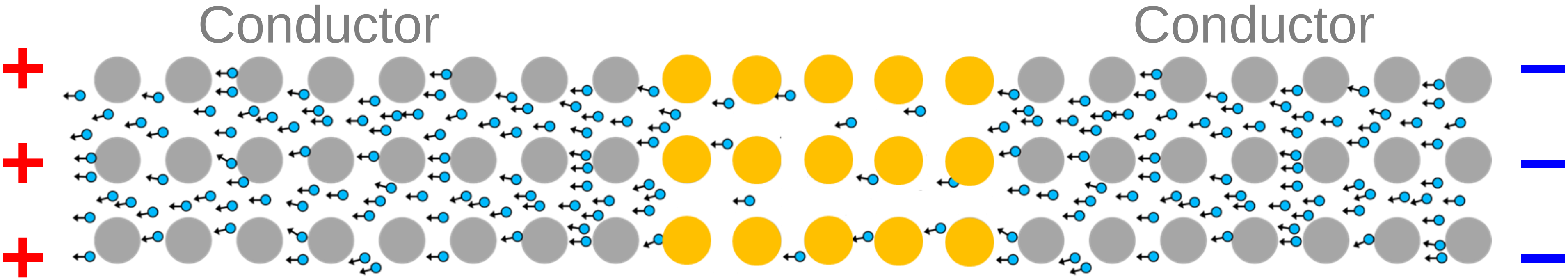


- When a voltage differential is applied, electrons flow freely and uniformly
- No voltage or potential drop across the ideal conductor
- Electrons don’t lose any energy as they flow
- 10Ω / 1000feet = 0.005Ω over 6 inches

  = 5.00mΩ over 152mm (SI)

Always

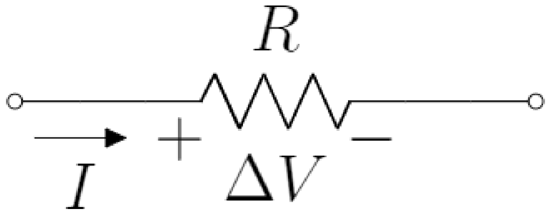
Resistors = Lower Conductivity, Fewer Free Electrons



- Electrons passing through a resistor will experience a **voltage drop** or **loss in energy** (remember, 1V = 1J/C)
- This energy loss is usually converted to heat (resistor = electrical friction)
- Loss of energy (per unit of charge) results in a drop in voltage across the resistor

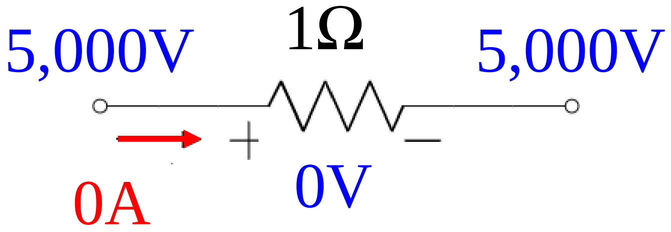
$$\Delta V = IR$$

Ohm’s Law

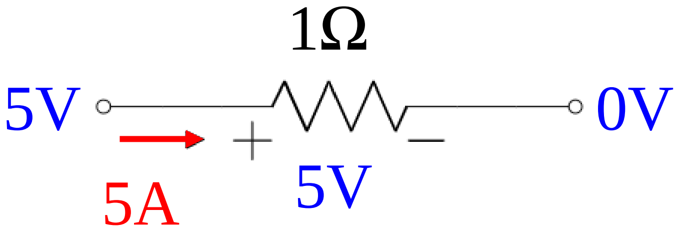


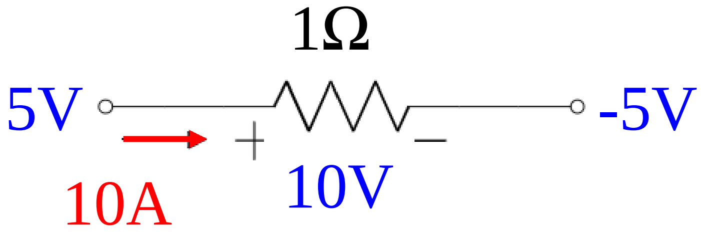
- Voltage drop (ΔV) across a **resistive** (R) material is proportional to the flowing current I

$$\Delta V = IR = V_{POS} - V_{NEG} = V_{FROM} - V_{TO}$$

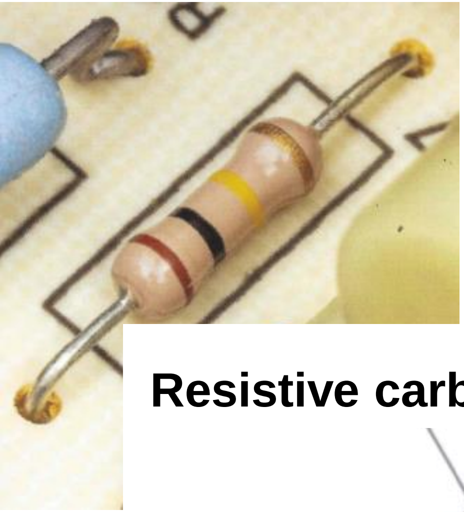


- The current, I, flows **into** the positive terminal of the voltage drop
- Positive current will flow **from** a higher voltage **to** a lower voltage

