Purdue University Department of Physics

Physics 53600
Electronics Techniques for Research

Now in PowerPoint!

Spring 2020 Semester

Prof. Matthew Jones

Essential Information

- Course web page, whereat can be found the syllabus: http://www.physics.purdue.edu/~mjones/phys53600_Spring2020
- Basic information:
  - Class time: Tuesday and Thursday, 10:30 am – 11:45 am
  - Lecture: Electrical Engineering Bldg. 222
  - Lab: Physics Bldg. 346
- Text is recommended but not required. Suggested books are given on the web page.
- Grading scheme:
  - Assignments (30%), 3 exams (40%), lab (30%)
- More information (particularly on the lab) to follow…

Review of Maxwell's Equations

- Differential form:

$$\nabla \cdot \boldsymbol{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\nabla \times \boldsymbol{B} = \mu_0 \left(\boldsymbol{J} + \epsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} \right)$$

$$\epsilon_0 = 8.85 \times 10^{-12} \text{ F/m}$$

$$\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$$

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$$

Divergence Theorem and Stokes' Theorem

$$\int_V (\nabla \cdot \boldsymbol{E}) dv = \oint_S \boldsymbol{E} \cdot d\boldsymbol{a}$$

$$\int_S (\nabla \times \boldsymbol{B}) \cdot d\boldsymbol{a} = \oint_C \boldsymbol{B} \cdot d\boldsymbol{l}$$

Review of Maxwell's Equations

- Integral form:

$$\oint_{S} \boldsymbol{E} \cdot d\boldsymbol{a} = \frac{Q_{inside}}{\epsilon_0}$$

$$\oint_{S} \boldsymbol{B} \cdot d\boldsymbol{a} = 0$$

$$\oint_{C} \boldsymbol{E} \cdot d\boldsymbol{l} = -\frac{d\phi_m}{dt}$$

$$\oint_{C} \boldsymbol{B} \cdot d\boldsymbol{l} = \mu_0 I + \mu_0 \epsilon_0 \frac{d\phi_e}{dt}$$

Current and Flux

- Electric current:

$$I = \int_S \boldsymbol{J} \cdot d\boldsymbol{a}$$

- Electric flux:

$$\phi_e = \int_S \boldsymbol{E} \cdot d\boldsymbol{a}$$

- Magnetic flux:

$$\phi_m = \int_S \boldsymbol{B} \cdot d\boldsymbol{a}$$

Review of Maxwell's Equations

- Corollary: charge conservation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \boldsymbol{J} = 0$$

- Corollary: force on a charge

$$\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

- Quasi-static equilibrium:
  - No motion of charges on "short" time scales

Units

- We will almost universally use SI units:
  - Charge: Coulomb
  - Energy: Joules
  - Time: Second
  - Electric potential: Volts = Joules/Coulomb
  - Electric current: Amperes = Coulombs/second
  - Electric field: Volts/meter
  - Resistance: Ohms
  - Capacitance: Farads

Electric Potential

- Force on a charge in an electric field:

$$\boldsymbol{F} = q\ \boldsymbol{E}$$

- Infinitesimal element of work needed to move a charge through a small displacement $d\boldsymbol{l}$:

$$dW = -q\ \boldsymbol{E} \cdot d\boldsymbol{l}$$

- Work needed to move the charge from point A to point B:

$$\int_A^B dW = U_B - U_A = -q\ \int_A^B \boldsymbol{E} \cdot d\boldsymbol{l}$$

- Electric potential difference, $\Delta V = \Delta U / q$

Conductors

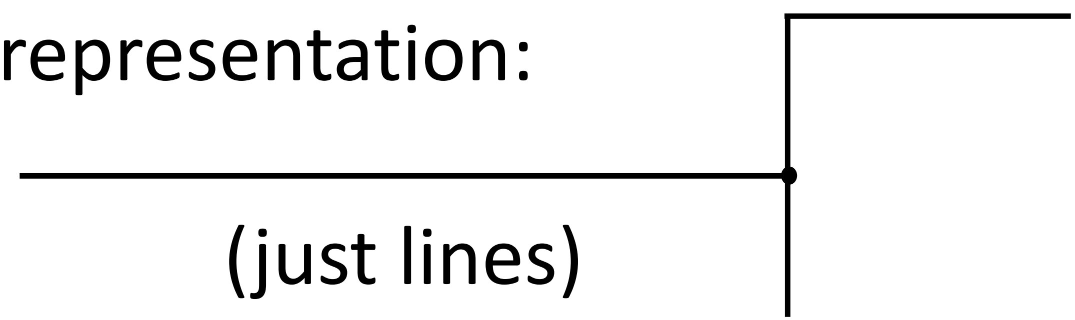
- Conductors are materials that contain *charge carriers* that can move
  - In metals, charge carriers are electrons
  - In solutions, charge carriers can be ions
  - In some crystals, charge carriers can be electrons or "holes"
- Is there an electric field in a conductor that is in a state of quasi-static equilibrium?

Conductors

- There is no electric field *inside* a conductor that is in a state of electrostatic equilibrium.
- Proof by contradiction:
  - Suppose it is in a state of quasi-static equilibrium
  - Suppose there was an electric field
  - It would exert a force on free charge carriers
  - They would then move
  - So it wouldn’t be in a state of quasi-static equilibrium
- Conductors can have a net charge, but it can only be present at the surface

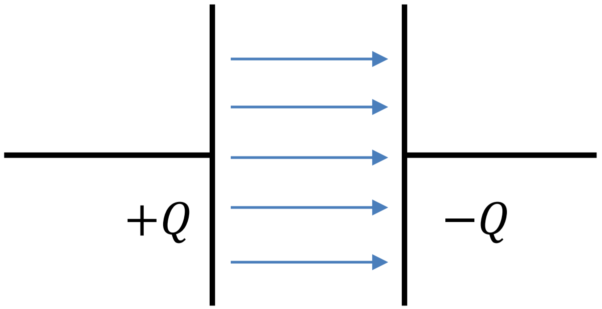
Conductors

- The electric potential at the surface of a conductor is constant
  - There is no electric field inside the conductor so it takes no work to move from one point on the surface to another point
- Schematic representation:



- Anything attached by lines is at the same electric potential.

Storing Energy in an Electric Field



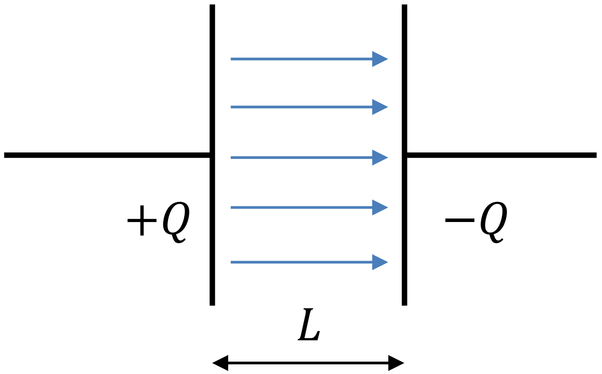
- Surface charge density:

$$\sigma = \frac{Q}{A}$$

- Electric field:

$$E = \frac{\sigma}{\epsilon_0}$$

Storing Energy in an Electric Field



- Work needed to move charge dQ from right to left:

$$dW = EL\,dq = \frac{QL}{\epsilon_0 A}\,dq$$

- Potential difference:

$$\Delta V = \frac{QL}{\epsilon_0 A}$$

Storing Energy in an Electric Field

- In general, moving a charge Q from one conductor to another conductor will induce a potential difference between them:

$$\Delta V = \frac{Q}{C}$$

- Parallel plate capacitor:

$$C = \frac{\epsilon_0 A}{L}$$

Storing Energy in an Electric Field

- How much energy is stored in the electric field?
- Work needed to charge a capacitor:

$$W = \int_0^Q \frac{q}{C}\,dq$$

$$= \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}C\,\Delta V^2$$

- This energy is stored in the electric field between the two capacitor plates

Constant Voltage Source

- With a capacitor, if we remove charge δq then the potential difference changes by

$$\delta(\Delta V) = \frac{\delta q}{C}$$

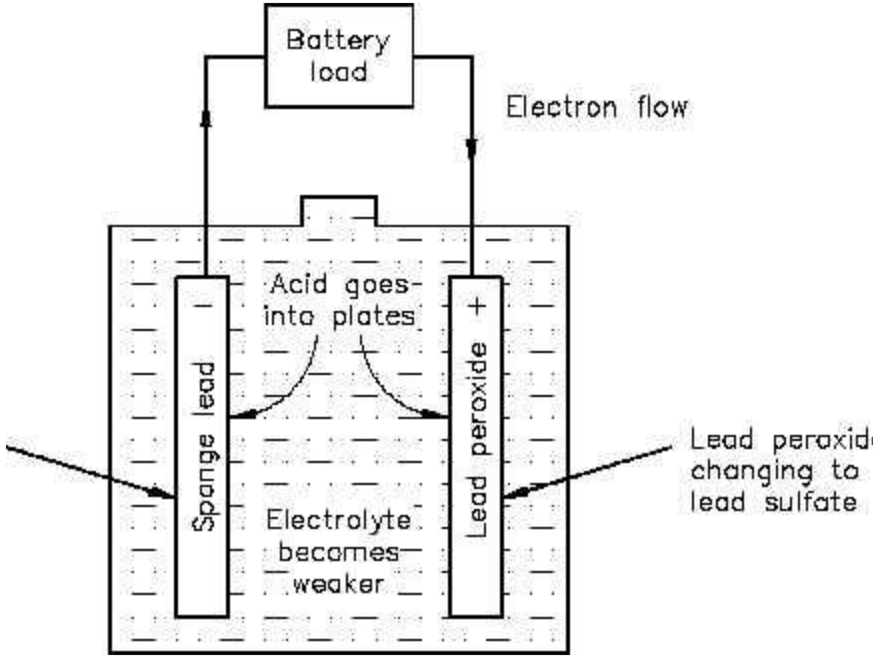
- If we had some way to replenish this charge, then the potential difference would remain constant
- A battery uses a chemical reaction to replenish the charge

Constant Voltage Source

- Lead-Acid battery cell:

$Pb + HSO_4^- \rightarrow PbSO_4 + H^+ + 2e^-$
(anode)

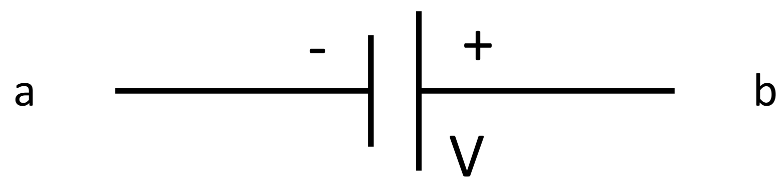
$PbO_2 + HSO_4^- + 3H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$
(cathode)



- If the electrons cannot be removed from the anode, then it develops an overall negative charge which repels the HSO_4^- ions and the reaction stops.

Constant Voltage Source

- Schematic symbol:



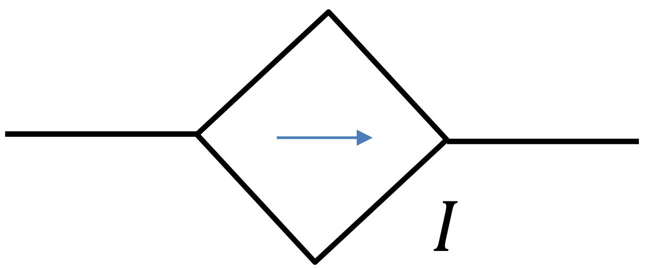
- Electrical potential:

$$V_b = V_a + V$$

- A constant voltage source produces the same potential difference, independent of the current

