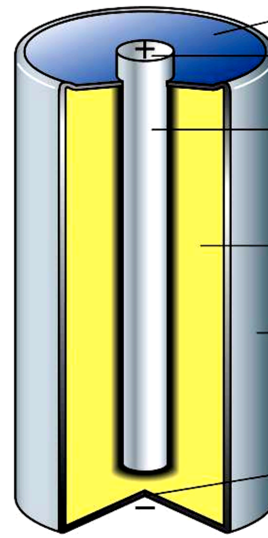
Physics 115
General Physics II

Session 21

Energy in E fields
Electric Current
Batteries
Resistance



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Lecture Schedule
(up to exam 2)

21-Apr	Mon	12	Specific Heats	18.4-18.6
22-Apr	Tues	13	Second Law	18.7-18.10
24-Apr	Thurs	14	Entropy	18.8-18.10
25-Apr	Fri	15	Charges	19.1-19.4
28-Apr	Mon	16	E field	19.5-19.66
29-Apr	Tues	17	Gauss law	19.7
1-May	Thurs	18	Electrical potential	20.1-20.3
2-May	Fri	19	Potential, conductors	20.4
5-May	Mon	20	Capacitors	20.5-20.6
6-May	Tues	21	Current	21.1-21.2
8-May	Thurs	22	Power, Series & Parallel Circuits	21.3-21.4
9-May	**Fri**		**EXAM 2 - Ch. 18,19,20**	

Today

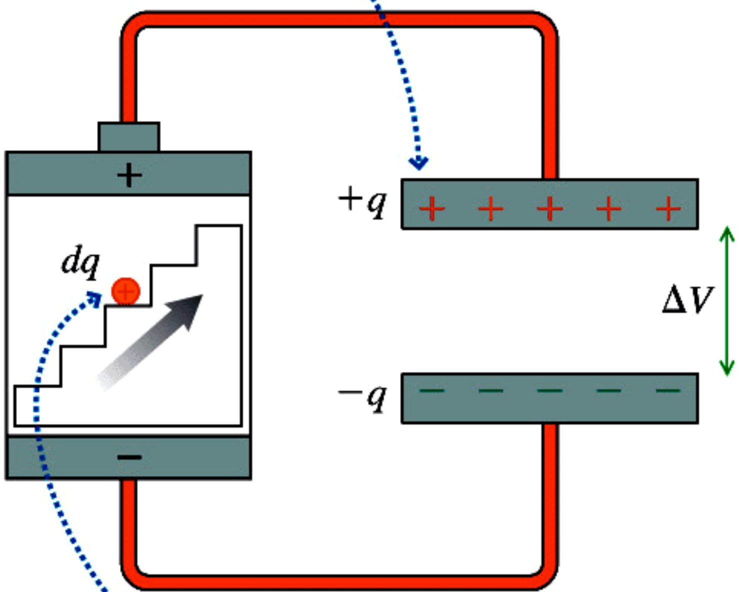
Announcements

- Exam 2 is this Friday 5/9
  - Covers material discussed in class from Chs 18, 19, 20
    - NOT Ch. 21
  - Same format and procedures as last exam
    - If you arranged to take exam 1 with section B, please do same for all remaining exams, OR email us to say you want to change
  - Practice questions have been posted in slides directory - we will review them in class Thursday

Last time

Energy Storage in a Capacitor

In capacitors, charge is stored on electrodes with potential difference ΔV. It takes work to move charge against the E field represented by ΔV !
The first bit of charge is easy to move: for an uncharged capacitor, V=0
Thereafter each bit of charge takes more work: V grows linearly with total Q on the capacitor, since V=Q/C.
The stored charge represents the work done, in potential energy: U = Q ΔV
Using calculus we find the total work done is $W_{TOTAL} = U_C = \frac{1}{2} Q \Delta V_C$



$$C = \frac{Q}{\Delta V_C} \rightarrow U_C = \frac{1}{2} C \Delta V_C^2 = \frac{Q^2}{2C}$$

Or, without calculus: since V grows linearly with total Q, average V = ½ Q/C, so total W = QV_{AVG} = ½ Q^2 /C

