PHY132H1F Introduction to Physics II
Class 13 – **Outline:**

- Kirchhoff's Loop Law
- Charging a capacitor
- Capacitance
- Equivalent capacitance of capacitors wired in parallel and series
- Energy of a capacitor
- Dielectrics
- Electric Current

FAIL
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Quick Ch. 30 reading quiz..

I have a capacitor whose capacitance is 1 Farad. This means

A. a current of 1 Amp flows through it when 1 Volt is applied across it.
B. 1 Coulomb is separated by 1 metre.
C. 1 Joule flows through it in 1 second.
D. it holds 1 Coulomb when 1 Volt is applied across it.
E. it attracts 1 Coulomb of charge with a force of 1 Newton.

Recall from last time: Batteries and emf

The electric potential difference between the terminals of an ideal battery is called its "emf".

"Electric potential difference" is also known as "voltage".

For example, a battery constructed to have an emf of 1.5V creates a 1.5 V potential difference between its positive and negative terminals.

The total potential difference of batteries in series is the sum of their individual potential differences:

$$\Delta V_{\text{series}} = \Delta V_1 + \Delta V_2 + \cdots \qquad \text{(batteries in series)}$$


In class discussion question
What total potential difference ($V_B - V_A$) is created by these three batteries?

A ─ | 3.0 V + | + 1.0 V − | − 3.0 V + | ─ B
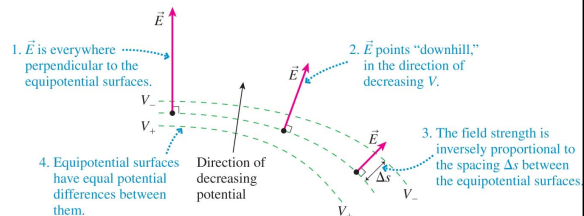
A. 1.0 V
B. 2.0 V
C. 5.0 V
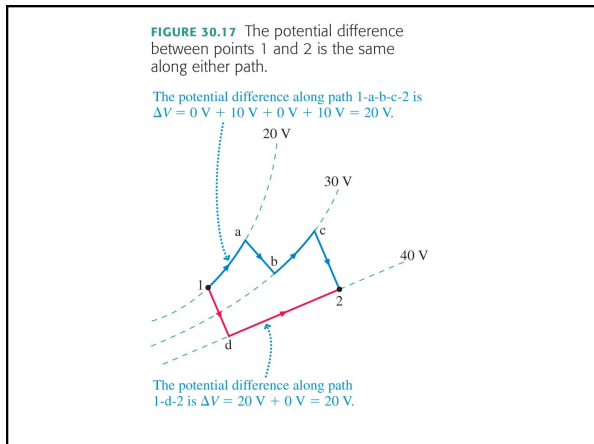D. 6.0 V
E. 7.0 V

The point:
- Electric Potential is a property of space.
- Every point has a certain value, and it must change from one side of a battery to another by its emf.
- Also, V is higher on the + side of a battery.

V=+3V   V=+2V   V=+5V

A ─ | 3.0 V + | + 1.0 V − | − 3.0 V + | B

Define this point to be V = 0
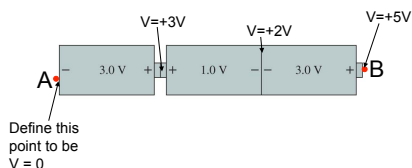
As you will explore in Practicals on Friday…

FIGURE 30.14 The geometry of the potential and the field.

1. $\vec{E}$ is everywhere perpendicular to the equipotential surfaces.

2. $\vec{E}$ points "downhill," in the direction of decreasing V.

3. The field strength is inversely proportional to the spacing Δs between the equipotential surfaces.

4. Equipotential surfaces have equal potential differences between them.

Direction of decreasing potential

1

FIGURE 30.17 The potential difference between points 1 and 2 is the same along either path.