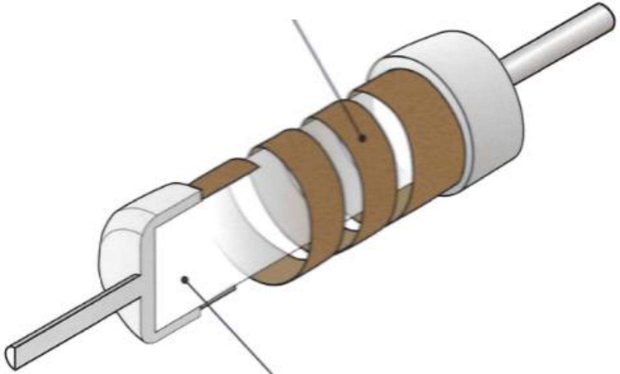




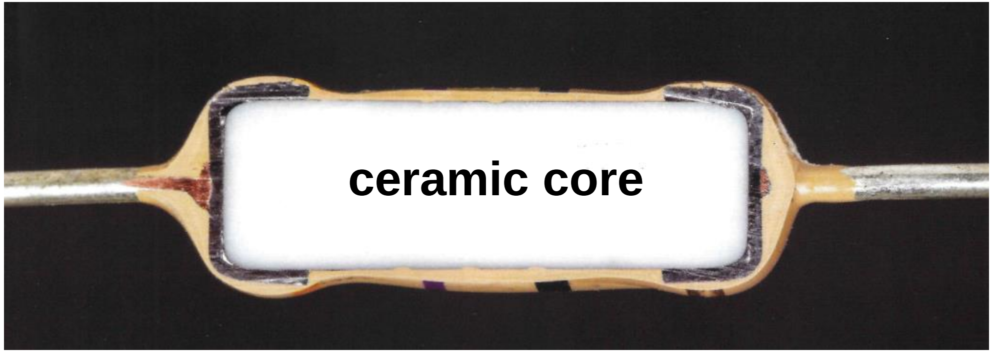
Inside a Carbon Film (Cheap!) Resistor



Resistive carbon film



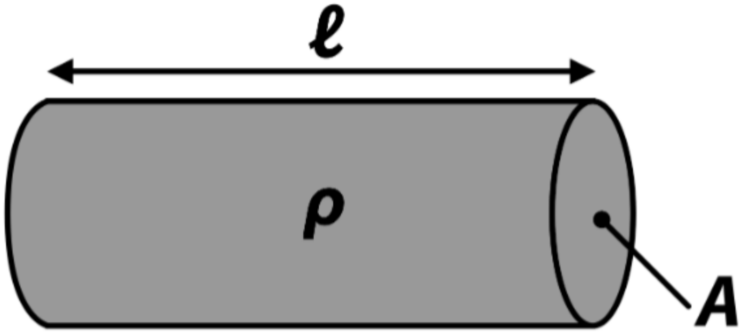
Ceramic core



Cross section

Outer coating removed

Resistance Is Affected by Geometry and Material Properties



$$R = \rho \frac{\ell}{A}$$

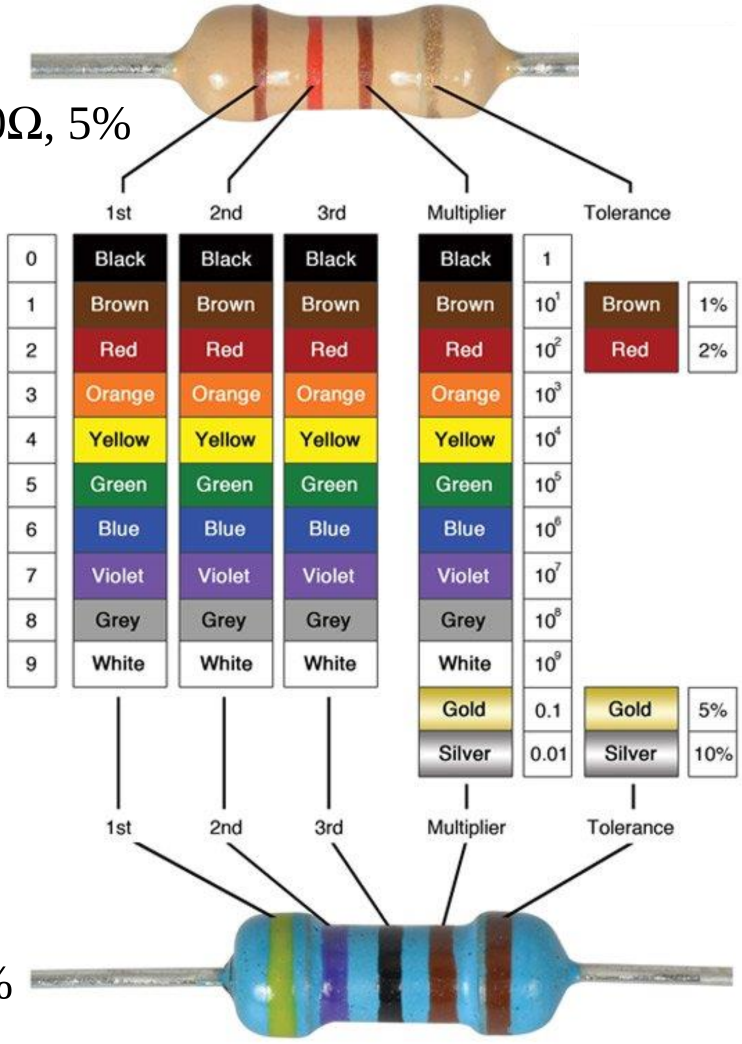
ℓ: length (m)
A: cross-sectional area (m^2)
ρ: **resistivity** ($\Omega \cdot m$)

Material	Resistivity (ρ, $\Omega \cdot m$)
Silver	1.62×10^{-8}
Copper	1.72×10^{-8}
Gold	2.44×10^{-8}
Carbon	1×10^{-5}
Silicon	2.3×10^{3}
Glass	$\sim 10^{12}$
Air	$\sim 10^{16}$

Resistor Color Code

$12 \times 10^1 = 120\Omega$, 5%

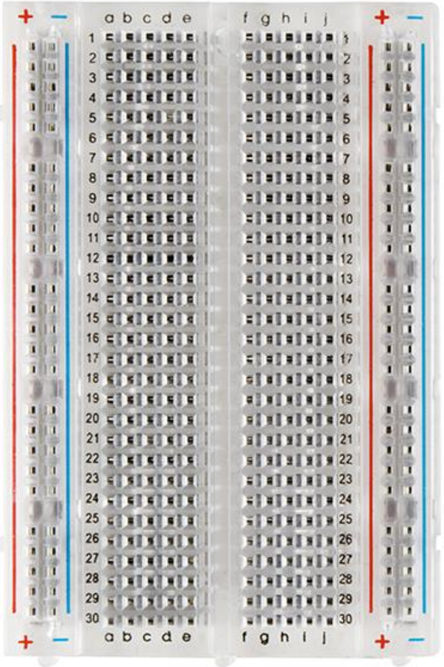
- First 2 (or 3) bands denote the first digits in the resistance value
- 3rd (or 4th) band denotes an order-of-magnitude multiplier (i.e. 10^x)
- Final band denotes the **tolerance**
  - ±5% is common for carbon film resistors (tan body)
  - ±1% is common for metal film resistors (blue body)



