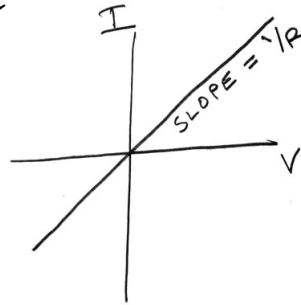


Resistance

- Ohm's law is only an approximation, and only for certain components called "resistors", but for them it is a *very* good approximation.



Physical Quantity

Unit

"R" resistance

Ω ohm

"G" conductance

Ω^{-1} mho

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

$$V = IR$$

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

$$I = VG$$

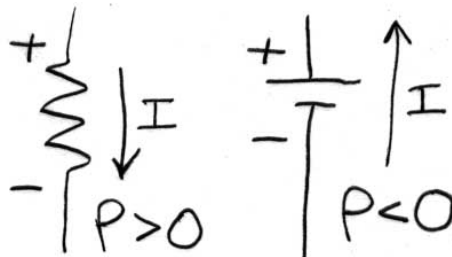
10

- Voltage, current, and power can be positive or negative
- Power is *positive* when electrical energy is deposited in a component (resistor, light bulb), but *negative* when energy is produced by it (battery discharging).

$$P = V \times I$$

$$P = I^2 R$$

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



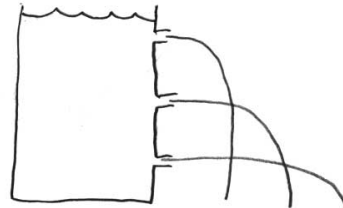
11

- 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 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 constant.
- DC circuits can generally be represented by fully-constrained simultaneous linear equations.

12

Bad Water Analogies

- Typical bad analogy →
- Electrons rarely jump from wires. They are confined to “steel pipes” (wires) and must return to the power source to avoid a net charge deficit.



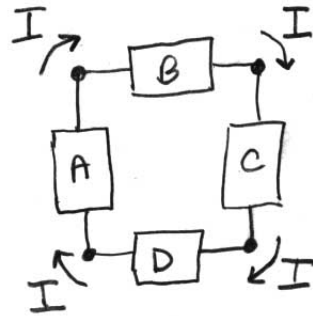
Water shoots further from the bottom hole of the tank because pressure is greater. Not so electrons!

13

Kirchoff's Current Law

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

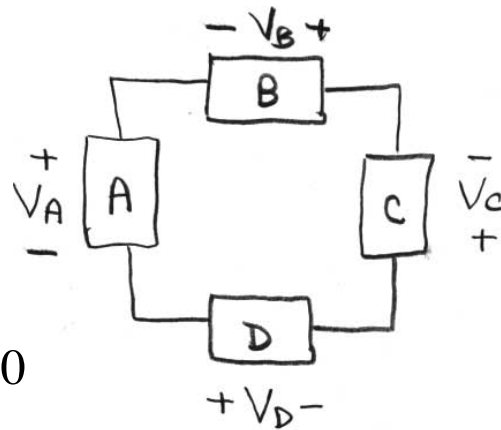
$$\sum_{node} I_{in} = \sum_{node} I_{out}$$



14

Kirchoff'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 (at the same node).



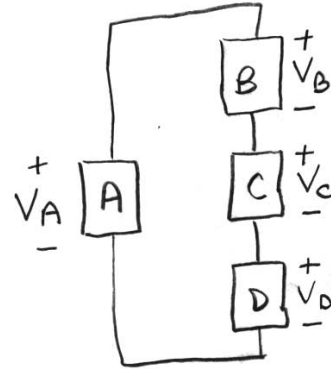
$$V_A + V_B + V_C + V_D = 0$$

15

Kirchoff's Voltage Law

- Typical schematic layout:
 - high-to-low → top-to-bottom
 - output-to-input → left-to-right
- In this configuration Kirchoff's Voltage Law reads:

$$V_A = V_B + V_C + V_D$$



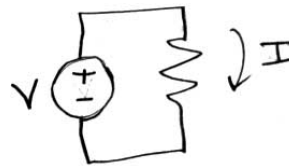
- Same voltage all along top wire.
- Same voltage all along bottom wire.
- Same voltage all along any wire (~ 0 resistance).

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Ideal Voltage and Current Sources

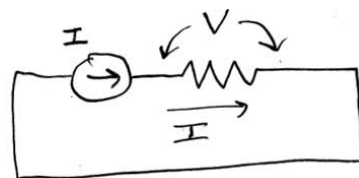
- Ideal voltage source holds *voltage* constant no matter what. Voltage placed across resistor “causes” current...

$$V = IR$$



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

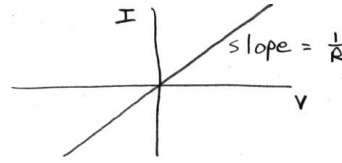
$$\frac{V}{R} = I$$



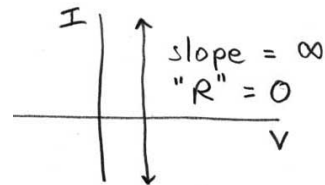
17

What is resistance (“output impedance”) of an ideal source?

