Electronics is cool

- Electronics has produced the most complex artificial systems in the known universe.
- Only biological systems are more complex, and among them, electrical (nervous) systems are the most complex and miraculous.
- Electronics can go blindingly fast (electrons in wires much lighter, more mobile, and more densely packed than ions in axons).
- You can build your own, cheap!
- You can learn a lot about math by understanding circuits, and a lot about the scientific method by debugging them.

Section 1 - DC

- DC stands for “Direct Current”
  (though you often hear “DC Voltage.”)
- Time-invariant
- Constant currents
- Constant voltages
- Resistors
- Linear (not differential) equations

Physical Quantities & Units

physical quantity = numerical value × unit

↑ normally shown in *italics*

Physical Quantity	Unit
"Q" charge	C coulomb
"I" current	A ampere (amp)

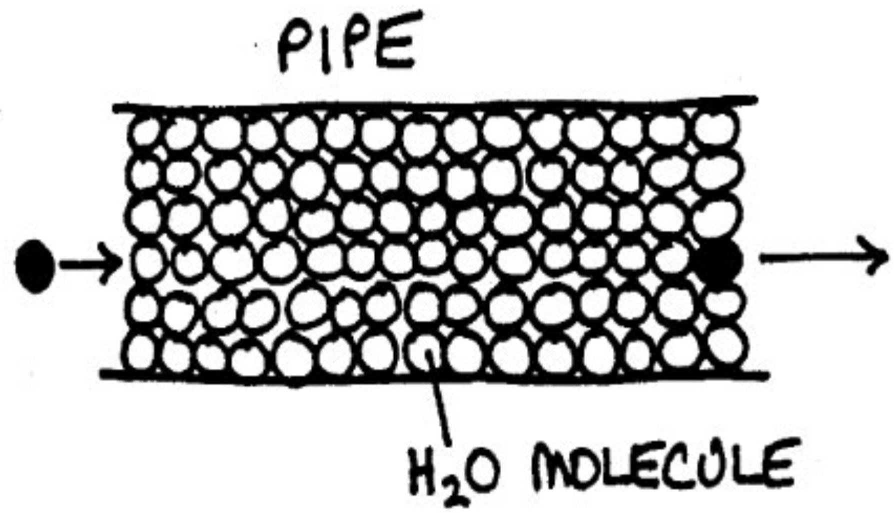
$$6.241\times10^{18}\,\text{electrons} = -1\text{C}$$

↑ thank you, Benjamin Franklin

$$1\text{A} = \frac{1\text{C}}{1\text{sec}},\quad I = \frac{Q}{t}$$

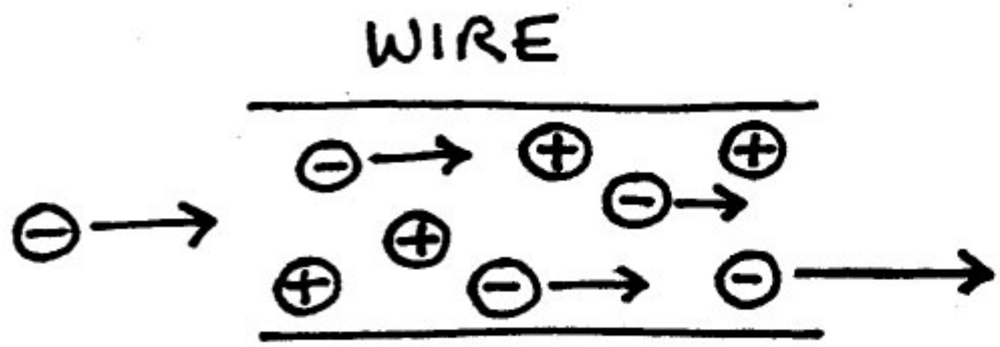
charge, like gallons
current, like gallons per second

Water Analogy



- Practically non-compressible; push one H_20 molecule in one end of steel pipe and one pops out the other end.
- Flow (current) limited by *viscosity* & *turbulence*.
- Pressure wave travels at ~ the speed of *sound*.
- Flow roughly proportional to *pressure*.

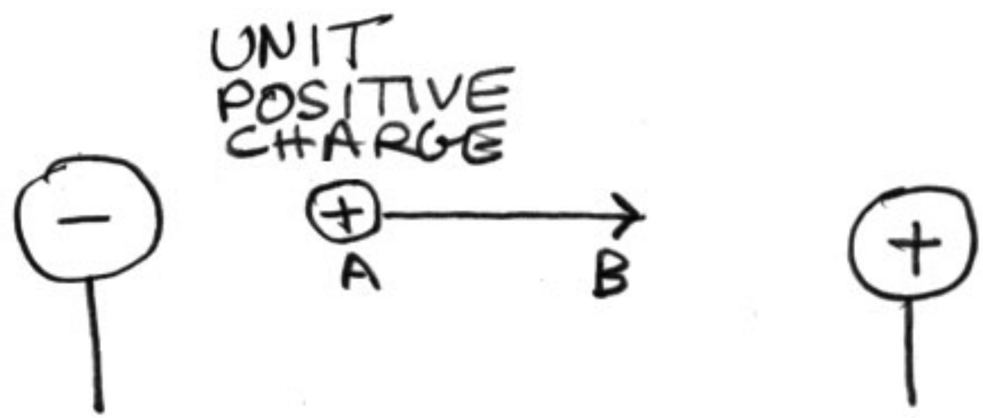
Electrons somewhat analogous



- Practically non-compressible - Nature really hates any buildup of *charge* in a small space.
- Flow (current) limited by *resistance* – bumping into atoms, not linear acceleration as in a vacuum, more like terminal velocity.
- Electric wave travels at ~ the speed of *light*.
- Flow roughly proportional to *voltage* – roughly equivalent to "electrical pressure".

What is Voltage, really?

- Sometimes called *electromotive force* (EMF) (not really a force) or *potential* (but not potential energy, though it does have to do with energy)
- The voltage difference between points A and B is the energy required to move a unit positive charge (along any path) from A to B.



- Moving from B to A yields the same voltage difference with an opposite sign.

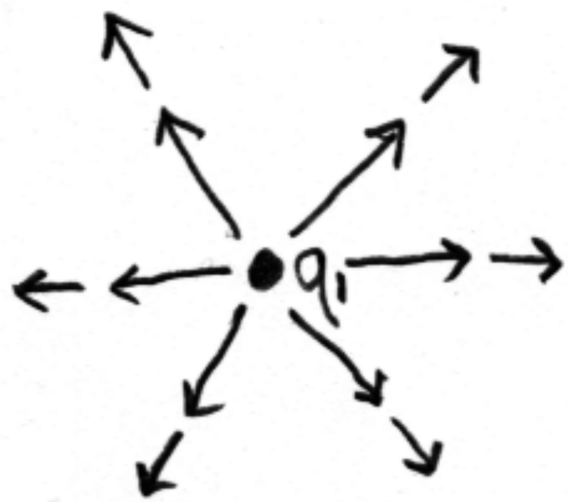
Electric Field: force on a unit test charge

- Force between two charges, q_1 and q_2

$$\vec{F} = k\frac{q_1 q_2}{r^2}\hat{r}$$

"^" means unit vector

- Electric field from a single charge q_1



$$\vec{E} = \frac{\vec{F}}{q_2}$$

Force on a test charge q_2 placed anywhere (normalized to a unit test charge)

Voltage is the integral of Electric Field

- Voltage between points A and B

$$V(A,B) = -\int_A^B \vec{E} \cdot \vec{ds}$$

Energy (force × distance) per unit test charge required to move from point A to B along unit steps $\overrightarrow{ds}$ in path through field $\vec{E}$.

- Electric field is (negative) gradient of Voltage.

$$\vec{E} = -\nabla V$$

Electric field $\vec{E}$ is vector.
Voltage is scalar.
(Note potential confusion between electric field $\vec{E}$ and energy E, a scalar)

- Voltage is energy per unit charge.
- In circuits, think about voltage as the pressure *difference* between two points, though voltage is technically not pressure.
- A single point can be said to have a voltage only relative to some reference point, often called the "circuit ground".
- Power is the brightness of the light bulb; energy is how much gas is in the tank of the generator.
- Power is energy per unit time.
- Power is voltage × current (think force × distance, though not exactly analogous dimensionally).

Physical Quantity	Unit
"F" force	N newton
"E" energy or "W" work	J joule
"V" voltage	V volt
"P" power	W watt

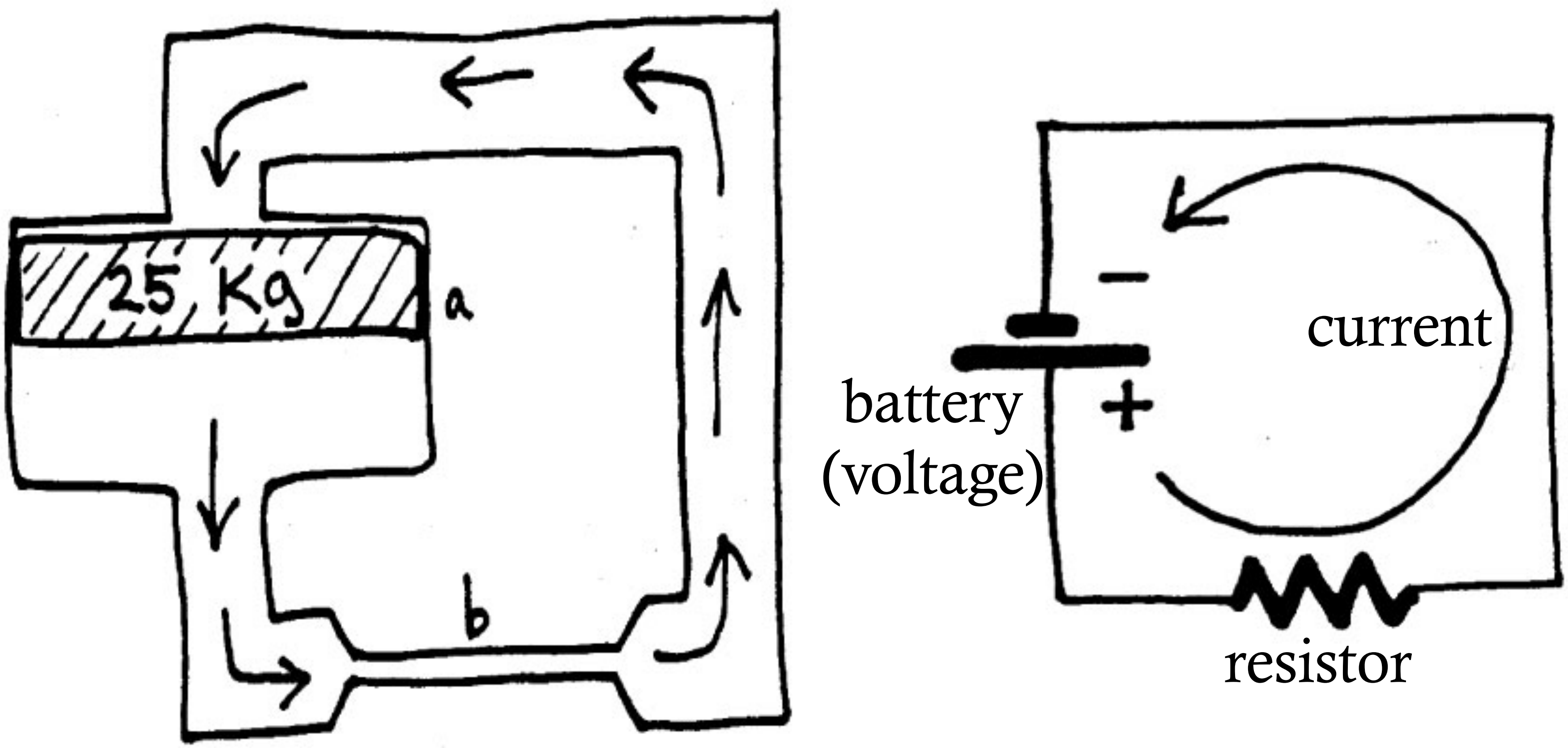
$$1\text{J (joule)} = 1\text{N (newton)} \times 1\text{M (meter)}$$

$$1\text{V (volt)} = 1\text{J (joule)} \ / \ 1\text{C (coulomb)}$$

$$1\text{W (watt)} = 1\text{V (volt)} \times 1\text{A (amp)} = \frac{1\text{J}}{1\text{C}} \times \frac{1\text{C}}{1\text{ sec}} = \frac{1\text{J}}{1\text{ sec}}$$

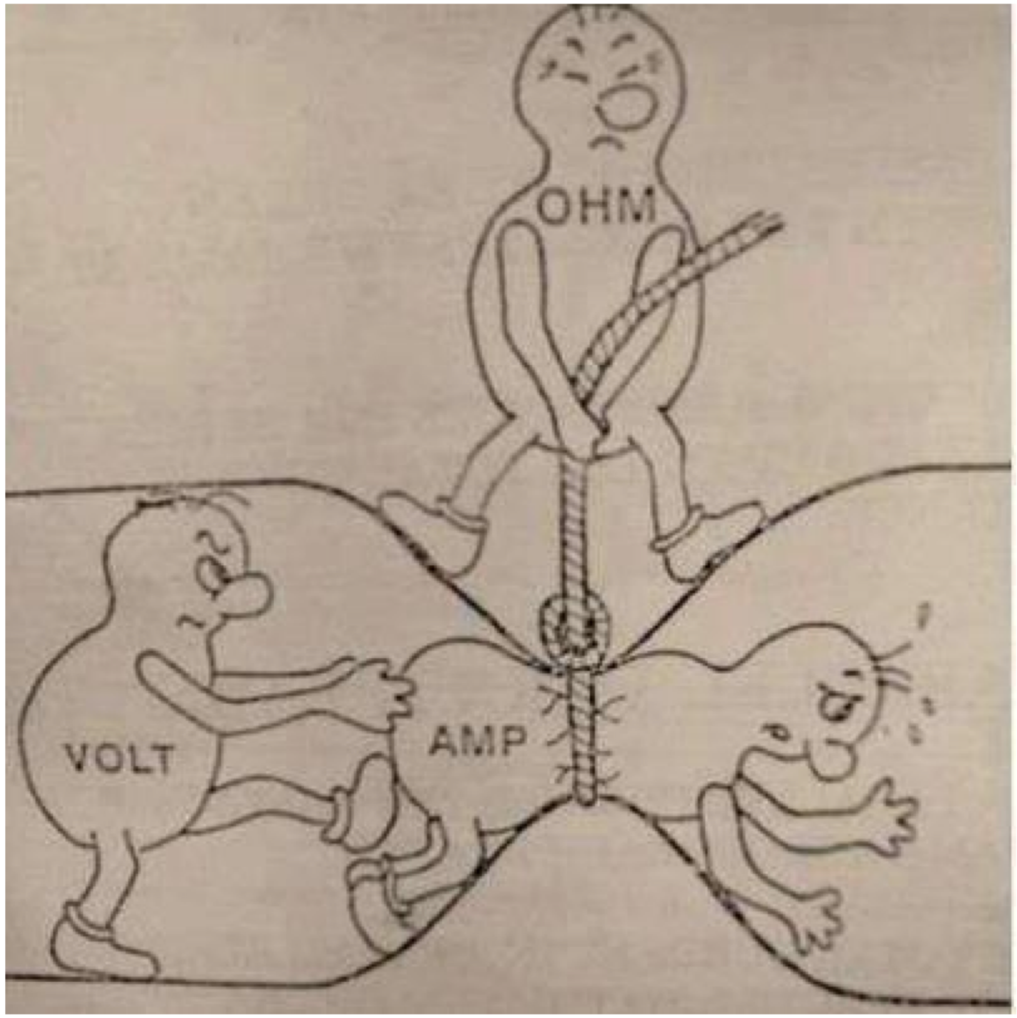
- Note distinction between V and V, as well as between W and W, confusing when hand-written. Also energy E and electric field $\vec{E}$.

Ohm's Law



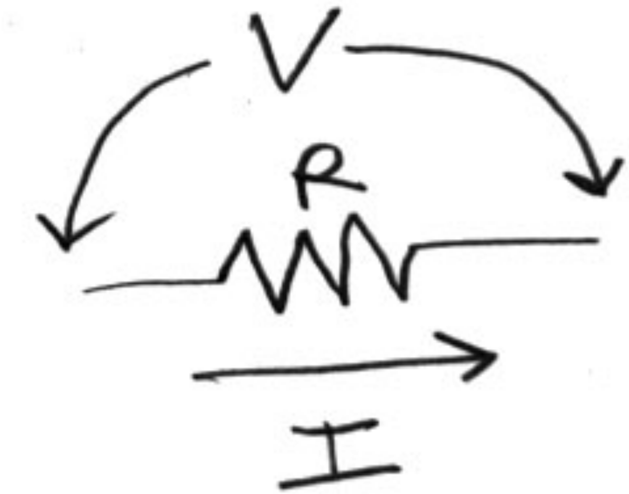
- Any good plumber understands it intuitively.
- Pressure source *a* "pushes" water through skinny pipe *b*.
- Note completed circle or "circuit", with fat pipe (wire).
- Charge does not build up anywhere.

Causality?



Pressure "causing" flow is a human construct…
Current also "causes" pressure drop across resistor.

Ohm's Law



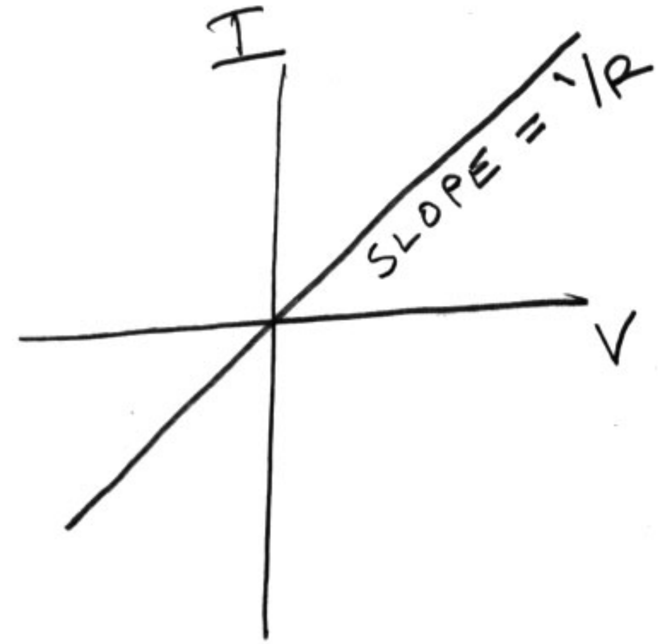
voltage *across* resistor
current *through* resistor

$$I = \frac{V}{R}$$ ⟵ more intuitive, given a voltage and a resistance, you get a current.

$$V = IR$$ ⟵ also true; "forcing" a certain current through the resistor "generates" a voltage drop.