$470 \times 10^1 = 4.7k\Omega$, 1%

Breadboarding Your Circuits

Topside

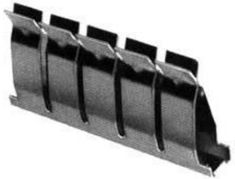


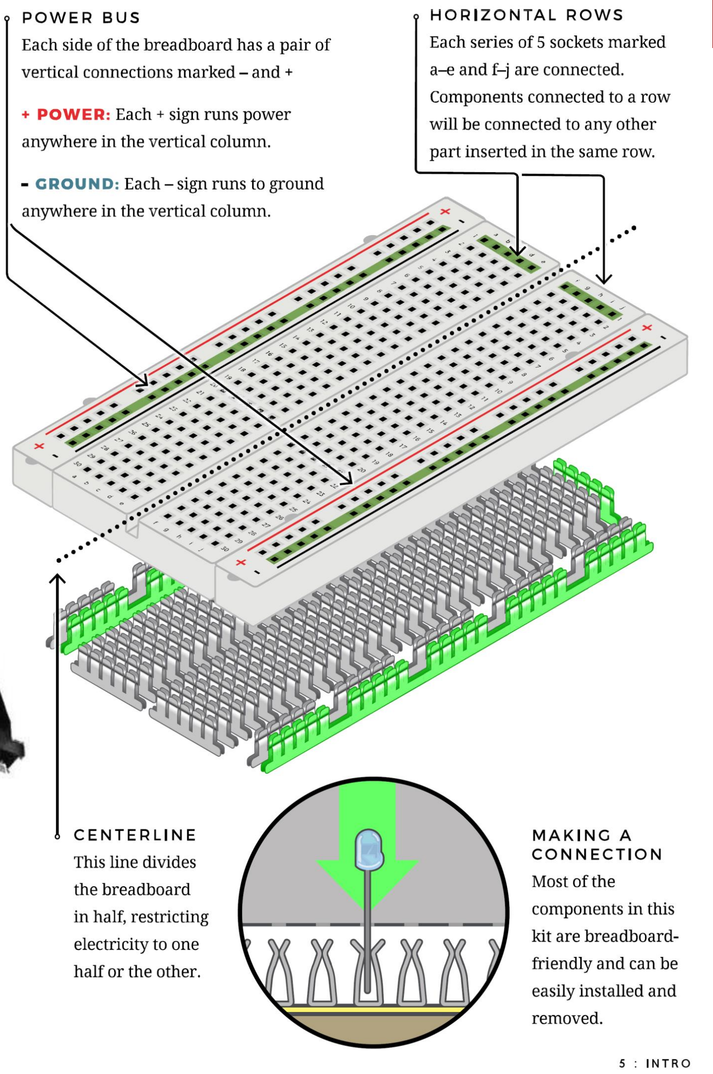
Underside

Power rails

Power rails

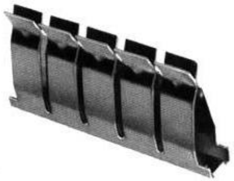
One row



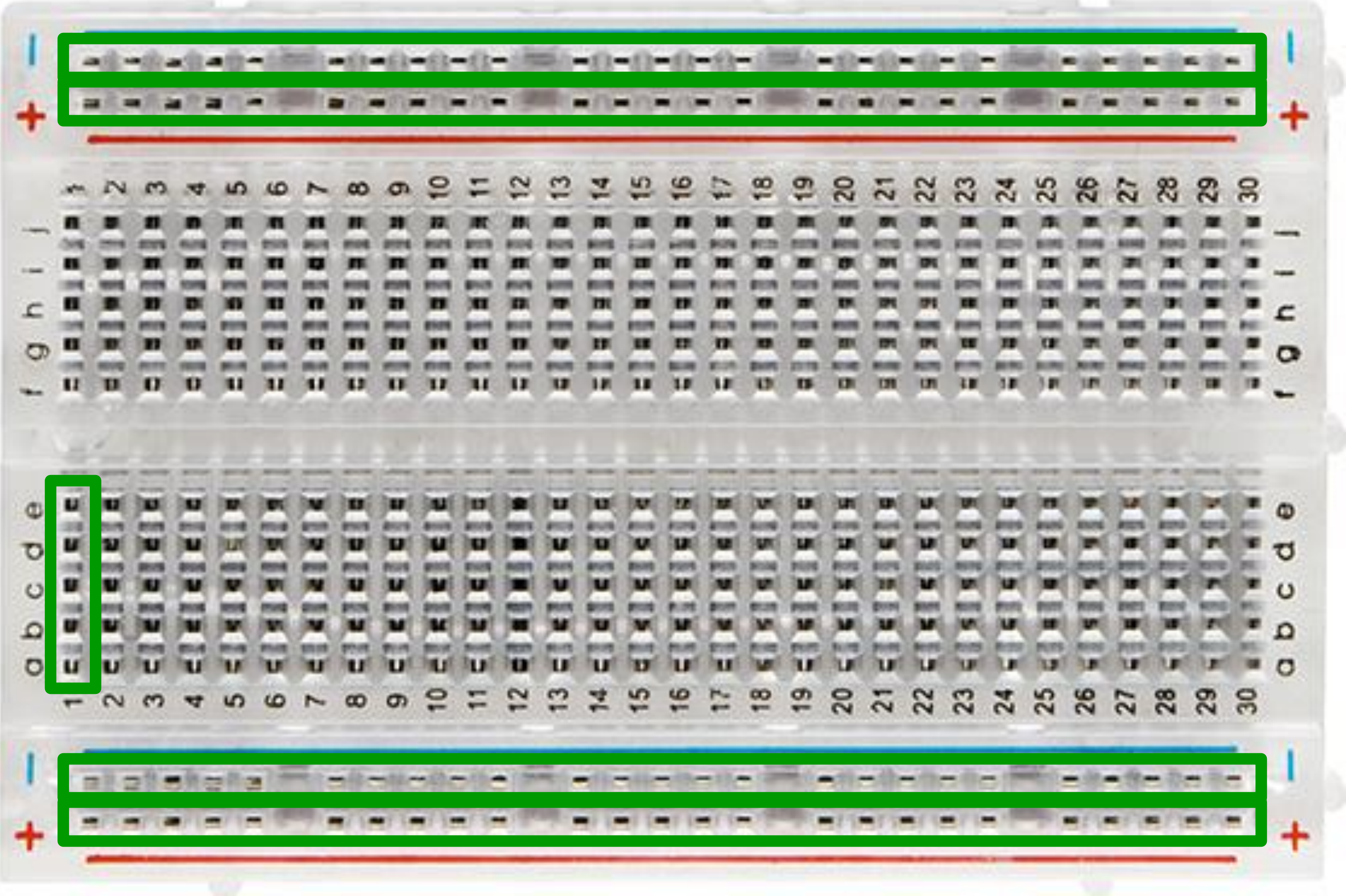


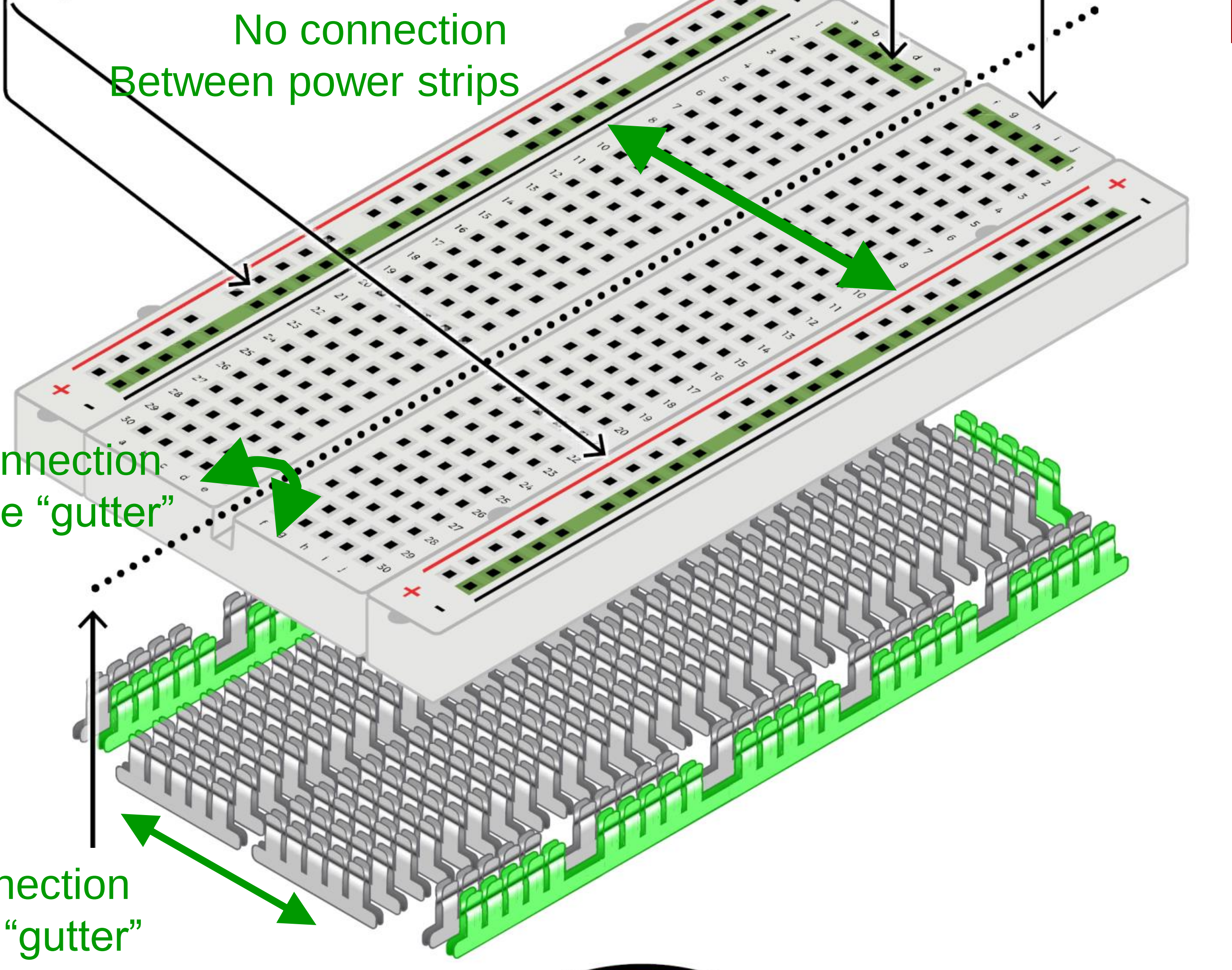
End strips are electrically connected

One row

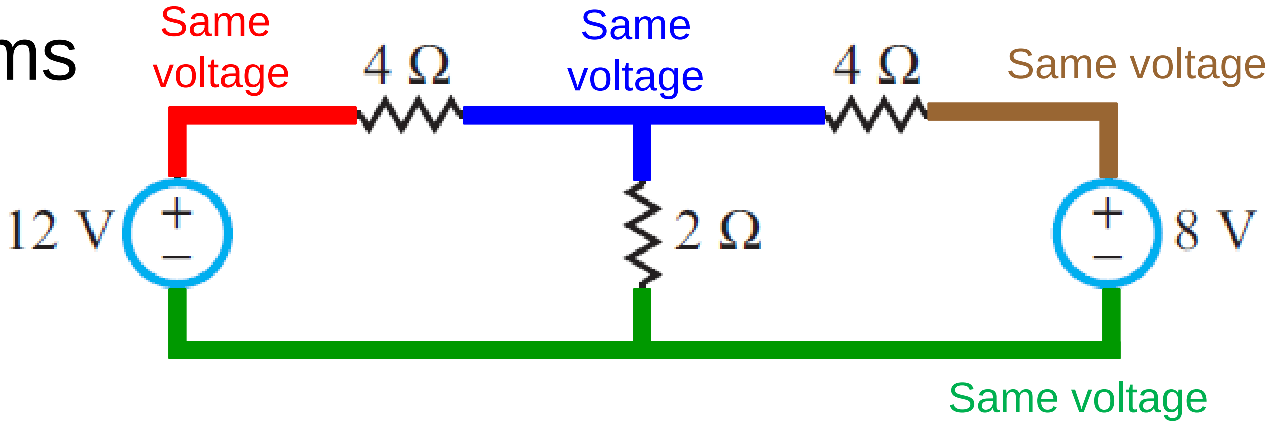


Each group of 5 is electrically connected



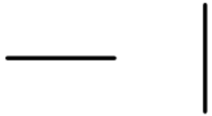
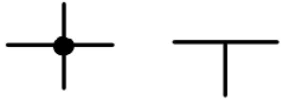
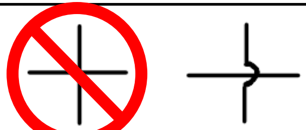
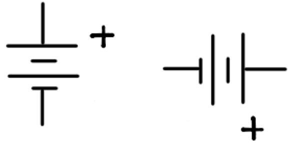
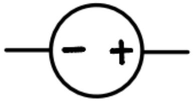
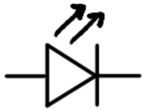

No connection
Between power strips
No connection
across the “gutter”
No connection
across the “gutter”

Schematic Diagrams

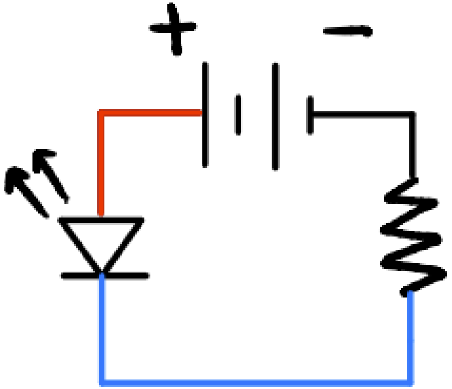


- Schematics represent **connections between** elements, not necessarily their relative or actual physical locations on a circuit board
- MODEL: Remember, every part of a node is at the same potential
- MODEL: Voltage does not drop across a node, only across circuit elements

Schematic Symbols

Connections	 Conductor (wire)	 Two conductors, joined	 Two conductors, not joined
Power Sources	 Battery	 Voltage Source	 Current Source
Other components	 Resistor	 LED (Light-Emitting Diode)	 Switch