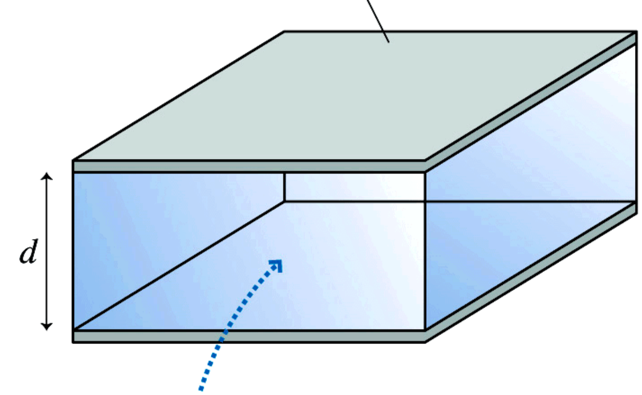
* What's this "charge escalator"? A source of energy (e.g, a battery) that "lifts" charge through the potential difference (against E force)

Energy density in an electric field

- The energy stored by a capacitor is the energy content of its electric field

$$U_C = \tfrac{1}{2} Q \Delta V_C, \quad Q = C\Delta V_C \rightarrow U_C = \tfrac{1}{2} C \Delta V^2$$

$$\tfrac{1}{2} C \Delta V^2 = \tfrac{1}{2}\left(\frac{\varepsilon_0 A}{d}\right)(Ed)^2 = \frac{\varepsilon_0}{2}(Ad)E^2$$



The capacitor's energy is stored in the electric field in volume Ad between the plates.

(Ad) = volume of space between plates

$$\text{energy density } u_E \equiv \frac{\text{energy stored}}{\text{storage volume}} = \frac{U_C}{Ad} = \tfrac{1}{2}\varepsilon_0 E^2$$

$$u_E = \frac{1}{2}\varepsilon_0 E^2$$

True for **any** region of space with ***E***, not just inside capacitors

Example: capacitor has d=1.0 mm, ΔV_C=500 V

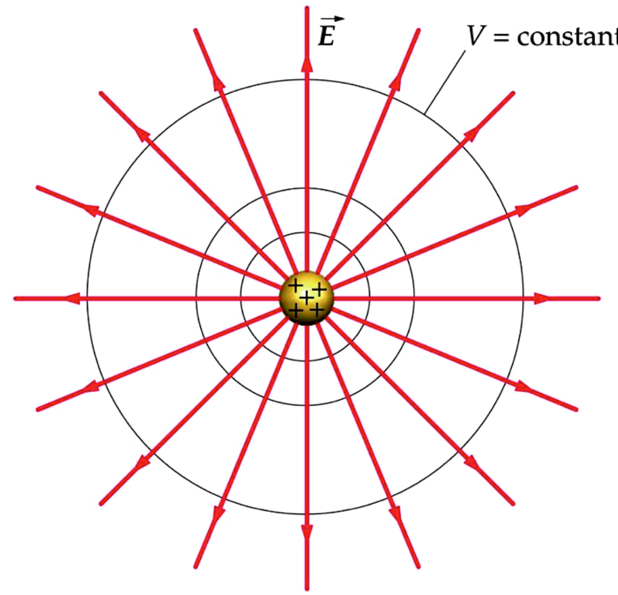
We don't need to know A or Q:

$$E = \frac{\Delta V_C}{d} = \frac{500 \text{ V}}{1.0 \times 10^{-3} \text{ m}} = 5.0 \times 10^5 \text{ V/m}$$

$$So \quad u_E = \tfrac{1}{2}\varepsilon_0 E^2 = \tfrac{1}{2}\left(5.0\times 10^5 \text{ V/m}\right)^2 / \left(4\pi \times 9.0 \times 10^9 \text{ Vm/C}\right) = 1.1 \text{ J/m}^3$$

Energy in the field of a spherical conductor

- For an isolated, spherical conductor with charge +Q and radius R



$$E_{outside} = \frac{kQ}{r^2}, \quad V_{surface} = \frac{kQ}{R}, \text{ for } V = 0 \text{ at } \infty$$

$$C = Q/V = R/k$$ ← Capacitance of an isolated sphere (other "electrode" is at infinity)

$$U = \tfrac{1}{2}\frac{Q^2}{C} = \frac{kQ^2}{2R}$$

The energy in the electric field around the sphere can be regarded as the energy stored in its capacitance, relative to a (fictional) negative electrode at R = ∞.

Deep thought: Notice when $R \to 0$, $U \to \infty$.
So a true point charge should have ***infinite energy!***
As far as we know, electrons are point particles…
(the Self-Energy Problem – how is an electron possible?)