Resistance

- Ohm's law is only an approximation, and only for components called *resistors,* but for them, linearity can be a *very* good approximation.



Physical Quantity		Unit	
"R"	resistance	Ω	ohm
"G"	conductance	Ω^{-1}	mho

$$1\Omega \quad (\text{ohm}) = 1\text{V} / 1\text{A}$$

$$1\Omega^{-1} \ (\text{mho}) = 1\text{A} / 1\text{V}$$

$$V = IR$$

$$I = VG$$

Note the symmetry between voltage and current

Resistor Color Code

1KΩ 10%

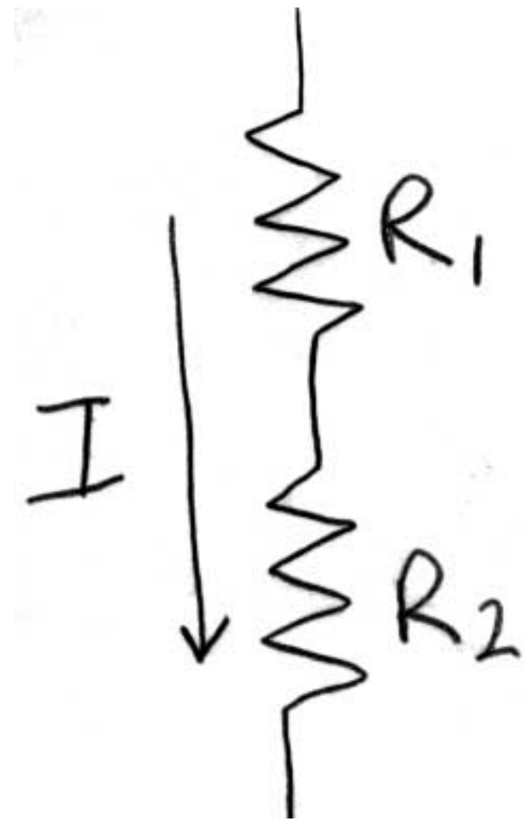
Typical range:
10 Ω – 10 MΩ

http://www.ealnet.com/m-eal/resistor/resistor.htm

Wattage of resistor (1/4 watt, 1/2 watt) specifies guaranteed maximum continuous power before failure.

Series Resistance R_S

- Same *current* through both resistors.
- Voltage across each resistor is proportional to its *resistance*.



$$V_1 = IR_1$$

$$V_2 = IR_2$$

- Total series voltage V_S is

$$V_S = V_1 + V_2$$

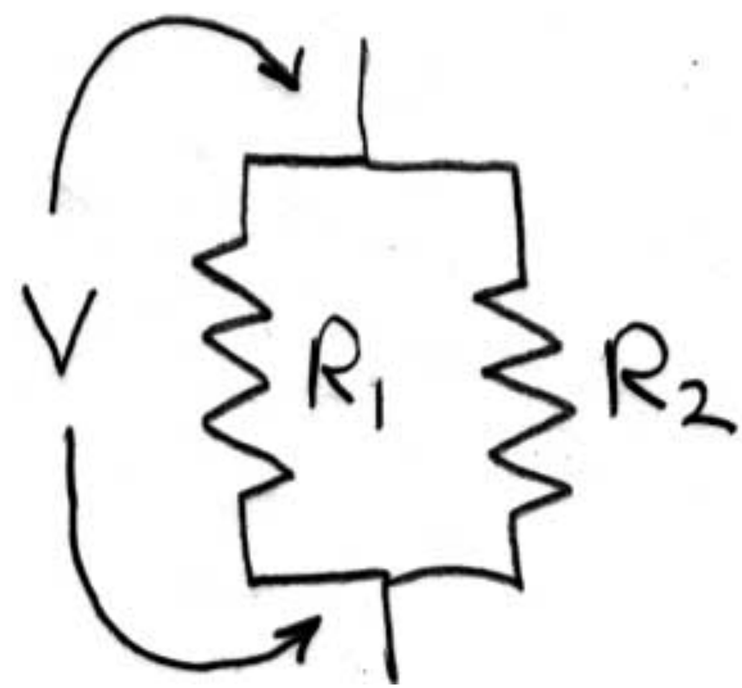
$$R_S = R_1 + R_2$$

Parallel Resistance R_P

- Same *voltage* across both resistors.
- Current through each resistor is proportional to its *conductance* (G).

$$I_1 = VG_1$$

$$I_2 = VG_2$$



- Total series current I_S is

$$I_P = I_1 + I_2$$

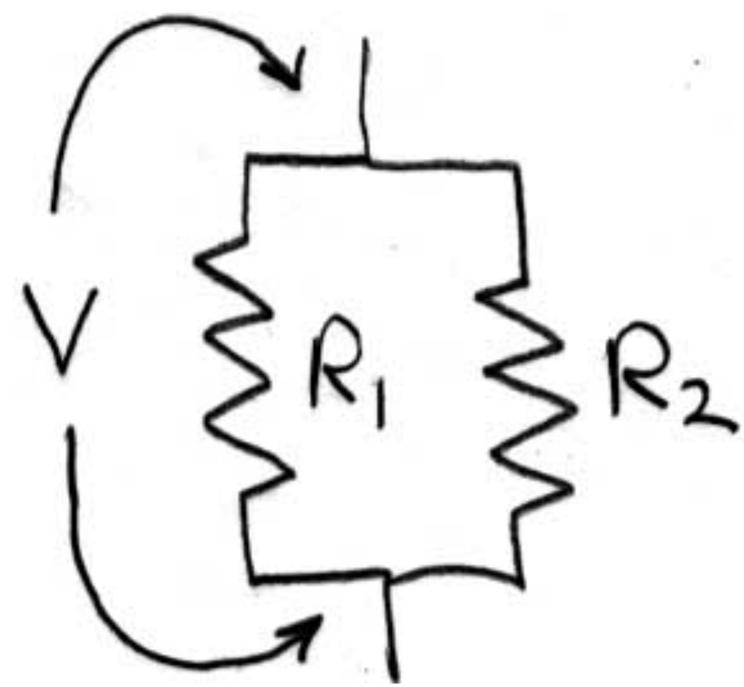
$$G_P = G_1 + G_2$$

Parallel Resistance R_P

- Reciprocal of the sum of the reciprocals.

$$G_P = G_1 + G_2$$

$$R_P = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}}$$



…often rewritten as the product over the sums.

$$R_P = \frac{R_1 R_2}{R_1 + R_2}$$

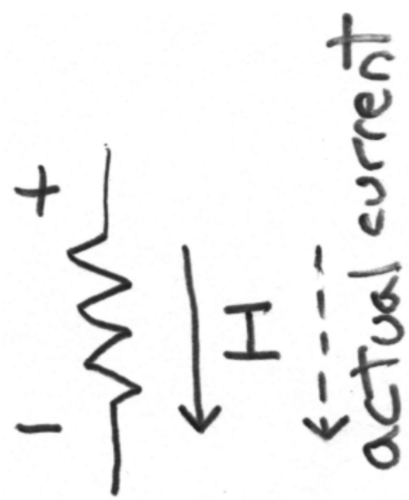
- Voltage, current, and power can be positive or negative, and the sign depends on how the voltage and current variables are defined in a given circuit.
- Power is *positive* when electrical energy is deposited in a component (resistor, light bulb, see **a**), but *negative* when energy is produced by it (battery discharging, see **b**).

$$P = V \times I$$

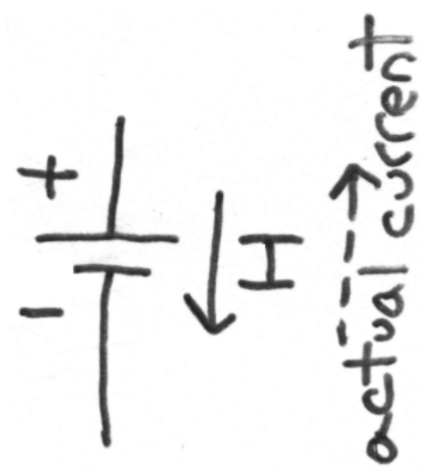
$$P = I^2 R$$

$$P = \frac{V^2}{R}$$

I is defined by convention as flowing from + to − voltage



a

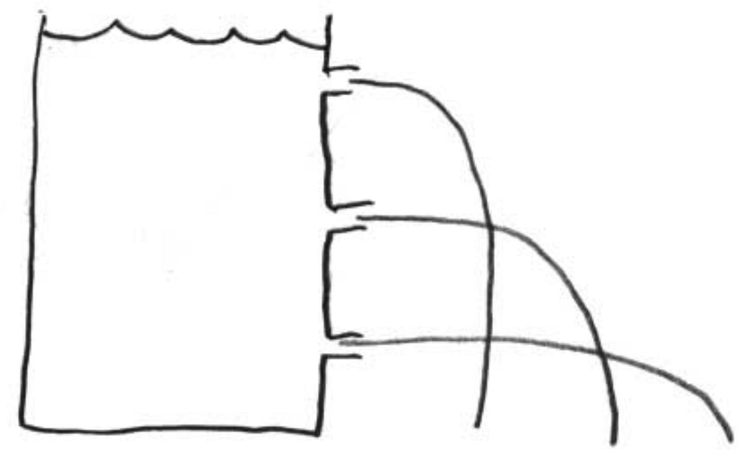


b

- Resistance is almost always positive, and is often considered constant, though not always (e.g. sensors such as photoresistors and thermistors).
- Voltage, current, and power can be positive or negative, constant or vary as functions of time: $V(t)$, $I(t)$, $P(t)$.
- We will first study DC ("direct current") circuits, where current, voltage, and power are assumed to be constant.
- DC circuits can generally be represented by fully-constrained simultaneous linear equations.

Bad Water Analogies

- Typical bad analogy ➔
- Electrons rarely jump from wires. They are confined to “steel pipes” (the wires) and must return to the power source to avoid an local charge build-up or deficit.

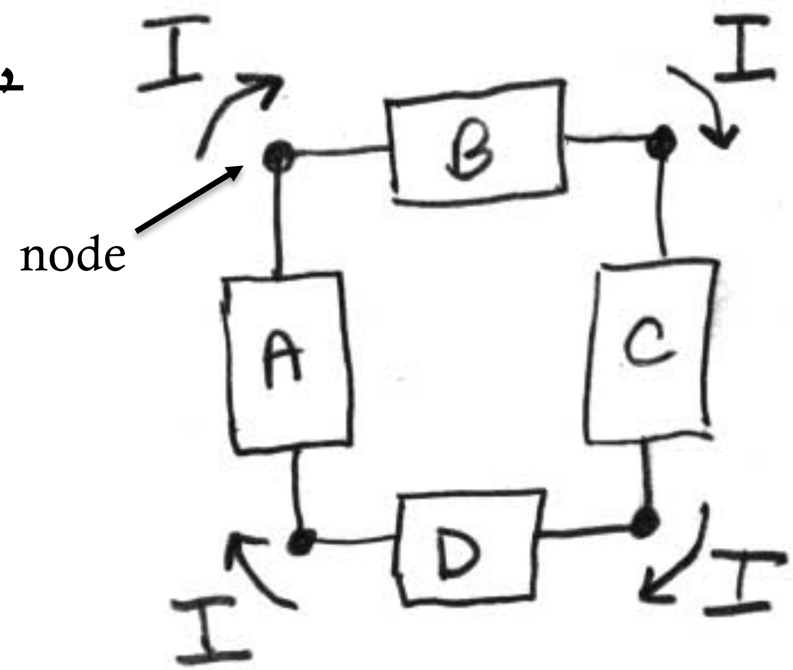


Water shoots further from the bottom hole of the tank because pressure is greater. Not analogous to electrons, which generally do not leave the wires.

Kirchoff's Current Law

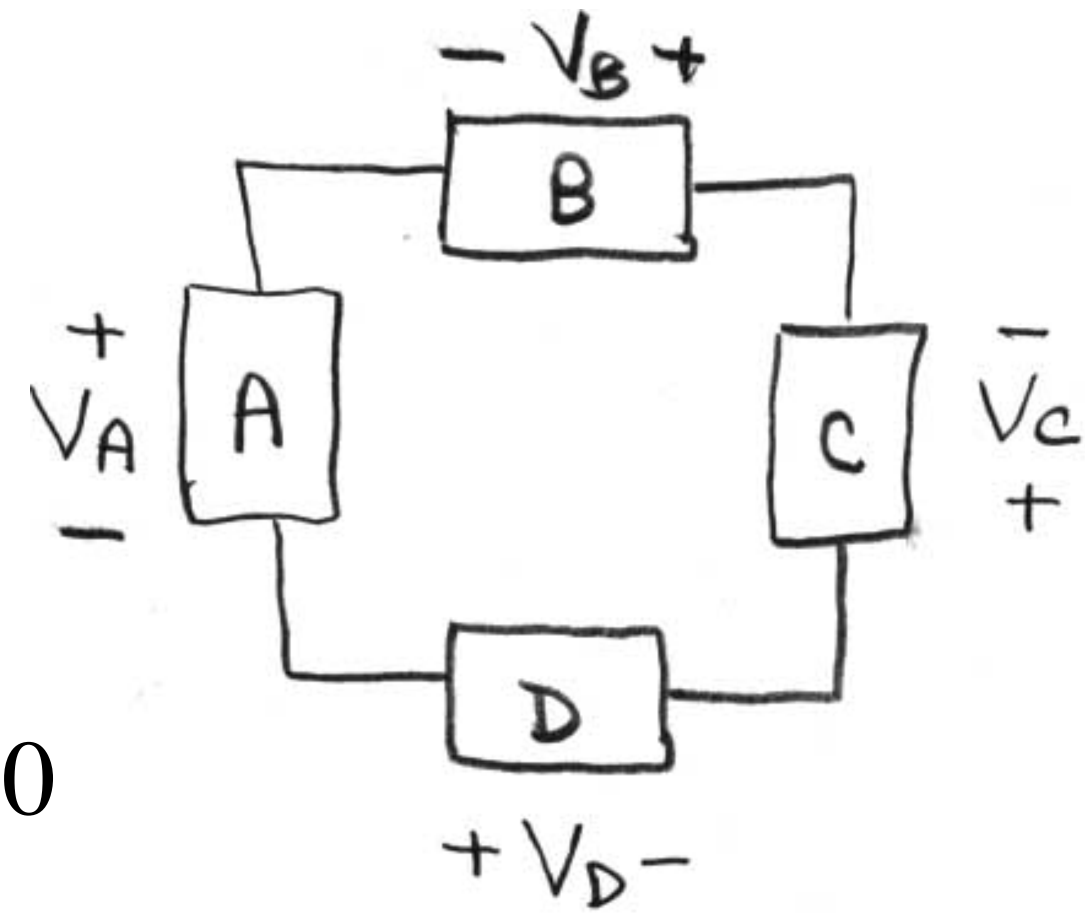
- Charge is virtually non-compressible.
- "Components" (A,B,C,D) connect at "nodes".
- Current around an *isolated* loop always completes the path, with I the same at every node, and local charge remaining near zero.
- <u>At *any* node in *any* circuit, total current *in* equals total current *out*.</u>

$$\sum_{node} I_{\text{in}} = \sum_{node} I_{out}$$



Kirchhoff's Voltage Law

- Voltages (like pressures) add. Around *any* loop (not just any isolated loop) the sum of the voltages must be zero.
- The voltage relative to circuit ground must end up where it started (the same at the same node).



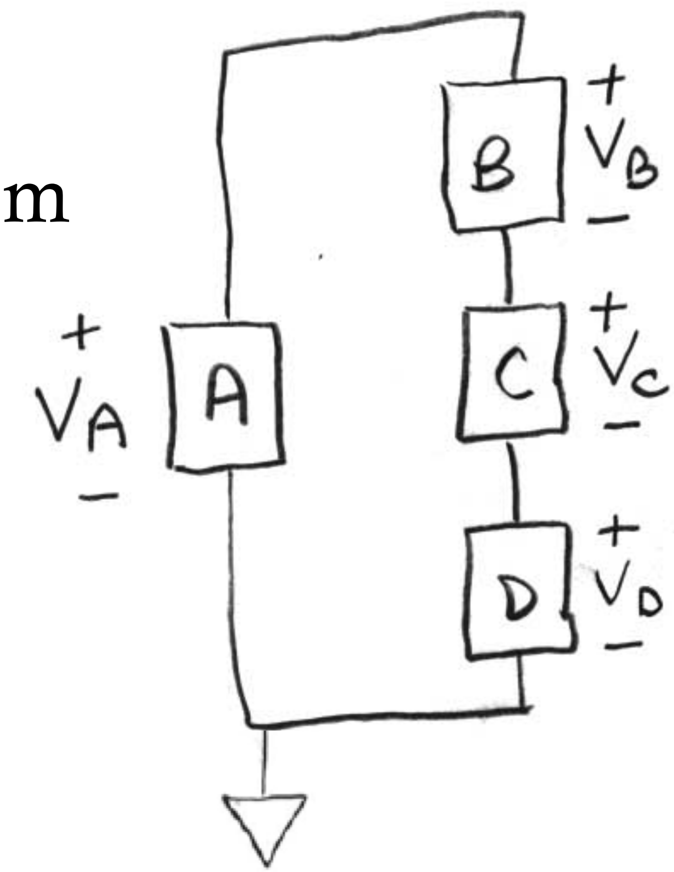
$$V_A + V_B + V_C + V_D = 0$$

Kirchhoff's Voltage Law (redrawn)

- Typical schematic layout:
  - high-to-low voltage: top-to-bottom
- In this configuration Kirchoff's Voltage Law reads:

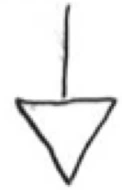
$$V_{\mathrm{A}} = V_{\mathrm{B}} + V_{\mathrm{C}} + V_{\mathrm{D}}$$

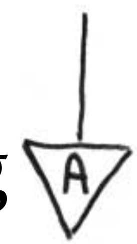
- Same voltage anywhere along any wire (V=IR and R=0), hence the concept of node.
- Same voltage between top wire and bottom wire (ground) .

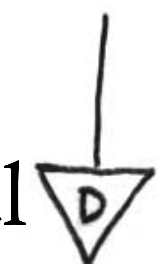


Which node is $V_{\mathrm{C}}+V_{\mathrm{D}}$ above ground? $V_{\mathrm{A}}-V_{\mathrm{B}}$?

Circuit Ground



- Defined as 0 volts, with other points in the circuit measured relative to it (voltage is always actually a difference).
- With a single-sided (not $\pm$) power supply, usually the negative (black) power lead. Caution! Black=hot in house wiring, the electrician's revenge.
- Scherz differentiates analog 

from digital 

to keep *digital* noise away from sensitive *analog* circuits.

