Thus far we have dealt almost exclusively with static situations. In fact, we've had no time dependence at all even when current was involved.
→ current was steady.

Let's talk a bit more about current as we begin to bring in time dependent features.

Current

What makes current flow?
- Inside a material (wire, other circuit elements), there will be resistance to the motion of charges (they scatter, heat up - thermal motion, etc.)
- You need some force to maintain the motion - the current. (like friction in 183)

With free electrons → constant push means accelerating charges. and thus increasing current!

In most materials → constant push means a constant flow!

Model of this is known as Ohm's Law,

$$\vec{J} = \sigma \vec{f}$$

current density ∝ force per unit charge.

The constant of proportionality, σ, is a material dependendent constant — conductivity.

(It is not surface charge!)

We can also rewrite this,

$$\vec{f} = \frac{1}{\sigma}\vec{J} = \rho \vec{J}$$

ρ is the resitivity $= 1/\sigma$

(not charge density!)

It's often the case that the force responsible for this motion is the Lorentz force,

$$\vec{f} = \frac{\vec{F}_{Lorentz}}{q} = \vec{E} + \vec{v} \times \vec{B}$$

And typically $\vec{v}$ & $\vec{B}$ are small enough where only $\vec{E}$ really affects the charges *(more later on this)

So,

$$\vec{J} = \sigma \vec{f} = \sigma(\vec{E} + \vec{v} \times \vec{B}) \simeq \sigma \vec{E}$$

this is Ohm's Law, which is really a Model that many materials seem to be able to be modeled by.

<u>Note:</u> $\vec{F} = m\vec{a}$ does not imply an increasing current even though $\vec{J} \propto \vec{v}$ (remember this?)

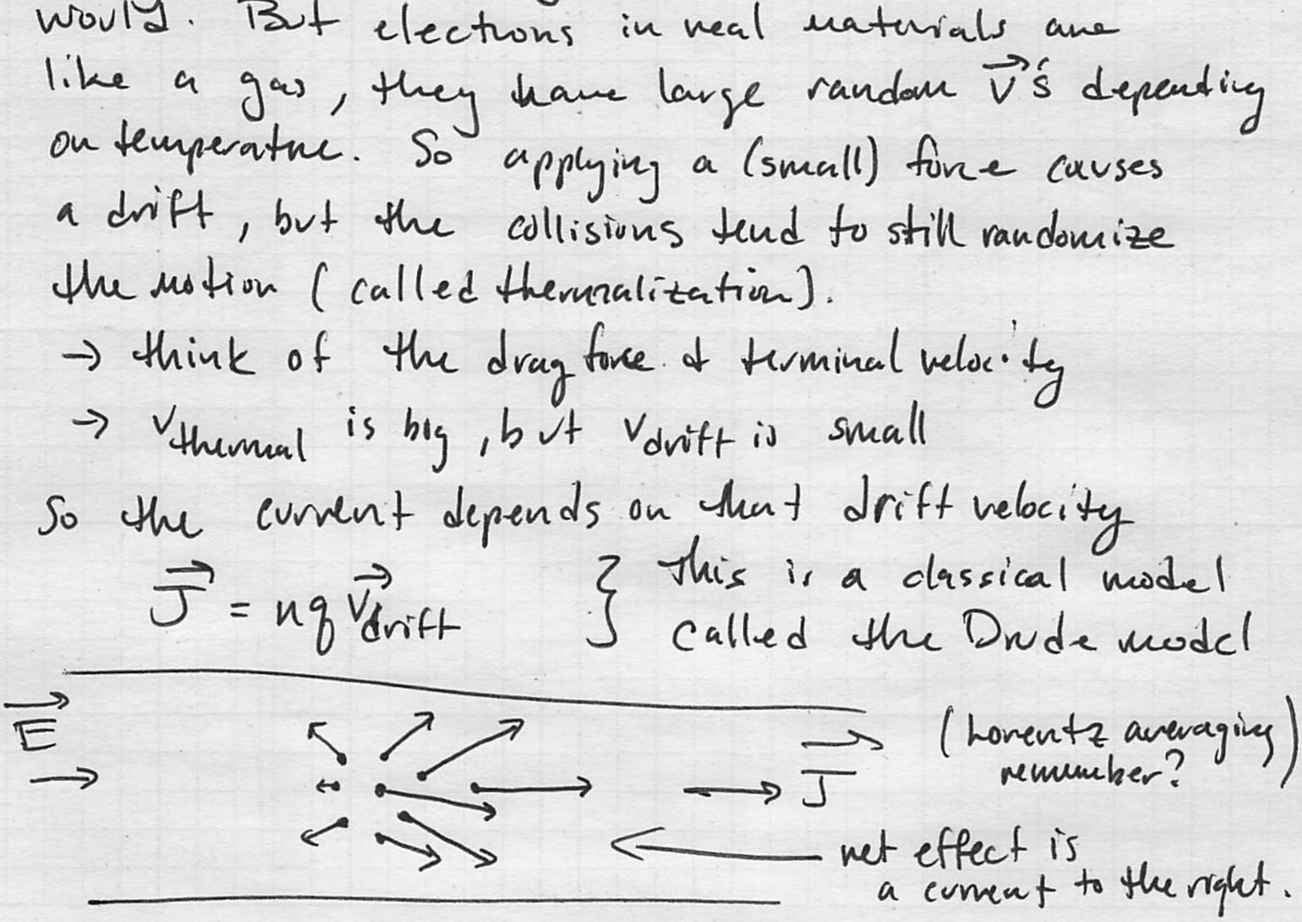
If they were no damping (collision, thermal losses), it would. But electrons in real materials are like a gas, they have large random $\vec{v}$'s depending on temperature. So applying a (small) force causes a drift, but the collisions tend to still randomize the motion (called thermalization).