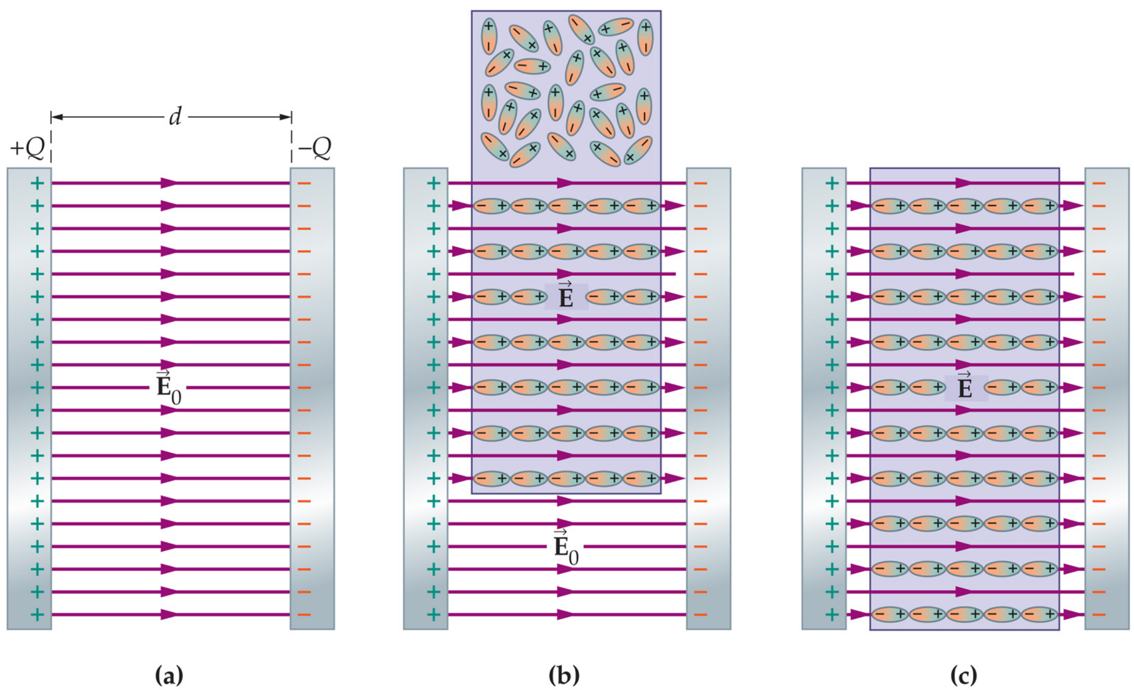
Demo: dielectric 'wants to go into' capacitor gap

Charge up a parallel plate capacitor (so Q on plates is fixed)

Plastic dielectric slab is pulled into the gap – why?

For fixed Q, more energy is stored in air-gap capacitor (κ = 1.0) than in dielectric-gap capacitor (κ > 1):

$$U_{AIR} = \frac{Q^2}{2C}, \quad U_D = \frac{Q^2}{2\kappa C} < U_{AIR}$$



Two ways to explain:

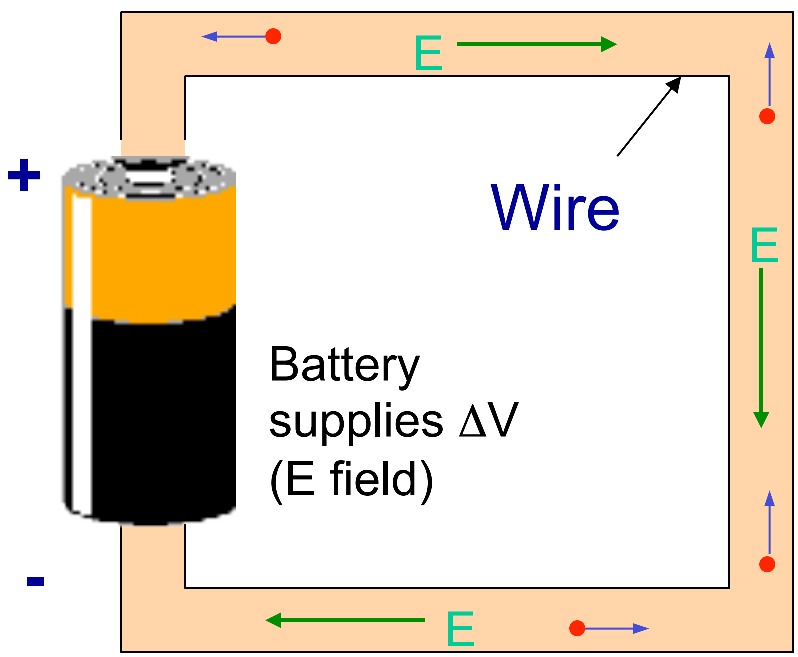
1. The polarized dielectric is attracted to the plates of the capacitor
2. Energy of system is reduced with dielectric in place (E field is reduced, so energy density is lower)
   - Systems move to lower energy states spontaneously

Did energy just disappear?

