Questions...

What does it mean to be "delocalized"? This is a quantum effect for small particles. Comes from wave/particle duality.

What is the difference between viscosity and electric resistance? How do resistors literally resist the flow of electrons (through friction?). Also, what determines conductivity properties of metal? They are analogous. One describes how fluids ‘resist’ flow, the other how charges are ‘impeded’ from flowing along a potential difference.

If an electrical current is powering a light bulb, is it doing work? Yes, in fact the rate at which it does work (Power) is typically important to us (Think unit of power...)

What exactly is current density? Sometimes, it is more convenient to talk about the current through a given surface in terms of amperes/square meter.
More Questions…

When a wire is cut, how do the forces on the electrons inside change? There is no longer a potential difference to force the charges in a particular direction, so motion is just thermal.

Can you explain what drift velocity is? If we were to visualize the current as actual moving charges within a region, the drift velocity would describe how fast they were going (~0.1 mm/s).

I remember in mamm phys, we talked about how we don't talk about resistance instead we focus on conductance...so what is the key difference between the two? It seems like they are dependent of one another, but very similar. They are reciprocals of each other.

What exactly does Ohm’s law measure, is it just the resistance produced when electrons move through a system? Ohm’s law describes the dependence of current on potential difference.
Charging a capacitor

The spacing between the plates of a 1.0 μF capacitor is 0.050 mm.

a. What is the surface area of the plates?
b. How much charge is on the plates if this capacitor is attached to a 1.5 V battery?

MODEL Assume the battery is ideal and the capacitor is a parallel-plate capacitor.
The figure shows two arbitrary electrodes charged to $\pm Q$.

It might appear that the capacitance depends on the amount of charge, but the potential difference is proportional to $Q$.

Consequently, the capacitance depends only on the geometry of the electrodes.
The figure shows a capacitor being charged.

As a small charge $dq$ is lifted to a higher potential, the potential energy of the capacitor increases by:

$$dU = dq \Delta V = \frac{q dq}{C}$$

The total energy transferred from the battery to the capacitor is:

$$U_C = \frac{1}{C} \int_0^Q q dq = \frac{Q^2}{2C}$$

The charge escalator does work $dq \Delta V$ to move charge $dq$ from the negative plate to the positive plate.

The instantaneous charge on the plates is $\pm q$. 
Capacitors are important elements in electric circuits because of their ability to store energy.

The charge on the two plates is $\pm q$ and this charge separation establishes a potential difference $\Delta V = q/C$ between the two electrodes.

In terms of the capacitor’s potential difference, the potential energy stored in a capacitor is:

$$U_C = \frac{Q^2}{2C} = \frac{1}{2} C(\Delta V_C)^2$$
- A capacitor can be charged slowly but then can release the energy very quickly.
- An important medical application of capacitors is the defibrillator.
- A heart attack or a serious injury can cause the heart to enter a state known as fibrillation in which the heart muscles twitch randomly and cannot pump blood.
- A strong electric shock through the chest completely stops the heart, giving the cells that control the heart's rhythm a chance to restore the proper heartbeat.
A capacitor charged to 1.5 V stores 2.0 mJ of energy. If the capacitor is charged to 3.0 V, it will store

A. 1.0 mJ
B. 2.0 mJ
C. 4.0 mJ
D. 6.0 mJ
E. 8.0 mJ
Two sheets of charge
Capacitor Equations

\[ \Delta V = E \Delta x = Ed \]

\[ E = 4\pi k_c \sigma = 4\pi k_c \frac{Q}{A} \quad \Rightarrow \quad Q = \left( \frac{A}{4\pi k_c} \right) E \]

\[ Q = \left( \frac{A}{4\pi k_c d} \right) \Delta V \]

\[ Q = C \Delta V \]

*4\pi k_c \text{ is often written as } "1/\varepsilon_0"*
Some basic electrical ideas

• **Conductor** – a material that permits some of its charges to move freely within it.

• **Insulator** – a material that permits some of its charges to move a little, but not freely.

• **Battery** – a device that creates and maintains a constant potential difference across its terminals.

\[ \Delta V = V_0 \text{ volts} \]

High end  Duracell  Low end
Charging a capacitor

• What is the potential difference between the plates?
• What is the field around the plates?
• How much charge is on each plate?
What can we determine about the charges on the capacitor plates are $Q_1$ and $Q_2$?

