## Physics 202, Lecture 7

## Today's Topics

- About Exam 1
- Capacitance (Ch. 26-II)
- Review
- Energy storage in capacitors
- Dielectric materials, electric dipoles
- Dielectrics and Capacitance

Next lecture: More information about Exam 1. Current and Resistance (Ch. 27-I)

## About the First Midterm Exam

The exam will be on Monday Oct 1 at 5:30-7:00pm.
Rooms: 2650 and 3650 Humanities

- McBurney students: contact me for special arrangements.
- If conflicts with exam time due to an evening course:
- Stay tuned for special arrangements.
- Be sure to have informed me via email by Friday at the latest.
- An $81 / 2 \times 11^{\prime \prime}$ double-sided formula sheet is allowed.
- Has to be self prepared: hand written or printed, but no Xerox.

Bring a calculator: but do not use programming functionality.

- Absolutely no communication functionality will be allowed.

F Format: word problems. More about this Thursday.

## First Midterm Exam

Chapters Covered:- Chapter 23: Electric Fields
- Chapter 24: Gauss's Law
- Chapter 25: Electric Potential
- Chapter 26.1-26.3: Capacitance

Exceptions: you will not be responsible for the material covered in sections 24.5, 25.7, 25.8.
$\square$ Office hours: I will be available in my office ( 5215 CH ) on Friday afternoon, from 1-2:30, 3:30-5:30. TA's are also available in the helproom as always.Review sessions:

- Sunday, Sept 30, 1-3 PM, Rennebohm (this room)
- Saturday, Sept 29, 7 PM, place TBA


## Capacitors: Summary

- Definition:

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

- Capacitance depends on geometry:


Parallel Plates
$C=\frac{\varepsilon_{o} A}{d}$

Cylindrical

$$
C=\frac{2 \pi \varepsilon_{o} L}{\ln \left(\frac{b}{a}\right)}
$$



Spherical
$C=4 \pi \varepsilon_{o} \frac{a b}{b-a}$

C has units of "Farads" or $F$ ( $1 \mathrm{~F}=1 \mathrm{C} / \mathrm{V}$ ) $\varepsilon_{0}$ has units of $\mathrm{F} / \mathrm{m}$

## Capacitors in Series and Parallel

$\square$ Parallel:
Example: Ch. 26 \#27, 28 (board)

$\square$ Series: $C_{s}=\left(\frac{1}{C_{1}}+\frac{1}{C_{2}}\right)^{-1}$


## Energy of a Capacitor

- How much energy is stored in a charged capacitor?
- Calculate the work provided (usually by a battery) to charge a capacitor to $+/-Q$ :

Incremental work $d W$ needed to add charge $d q$ to capacitor at voltage $V$ :

$$
d W=V(q) \cdot d q=\left(\frac{q}{C}\right) \cdot d q
$$



- The total work $W$ to charge to $Q$ is then given by:



## Capacitor Variables

- The total work to charge capacitor to $Q$ equals the energy $U$ stored in the capacitor:

$$
U=\frac{1}{C} \int_{0}^{Q} q d q=\frac{1}{2} \frac{Q^{2}}{C}
$$

- In terms of the voltage $V$ :

$$
U=\frac{1}{2} C V^{2}
$$

You can do one of two things to a capacitor :


## Example (I)

- Suppose the capacitor shown here is charged to $Q$. The battery is then disconnected.

- Now suppose the plates are pulled further apart to a final separation $d_{1}$.
- How do the quantities $Q, C, E, V, U$ change?
- Q: remains the same.. no way for charge to leave.
- C: decreases.. capacitance depends on geometry
- $\boldsymbol{E}$ : remains the same... depends only on charge density
- $V$ : increases.. since $C \downarrow$, but $Q$ remains same (or $d \uparrow$ but $E$ the same)
- $\boldsymbol{U}$ : increases.. add energy to system by separating
- How much do these quantities change?.. See board.

Answers:

$$
C_{1}=\frac{d}{d_{1}} C
$$

$$
V_{1}=\frac{d_{1}}{d} V
$$

$$
U_{1}=\frac{d_{1}}{d} U
$$

## Example (II)

- Suppose the battery ( $V$ ) is kept attached to the capacitor.
- Again pull the plates apart from $d$ to $d_{1}$.

- Now what changes?
- $\boldsymbol{C}$ : decreases (capacitance depends only on geometry)
- $V$ : must stay the same - the battery forces it to be $V$
- Q: must decrease, $Q=C V$ charge flows off the plate
- $\boldsymbol{E}$ : must decrease $\left(E=\frac{V}{D}, E=\frac{\sigma}{E_{0}}\right)$
- U: must decrease ( $U=\frac{1}{2} C V^{2}$ )
- How much do these quantities change?.. See board.