Where did the energy go?

Electrodynamics: Electric *Currents* and *Circuits*

- Wires (conductors) channel and contain electric fields
- Battery provides a source of potential difference
- Fields point *away* from positive terminal, towards negative
- We imagine positive charge flowing in direction of field lines
  - Actually, electrons (-) flow in *opposite* direction (Ben Franklin's error!)



Electrons' *actual* direction of motion

E → Electric *field* direction
("conventional current")

Electric Current = flow of charge
1 ampere (A) = 1 C / sec

$$I = \frac{\Delta Q}{\Delta t}$$

Andre
Ampère,
1775-1836

Current and voltage

- We say the battery's ***E*** field supplies an *electric potential* (or *Electromotive Force,* EMF) to charges in the conducting wires

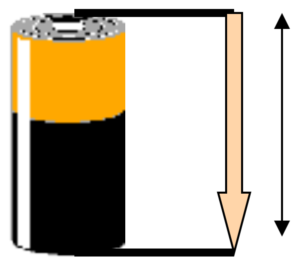
    Useful analogy: electric current is like flow of water

    – Voltage = pressure causing flow

    – Current = rate of flow

Analogy to water flow due to gravity

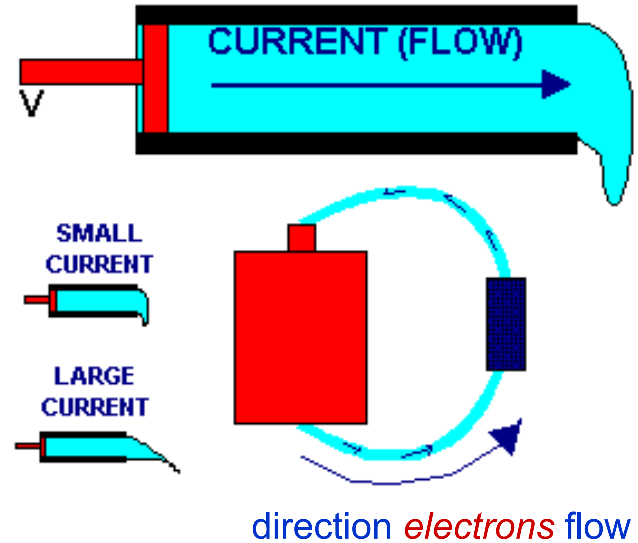
gh = PE per kg
kg/sec = flow rate
Power = (kg/sec)·*g*·*h*