A. $Q_1$ equals $Q_2$
B. $Q_1$ equals $-Q_2$
C. They can have different magnitude but need to have opposite signs
D. They can have different magnitude but need to have the same signs
E. None of the above
F. Depends on the situation
Why are the charges the same magnitude and opposite sign?
What would happen to the voltage if you first disconnected the battery and pulled the plates further apart?

A. The potential difference would increase
B. The potential difference would decrease
C. The potential difference would stay the same
D. Not enough information
What would happen to the voltage if I keep it connected to the battery and pulled the plates further apart?

A. Potential difference would increase
B. Potential difference would decrease
C. Potential difference would stay the same
D. Not enough information
What would happen to the charge on either plate if I keep it connected to the battery and pulled the plates further apart?

A. The charges would increase
B. The charges would decrease
C. The charges would stay the same
D. Not enough information
Cap #1 is charged by connecting it to a battery. Cap #2 is not charged but otherwise is the same as C#1. C#1 is disconnected from the battery and connected to C#2. How does the magnitude of the E field in C#1 change?

A. Same
B. Bigger by ~X2
C. Bigger but not by ~X2
D. Smaller by ~X2
E. Smaller but not by ~X2
F. Can’t tell
What happens if we fill half the gap between plates with a conductor?

A. The electric field inside the conductor is the same as outside
B. The electric field inside the conductor is opposite to the field outside
C. The electric field inside the conductor is zero
D. Not enough information
Conductors

• Putting a conductor inside a capacitor eliminates the electric field inside the conductor.

• The distance, $d'$, used to calculate the $\Delta V$ is only the place where there is an $E$ field, so putting the conductor in reduces the $\Delta V$ for a given charge.

\[ C = \frac{1}{4 \pi k_c} \frac{A}{d'} \]
Consider what happens with an insulator

- We know that charges separate even with an insulator.
- This reduces the field inside the material, just not to 0.
- The field reduction factor is defined to be $\kappa$.

$$E_{\text{inside material}} = \frac{1}{\kappa} E \quad \text{if no material were there}$$
Screening
Charged objects in Conducting Solids

• What happens if you place a charged object into a neutral conductor?
  – Positive ions are fixed in the solid
  – Some negative charges (shared electrons) are free to move
Charged objects in Conducting Fluids

• What happens if place a charged object into a neutral fluid?
  – Opposite charged ions are attracted to object
  – Like charged ions are repelled
  – Thermal energy keeps ions moving
Foothold ideas: Electric charges in materials

• **Electroneutrality** – opposite charges in materials attract each other strongly. Pulling them apart to create a charge unbalance costs energy.

• If a charged object is placed in an ionic solution, it tends to draw up ions of the opposite type and push away ones of the same type.
  
  – Result: the charge is **shielded**. As you get farther away from it the “apparent charge” gets less.

  – The scale over which this happens is called the **Debye length**, \( \lambda_D \).
Electric currents
Electric circuit elements

• **Batteries** — devices that maintain a constant electrical potential difference across their terminals

• **Wires** — charges flow quickly need very little forces to move

• **Resistances** — charges need a larger force to move. Examples are Resistors and Lightbulbs
Foothold ideas: Currents

- **Charge is moving:** How much?
- **How does this relate to the individual charges?**
- **What pushes the charges through resistance?** Electric force implies a drop in $V$!

$\begin{align*}
I &= \frac{\Delta q}{\Delta t} \\
I &= q \ n \ A \ v \\
F_e &= qE \\
\Delta V &= -\frac{E}{L}
\end{align*}$
• Current proportional to change in Electrical Potential

• Does R depend on the Area of the resistor?

• Does R depend on the length of the resistor?