Constant Current Source

- A constant current source produces the same current, independent of the potential difference



Motion of Charges in Matter

- Empirical observation: the motion of charges through conductors dissipates heat
- The dissipation of heat reduces the electrical potential energy of charge carriers

$$P = I\,\Delta V$$

$$\Delta V = I\,R$$

(Ohm's law)

Microscopic Model

- The average velocity (drift velocity) of charge carriers is proportional to the electric field:

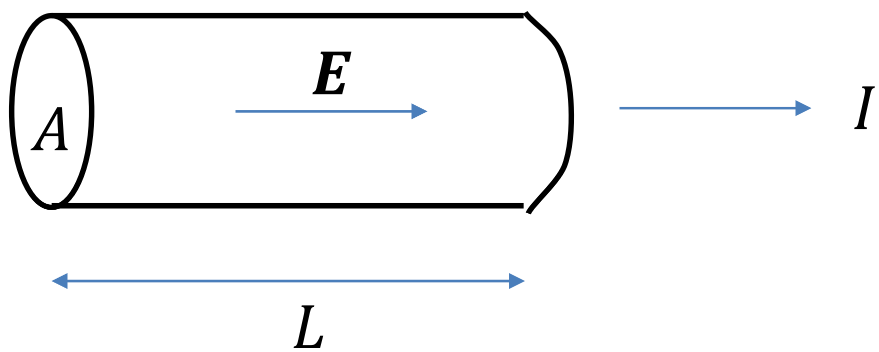
$$\boldsymbol{v} = \mu\, \boldsymbol{E}$$

- Current density:

$$\boldsymbol{J} = n\, q\, \mu\, \boldsymbol{E}$$

  - Charge carrier density: n
  - Carrier charge: q
  - Charge carrier mobility: μ
- The product, $n\, q\, \mu \equiv \sigma$, is called the conductivity.

Resistance



- Electric field in the material is constant:

$$E = \frac{\Delta V}{L}$$

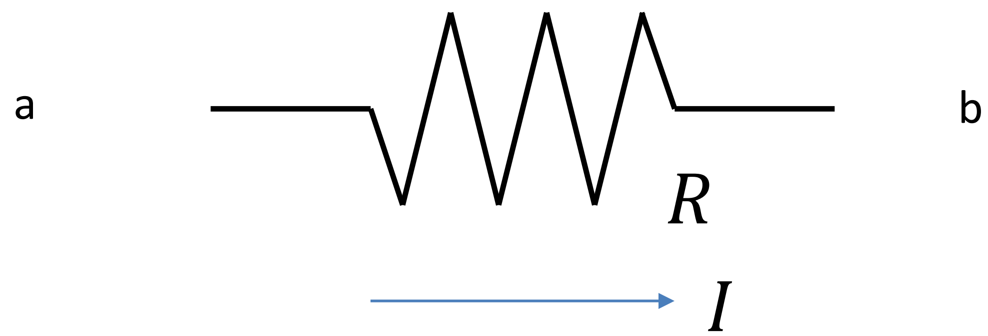
- Total current flowing through the material:

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

- Resistance, $R = L/\sigma A$

Resistance

- Schematic representation:



- Electrical potential:

$$V_b = V_a - IR$$

- Charge carriers lose electrical potential energy when flowing through the resistor

Circuits

- An “open circuit” is the same as an infinite resistance
  - No current can flow through an open circuit
- A “short circuit” is the same as zero resistance
  - There is no potential difference across a short circuit
- Most useful circuits allow current to flow through various circuit elements
- To conserve charge, current must flow in a loop

Circuits

- We are usually interested in determining the dependent quantities (current or voltage) in terms of the independent quantities (voltage or current)
- Next, we will develop a systematic set of rules for analyzing circuits.