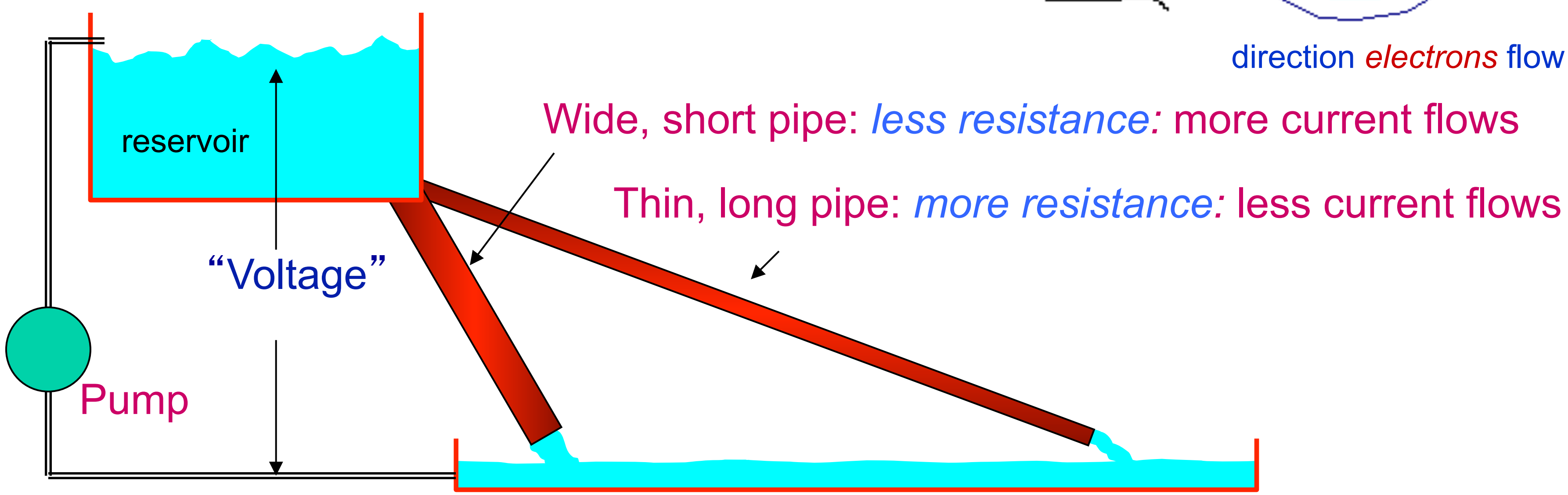


V (volts) = PE per coulomb
I (C/sec=amps) = flow rate
Power = *V*·*I*

Electrical voltage : current *as* Water pressure : current

- Can think of electric current like water flow in a closed system
  - high current: lots of water per second
  - low current: trickle of water
  - current flows around a *loop* (circuit) of pipe
  - battery provides *pressure* to make water flow
- Battery is like reservoir of elevated water
  - Higher tank = bigger *potential*, or voltage
- Imagine wires as tubes that let water drain
  - *Resistance* depends on length and diameter

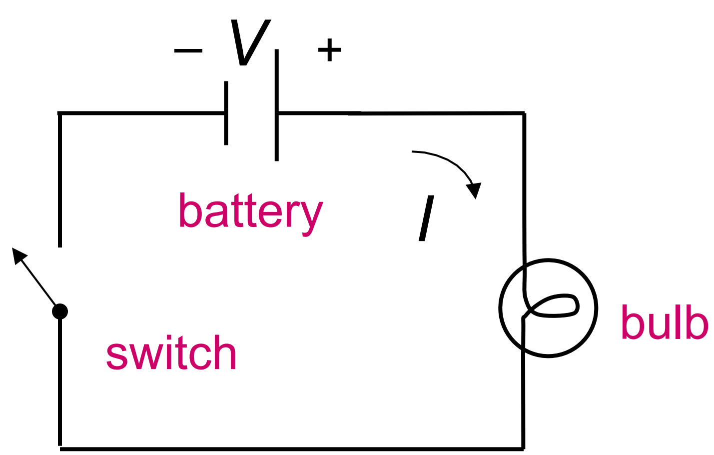




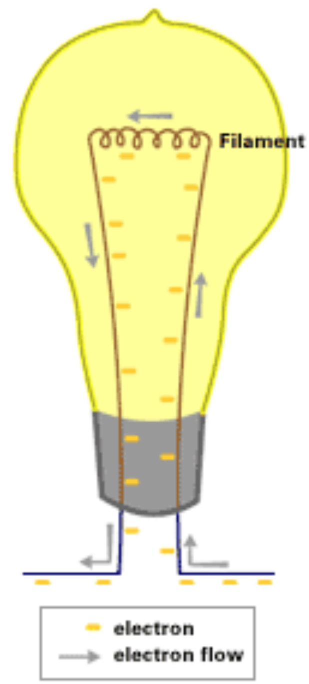
Need to make a *complete circuit* (path for charge flow)

- Must provide a *closed path* for current to flow through bulb under "pressure" from battery
  - Charge cannot just disappear! Battery has to have electrons returned
- Any gap in path *interrupts* current flow
  - We call that a *switch*
  - Acts like valve in water system

In "circuit diagram" form:



In a closed circuit,
current flows *around* the loop.
Switch *interrupts* flow, turns off bulb.



Current flowing through the high resistance filament heats it, and makes it white-hot.

Batteries and Electro-Motive Force (EMF)

Battery = chemical source of electric energy. Chemical reactions create potential difference by moving positive ions to one electrode and negative ions to the other.