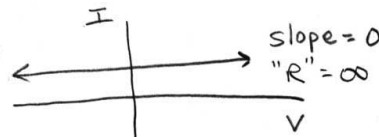
Recall for a resistor it is $1/\text{slope}$ on plot of I vs. V .



Ideal *voltage* source, zero output impedance.



Ideal *current* source, infinite output impedance.



18

Series Resistance R_S

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

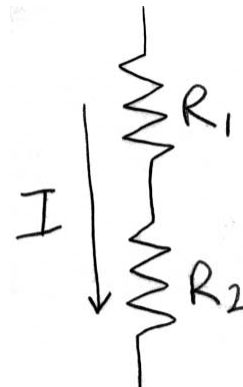
$$V_1 = IR_1$$

$$V_2 = IR_2$$

- Total series voltage V_S is

$$V_S = V_1 + V_2$$

$$R_S = R_1 + R_2$$



19

Parallel Resistance R_P

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

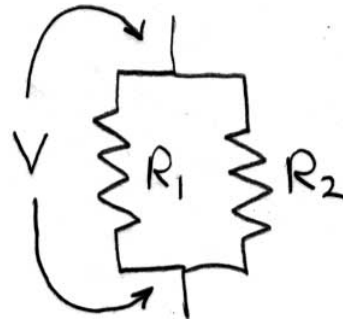
$$I_1 = VG_1$$

$$I_2 = VG_2$$

- Total series current I_S is

$$I_P = I_1 + I_2$$

$$G_P = G_1 + G_2$$



20

Parallel Resistance R_P

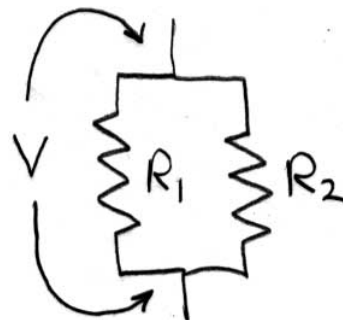
- Reciprocal of the sum of the reciprocals.

$$G_P = G_1 + G_2$$

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

- Product over the sums.

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



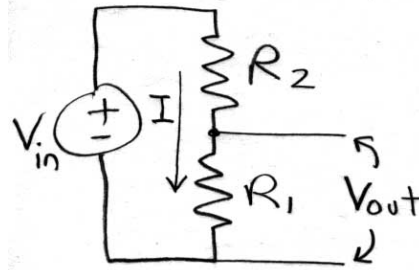
21

Voltage Divider

- View as “system” with voltage input and output.
- Same *current* through both resistors.
- Voltage across each resistor is proportional to its *resistance*.

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



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



22

Circuit Ground



- Defined as 0 volts, other points in the circuit are measured relative to it (voltage is always a difference).
- With a single-sided 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.

23

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.

24

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.

25

Safety - Electrocution

- 110 volts AC can kill (>500 deaths/year in US)
- Skin resistance $\sim 1\text{M}\Omega$ \gg internal resistance of tissue; minimum at 60 Hz.
- 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 soles and keeps 1 hand in pocket.
 - Bird 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.

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Safety – Wall Socket

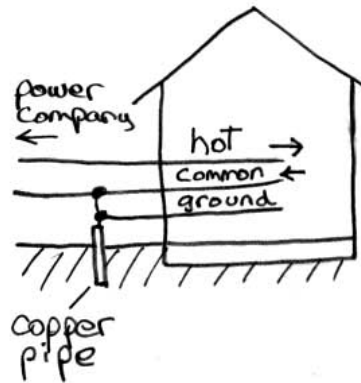
- Current comes out *hot* lead (small rectangular hole) and returns through *common* (or “neutral”) lead (large rectangular hole). Size difference prevents 2-lead devices like lamps from being plugged in backwards, which would make the outer part of the lamp socket hot.
- *Earth ground* (round hole) connects to pipe in the ground where power enters the house.



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Safety – Wall Socket

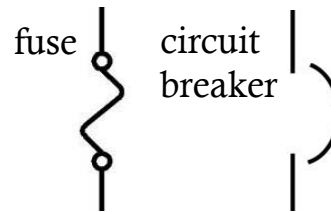
- Ground Fault Interrupter (GFI) in kitchen and bathroom disables power if current out *hot* lead does not match that returning in *common* lead (it may be going through human instead).
- To the electrician, black is *hot*, to electrical engineer it is *circuit ground*. What's with that ?



28

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.
- Heat is dissipated where there is resistance to the current in a circuit, $P=I^2R$ (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 to 120V circuits to 15A-30A.



29

Safety – Static/Lightening

- Static is safe to humans; although very high voltage (50,000 V/inch), current is very low. Generally due to friction and dry conditions.
- 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.