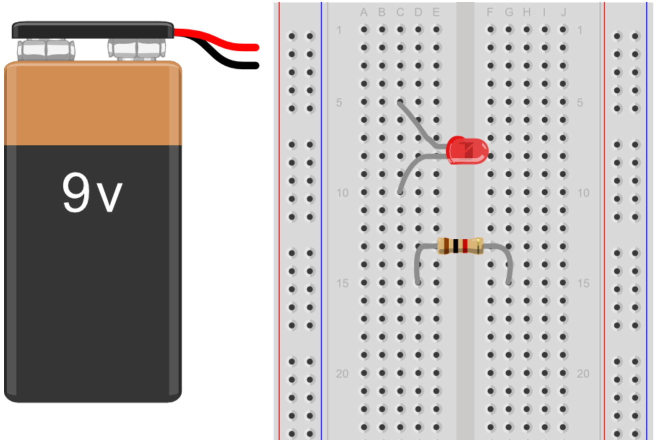
Schematic vs. Breadboard Wiring



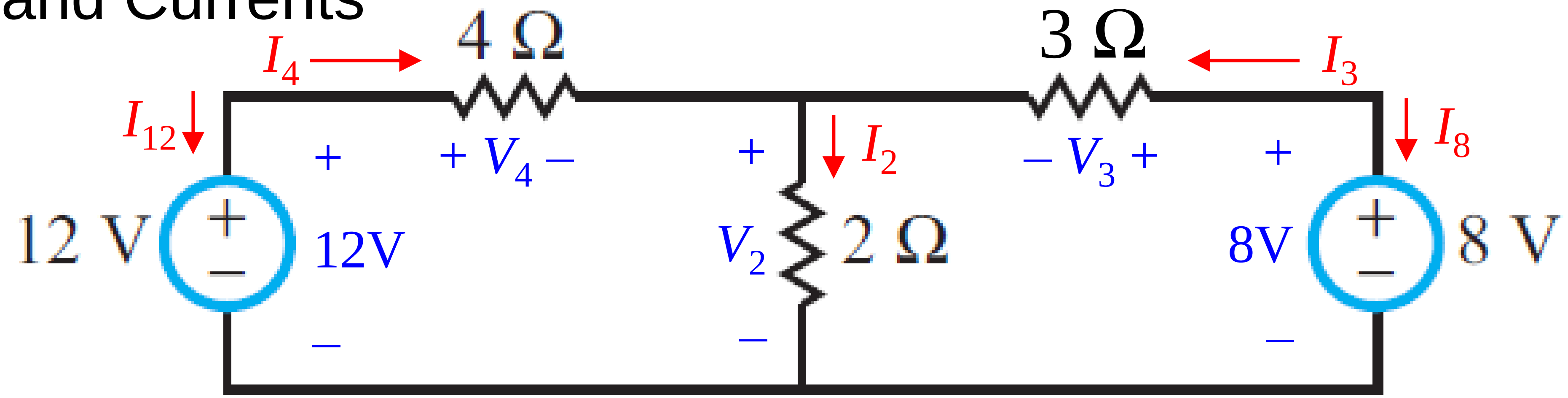
- Schematics show **how** components are connected, **not where they are**

- Use **side rails** for your power connections.

- Use **colors** to make it easier to follow a circuit.
- Standard: **Red/Black** for power connections.



Labeling Voltages and Currents



- When analyzing circuits, every element generally has a **voltage difference across** it and a **current through** it
- For resistors, **current** enters the positive terminal
- Not sure which way to draw ΔV or I ? Guess! It will work out either way!

Always

Kirchhoff's Current Law (KCL) and Voltage Law (KVL)

$$\sum I_{in} = \sum I_{out}$$

What goes in,
must come out

KCL

$$\sum V_{up} = \sum V_{down}$$

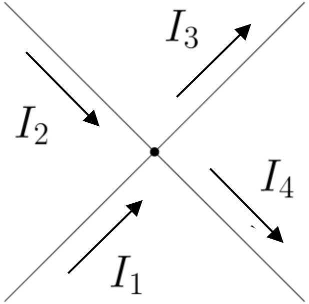
What goes up,
must come down

KVL

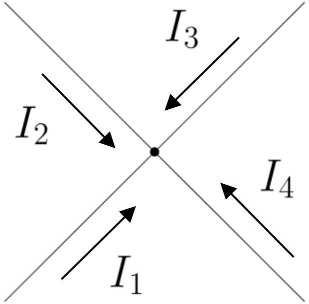
Always

Kirchhoff's Current Law (KCL)

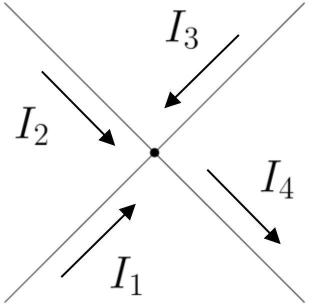
$$\sum I_{in} = \sum I_{out}$$



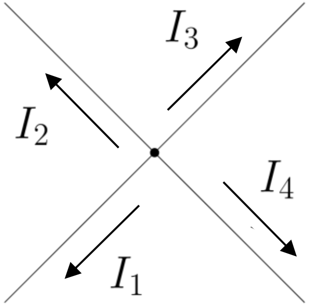
$$I_1 + I_2 = I_3 + I_4$$



$$I_1 + I_2 + I_3 + I_4 = 0\text{A}$$



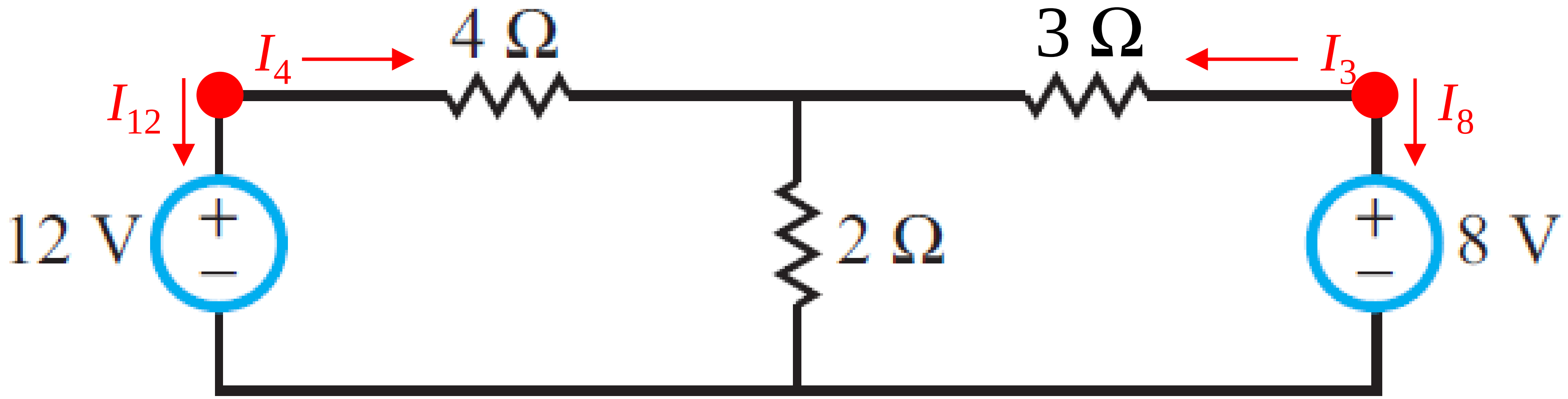
$$I_1 + I_2 + I_3 = I_4$$



$$0\text{A} = I_1 + I_2 + I_3 + I_4$$

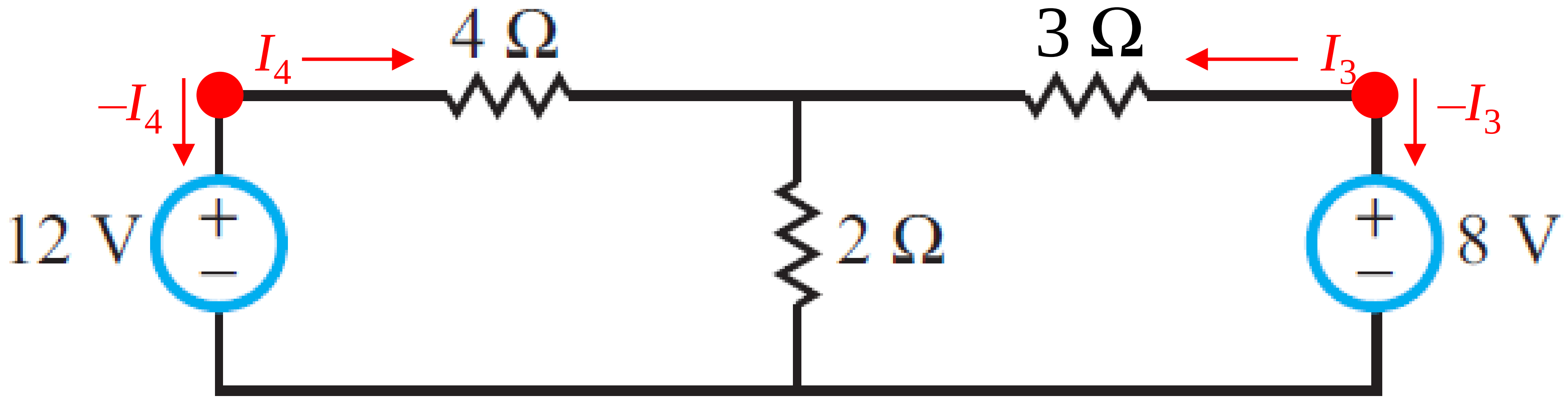
Kirchhoff's Current Law (KCL)

$$\sum I_{in} = \sum I_{out}$$



Kirchhoff's Current Law (KCL)