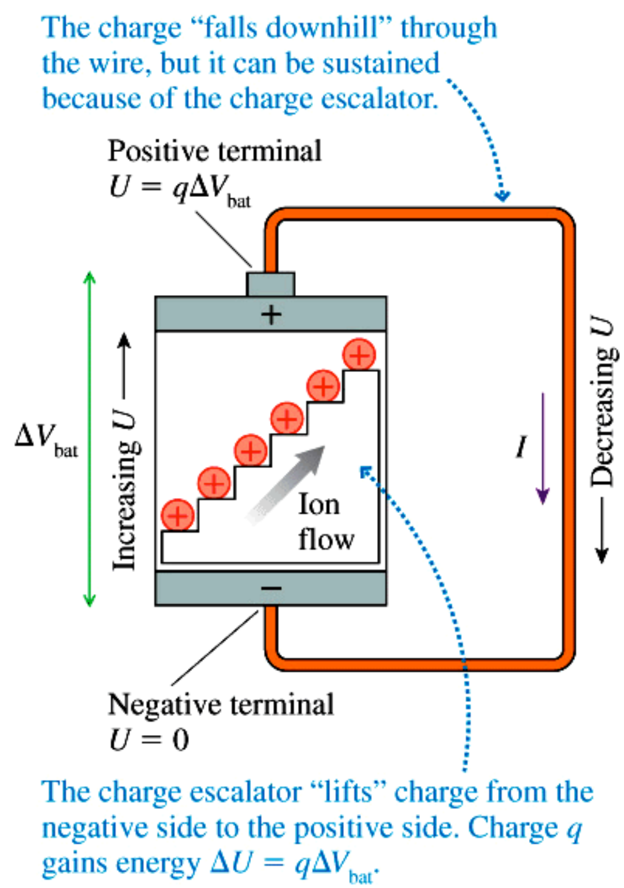
The potential difference ΔV_{bat} is determined by the chemistry of the battery (e.g., carbon and zinc in an old-fashioned dry cell)

ΔV_{bat} remains fairly constant until the chemicals are exhausted - the battery goes "dead".

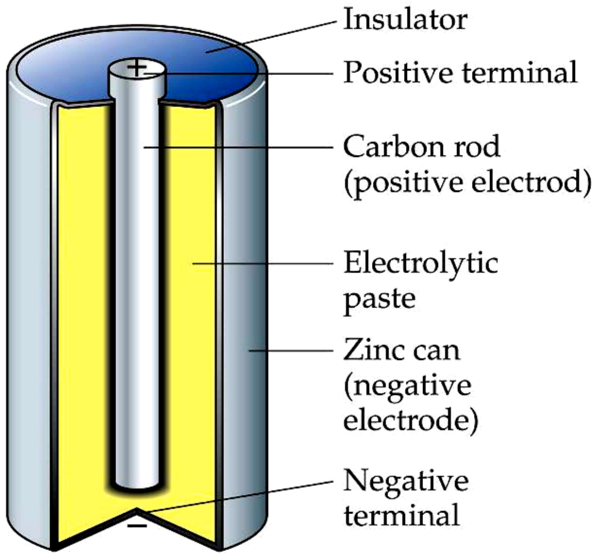
The term EMF (electromotive force), symbol $\mathcal{E}$, is used to describe the work done per unit charge by the battery: $\mathcal{E} = W_{chem}/q = \Delta V_{bat}$.

Remember: no force involved! EMF is just the potential difference maintained by a source.

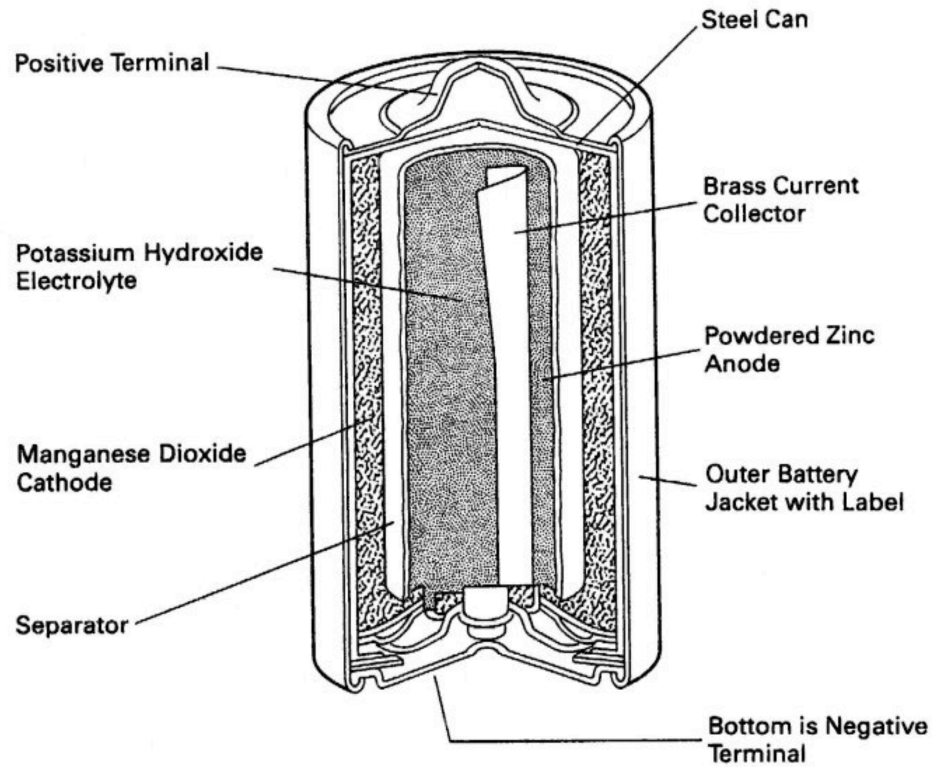
(A real battery has "internal resistance" that increases as the chemicals are used up, and limits current flow – more on this later)