Chassis Ground

- Metal box used for shielding from electromagnetic noise.
- Often the same as circuit ground.
- Beware of getting shocked if metal chassis is not also connected to "earth ground" (next slide). For this reason, most modern equipment has a plastic housing, especially if not using a 3-wire power cord with an earth ground.

Earth Ground

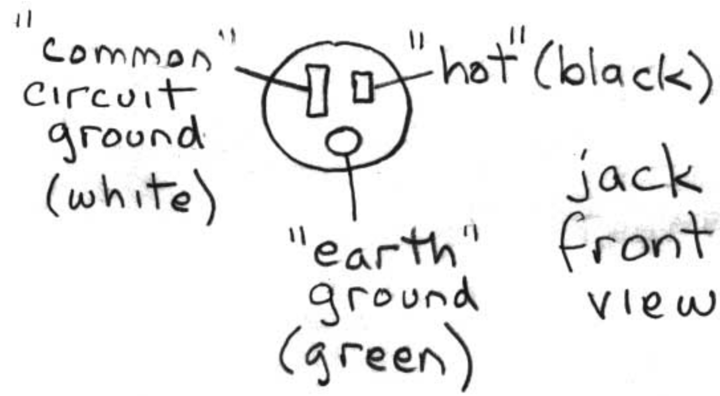
- Copper pipe struck into the ground.
- One of the few cases where the non-compressibility of electrons does not apply; You can pour large numbers of electrons into the earth without raising its voltage, as pouring water into the ocean does not raise the sea level.
- Earth ground is important to consider for safety, since when touching a circuit with one's finger, one's feet on the floor can complete a dangerous circuit that includes the heart.

Safety - Electrocution

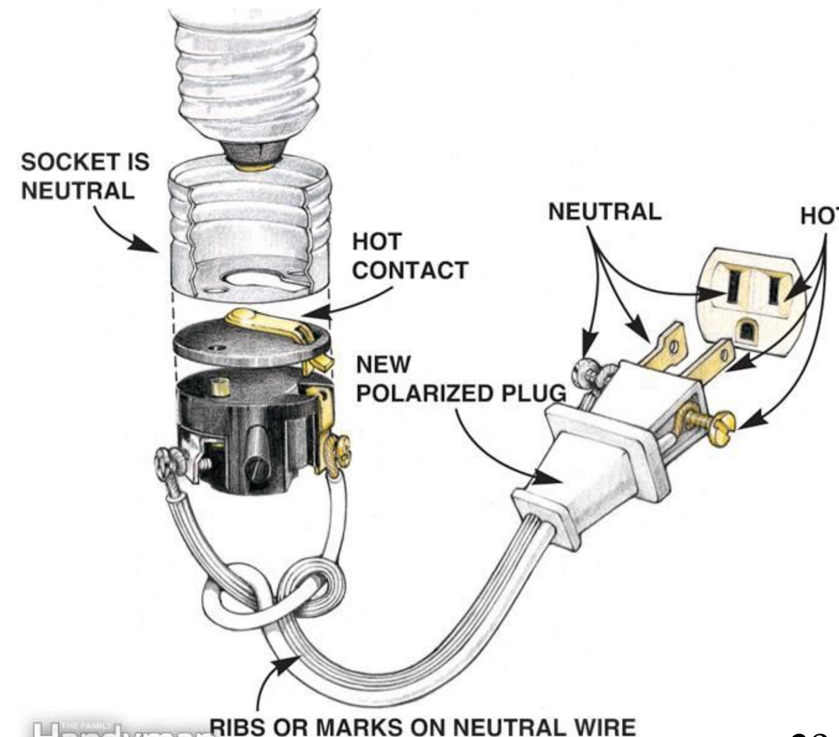
- 110 volts AC can kill (>500 deaths/year in US)
- Skin resistance ~1MΩ >> internal resistance of tissue; minimum at 60 Hz ("impedance" can vary with frequency, as we shall see).
- Water, especially with salt (sweat; ocean) reduces skin resistance (used in lie detectors).
- Usually by inducing arrhythmia. Keep current away from heart.
  - Electricians wear dry shoes with rubber souls and keep 1 hand in pocket.
  - Birds sitting on one power line don't get shocked.
- Can cause tetanus; you can't let go and neither can the person who grabs you to pull you away.

Safety – Wall Socket

- Current comes "out"* *hot* lead (small rectangular hole) and "returns" through *common* (or "neutral") lead (large rectangular hole).



- Size difference prevents 2-lead devices like lamps from being plugged in backwards, which would make the outer part of the lamp socket hot.
- *Earth ground* (round hole) connects to pipe in the ground where power enters the house.

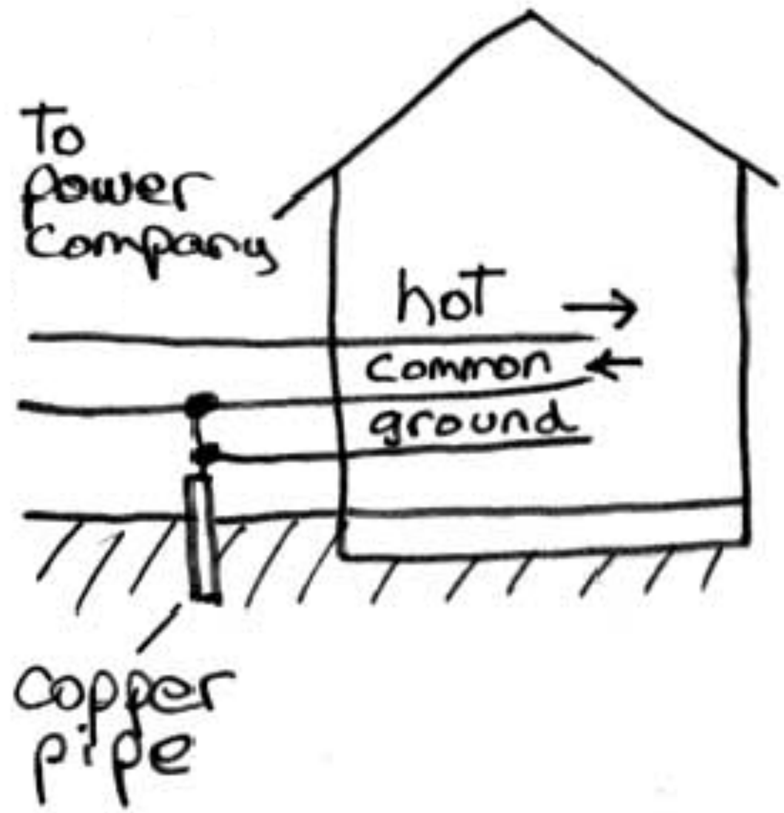


* alternating current (AC) actually goes both ways.

Safety – Wall Socket

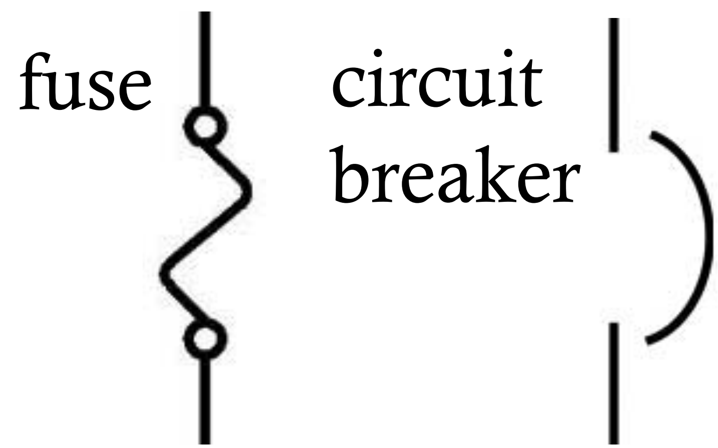
- Ground Fault Interrupter (GFI) in kitchen and bathroom disables power if current out *hot* lead does not match current returning in *common* lead (may be going through human to ground instead).

- To the electrician, black is *hot*, to electrical engineer it is *circuit ground*.



Safety – Fire

- Even low power can heat things up over time especially with an unlimited power source (wall socket); Energy is integral of power over time.
- Temperature equilibrates with dissipation of heat through conductivity, convection, and radiation.
- Heat is generated where there is resistance to the current in a circuit, $P = I^2 R$ (bad contact in wall socket or extension cord for space heater).
- *Fuses* (low melting metal with higher resistance) and *circuit-breakers* (thermal or magnetic) form weak link, typically limiting 120V circuits to 15A or 30A.



Safety – Static/Lightening

- Static due to friction and dry conditions generally safe to humans; although very high voltage (50,000 V/inch), current is very low.
- Static can destroy integrated circuits (ICs), especially with field-effect (high impedance) transistors. ICs come in conductive packages and personnel wear grounded wrist-straps.
- Lightening (and static) is plasma and does not obey Ohm's law. Generally safe inside a car.

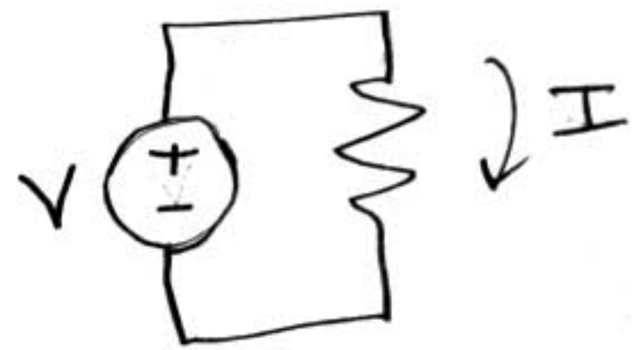
Safety – Lab

- Solder contains lead. Do not eat it. The smoke from soldering comes primarily from "flux", a resin core in the solder that cleans the surfaces being soldered.
- Turn off the soldering irons at the end of the lab. If you drop one, don't grab for it.
- Clipping wires can send fragments flying. Be careful of your own and other's eyes.
- Don't use large power supplies in the lab, as they can damage the MicroBLIP, computers, and can make components smoke.

Ideal Voltage and Current Sources

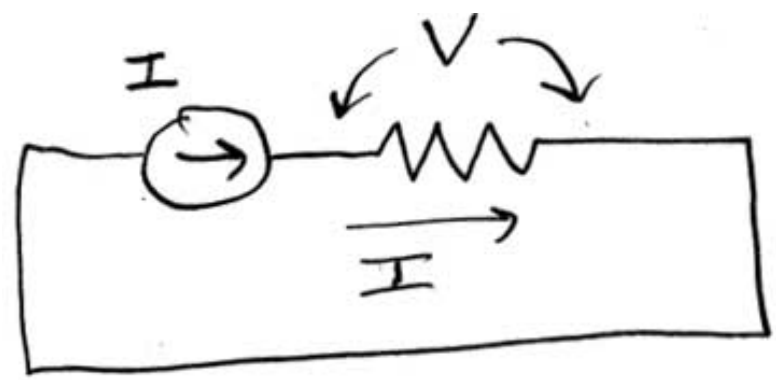
- Ideal voltage source holds *voltage* constant no matter what. Voltage placed across resistor "causes" current…

$$I = \frac{V}{R}$$



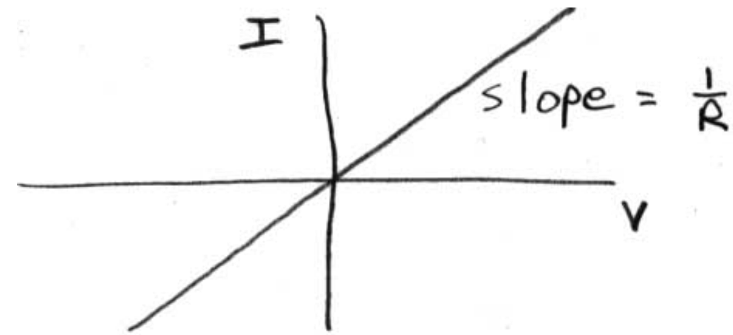
- Ideal current source holds *current* constant no matter what. Current forced through resistor "causes" voltage…

$$V = IR$$

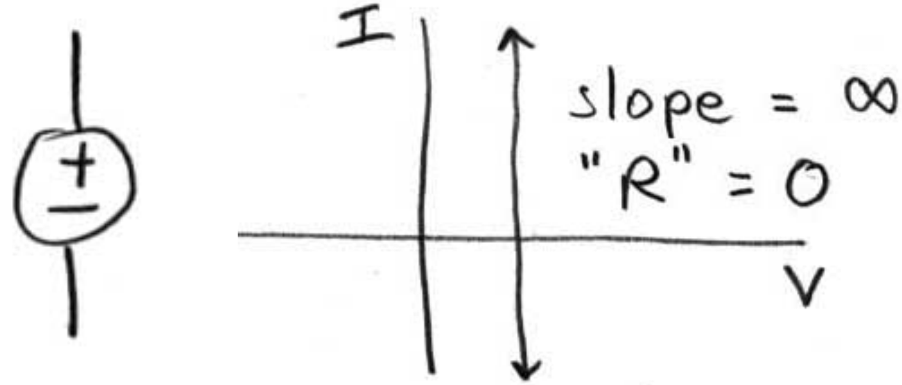


What is resistance ("output impedance") of ideal voltage and current sources?

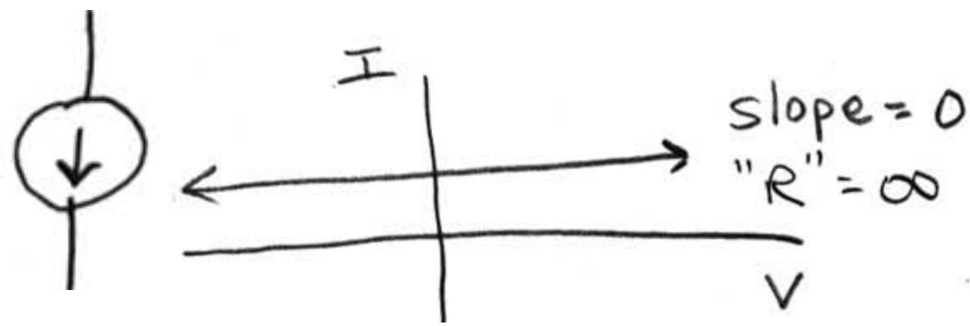
Recall for a resistor it is 1/slope on plot of I vs. V.



Ideal *voltage* source has *zero* output impedance.



Ideal *current* source has *infinite* output impedance.



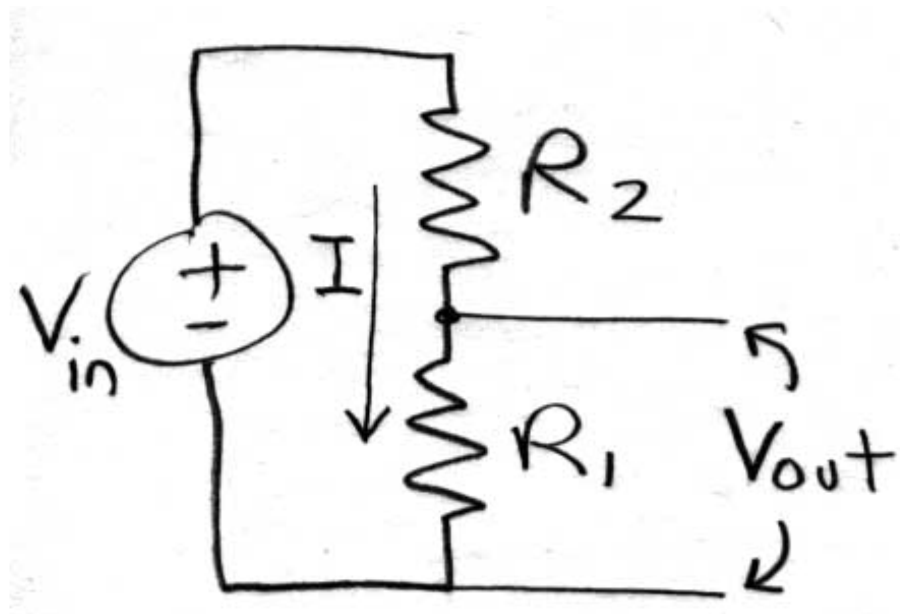
Voltage Divider

- View as "system" with voltage input and output.
- Same *current* through both resistors (assuming no current going to the output.
- Therefore, voltage across each resistor is proportional to its *resistance*.