$$\sum I_{in} = \sum I_{out}$$



$$0\text{A} = I_4 + I_{12}$$
$$-I_4 = I_{12}$$

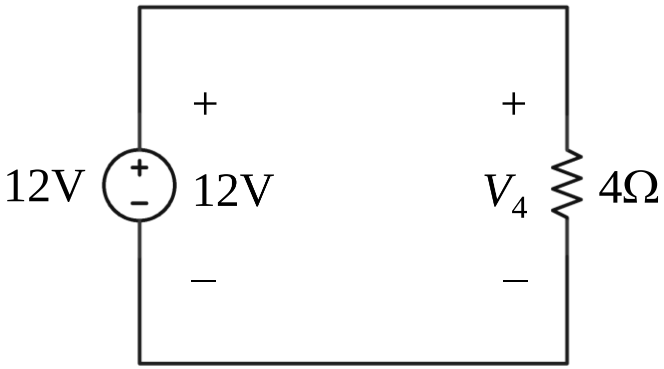
Always

$$0\text{A} = I_3 + I_8$$
$$-I_3 = I_8$$

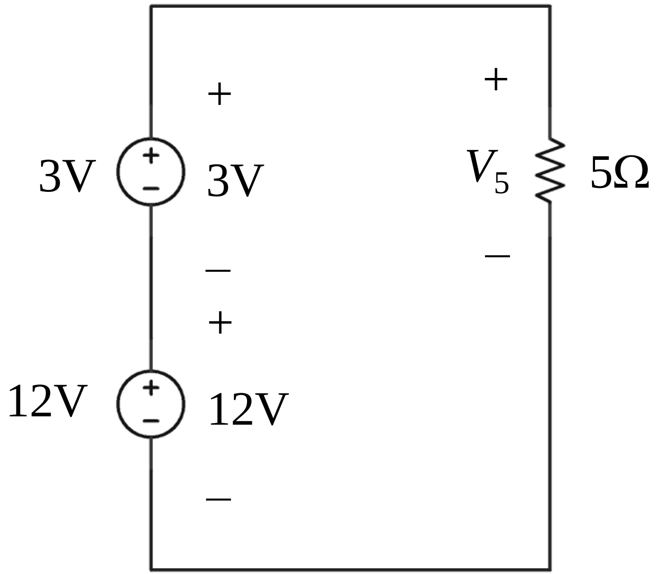
Changing the direction of a current changes its sign

Kirchhoff's Voltage Law (KVL)

$$\sum V_{up} = \sum V_{down}$$



$12\text{V} = V_4$



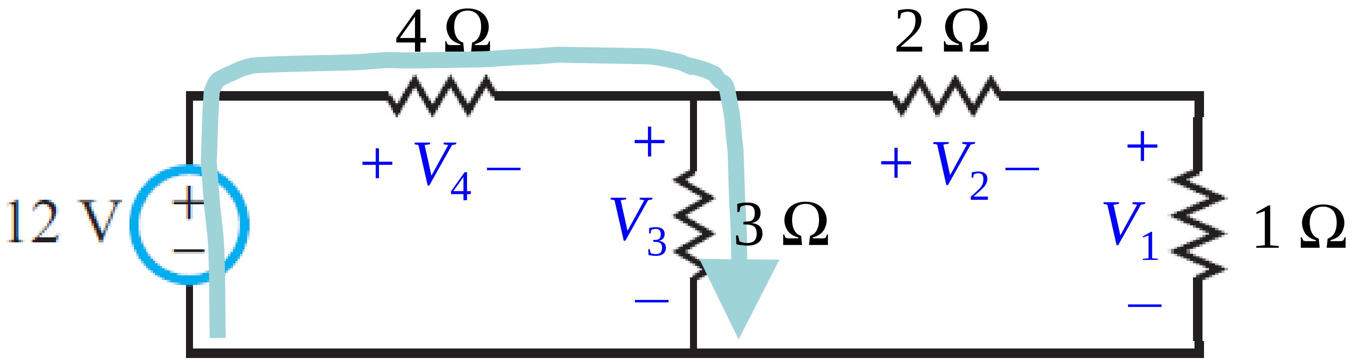
$12\text{V} + 3\text{V} = V_5$

Independent of ground!

Kirchhoff's Voltage Law (KVL)

$$\sum V_{up} = \sum V_{down}$$

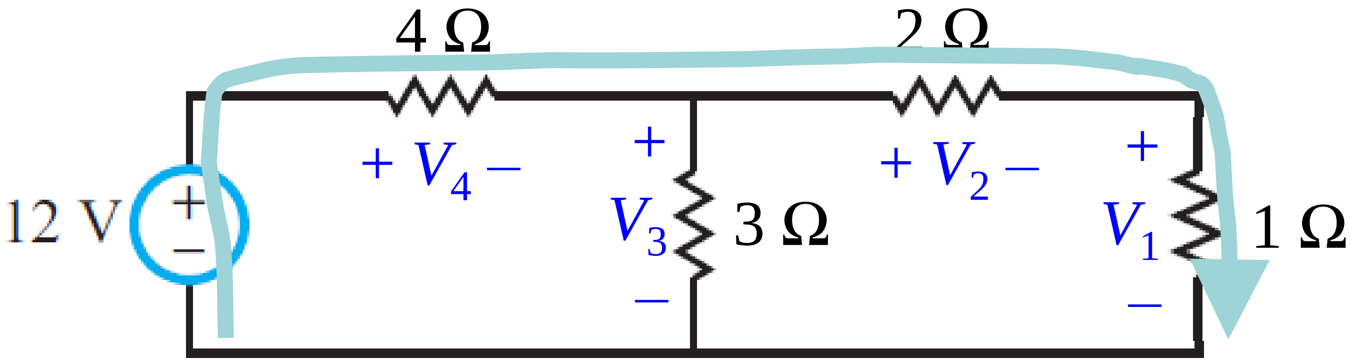
Write Three (3) KVL Equations



$$12\text{V} = V_4 + V_3$$

Kirchhoff's Voltage Law (KVL)
Write Three (3) KVL Equations

$$\sum V_{up} = \sum V_{down}$$



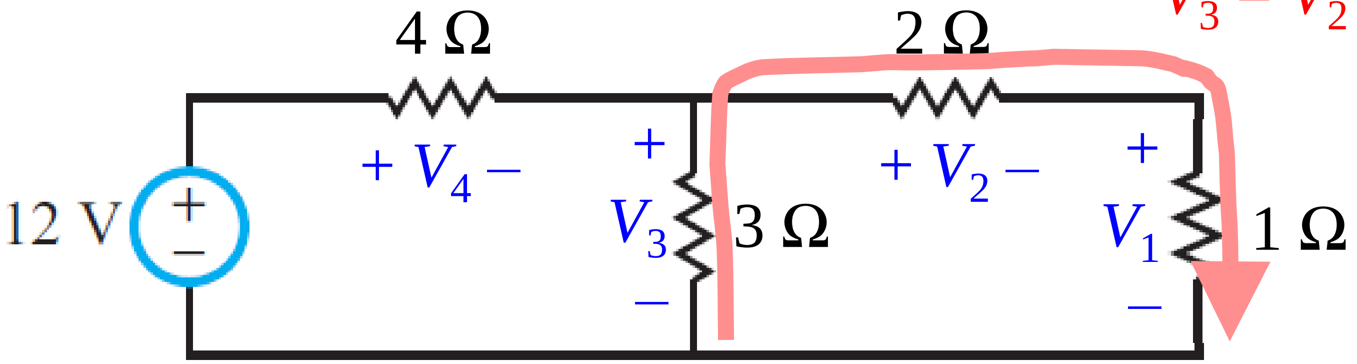
$12V = V_4 + V_3$

$12V = V_4 + V_2 + V_1$

Kirchhoff's Voltage Law (KVL)
Write Three (3) KVL Equations

$$\sum V_{up} = \sum V_{down}$$

$V_3 = V_2 + V_1$



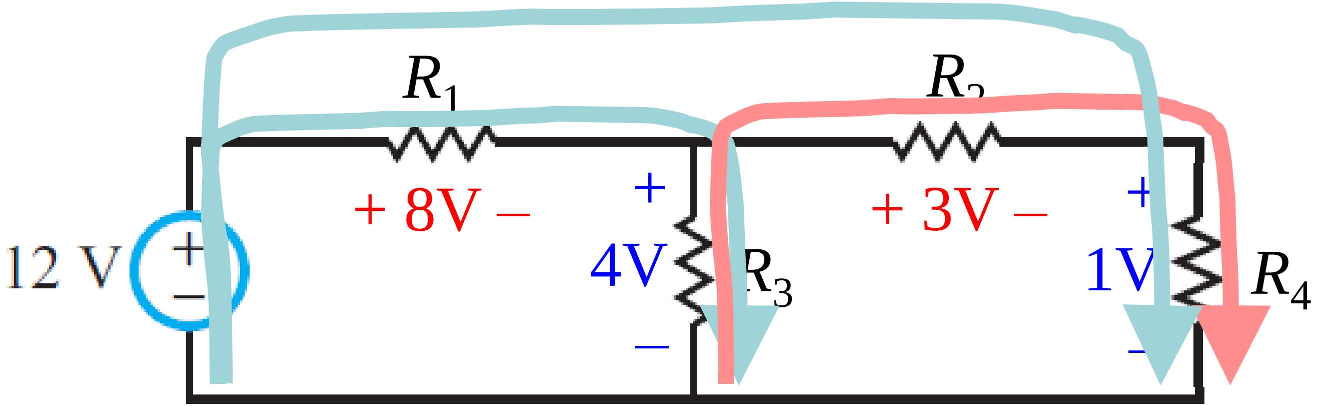
$12V = V_4 + V_3$

$12V = V_4 + V_2 + V_1$

Kirchhoff's Voltage Law (KVL)