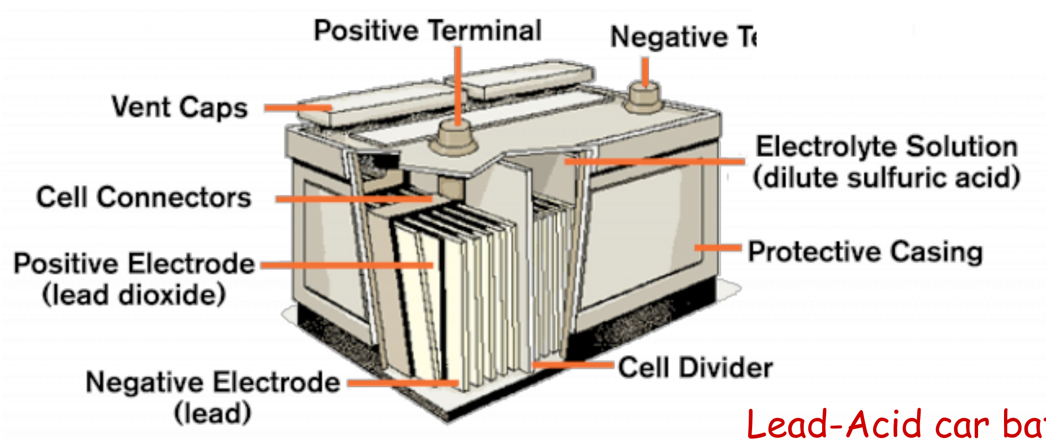
Inside batteries



Carbon-zinc
("dry cell": G. Leclanché, 1866)



"alkaline battery":
Cathode (-) = Zinc
powder in alkaline
gel, carbon-
manganese anode (+)
Lewis Urry, c. 1950



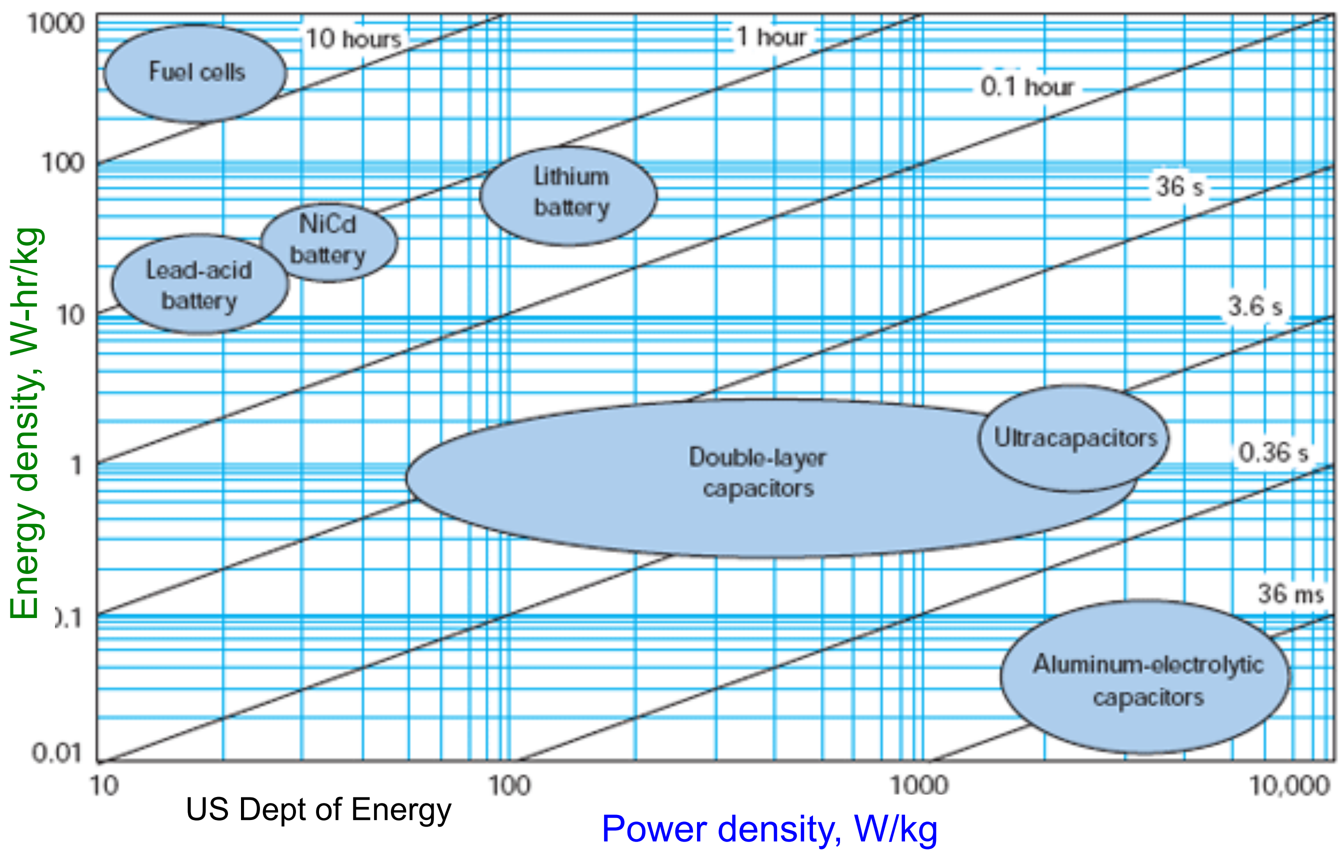
Lead-Acid car battery
("wet cell": 1859, Gaston Planté,)