The potential difference along path 1-a-b-c-2 is $\Delta V = 0 \text{ V} + 10 \text{ V} + 0 \text{ V} + 10 \text{ V} = 20 \text{ V}.$

20 V

30 V

a

c

b

40 V

1

2

d

The potential difference along path 1-d-2 is $\Delta V = 20 \text{ V} + 0 \text{ V} = 20 \text{ V}.$
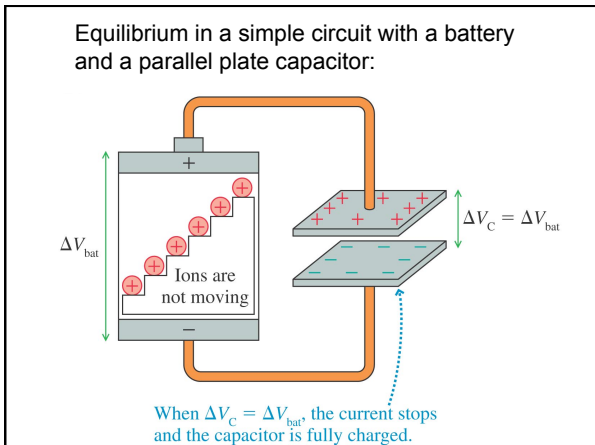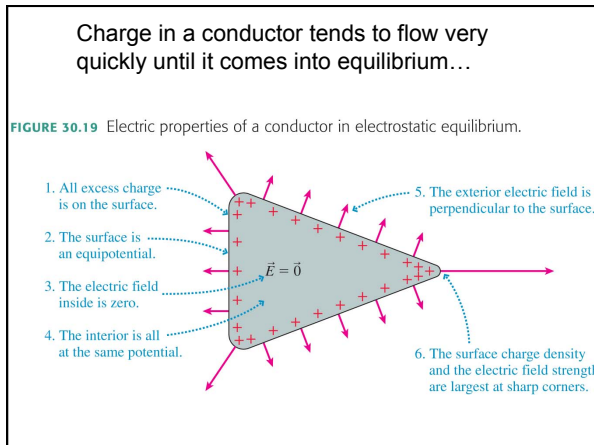
Kirchhoff's Loop Law

For any path that starts and ends at the same point

$$\Delta V_{\text{loop}} = \sum_i (\Delta V)_i = 0$$

Stated in words, **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 meaning is simply that **electric potential** is a property of *space*; it doesn't matter how you got there.)

Charge in a conductor tends to flow very quickly until it comes into equilibrium…

FIGURE 30.19 Electric properties of a conductor in electrostatic equilibrium.

1. All excess charge is on the surface.

2. The surface is an equipotential.

3. The electric field inside is zero.

4. The interior is all at the same potential.

$\vec{E} = \vec{0}$

5. The exterior electric field is perpendicular to the surface.

6. The surface charge density and the electric field strength are largest at sharp corners.

Equilibrium in a simple circuit with a battery and a parallel plate capacitor:

ΔV_{bat}

$\Delta V_{\text{C}} = \Delta V_{\text{bat}}$

+

−

Ions are not moving

When $\Delta V_{\text{C}} = \Delta V_{\text{bat}}$, the current stops and the capacitor is fully charged.
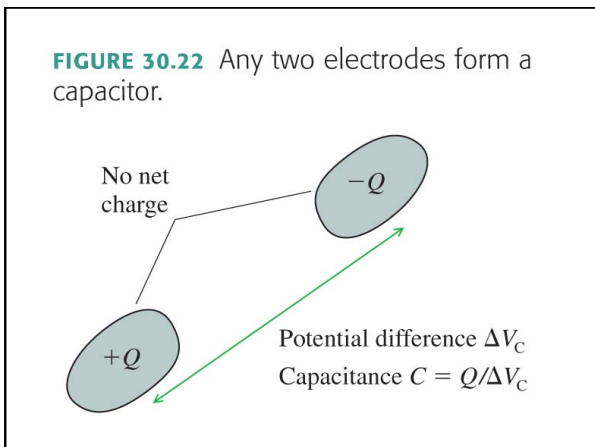
Capacitance and Capacitors