→ think of the drag force & terminal velocity

→ $v_{thermal}$ is big, but v_{drift} is small

So the current depends on that drift velocity

$$\vec{J} = nq\vec{v}_{drift}$$ } this is a classical model called the Drude model



Comment! σ depends on the material

Materials w/ large conductivity are good conductors. (you only need a small force to get a large flow)

- Copper is used in most household wiring

$$\underbrace{\sigma_{cu} \simeq 6 \cdot 10^{7} \frac{C/s \cdot m^2}{N/C}} = \frac{C^2 s}{kg\, m^3} = \frac{1}{Ohm\, m} = \frac{1}{\Omega m}$$

- This is a huge conductivity. By contrast, wood (an insulator) has $\sigma_{wood} \simeq 10^{-8}$ to $10^{-11} \frac{1}{\Omega m}$
- A resistor in a circuit would be more like 10^{+3} or $10^{+[illegible]}\,1/\Omega m$ ("mid range")

Comment: I thought $E = 0$ in metals!

For static situations, yes that's true,

$\vec{J} = \sigma \vec{E}$ so if $\vec{J} = 0$ then $\vec{E} = 0$.

For a metal σ is very large ($\sigma \to \infty$),

so that $\vec{E} = \vec{J}/\sigma \to 0$ even if there's finite current.

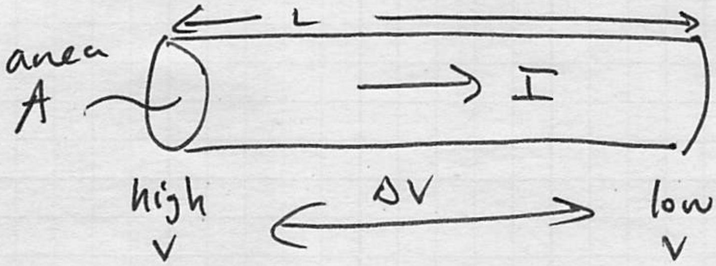
That is, very small $\vec{E}$ fields are needed to drive currents in metals. and in our approximation that $\sigma \to \infty$, $\vec{E} \to 0$ still in this case.

Final Comment: As there are collisions and thermal losses when driving current, the power dissipated in the system must be

$$P = \Delta V\, I = \frac{\text{work}}{\text{charge}} \cdot \frac{\text{charge}}{\text{second}}$$

Example: Uniform Conducting Wire

Here's a bit of wire,



We can use Ohm's Law,

$$\vec{J} = \sigma \vec{E}$$

to find 184's Ohm's.

the current density is uniform: $J = I/A$

* here the electric field is also uniform: $E = \dfrac{\Delta V}{L}$

(* we will come back to this)

so,

$$\frac{I}{A} = \sigma \frac{\Delta V}{L} \Rightarrow \Delta V = \frac{L}{\sigma A} I$$

We can call $\dfrac{L}{\sigma A} = R$ the resistance of the material

R depends on the geometry and the resistivity of the material. In this case,

$$R = \frac{L}{\sigma A} = \rho \frac{L}{A} \quad \text{where } \rho = 1/\sigma \text{ (remember!)}$$

$[R] = \text{Ohms} = [\Omega]$ so $\underline{\Delta V = RI}$ (like 184)

Real wires have small E-fields in them and thus small ΔV's. They are measurable, too!

But, big ΔV's occur across resistive elements; hence, we often focus on them!