BTW: Storing electrical energy is a hot topic

- Batteries are a major issue for "green" vehicles
- Two aspects to energy storage: how much, how fast is it needed?
  - Energy density = joules / kg (how much energy)
  - Power density = kW / kg (how fast energy can be delivered)

Batteries →
Lots of energy, moderate energy/sec for a long time

Capacitors →
less total energy but available very quickly



US Dept of Energy

Current, voltage and resistance

- Conventional current I = flow of + charge
  - Really: electrons move in opposite direction
  - Electrons are very light, have to diffuse their way through atoms
  - Follow a long random walk from one end of battery to other!
    - May take an hour for a given electron to go through circuit
    - But bulb lights up right away...?
      - Like a garden hose: flow starts right away, but you must wait to get cold water (= water parcel just out of faucet)
- Current is proportional to V, inversely proportional to R

$$I \propto V \Rightarrow I = const(V) = \left(\frac{1}{R}\right)V$$

Ohm's Law

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

R = Resistance of circuit element

Unit of R = Volt per ampere = Ohm (Ω)

R is a property of a given object (device, wire, circuit element)

Conductivity and Resistivity

Resistivity ρ -> intrinsic property of *material* -> like density vs mass
Resistance ***R*** -> property of a particular *object*

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

Resistivity units: Ohm-meters

*BTW: the inverse of resistance is conductance; its unit is the MHO * (no kidding)* (℧)
and the inverse of resistivity is

$$\sigma = \text{conductivity} = \frac{1}{\rho} \quad (mho/m)$$

TABLE 28.2 Resistivity and conductivity of conducting materials

Material	Resistivity (Ω m)	Conductivity (Ω^{-1}m^{-1})
Aluminum	2.8×10^{-8}	3.5×10^{7}
Copper	1.7×10^{-8}	6.0×10^{7}
Gold	2.4×10^{-8}	4.1×10^{7}
Iron	9.7×10^{-8}	1.0×10^{7}
Silver	1.6×10^{-8}	6.2×10^{7}
Tungsten	5.6×10^{-8}	1.8×10^{7}
Nichrome*	1.5×10^{-6}	6.7×10^{5}
Carbon	3.5×10^{-5}	2.9×10^{4}

*Nickel-chromium alloy used for heating wires

* Official SI unit is the siemens (S) but use of the mho cannot be suppressed...

Resistivity is temperature dependent, and Ohm's linear V vs I relation works only approximately for many materials.
(Some circuit devices are specifically designed to be non-linear: transistors, capacitors.... More later)

Clicker Quiz 14

- Which one of the following is **correct**?
  - A. If we put a sheet of dielectric ($k > 1$) into a parallel plate capacitor's air gap, the capacitance gets **smaller**
  - B. Resistance of a given wire does **not** depend upon the material of the conductor
  - C. The "ohm" is a joke devised by MIT students, not an accepted physical unit for resistance.
  - D. **All** of the above are incorrect