The ratio of the charge Q to the potential difference ΔV_{C} is called the **capacitance** C:
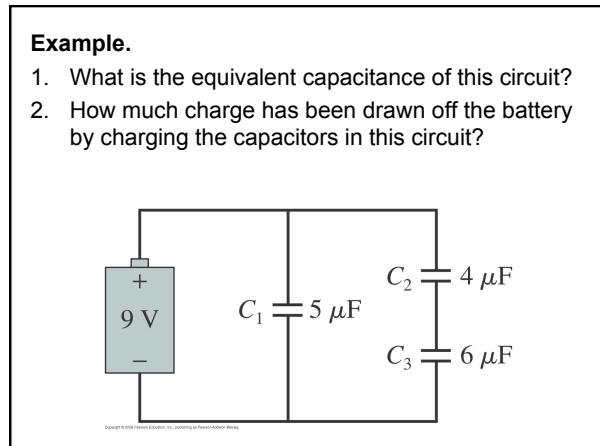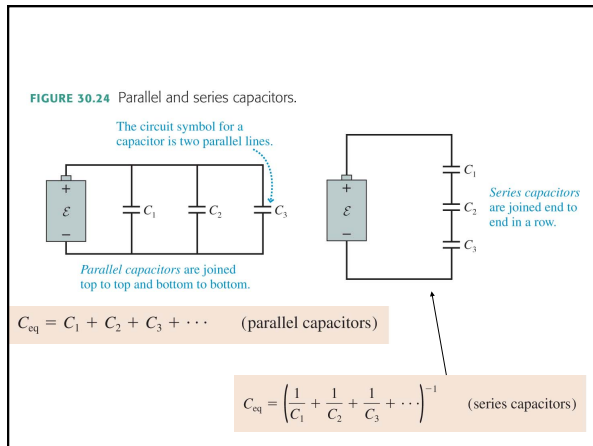
$$C \equiv \frac{Q}{\Delta V_{\text{C}}} = \frac{\epsilon_0 A}{d} \qquad \text{(parallel-plate capacitor)}$$

Capacitance is a purely *geometric* property of two electrodes because it depends only on their surface area and spacing. The SI unit of capacitance is the **farad**:
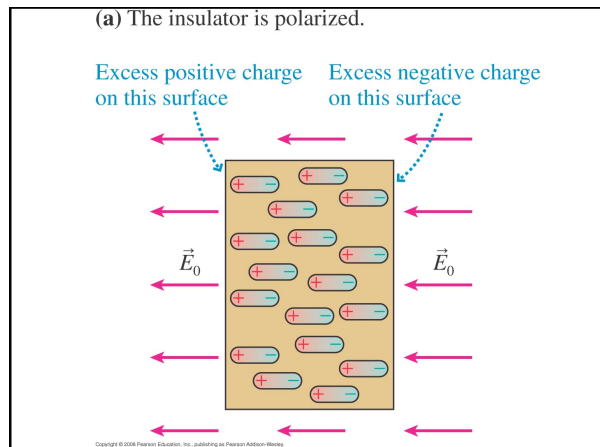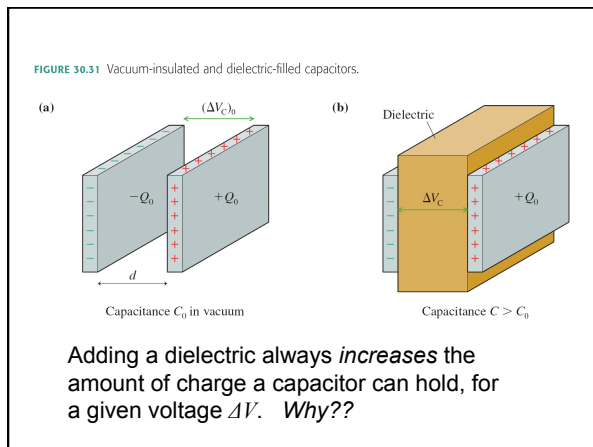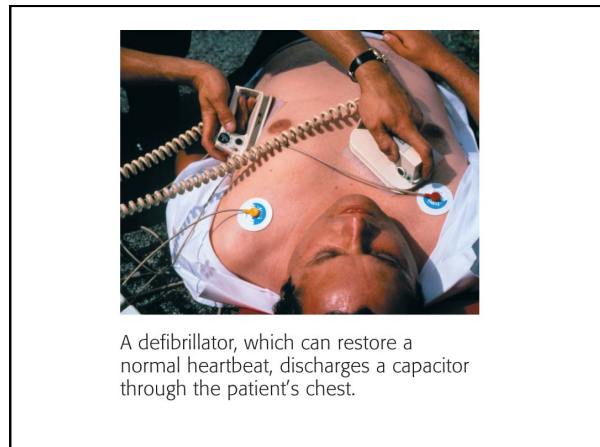 1 farad = 1 F = 1 C/V.
The charge on the capacitor plates is directly proportional to the potential difference between the plates.

$$Q = C\Delta V_{\text{C}} \qquad \text{(charge on a capacitor)}$$

FIGURE 30.22 Any two electrodes form a capacitor.

No net charge

$-Q$

$+Q$

Potential difference ΔV_{C}
Capacitance $C = Q/\Delta V_{\text{C}}$

FIGURE 30.24 Parallel and series capacitors.

The circuit symbol for a capacitor is two parallel lines.