$$\sum V_{up} = \sum V_{down}$$

Example: $V_1 = ?\quad V_2 = ?$



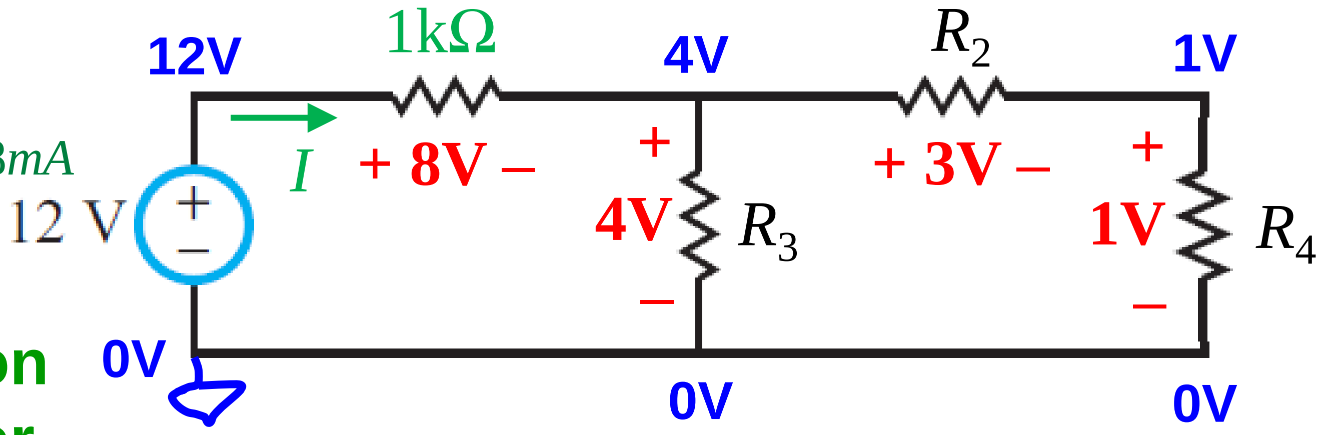
12V = 8V + 4V

12V = 8V + 3V + 1V

4V = 3V + 1V

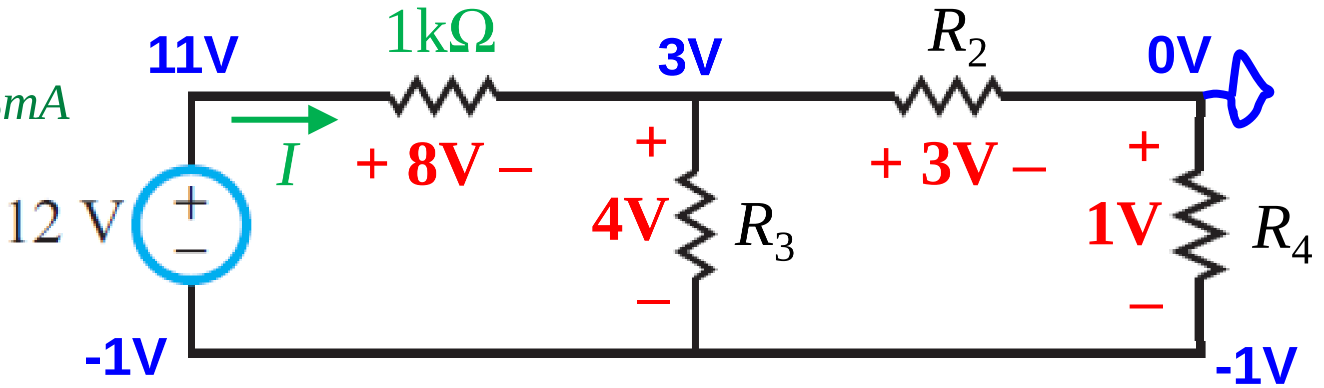
Reference Voltage (Ground)

$$I = \frac{\Delta V}{R} = \frac{12V - 4V}{1k\Omega} = 8mA$$



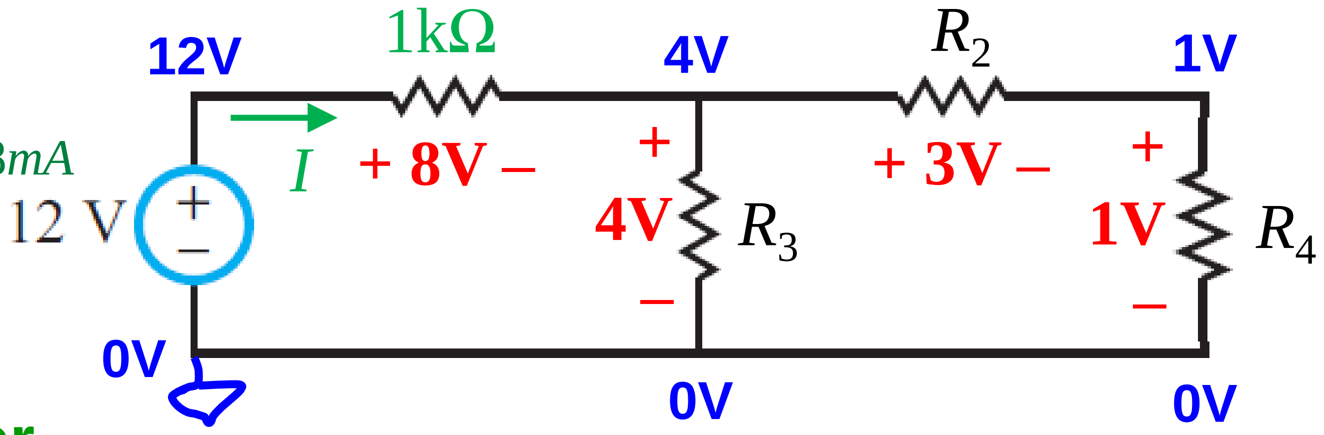
Ground location does not matter

$$I = \frac{\Delta V}{R} = \frac{11V - 3V}{1k\Omega} = 8mA$$



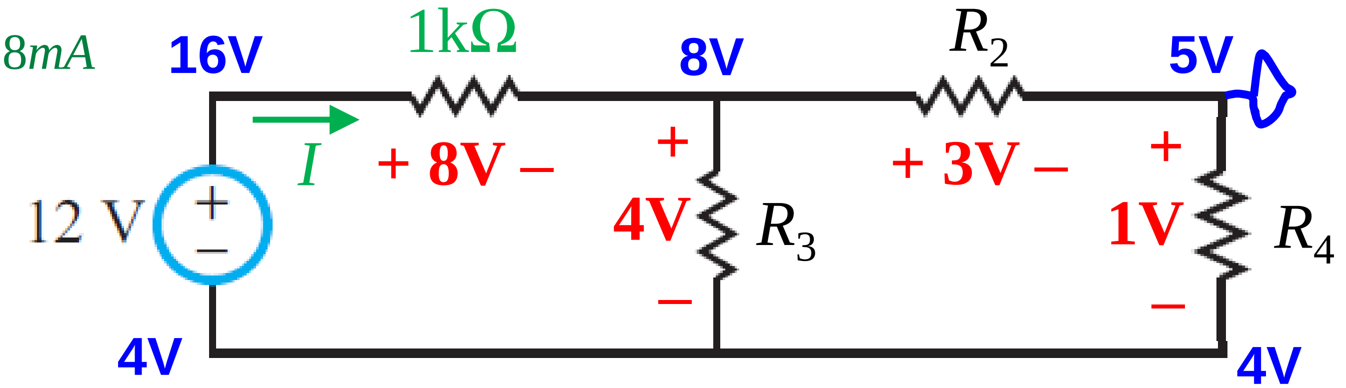
Reference Voltage (Ground)