1. R Increases
2. R decreases
3. R remains the same
4. Depends on material

\[ \Delta V = IR \]
## Units

<table>
<thead>
<tr>
<th>Physical Quantity</th>
<th>Unit</th>
<th>Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current $(I)$</td>
<td>Ampere</td>
<td>Coulomb/sec</td>
</tr>
<tr>
<td>Voltage $(V)$</td>
<td>Volt</td>
<td>Joule/Coulomb</td>
</tr>
<tr>
<td>E-Field $(E)$</td>
<td>Newton/Coulomb = Volt/meter</td>
<td></td>
</tr>
<tr>
<td>Resistance $(R)$</td>
<td>Ohm</td>
<td>Volt/Ampere</td>
</tr>
<tr>
<td>Capacitance $(C)$</td>
<td>Farad</td>
<td>Volt/Coulomb</td>
</tr>
<tr>
<td>Power $(P)$</td>
<td>Watt</td>
<td>Joule/sec</td>
</tr>
</tbody>
</table>
Resistivity and Conductance

• The resistance factor in Ohm’s Law separates into a geometrical part \((L/A)\) times a part independent of the size and shape but dependent on the material. This coefficient is called the \textit{resistivity} of the material \((\rho)\).

• Its reciprocal \((g)\) is called \textit{conductivity}. \textit{(The reciprocal of the resistance is called the conductance \((G)\).)}

\[
R = \rho \frac{L}{A} = \frac{1}{g} \frac{L}{A} = \frac{1}{G}
\]
Analogy: Water flow

- Water flow is a useful analogy to electric currents because water
  - can divide
  - is conserved and cannot be compressed.
Sketch a water analogue for the following circuit

Q: What about the water analogy for capacitors?
Very useful heuristic

– Wires have very small resistance (e.g. 1 foot of 13 gauge wire has a resistance of 0.002 Ohm) This $R$ is generally negligibly small compared to other resistances in the circuit through which current flows, so we can approximate it as zero resistance.

• The Constant Potential Corollary (CPC)
  – Along any part of a circuit with 0 resistance, then $\Delta V = 0$, i.e., the voltage is constant
Questions...

Why is it necessary to study so many differential models simultaneously? Each model has some useful parts, but there are things that don’t quite work (ex. water flow and cross-sectional area)
does electricity always flow down a GRADIENT like the board and nail example? Yes

capacitors simple " maintain a charge separation in response to a voltage differential across its plates" - what does this even mean? The charges are building up on the opposite plates. They do this because of a potential difference

How is capacitance analogous to resistance? How is it described by the second principle? Both will impeded the current. Resistors do it at a constant rate, while capacitors do over time – as the capacitor becomes fully charged, no more less and less current
Questions...

How does multiplying the current times the voltage drop tell us how much work is done? Isn't the work equal to a force times a displacement? **When in doubt, look at your units. Remember, work is a transfer of energy into or out of the system**

Where exactly does the energy that was stored in a battery go when it's used up? **Depends on the element. Could be just heat, could be spinning a motor**
Foothold ideas: Kirchhoff’s principles

1. **Flow rule**: The total amount of current flowing into any volume in an electrical network equals the amount flowing out.

2. **Ohm’s law**: in a resistor, \( \Delta V = IR \)

3. **Loop rule**: Following around any loop in an electrical network the potential has to come back to the same value (sum of drops = sum of rises).
For a junction, the law of conservation of current requires that:

\[ \sum I_{\text{in}} = \sum I_{\text{out}} \]

where the \( \Sigma \) symbol means summation. This basic conservation statement is called Kirchhoff’s junction law.
The Loop Rule

- For any path that starts and ends at the same point:
  \[ \Delta V_{\text{loop}} = \sum (\Delta V)_i = 0 \]
- The sum of all the potential differences encountered while moving around a loop or closed path is zero.
- This statement is known as **Kirchhoff’s loop law**.
The current through the 3 Ω resistor is

A. 9 A
B. 6 A
C. 5 A
D. 3 A
E. 1 A
The most basic electric circuit is a single resistor connected to the two terminals of a battery.

Figure (a) shows a literal picture of the circuit elements and the connecting wires.

Figure (b) is the circuit diagram.

This is a **complete circuit**, forming a continuous path between the battery terminals.
Analyzing the Basic Circuit

1. Draw a circuit diagram.

2. The orientation of the battery indicates a clockwise current, so assign a clockwise direction to $I$.

$$\Delta V_{\text{bat}} = +\mathcal{E}$$

$$\Delta V_{\text{res}} = -IR$$

3. Determine $\Delta V$ for each circuit element.
The figure shows two identical lightbulbs in a circuit.

The current through both bulbs is exactly the same!