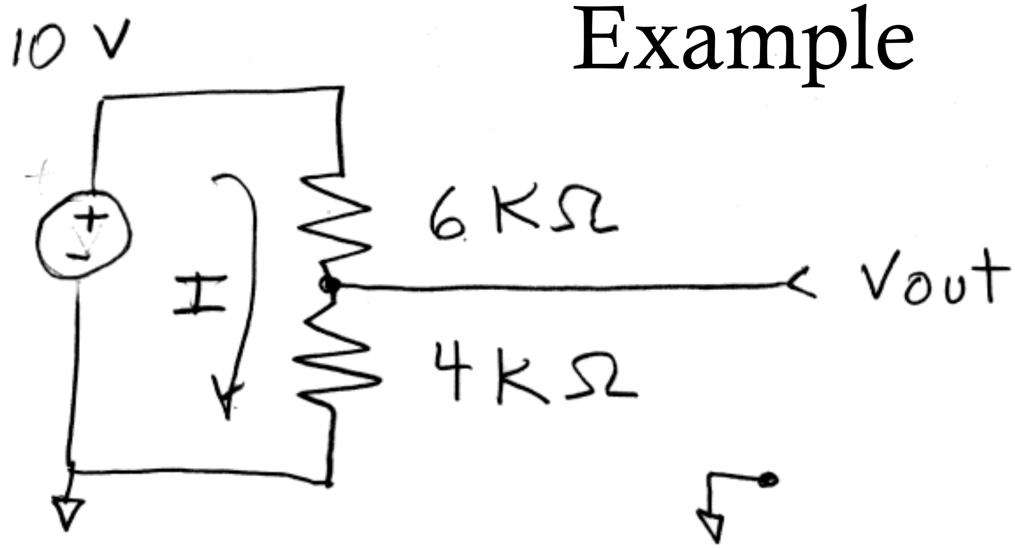
$$I = \frac{V_{\text{in}}}{R_1 + R_2}$$

resistance adds in *series*

$$V_{\text{out}} = IR_1 = \frac{R_1}{R_1 + R_2} V_{\text{in}}$$



Example



Voltage "Divider"

Same I through both resistors

total resistance 10 KΩ

$$I = \frac{10V}{10K\Omega} = 1\,ma$$

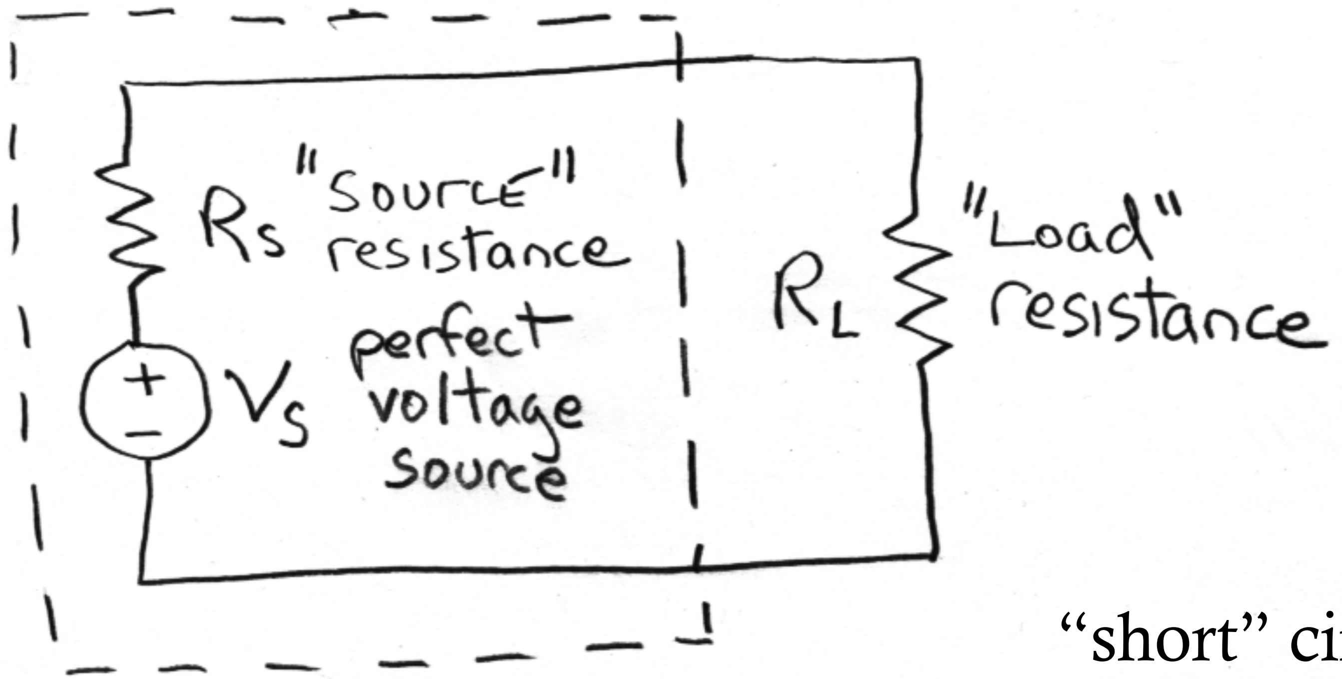
$$Vout = 1ma \cdot 4K\Omega = 4V$$

leaves 6V across top resistor

Voltage across each resistor proportional to its resistance.

Real Voltage Source

$R_{\text{Source}} << R_{\text{Load}}$



"short" circuit

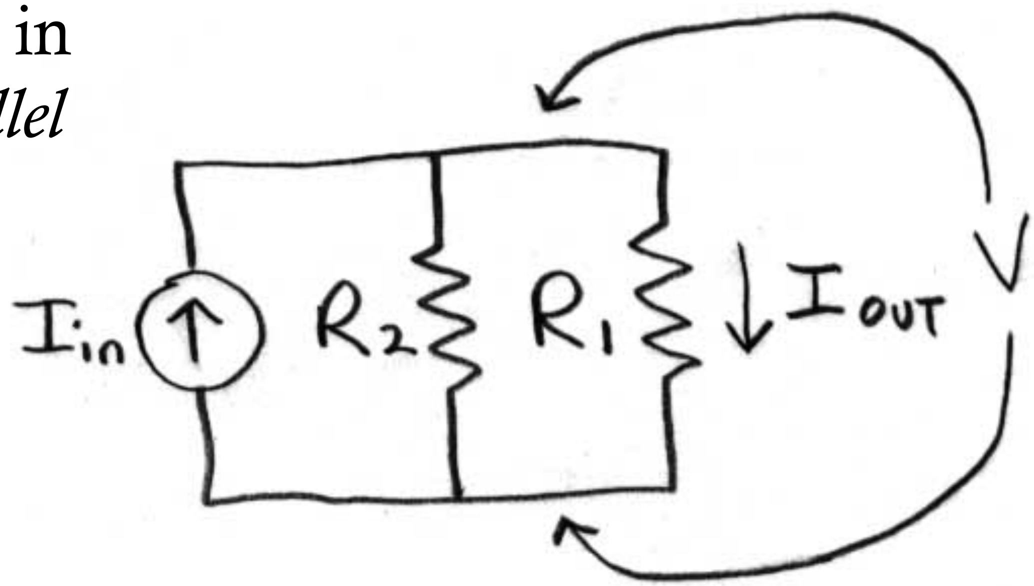
- Limits maximum current to $\frac{V_S}{R_S}$ when $R_L = 0\ \Omega$
- Car batteries have low R_s to deliver high currents.

Current Divider

- View as "system" with current input and output.
- Same *voltage* across both resistors.
- Current through each resistor is proportional to its *conductance*.

$$I_{in} = V\left(G_1 + G_2\right)$$

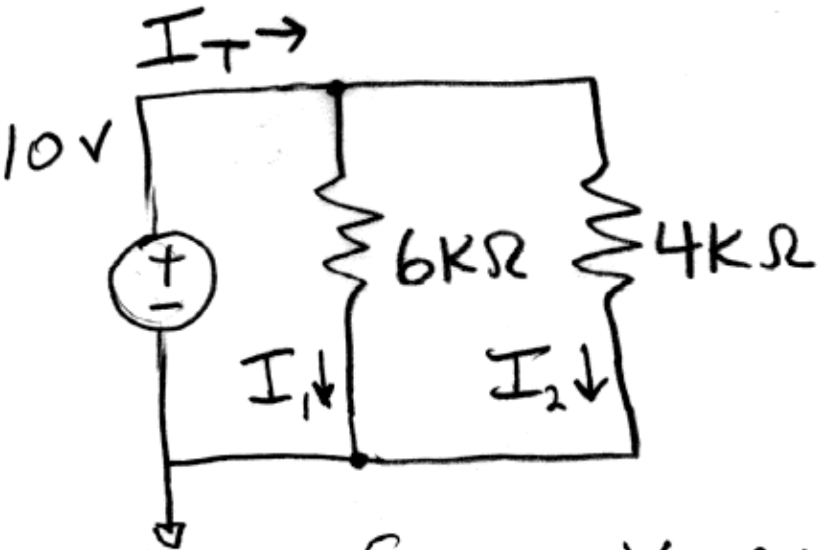
conudctance adds in *parallel*



$$I_{out} = VG_1 = \frac{R_2}{R_1 + R_2} I_{in}$$

Example

(should move this slide to after 37 next year)



Parallel Resistors

Same V across both resistors

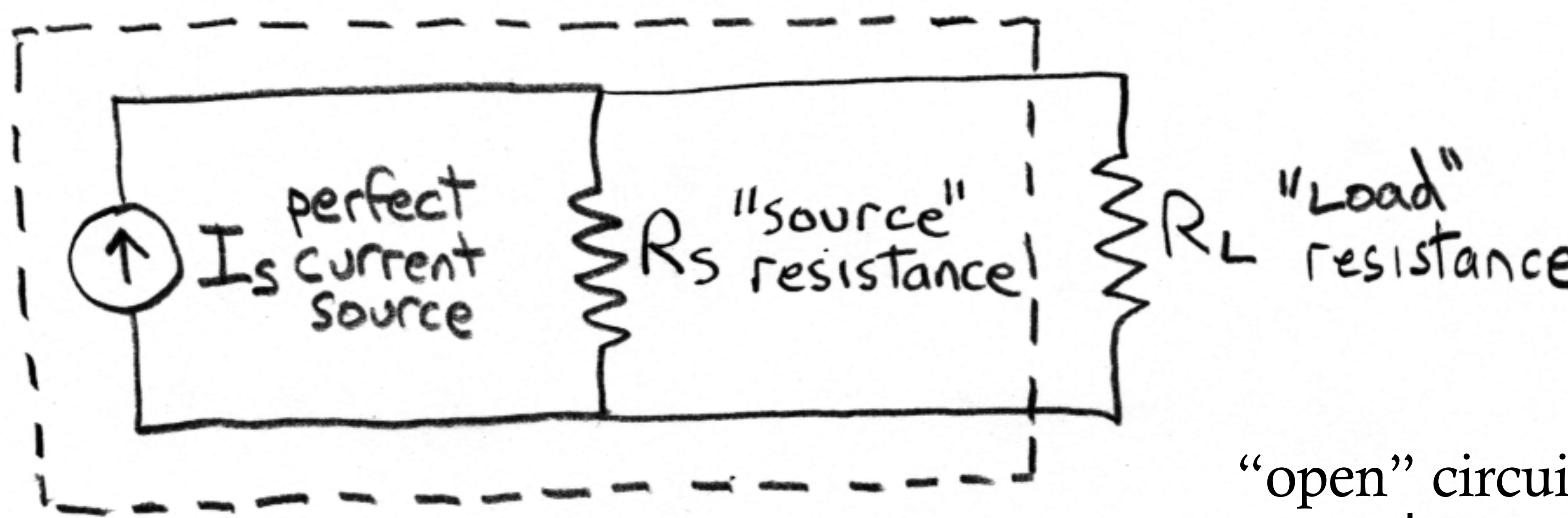
$I_1 = 10V / 6K\Omega = 1.66\ ma$

$I_2 = 10V / 4K\Omega = 2.5\ ma$

$I_T = 4.16$

Real Current Source

$$R_{\text{Source}} >> R_{\text{Load}}$$



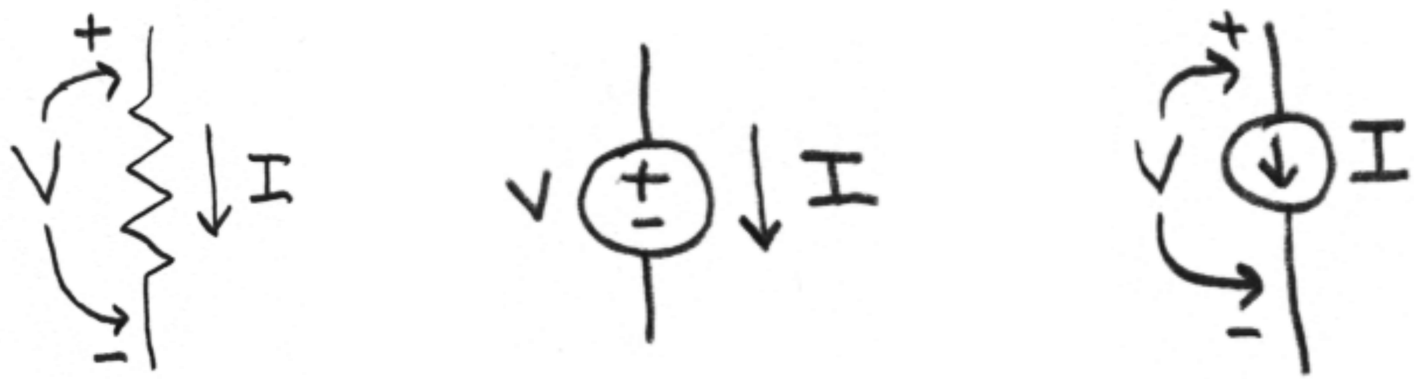
"open" circuit

- Limits maximum voltage to $I_S R_S$ when $R_L = \infty\ \Omega$
- Static electricity has high R_s to deliver high voltages (at low currents).
- Why do we need ideal current and voltage sources? (as offsets in the linear equations for DC circuits)

More about positive and negative power.

- The voltage across any component and the current through it are always defined as being in the same "direction," with the current running through the component from + to – voltage.

directions voltage and current variables defined by convention



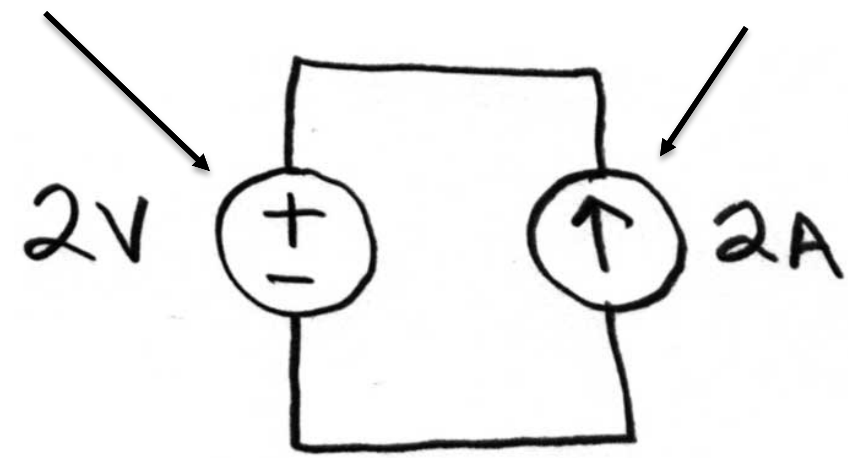
- In a resistor, this always leads to positive power (power delivered *to* the component, making it warm). They are passive devices obeying Ohm's law (recall the current vs. voltage graph).
- Voltage and current sources normally show negative power (power delivered *from* the component), but only when *they* are the cause of resulting current or voltage. When a battery is charged by an external source, it exhibits *positive* power.

Example: positive and negative power.

- Voltage and current sources can be forced to produce positive power, as in this circuit where the current source is "charging" a battery (voltage source), forcing current to flow into the battery "against" the voltage.

$$P = 2V \times 2A = +4\text{W}$$

$$P = (-2V) \times 2A = -4\text{W}$$

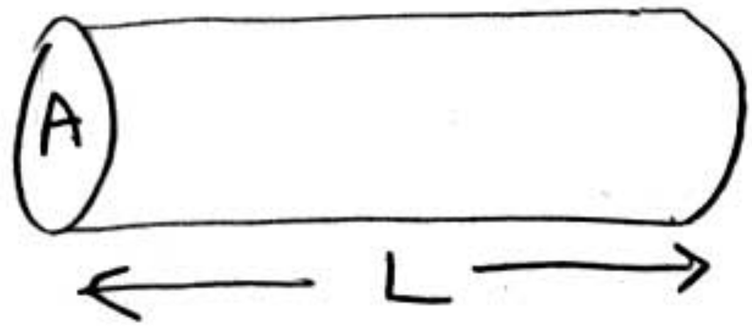


- The current source is delivering power to the voltage source.
- Total power for the circuit is zero (energy is conserved).

Resistivity of materials

- A resistor consists of a material with a shape.

assume a cylinder
length *L*, area *A*



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

- *Resistivity* ρ in ohm-meters

insulator (glass, quartz)	10^{16}-10^{10}	ΩM
semi-conductor (silicon)	10^{3}-10^{-5}	ΩM
conductors (metal)	10^{-6}-10^{-8}	ΩM
superconductor	0	ΩM

- *Conductivity* $\sigma \equiv \frac{1}{\rho}$

American Wire Gauge (AWG)

AWG number (solid)	Diameter (inches)	Resistance per 1000 ft (ohms)
20	0.0320	10
18	0.0403	6.4
16	0.0508	4.0
14	0.0640	2.5 *

* 14-gauge has twice diameter of 20-gauge and ¼ resistance

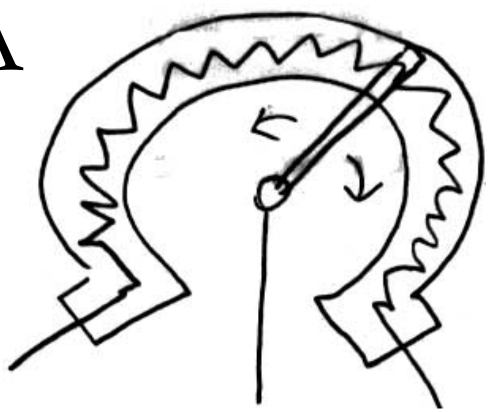
- Although we have been assuming wire has zero resistance, over long distances the resistance does become significant.
- The table above is for copper wire.
- Copper has a lower resistivity than silver or gold (!)
- Gold used for contacts because it doesn't corrode.

Potentiometer – “Pot”

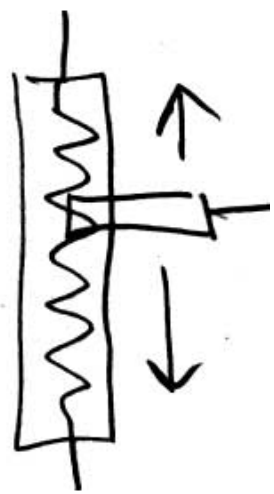
Three-terminal device: fixed resistor with a movable wiper.

Physically: (A) single-turn wiper on a circular resistor, (B) “linear” wiper on straight resistor, (C) multi turn wiper on spiral resistor (accurate).

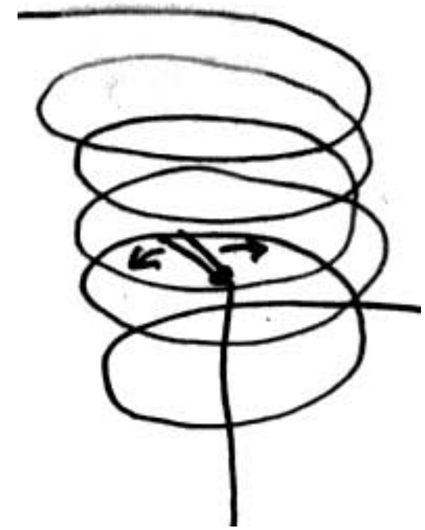
A



B



C



Linear vs. Logarithmic (audio) taper.