$$I = \frac{\Delta V}{R} = \frac{12V - 4V}{1k\Omega} = 8mA$$

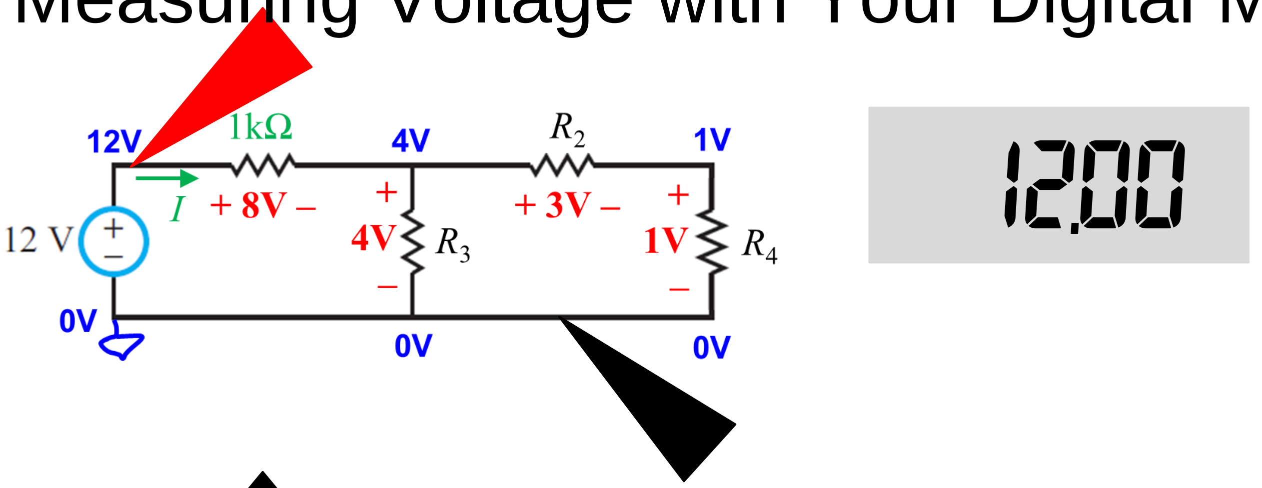


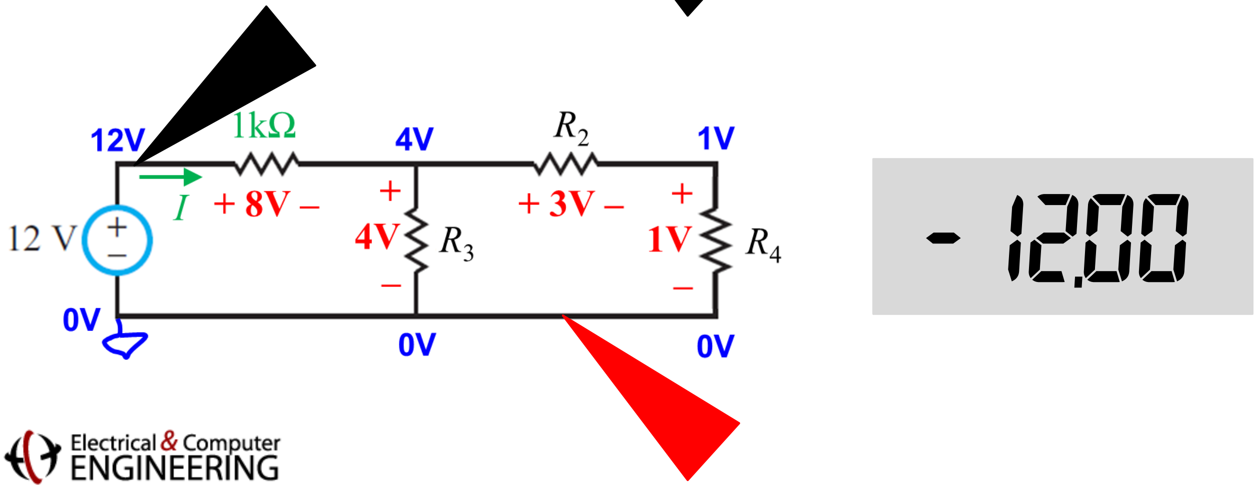
Ground value does not matter

$$I = \frac{\Delta V}{R} = \frac{16V - 8V}{1k\Omega} = 8mA$$



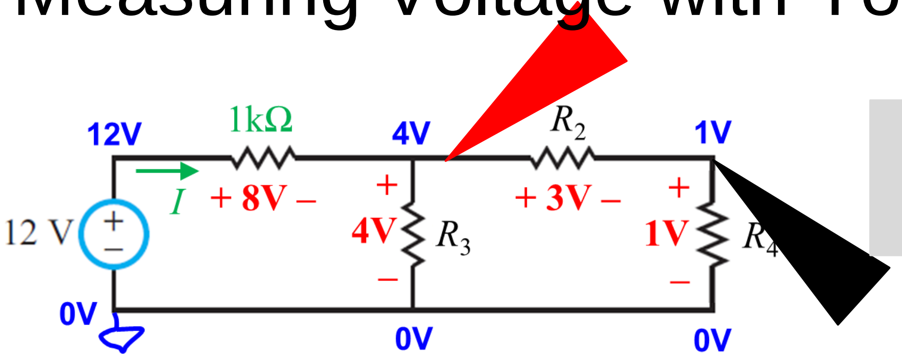
Measuring Voltage with Your Digital Multimeter (DMM)

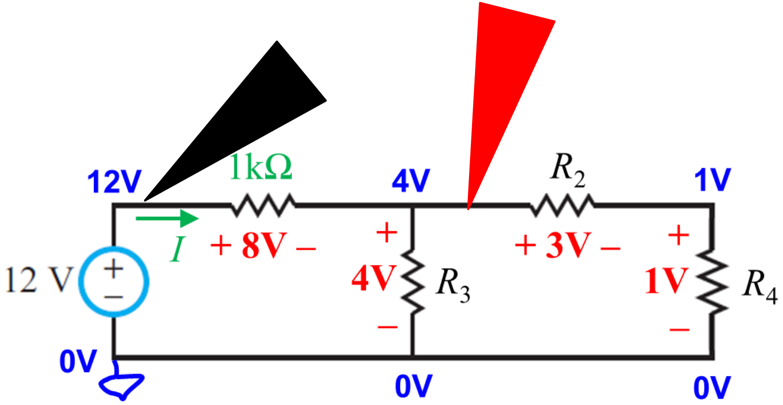




$V_{RED} - V_{BLACK}$

Measuring Voltage with Your Digital Multimeter (DMM)

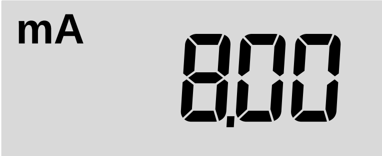


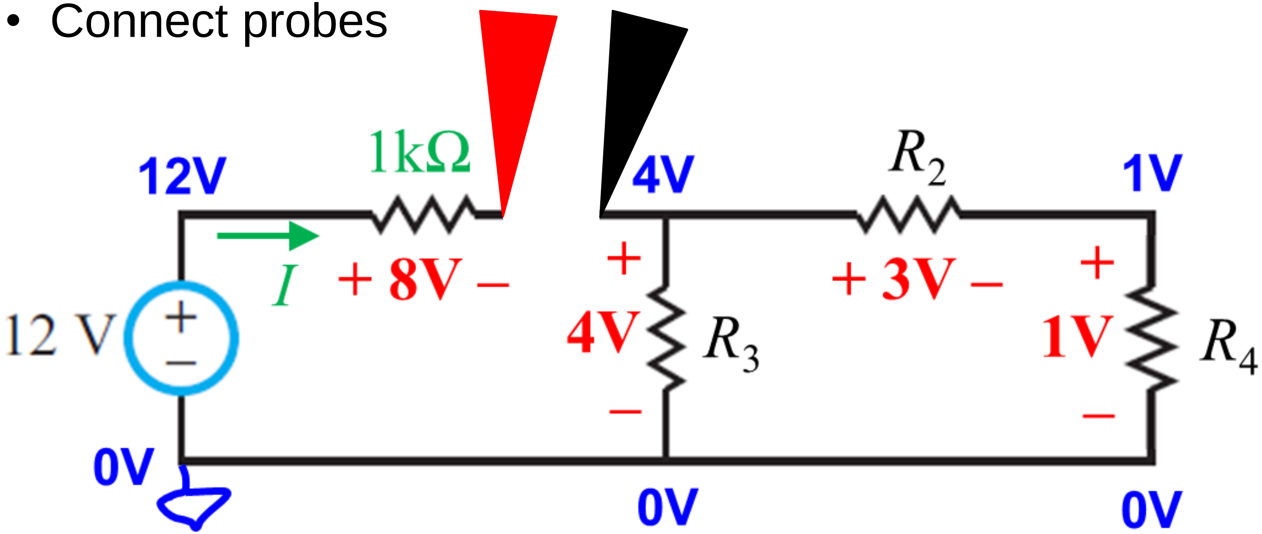


$$V_{RED} - V_{BLACK}$$

Measuring Current with Your Digital Multimeter (DMM)

- Current must flow THROUGH the DMM for it to be measured!
- Break open the circuit
- Connect probes

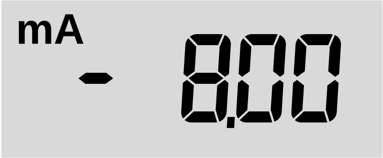


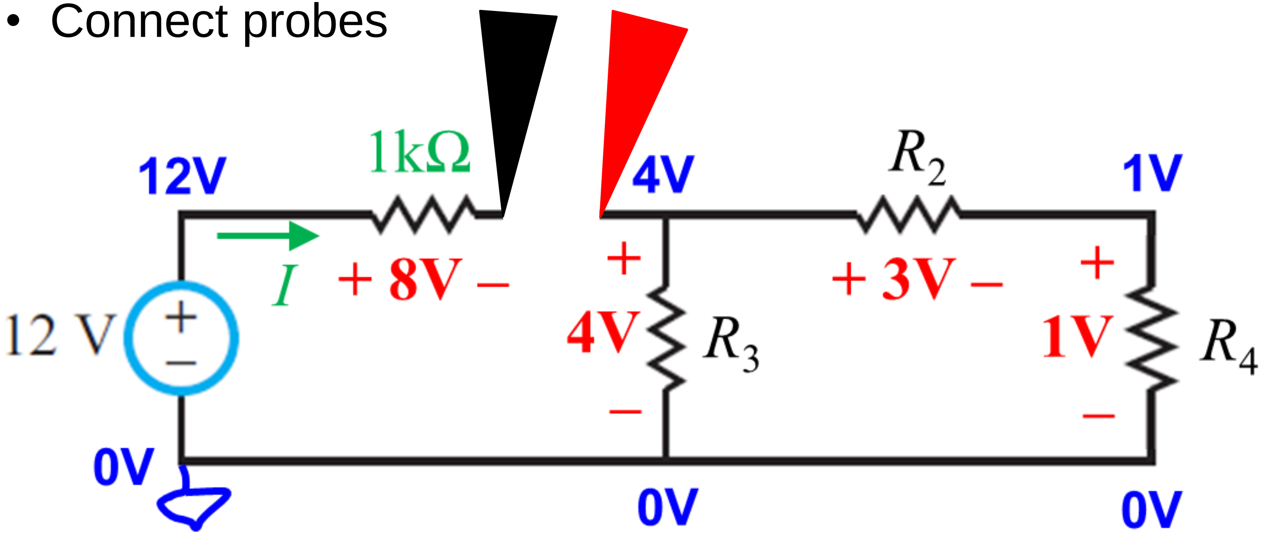


$I_{Into\ Red} = I_{Out\ of\ Black}$

Measuring Current with Your Digital Multimeter (DMM)