Answers:

$$
C_{1}=\frac{d}{d_{1}} C
$$

$$
E_{1}=\frac{d}{d_{1}} E
$$

$$
U_{1}=\frac{d}{d_{1}} U
$$

## Where is the Energy stored?

- Claim: energy is stored in the electric field itself.
- Consider the example of a constant field generated by a parallel plate capacitor:

$$
\frac{\cdots \uparrow \uparrow \uparrow \uparrow T}{1+Q}+\frac{1}{2} \frac{Q^{2}}{C}=\frac{1}{2} \frac{Q^{2}}{\left(A \varepsilon_{0} / d\right)}
$$

- The electric field is given by:

$$
E=\frac{\sigma}{\varepsilon_{0}}=\frac{Q}{\varepsilon_{0} A} \quad \Rightarrow \quad U=\frac{1}{2} \varepsilon_{0} E^{2} A d
$$

- The energy density $u$ in the field is given by:

$$
u=\frac{U}{\text { volume }}=\frac{U}{A d}=\frac{1}{2} \varepsilon_{0} E^{2}
$$

Units: $\frac{J}{m^{3}}$

## Question

- A parallel plate capacitor is holding a charge q. The capacitor is not connected to a battery.
If plates are pulled apart, what happens to the stored energy?


## Increases

Decreases


Stays the same

## Arguments:

* volume increases, E same
* work done to it when
plates are being pulled apart

pull


## Dielectrics

- Empirical observation:

Inserting a non-conducting material (dielectric) between the plates of a capacitor changes the VALUE of the capacitance.

- Definition:

The dielectric constant of a material is the ratio of the capacitance when filled with the dielectric to that without it:

$$
\kappa=\frac{C}{C_{0}}
$$

$\kappa$ values are always > 1 (e.g., glass $=5.6$; water $=80$ )
INCREASE the capacitance of a capacitor
They permit more energy to be stored on a given capacitor:

$$
U^{\prime}=\frac{C V^{2}}{2}=\frac{\kappa C_{0} V^{2}}{2}=\kappa U
$$

## Dielectric Materials

Dielectrics are electric insulators:

- Charges are not freely movable, but can still have small displacements in an external electric field
- Atomic view: composed of permanent (or inducible) electric dipoles



## Electric Dipole in External E Field

$\square$ Electric dipole moment p.


Electric dipole moment in constant E field


| Net Force $\quad \sum \vec{F}=0$ |  |
| :--- | :--- |
| Net Torque | $\vec{\tau}=\vec{p} \times \vec{E}$ |
| Potential energy | $\mathrm{U}=-\vec{p} \bullet \vec{E}$ |

## Quick Quiz 1

$\square$ Which of the following configurations has the highest potential energy?

Points at $45^{\circ}$


Points towards the E field
$\rightarrow \quad$ Points against the E field


Points normal to the E field


## Quick Quiz 2

$\square$ An electric dipole moment initially points at $45^{\circ}$ with respect to the $x$ axis. When an external $E$ field in the positive $x$ direction is applied, what will happen?

No change

$\rightarrow \quad$ Points towards the E field


Points against the E field


Points normal to the E field


## Dielectrics In External Field

$\square$ Alignment of permanent dipoles in external field


Zero
© external field


Applying external $E$ field


Equilibrium

Induced field by non-permanent dipoles

Note: induced field always opposite to the external field $\mathrm{E}_{0}$

## Insert Dielectrics In Between Conductor Plates


(a)

(b)

## Parallel Plate Example Example: ch. 26 \#47 (board)

- Deposit a charge $Q$ on parallel plates filled with vacuum (air)-capacitance $C_{0}$
- Disconnect from battery

- The potential difference is $V_{0}=Q / C_{0}$.

Now insert material with dielectric constant $\kappa$.
Charge $Q$ remains constant
Capacitance increases $C=\kappa C_{0}$
Voltage decreases from $V_{0}$ to:

$$
V=\frac{Q}{C}=\frac{Q}{\kappa C_{0}}=\frac{V}{\kappa}
$$

Electric field decreases also:

$$
E=\frac{V}{d}=\frac{V_{0}}{d \kappa}=\frac{E_{0}}{\kappa}
$$

## Dielectric Constant For Various Materials

| Approximate Dielectric Constants and Dielectric Strengths of Various Materials at Room Temperature |  |  |
| :---: | :---: | :---: |
| Material | Dielectric Constant $\boldsymbol{\kappa}$ | Dielectric Strength ${ }^{\text {a }}$ $\left(10^{6} \mathrm{~V} / \mathrm{m}\right)$ $\left(10^{6} \mathrm{~V} / \mathrm{m}\right)$ |
| Air (dry) | 1.00059 | 3 |
| Bakelite | 4.9 | 24 |
| Fused quartz | 3.78 | 8 |
| Mylar | 3.2 | 7 |
| Neoprene rubber | 6.7 | 12 |
| Nylon | 3.4 | 14 |
| Paper | 3.7 | 16 |
| Paraffin-impregnated paper | 3.5 | 11 |
| Polystyrene | 2.56 | 24 |
| Polyvinyl chloride | 3.4 | 40 |
| Porcelain | 6 | 12 |
| Pyrex glass | 5.6 | 14 |
| Silicone oil | 2.5 | 15 |
| Strontium titanate | 233 | 8 |
| Teflon | 2.1 | 60 |
| Vacuum | 1.00000 | - |
| Water | 80 | - |

[^0]laws in the materials.
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## Use of Dielectric Material

$\square$ Non-conducting dielectric material can be inserted in between conductor ends to increase capacitance.


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[^0]:    The dielectric strength equals the maximum electric field that can exist in a dielectric without
    electrical breakdown. Note that these values depend strongly on the presence of impurities and