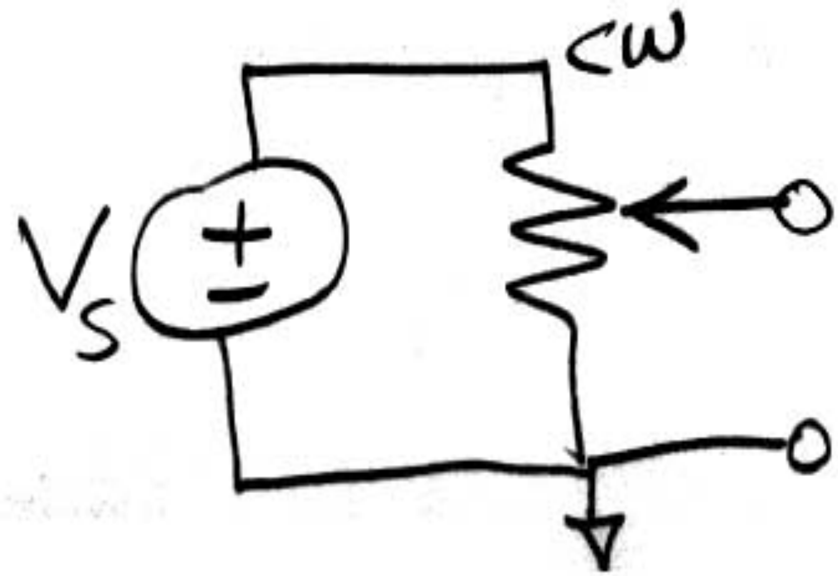
Potentiometer – "Pot"

- Ignore one lead and you have a simple two-lead variable resistor.

sometimes drawn as

- Typical use: producing a variable fraction of voltage source V_S; pot provides both resistors of a voltage divider with output between 0 and V_S.

"cw" wiper at this end when turned clockwise



Real Resistors and Pots

- Resistors generally 1Ω to 20MΩ
- 5% tolerance ¼ or ½ watt common

ceramic for high wattage

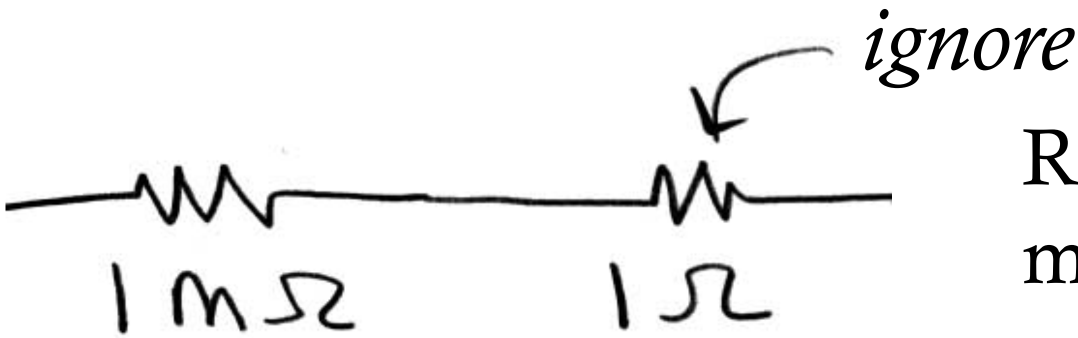
accurate linear pot

stereo log taper pot

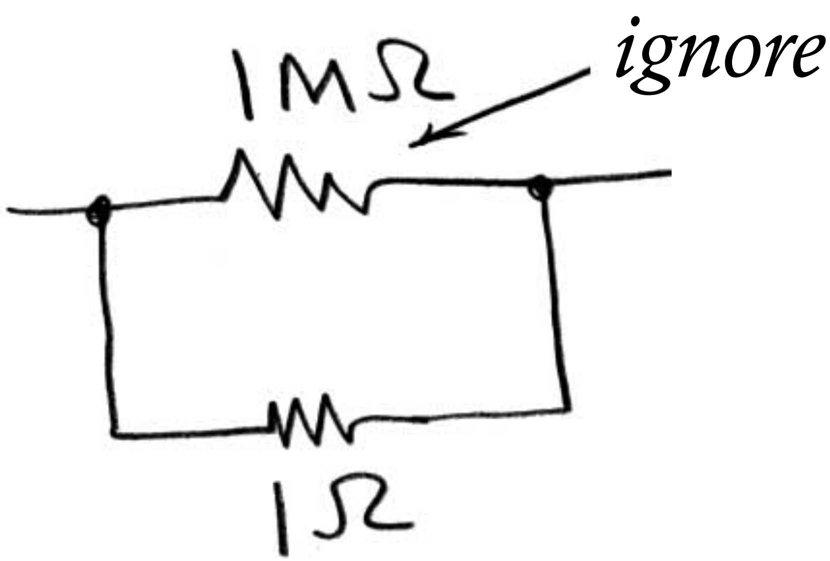
“trim” pot

What to Ignore…

- Estimate the total resistance:



Resistors in *series*:
much smaller resistor is essentially a "short circuit" or piece of wire. ~1MΩ

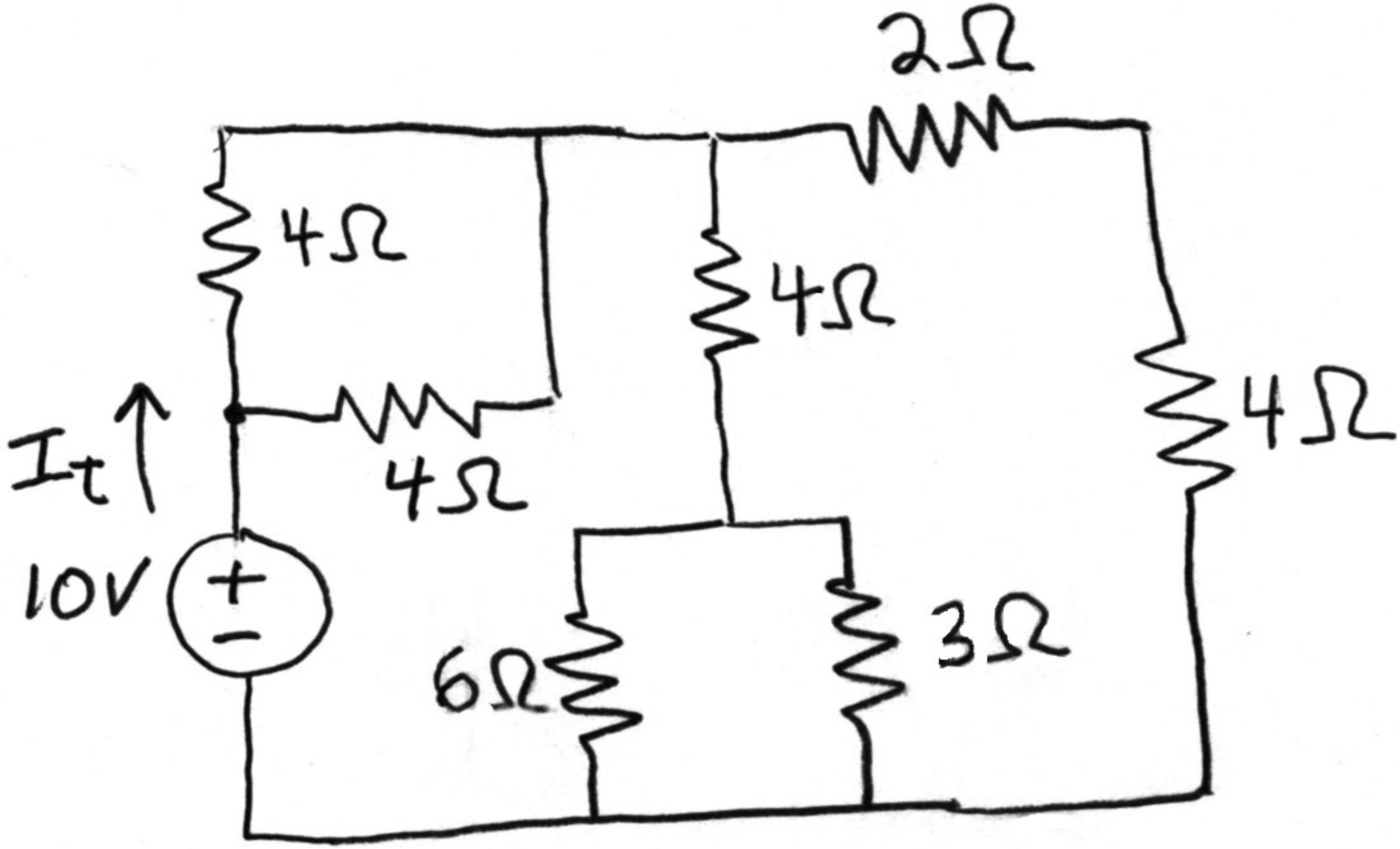


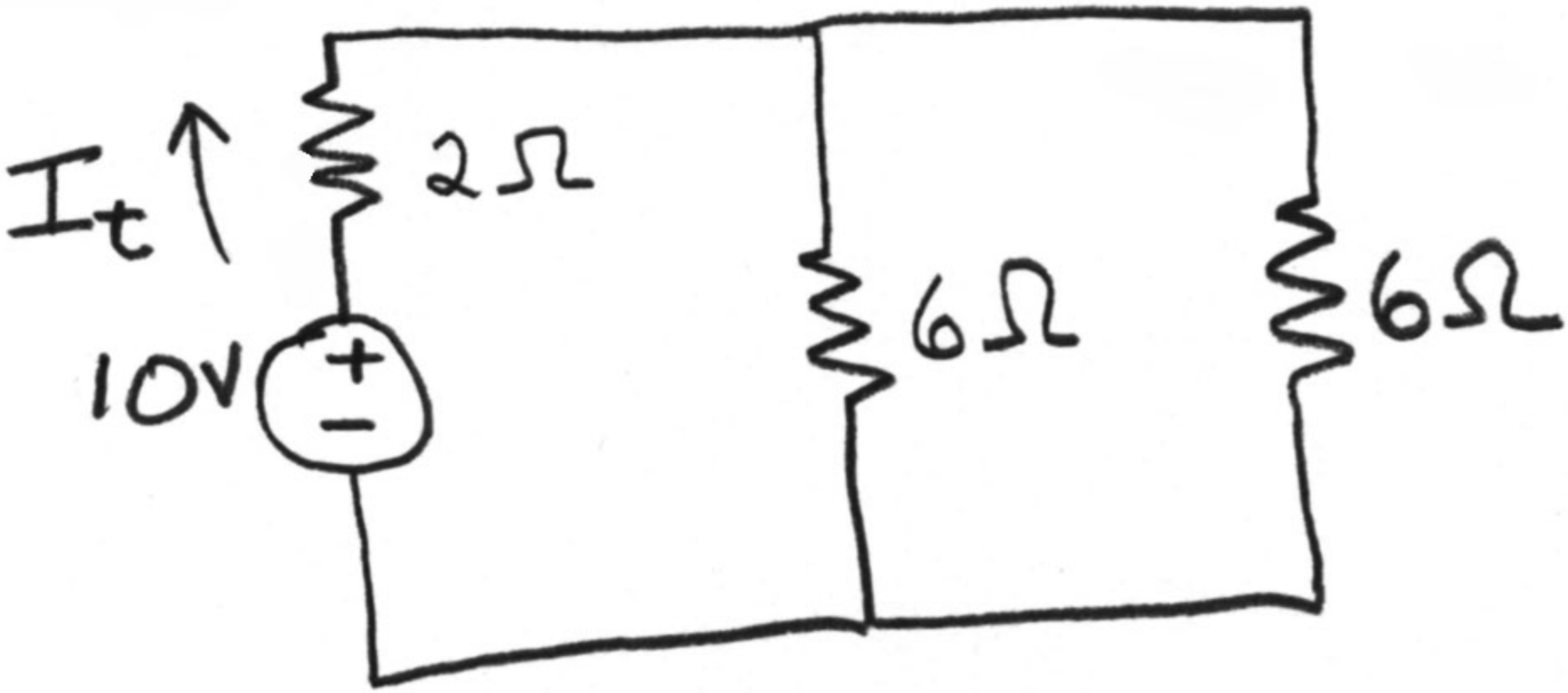
Resistors in *parallel*:
much larger resistor is essentially a "open circuit" or insulator. ~1Ω

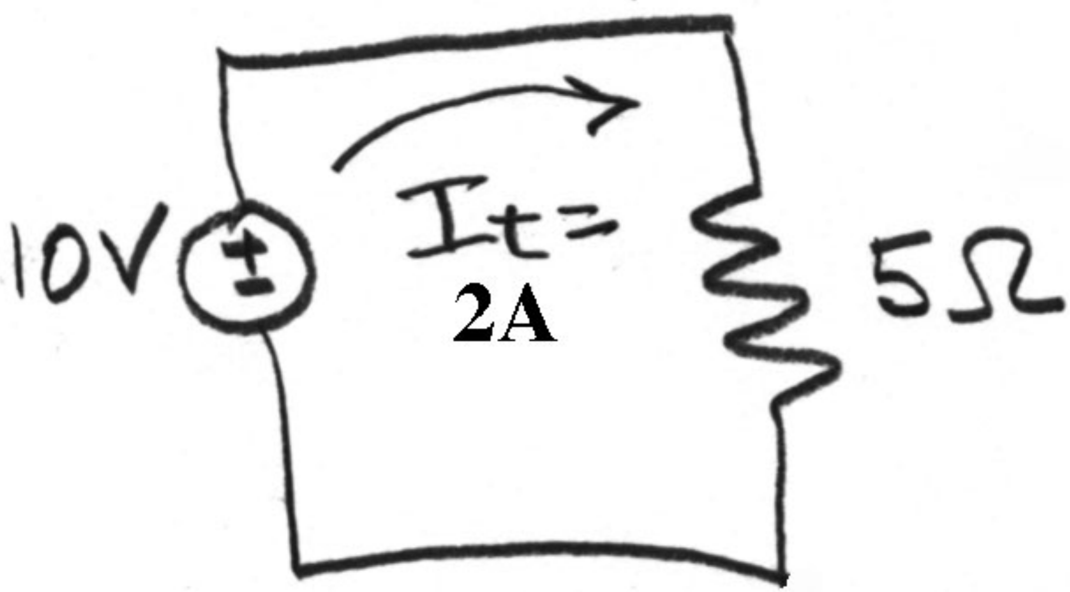
- Keep tolerance of resistors in mind (e.g. 5%).