- Current must flow THROUGH the DMM for it to be measured!
- Break open the circuit
- Connect probes



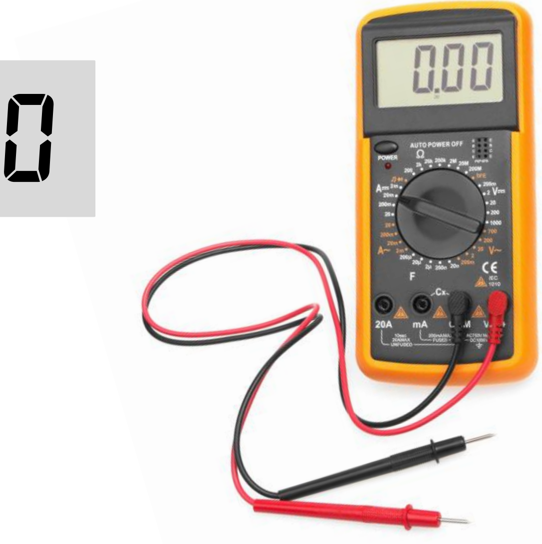


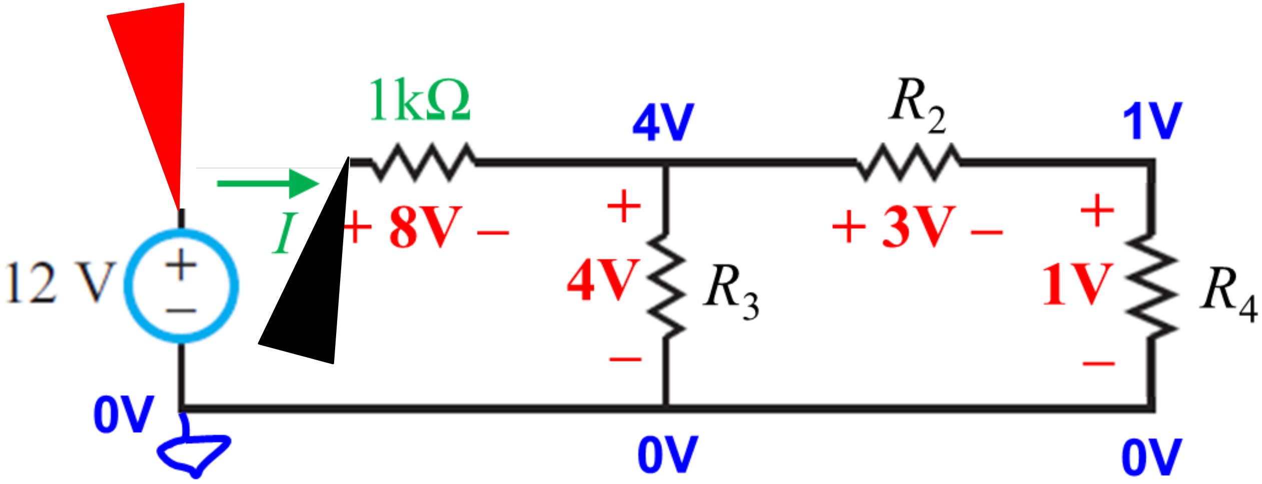
$I_{Into\ Red} = I_{Out\ of\ Black}$

Measuring Current with Your Digital Multimeter (DMM)

- Current must flow THROUGH the DMM for it to be measured!
- Break open the circuit
- Connect probes

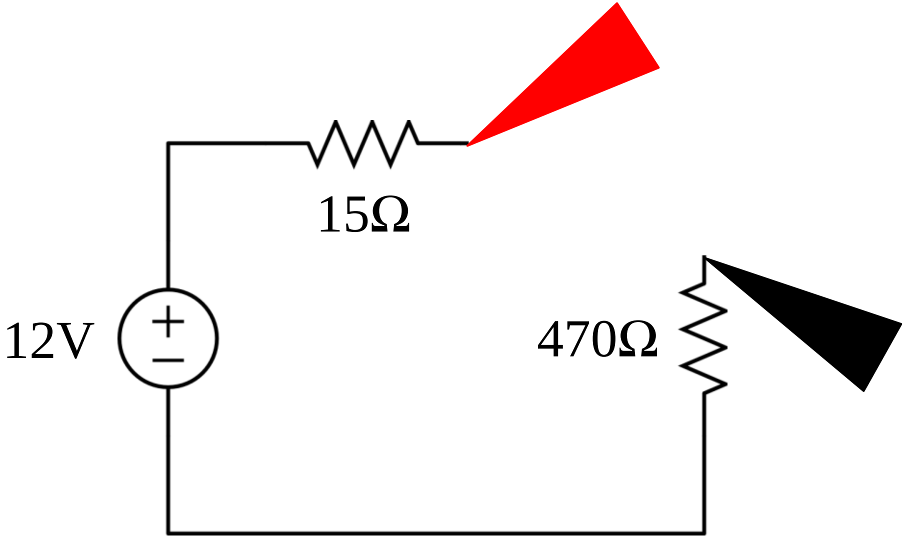
mA 8.00





$$I_{\text{Into Red}} = I_{\text{Out of Black}}$$

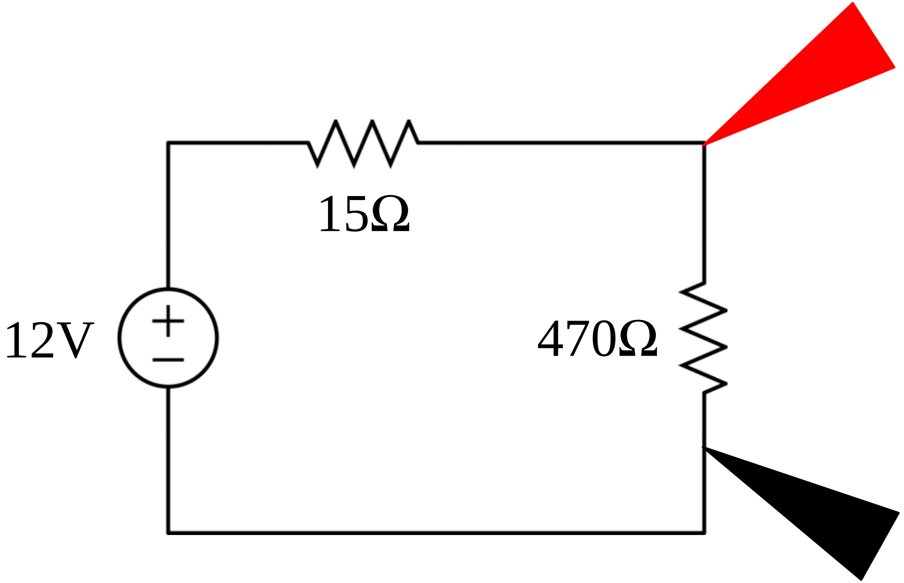
Be Careful When You Are Measuring Current



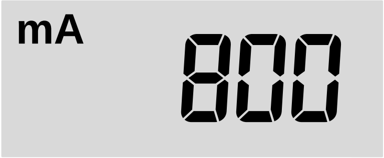
$$24.74mA = \frac{12V}{15\Omega + 470\Omega}$$

$$I_{Into\ Red} = I_{Out\ of\ Black}$$

Be Careful When You Are Measuring Current



$$800mA = \frac{12V}{15\Omega}$$

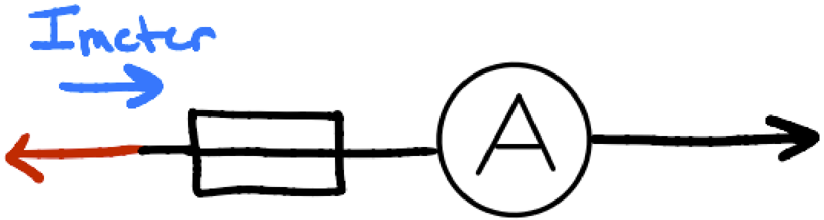


Rest in Peace…

$I_{Into\ Red} = I_{Out\ of\ Black}$

Be Careful When You Are Measuring Current

- Because current travels through the sensitive DMM, excess current can destroy it! :(
- DMMs include a fuse that "blows" or self-destructs when excess current starts to flow
- By giving its life, the $0.25 fuse can protect the $10 - $1,000 DMM



Fuse

Schematic Symbol

Damaged Fuse

Sources: Digikey

Objectives of this Lecture

- Ideal voltage sources and current sources each have one job
- Circuit nodes
- Conductors and resistors
- Ohm’s Law

- Kirchhoff’s Current Law (KCL)
- Kirchhoff’s Voltage Law (KVL)

What Do You Need to Do Next?

1. Take the **Lecture 2 Quiz** on canvas**!**

2. Check out Piazza and Gradescope

3. Take a look at HW01, Note 01, and Lab 1