It’s not the current that the bulbs use up, it’s energy.

The battery creates a potential difference, which supplies potential energy to the charges.

As the charges move through the lightbulbs, they lose some of their potential energy, transferring the energy to the bulbs.
The potential difference across the 10 Ω resistor is

A. 30 V
B. 20 V
C. 15 V
D. 10 V
E. 5 V
What things about the resistors in this circuit are the same for all three?

A. Current $I$.

B. Potential difference $\Delta V$.

C. Resistance $R$.

D. A and B.

E. B and C.
Electric Power

- The rate at which electric energy is depleted from a battery or dissipated (into heat or light) in a resistor is

\[ \text{Power} = I \Delta V \]
- The power supplied by a battery is:
  \[ P_{\text{bat}} = IE \] (power delivered by an emf)

- The units of power are J/s or W.

- The power dissipated by a resistor is:
  \[ P_R = \frac{dE_{\text{th}}}{dt} = \frac{dq}{dt} \Delta V_R = I \Delta V_R \]

- Or, in terms of the potential drop across the resistor:
  \[ P_R = I \Delta V_R = I^2R = \frac{(\Delta V_R)^2}{R} \] (power dissipated by a resistor)
A 90 Ω load is connected to a 120 V battery. How much power is delivered by the battery?

\[
I = \frac{120 \text{ V}}{90 \Omega} = 1.33 \text{ A}
\]

\[
P = (1.33 \text{ A})(120 \text{ V}) = 160 \text{ W}
\]
A current-carrying resistor dissipates power because the electric force does work on the charges.

The electric field causes electrons to speed up. The energy transformation is $U \rightarrow K$.

Collisions transfer energy to the lattice. The energy transformation is $K \rightarrow E_{th}$.
Which resistor dissipates more power?

A. The 9 Ω resistor.
B. The 1 Ω resistor.
C. They dissipate the same power.
Which has a larger resistance, a 60 W lightbulb or a 100 W lightbulb?

A. The 60 W bulb.
B. The 100 W bulb.
C. The resistances are the same.
D. There is not enough information to tell.

\[ P = \frac{(\Delta V)^2}{R} \]

with both used at \( \Delta V = 120 \, \text{V} \)
The power of light

How much current is “drawn” by a 100 W lightbulb connected to a 120 V outlet?

**MODEL** Most household appliances, such as a 100 W lightbulb or a 1500 W hair dryer, have a power rating. The rating does *not* mean that these appliances *always* dissipate that much power. These appliances are intended for use at a standard household voltage of 120 V, and their rating is the power they will dissipate *if* operated with a potential difference of 120 V. Their power consumption will differ from the rating if they are operated at any other potential difference.
The power of light

**SOLVE** Because the lightbulb is operating as intended, it will dissipate 100 W of power. Thus

\[ I = \frac{P_R}{\Delta V_R} = \frac{100 \text{ W}}{120 \text{ V}} = 0.833 \text{ A} \]

**ASSESS** A current of 0.833 A in this lightbulb transfers 100 J/s to the thermal energy of the filament, which, in turn, dissipates 100 J/s as heat and light to its surroundings.
Which bulb is brighter?

\[ P = I^2R \] and both have the same current.

A. The 60 W bulb.
B. The 100 W bulb.
C. The brightnesses are the same.
D. There is not enough information to tell.
In the two cases shown here a battery is connected up to a box containing some identical bulbs.
The battery maintains a constant potential difference $V_0$ across its terminals.
Which bulbs will be brighter?
1. A in #1
2. B in #1
3. A&B in #1 (equal)
4. A in #2
5. B in #2
6. A&B in #2 (equal)
7. All 4 equal
8. Other
This circuit has two identical light bulbs burning with equal brightness and a single 12 V battery. When the switch is closed, the brightness of bulb A

A. increases
B. decreases
C. decreases to 0
D. remains the same
Which of the bulbs in the following circuit is (are) the brightest?

A. A
B. B
C. C
D. D
E. B and C
F. A and D
G. Something else
H. You can’t tell from the information given