Simplifying resistor networks

Example: compute currents through each resistor

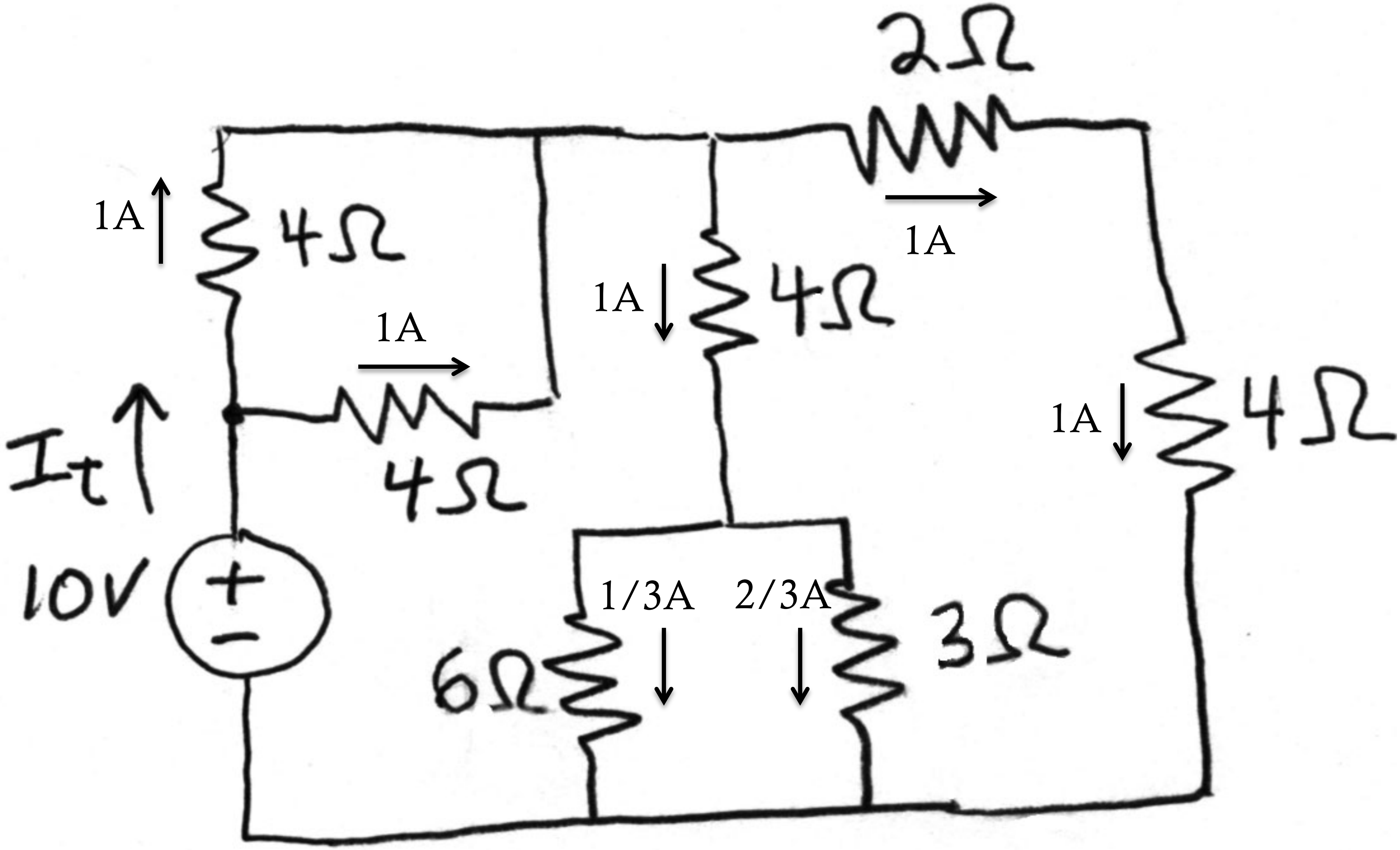






Equivalent simplified circuits

With total of 2A, compute individual currents



Thevenin Equivalent

ANY NETWORK OF

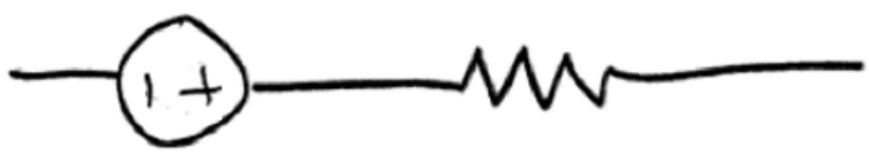
 's ,

 I 's

and

v  's

can be redrawn as



Norton Equivalent

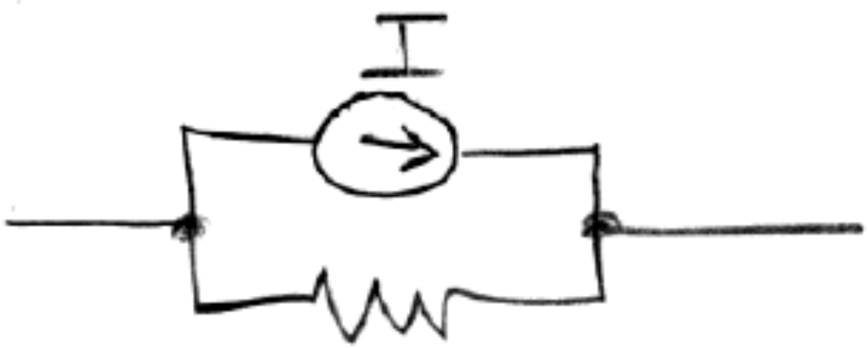
ANY NETWORK OF

 's,  I's

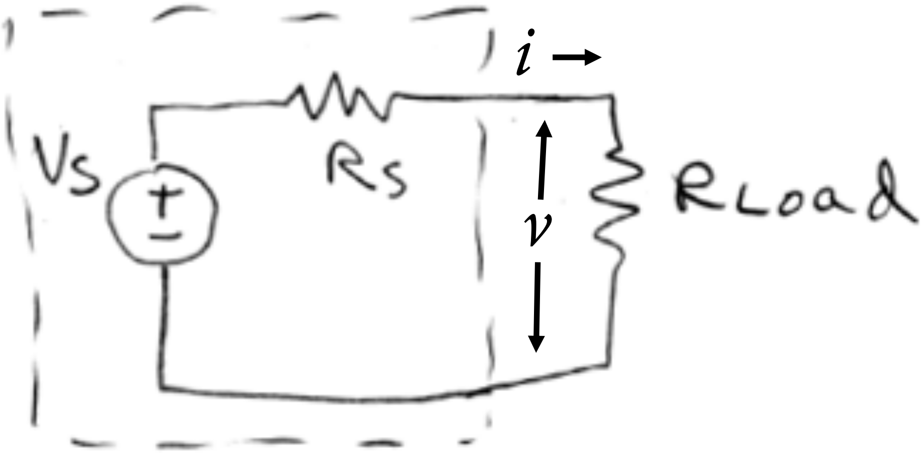
and

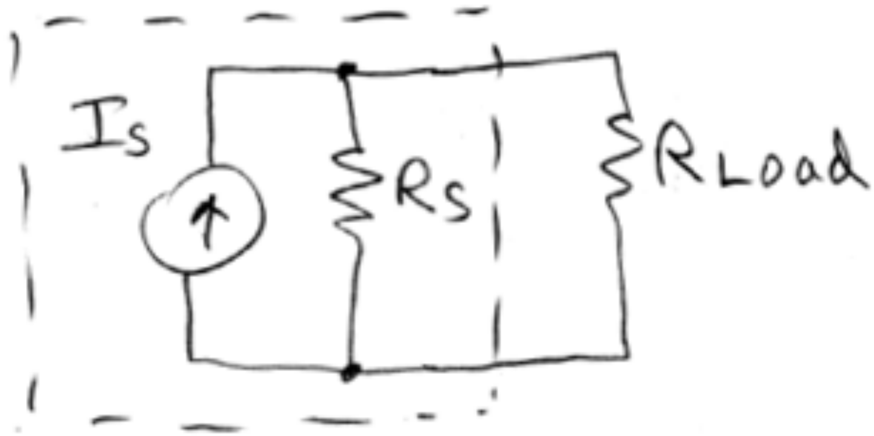
 V's

Can be redrawn as



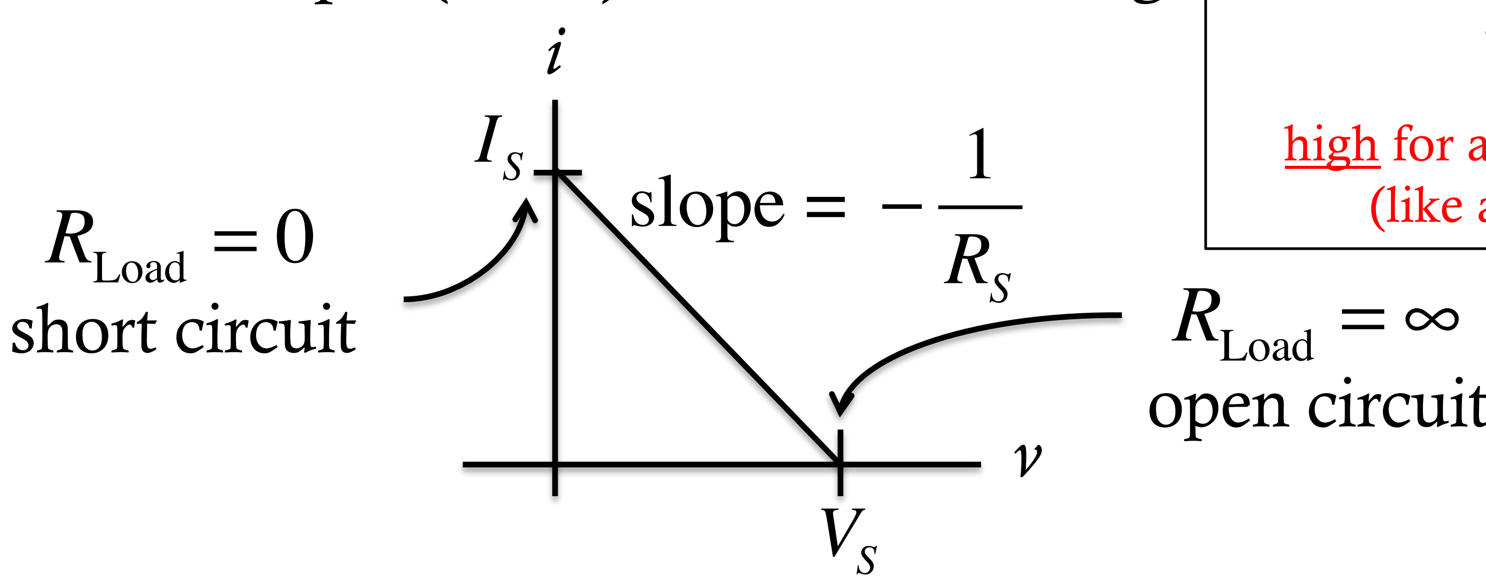
These 2 sources behave the same with respect to R_{Load} if $I_S = \dfrac{V_S}{R_S}$





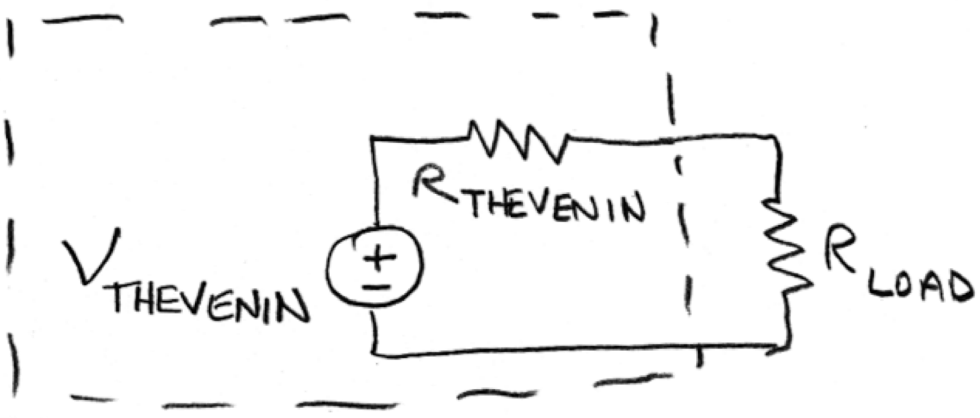
R_S (source resistance) also called "output impedance" should be:
low for a real *voltage* source (like a battery)
and
high for a real *current* source (like a leaky faucet).

Output (Load) Current vs. Voltage

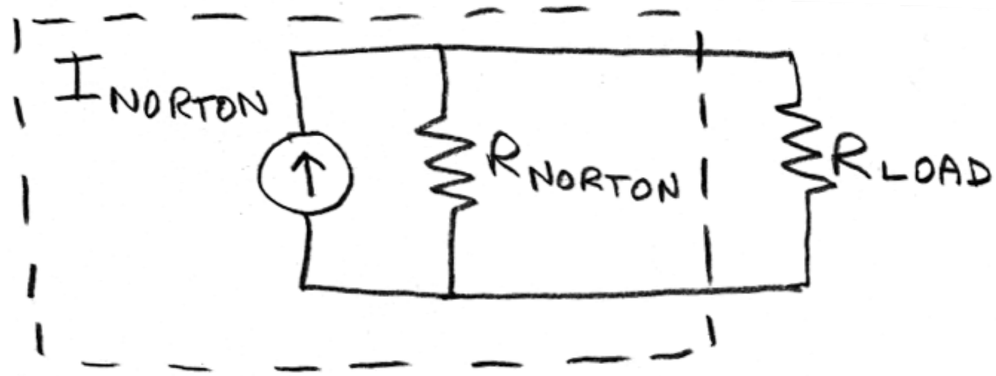


These two types of sources are called "Thevenin" and "Norton"

Two sources behave the same with respect to R_{Load} if $I_{\text{Norton}} = \dfrac{V_{\text{Thevenin}}}{R_{\text{Thevenin}}}$

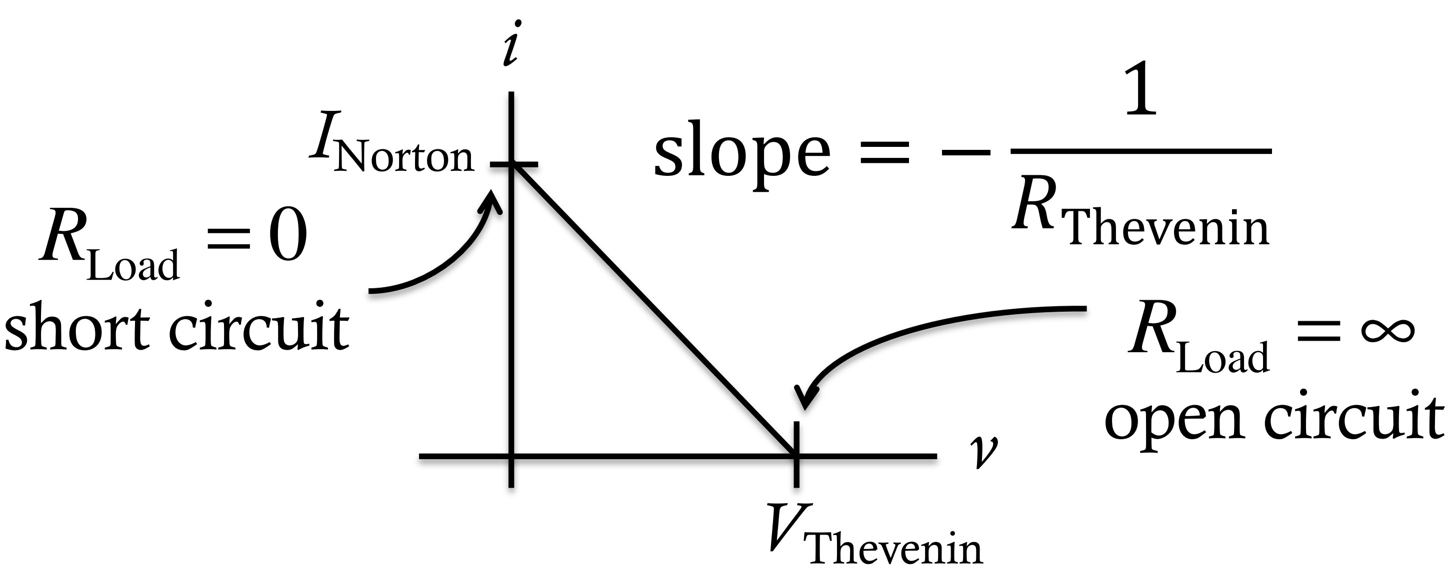


Thevenin equivalent



Norton equivalent

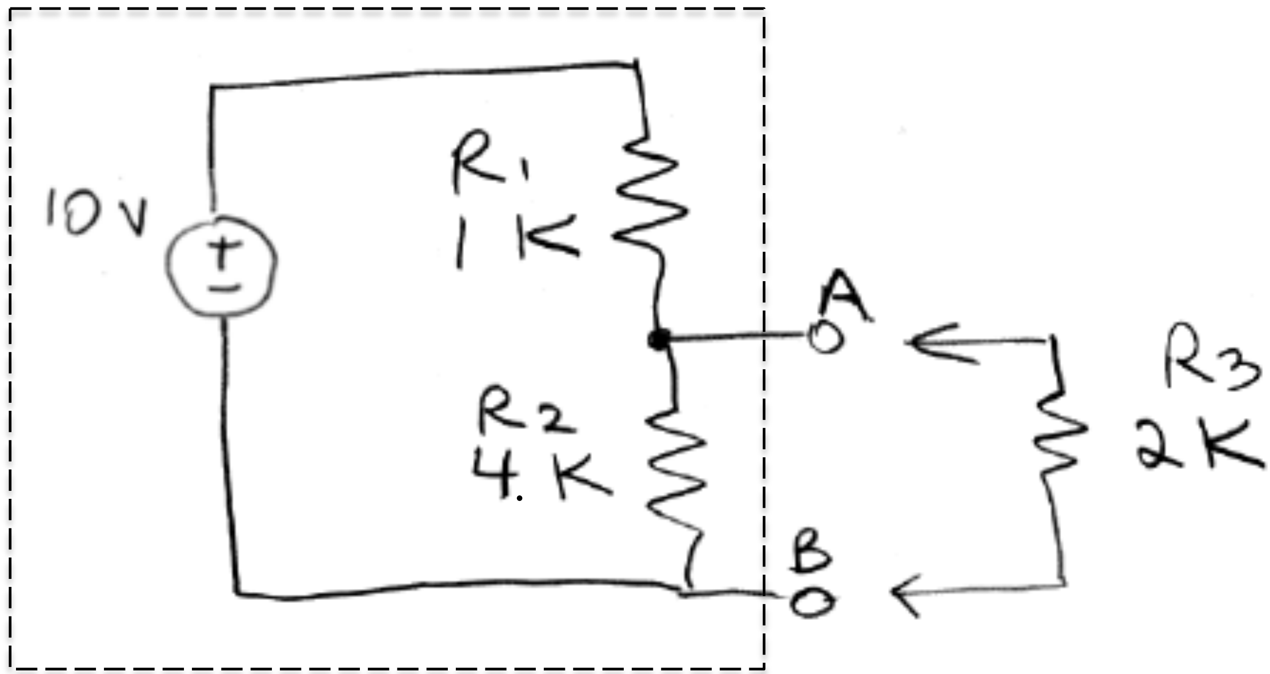
Output (Load) Current vs. Voltage



By definition:
$R_{\text{Thevenin}} = R_{\text{Norton}}$
(same as R_S on previous slide)

Thevenin Equivalent - Example

What is current through R_3 ?



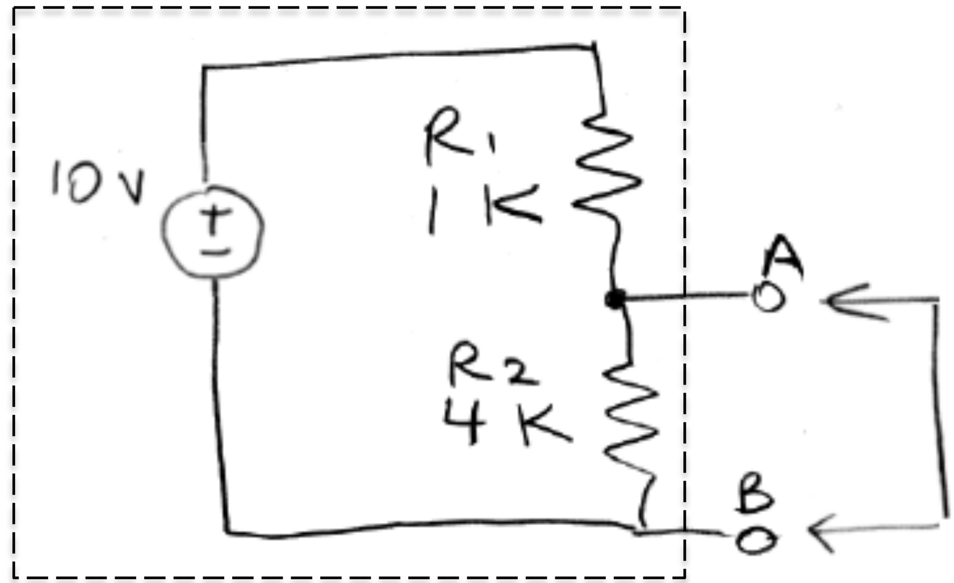
- Find V_{THEV} of "branch" (2-node component)
  - Compute voltage between A and B without R_3 "open circuit"

$$V_{\text{THEV}} = 10\text{V}\ \frac{4\text{K}}{1\text{K} + 4\text{K}} = 8\text{V}$$

(continued….)

- Now, to find I_{NORT}
  - Short the output, compute current through "short circuit"

$$I_{\text{NORT}} = \frac{10\text{V}}{1\text{K}\Omega} = 10\text{mA}$$

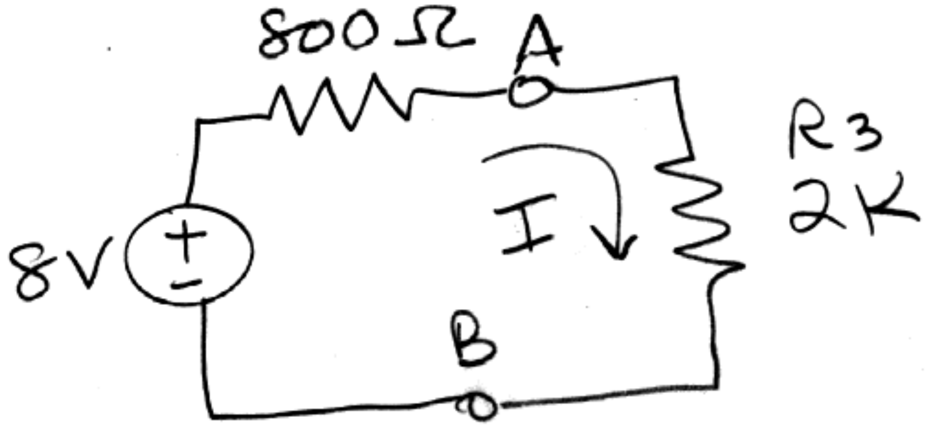


- Use V_{THEV} to find R_{THEV} given I_{NORT}.

$$R_{\text{THEV}} = \frac{8\text{V}}{10\text{mA}} = 800\Omega$$

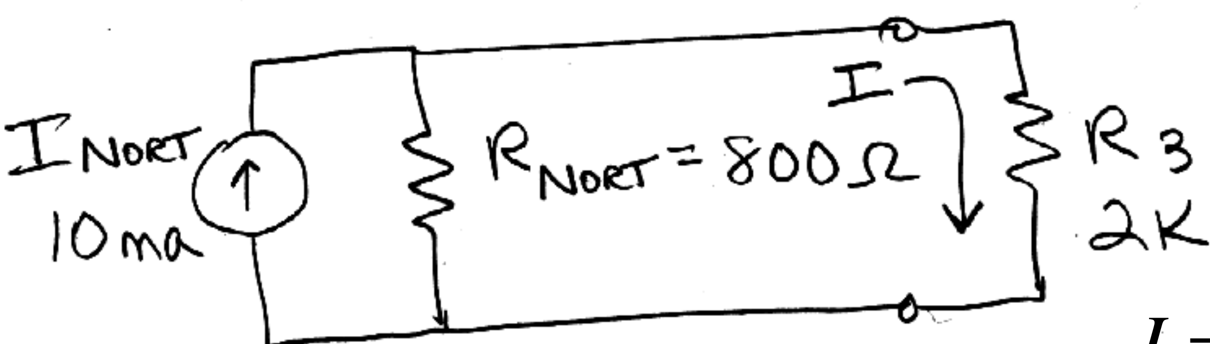
(continued….)