$\mathcal{E}$ ... C_1 ... C_2 ... C_3

Parallel capacitors are joined top to top and bottom to bottom.

$\mathcal{E}$ ... C_1 ... C_2 ... C_3

Series capacitors are joined end to end in a row.

$$C_{eq} = C_1 + C_2 + C_3 + \cdots \quad \text{(parallel capacitors)}$$

$$C_{eq} = \left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots \right)^{-1} \quad \text{(series capacitors)}$$

Example.
1. What is the equivalent capacitance of this circuit?
2. How much charge has been drawn off the battery by charging the capacitors in this circuit?

9 V

$C_1 = 5\ \mu F$

$C_2 = 4\ \mu F$
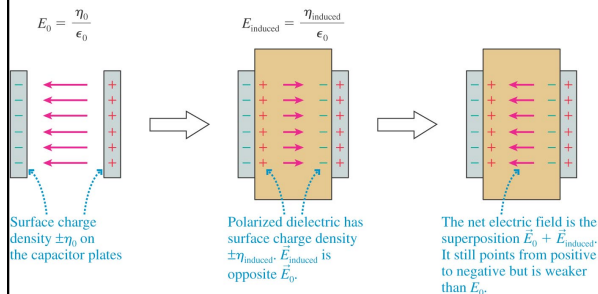
$C_3 = 6\ \mu F$

The Energy Stored in a Capacitor

- 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

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

A defibrillator, which can restore a normal heartbeat, discharges a capacitor through the patient's chest.

FIGURE 30.31 Vacuum-insulated and dielectric-filled capacitors.

(a)

$(\Delta V_C)_0$

$-Q_0$ ... $+Q_0$

d

Capacitance C_0 in vacuum

(b)

Dielectric

ΔV_C ... $+Q_0$

Capacitance $C > C_0$

Adding a dielectric always *increases* the amount of charge a capacitor can hold, for a given voltage ΔV.   *Why??*

(a) The insulator is polarized.

Excess positive charge on this surface

Excess negative charge on this surface

$\vec{E}_0$ ... $\vec{E}_0$

- When you add the dielectric, it reduces the electric field or voltage for the same charge.
- Therefore, it increases the amount of charge you can hold for a given voltage.

$E_0 = \dfrac{\eta_0}{\epsilon_0}$

$E_{induced} = \dfrac{\eta_{induced}}{\epsilon_0}$

Surface charge density $\pm\eta_0$ on the capacitor plates

Polarized dielectric has surface charge density $\pm\eta_{induced}$. $\vec{E}_{induced}$ is opposite $\vec{E}_0$.

The net electric field is the superposition $\vec{E}_0 + \vec{E}_{induced}$. It still points from positive to negative but is weaker than $\vec{E}_0$.

Dielectrics

- The dielectric constant, like density or specific heat, is a property of a material.
- Easily polarized materials have larger dielectric constants than materials not easily polarized.
- Vacuum has $\kappa = 1$ exactly.
- **Filling a capacitor with a dielectric increases the capacitance by a factor equal to the dielectric constant.**

$$C = \frac{Q}{\Delta V_C} = \frac{Q_0}{(\Delta V_C)_0/\kappa} = \kappa\frac{Q_0}{(\Delta V_C)_0} = \kappa C_0$$

Electric Current

- Pushing on the sea of electrons with an electric field causes the entire sea of electrons to move in one direction like a gas or liquid flowing through a pipe.

- This net motion, which takes place at the **drift speed** v_d, is superimposed on top of the random thermal motions of the individual electrons.

- The **current** is proportional to the number of charge carriers *per second* that pass through a cross section of a wire or other conductor.

In Class Discussion Question

Why does the light in a room come on almost instantly when you flip a switch several meters away?

A. Electrons travel at the speed of light through the wire.
B. The wire between the switch and the bulb is already full of electrons. Starting the flow of electrons from the switch into the wire almost immediately causes electrons to flow from the other end of the wire into the lightbulb.
C. The switch sends a radio signal which is received by a receiver in the light which tells it to turn on.
D. Optical fibers connect the switch with the light, so the light travels from switch to the light at the speed of light in an optical fiber.

Before Next Class:

- Try all the suggested end-of-chapter problems for Chapter 30, posted on the Materials part of the web-site.

- Please read Chapter 31 on Current and Resistance before Monday's class. This is where we finally learn *Ohm's Law!!*

- In Practicals on Friday you will be using a voltmeter to map equipotentials on special conductive paper.

See you Monday!