- Use V_{THEV} to find I through R_3.



$$I = \frac{8V}{2K+800\Omega} \cong 3mA$$

- Use I_{NORT} to find I through R_3.

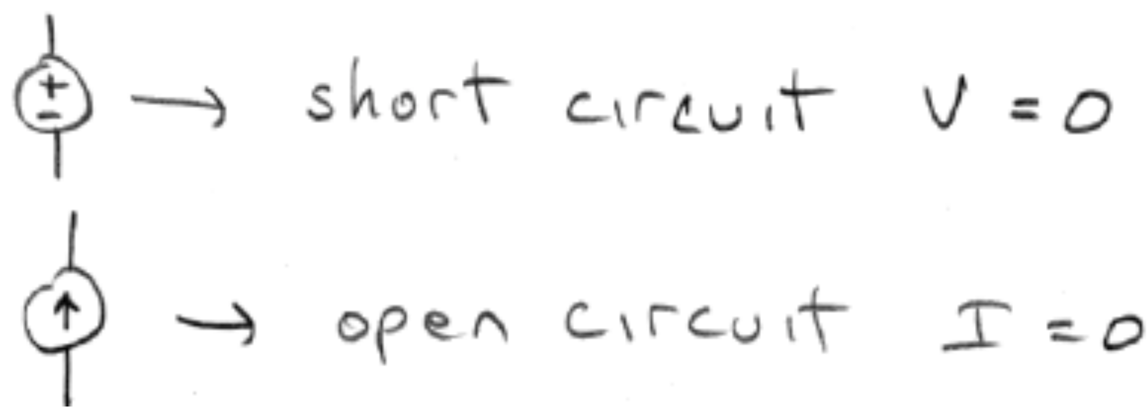


Use the current divider equation

$$I = I_{NORT} \frac{R_{NORT}}{R_3+R_{NORT}} \cong 3mA$$

Superposition Theorem

- The current in a branch (or voltage across) is the sum of the currents (or voltages) produced by each source individually, *with all other sources set to 0.*
- The currents through (and voltages across) each component add independently (linearly).
- Setting a voltage source to 0 V means a short circuit (piece of wire).
- Setting a current source to 0 A means an open circuit (removed).

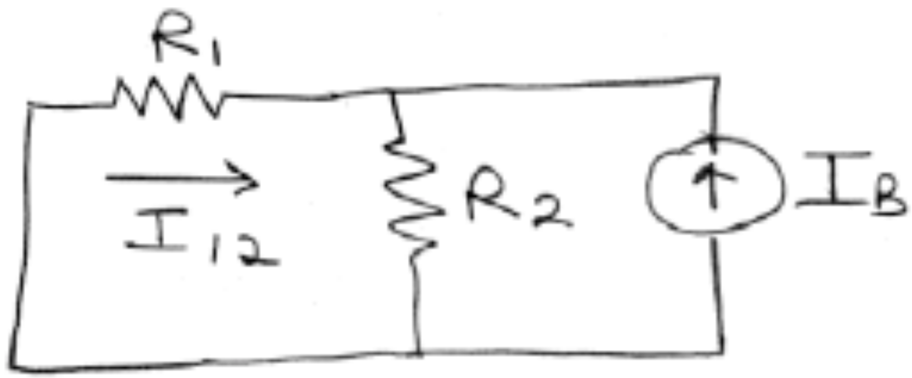


Superposition Theorem - Example

Solve for I_1 as the sum of two currents, I_{11} and I_{12}

Setting I_B to zero (open circuit)

$$I_{11} = \frac{V_A}{R_1 + R_2}$$



Setting V_A to zero (short circuit)

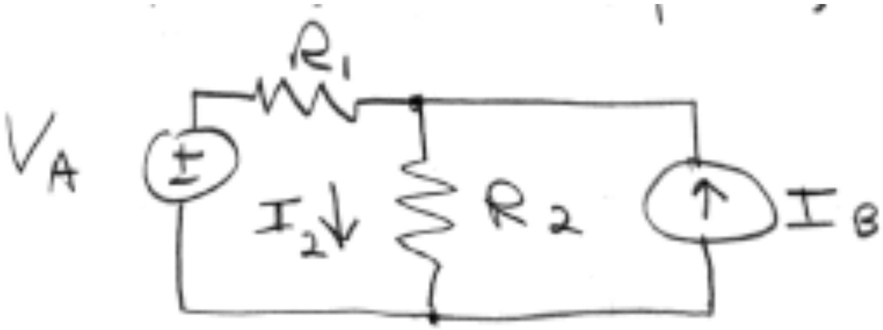
$$I_{12} = -\frac{I_B R_2}{R_1 + R_2}$$

Current divider, current going the other way.

Add the two independent currents together:

$$I_1 = I_{11} + I_{12} = \frac{V_A - I_B R_2}{R_1 + R_2}$$

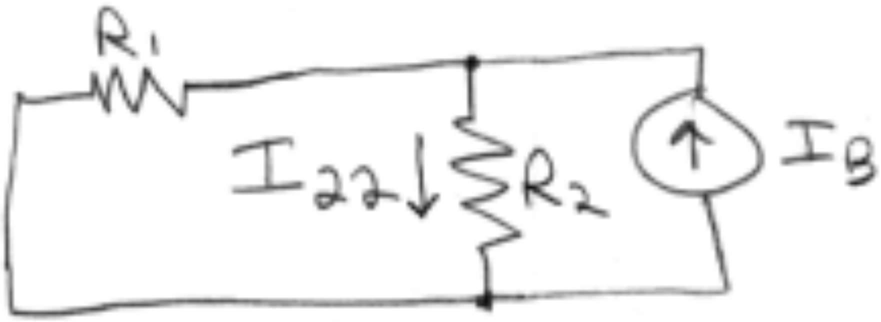
Superposition Theorem – Example (cont.)



Solve for I_2 as the sum of two currents, I_{21} and I_{22}

Setting I_B to zero (open circuit)

$$I_{21} = \frac{V_A}{R_1 + R_2}$$



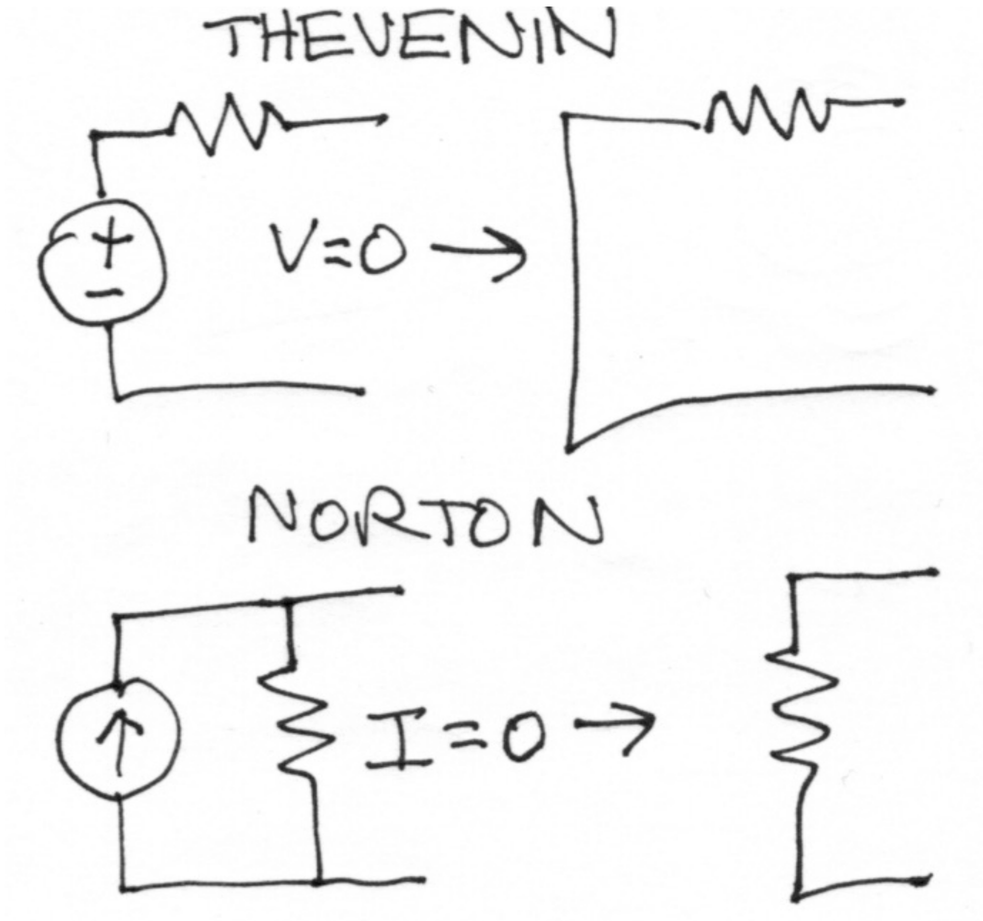
Setting V_A to zero (short circuit)

$$I_{22} = \frac{I_B R_1}{R_1 + R_2}$$

Add the two independent currents together:

$$I_2 = I_{21} + I_{22} = \frac{V_A + I_B R_1}{R_1 + R_2}$$

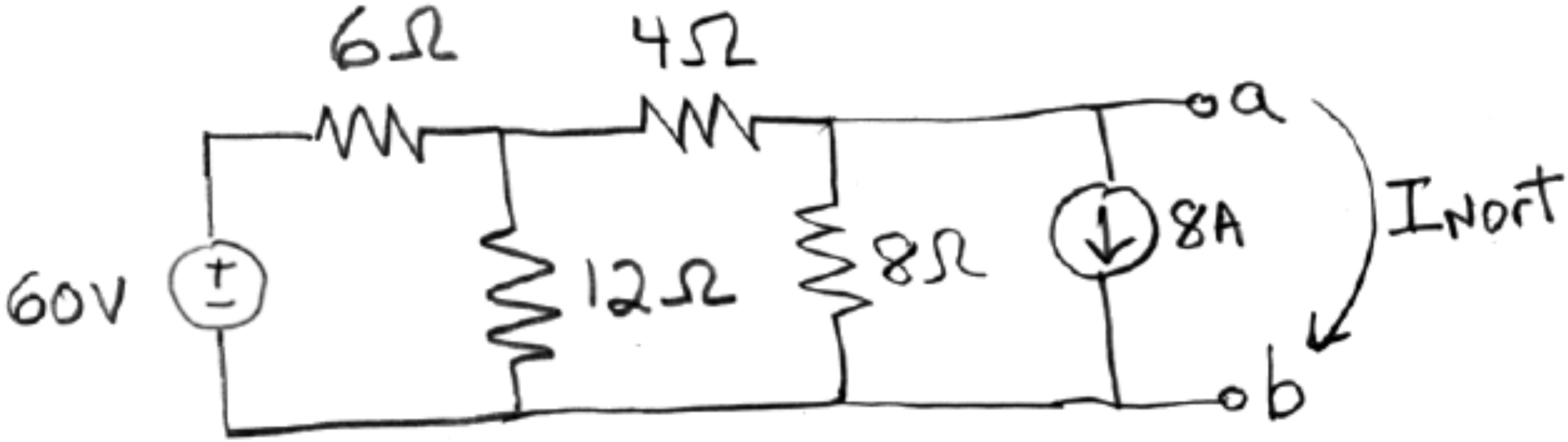
Finding Thevenin/Norton Resistance, Using Superposition



- $R_{Thevenin} = R_{Norton}$ is the resistance when the voltage and current sources are set to 0.

Superposition Theorem – Another Example

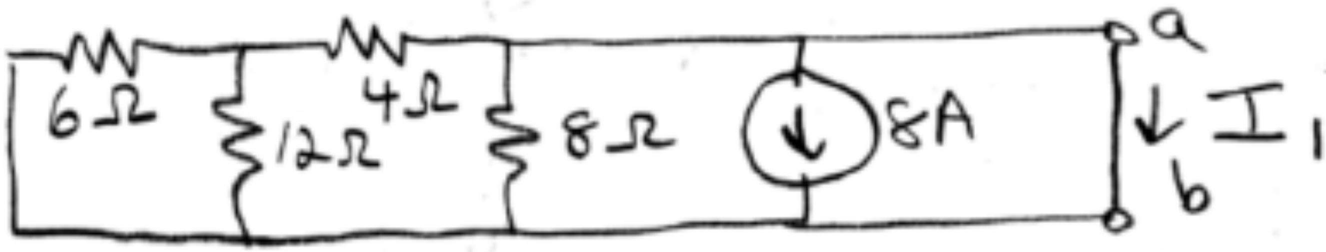
Find Norton equivalent I_{NORT} from *a* to *b*, and R_{NORT}, using Superposition.



I_{NORT} is the current through a short circuit from *a* to *b*.

Break I_{NORT} into 2 components: $$I_{NORT} = I_1 + I_2$$

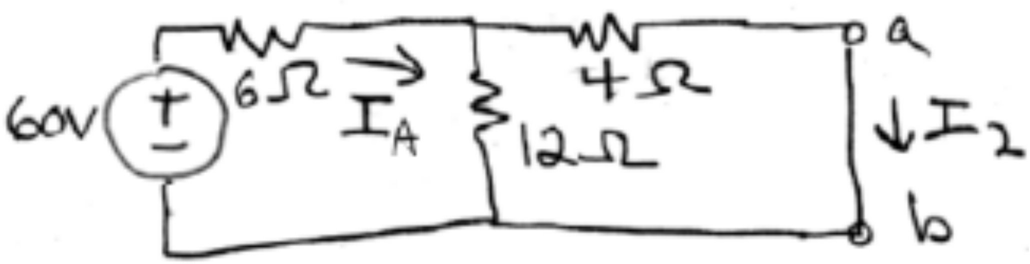
I_1 from current source with voltage source at 0V (short circuit). Ignore all resistors, since all current goes through short from *a* to *b.*



$$I_1 = -8\text{A}$$

current going the other way.

I_2 from current source with current source at 0 A (open circuit). Ignore 8 Ω resistor since it is parallel to short from *a* to *b.*



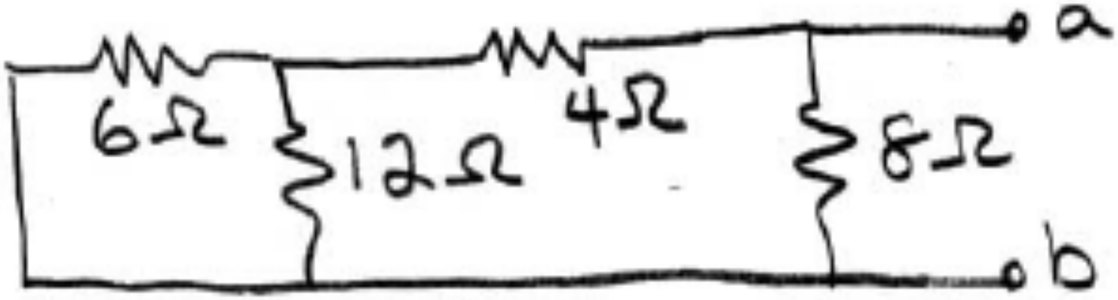
$$I_A = 60/(6 + (12 \times 4)/(12 + 4))$$

$$I_2 = I_A(12/(12 + 4)) = 5A$$

$$I_{NORT} = I_1 + I_2 = -8\text{A} + 5\text{A} = -3\text{A}$$

To find R_{NORT} :

- Set all voltage and current sources to 0 and find total resistance between *a* and *b*.
- This is R_{NORT} (which is the same as R_{THEV})

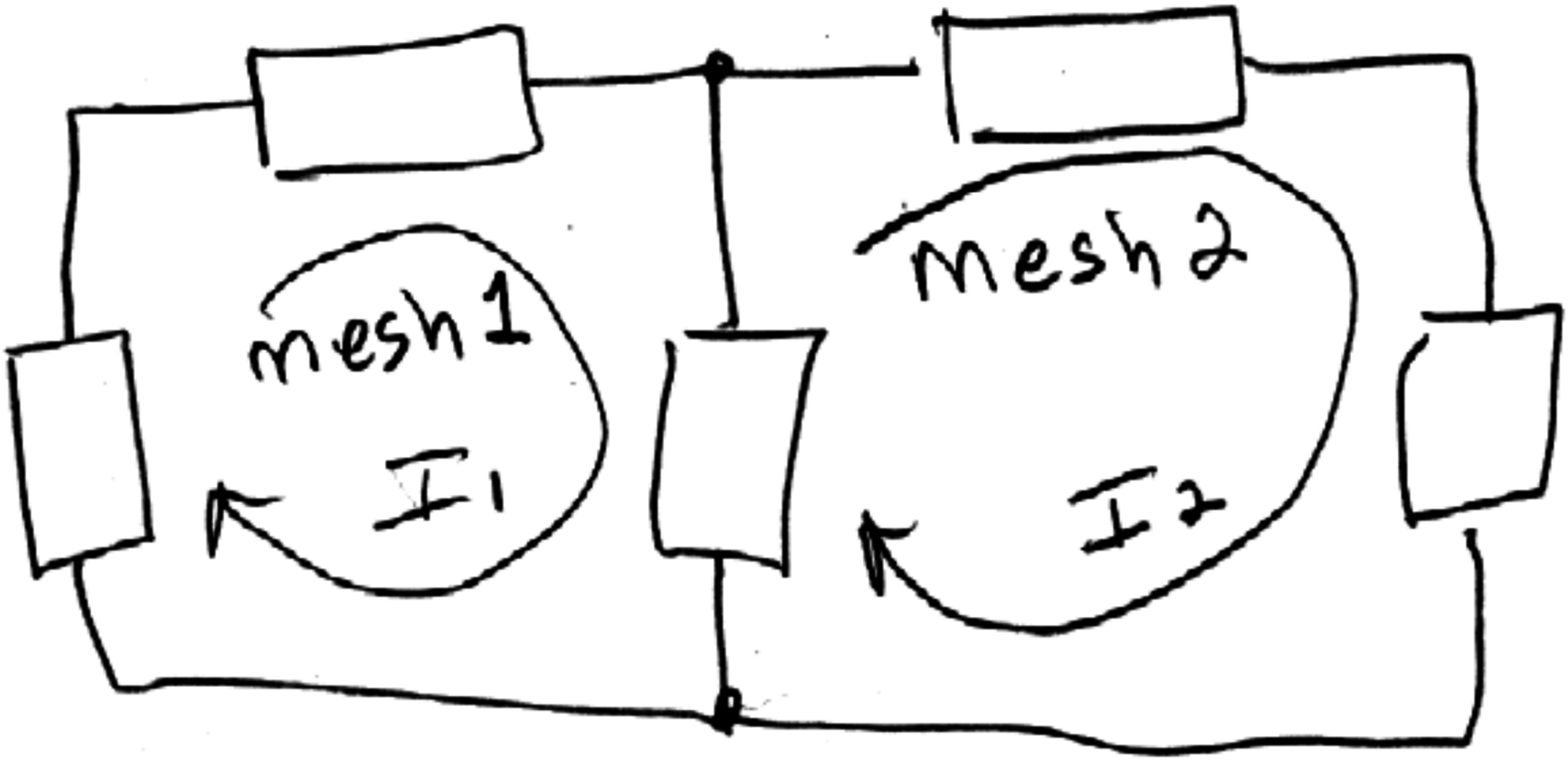


simplify using parallel resistors $(6\times 12)/(6+12)=4$

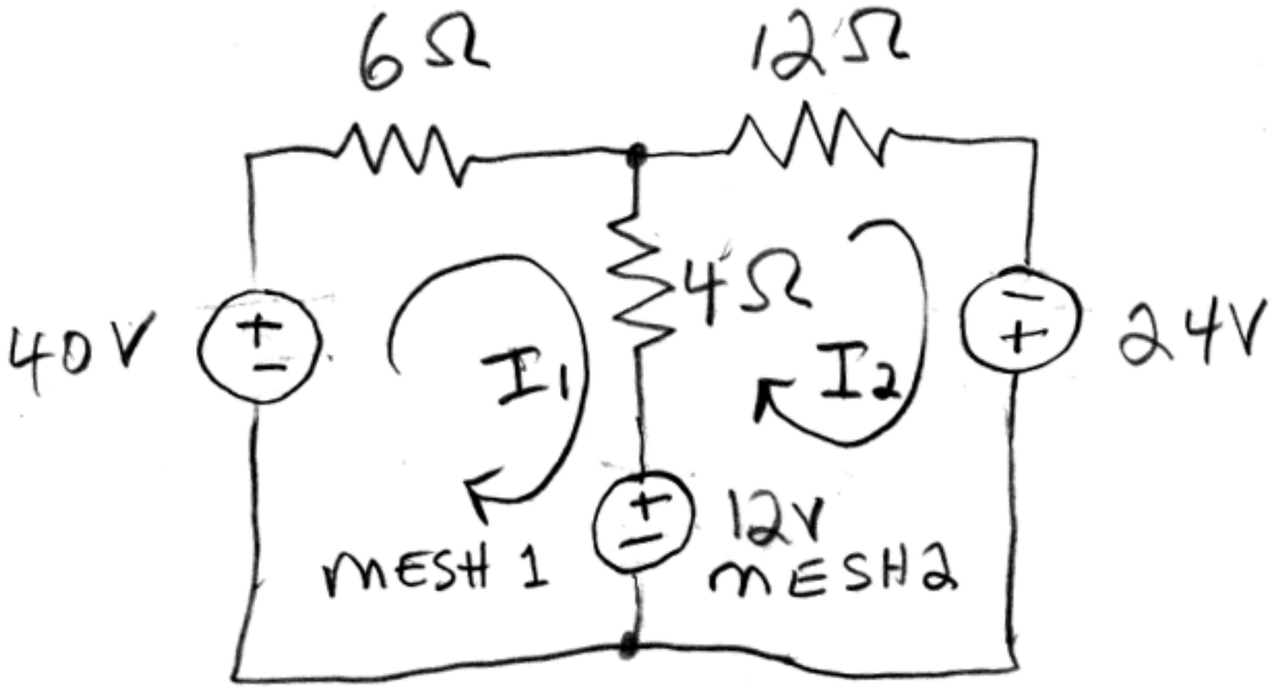
simplify further to two 8 ohm resistors in parallel, so

$$R_{\mathrm{NORT}} = R_{\mathrm{THEV}} = 4\Omega$$

Mesh analysis yield simultaneous linear equations.



Example of a Mesh



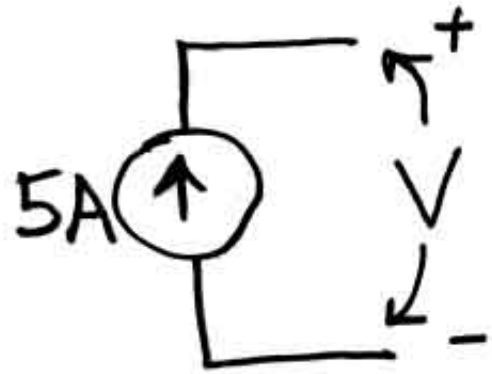
USING KIRCHHOFF'S VOLTAGE LAW

$$10I_1 - 4I_2 = 28$$

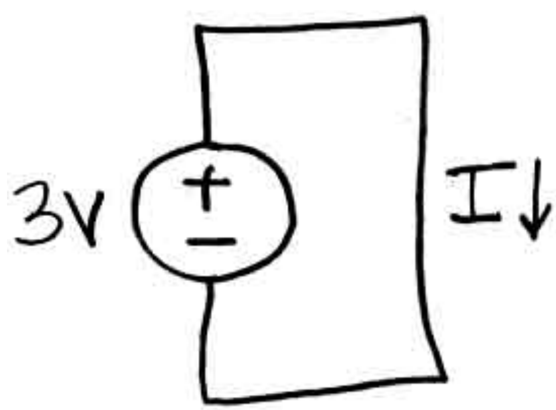
$$-4I_1 + 16I_2 = 36$$

DC Circuits without solutions

- There are basically 2 illegal DC circuits
  - Current source with open circuit: $V = \infty$

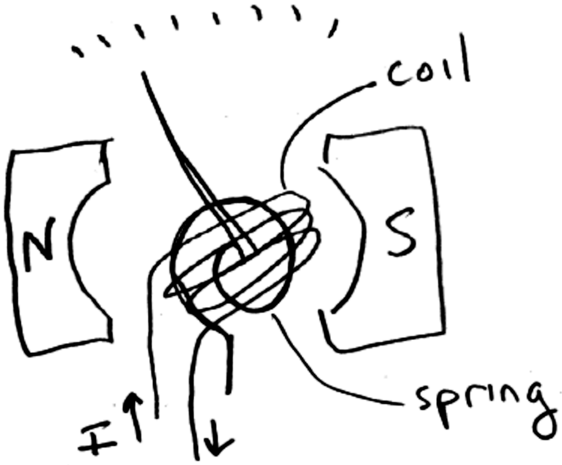


  - Voltage source with short circuit: $I = \infty$



Analog Volt-Ohm-Meter (VOM)

classic galvanometer Ⓖ



tiny current (50 μA)
Through coil
moves needle
Coil has ~0Ω resistance

symbol | what's inside

voltmeter

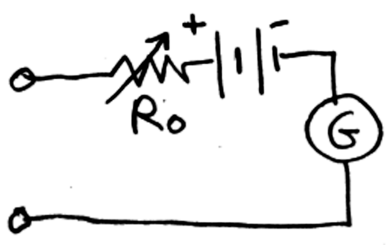
your meter ↓

R_s is big, 1mΩ-1gΩ
("s" for series)

ammeter

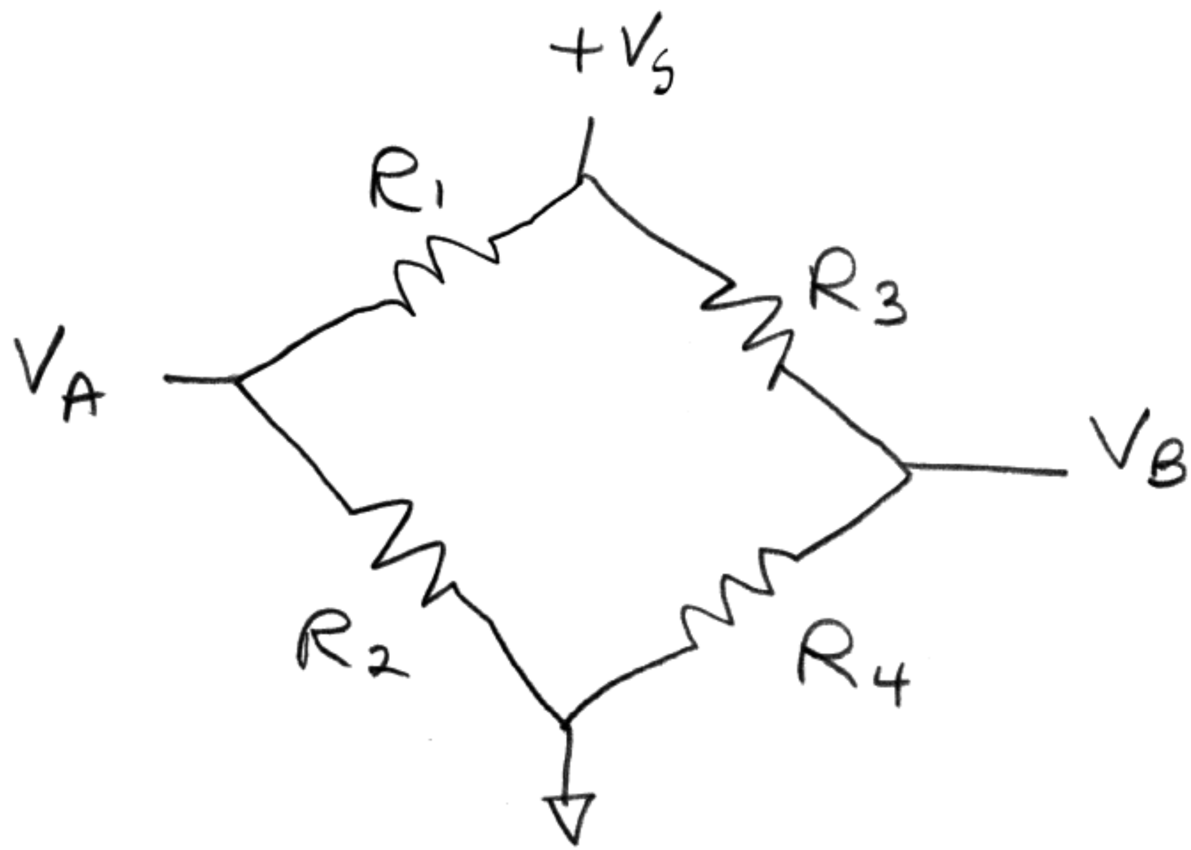
R_p is small < 1Ω
("p" for parallel
Easy to destroy meter!!

ohmmeter



R_o used to adjust offset.
injects current...
only use on isolated, non-powered resistors.

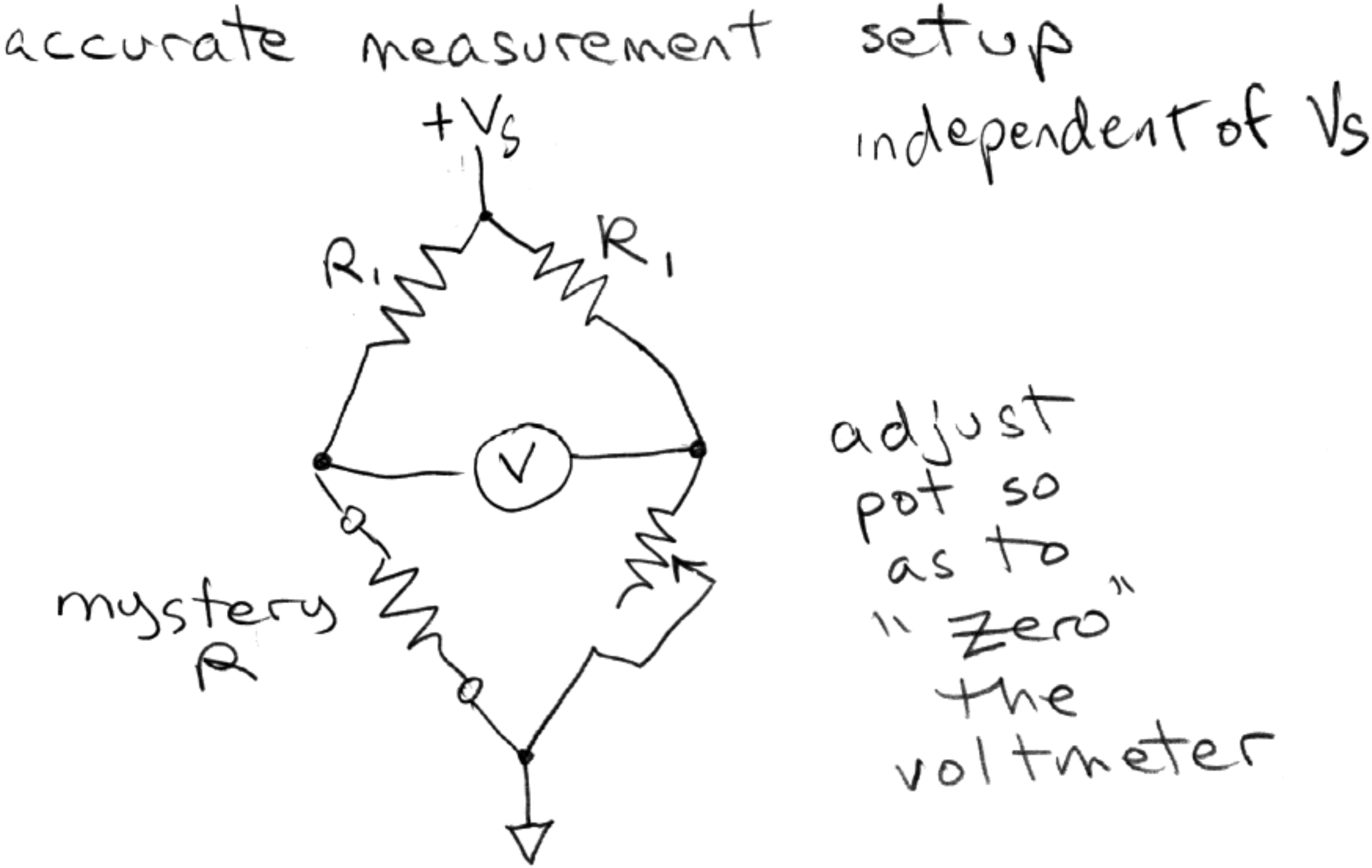
Wheatstone Bridge



$$V_A = V_B \text{ when } \frac{R_1}{R_2} = \frac{R_3}{R_4}$$

- 2 voltage dividers

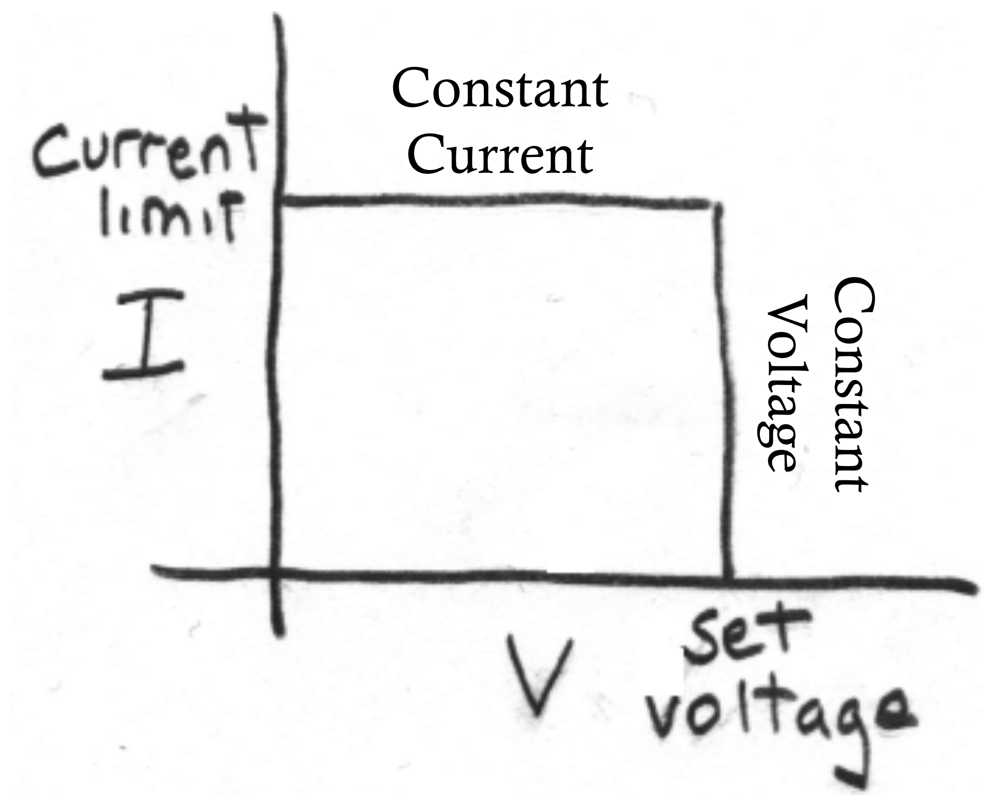
Wheatstone Bridge



- Like a mechanical balance for measuring weight

Regulated Power Supply – Perfect but not Linear.

- It provides constant voltage (perfect voltage source) up to a certain current limit.
- Above that current limit, it provides constant current (perfect current source) but with a voltage that can drop to zero.
- Not a linear system.



set voltage & current limit

"CV"
Constant Voltage during normal operation.

"CC"
Constant Current when current limit is reached.

Review of DC

- Constant perfect voltage and current sources, along with resistors, comprise circuits that produce a single solution (or no solution) based on linear simultaneous equations, in which each component obeys its own internal rule.
- Any branch made of the above components has a Thevenin and Norton equivalent. If the Thevenin/Norton resistance is non-zero, these represent real-world (non-perfect) voltage and current sources, respectively.
- Any branch consisting of only resistors can be simplified to a single resistor.