Plan for Lecture 6:

1. Electrostatic capacitance (Chapter 26)
2. Voltage and capacitance in circuits
3. Energy storage in capacitors
i-clicker exercise
Exam feedback
A. Exam was too easy
B. Exam was too hard
C. Exam was about right

i-clicker exercise
Would you like to schedule a session to go over the exam?
A. Yes
B. No

i-clicker exercise
On the possibility of an optional 4th exam
A. Would like to take a 4th exam
B. Would not like to take a 4th exam
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<th>Topic</th>
<th>Text Sections</th>
<th>Problem Assignments</th>
<th>Assignment Due Date</th>
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<td>Coulomb's law</td>
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<td>02/28/2012</td>
<td>Exam</td>
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Remember to send in your chapter reading questions...
The Physics Department will host a reception for all prospective Physics majors on Monday, February 13 from 3-4:30 p.m. in the Olin foyer.

Wake Forest Research Fellowship Program  http://college.wfu.edu/research-fellowship/

Purpose
The Wake Forest Research Fellowship Program is designed to encourage individual Wake Forest undergraduates to join their professors as junior partners on scholarly research and creative projects. These mentored projects provide invaluable opportunities for students to experience the excitement of performing innovative scholarly work.

About the Award
These projects are performed during the 10 weeks of the Wake Forest University summer school sessions. The award provides a $4,000.00 stipend. If on-campus housing is desired, the award will also provide for one-half the cost of a double room for both summer sessions. So that students can devote their entire energies toward their projects, Wake Forest Research Fellowship recipients may not enroll in summer school courses. It is hoped that many projects begun in the Fellowship program might continue in the form of independent study or directed research courses in subsequent years.

If required for the work, the student and mentor may request up to $500 support for supplies.

Qualifications and Requirements
Student applicants must have a cumulative 3.0 grade point average at the time of application. Sophomore standing (25 or more hours passed) is required by the time the research project begins.

Proposals are due by February 22, 2012.
Electric potential for constant electric field:

\[ E = \frac{\sigma}{\varepsilon_0} \hat{i} \]

\[ V = -\int_{x_{ref}}^{x} E \cdot ds \]

\[ = -\int_{0}^{x} \frac{\sigma}{\varepsilon_0} dx' \]

\[ = -\frac{\sigma}{\varepsilon_0} x \quad \text{for} \quad 0 \leq x \leq d \]

\[ \Delta V = V(d) - V(0) = -\frac{\sigma}{\varepsilon_0} d \]

\[ \sigma = \frac{Q}{A} \quad \Rightarrow \Delta V = -Q \frac{d}{A \varepsilon_0} \]
Electric potential between parallel plates with charge $Q$.

The electric field $E$ between the plates is given by

$$E = \frac{\sigma}{\varepsilon_0} \hat{i}$$

The potential difference $\Delta V$ between the plates at $x=0$ and $x=d$ is

$$\Delta V = V(d) - V(0) = -\frac{\sigma}{\varepsilon_0} d$$

The charge density $\sigma$ is related to the charge $Q$ and area $A$ of the plates as

$$\sigma = \frac{Q}{A} \quad \Rightarrow \Delta V = -Q \frac{d}{A \varepsilon_0}$$

$$\Delta V = -\frac{Q}{A \varepsilon_0 / d} \equiv -\frac{Q}{C}$$

$$\Rightarrow C = A \varepsilon_0 / d$$
General formulation of capacitance

Ignoring sign:

\[ Q = C \Delta V \]

Charge on + and – terminals of capacitor

Voltage drop across capacitor terminals

Units:

\[ C = \frac{\text{Coulombs}}{\text{Volt}} \equiv \text{Farad} \]

For parallel plate capacitors in vacuum (or air):

\[ C = \frac{A \varepsilon_0}{d} \]

For parallel plate capacitors in dielectric medium:

\[ C = \frac{A \kappa \varepsilon_0}{d} \]

\( \kappa \equiv \text{dielectric constant (typically} \kappa > 1) \)
Cylindrical geometry capacitor:

\[ \mathbf{E} = \frac{Q}{2\pi \varepsilon_0 L} \hat{r} \quad \text{for} \quad a \leq r \leq b \]

\[ V_b - V_a = -\int_a^b \mathbf{E} \cdot d\mathbf{r} \]

\[ = -\frac{Q}{2\pi \varepsilon_0 L} \int_a^b \frac{dr}{r} \]

\[ = -\frac{Q}{2\pi \varepsilon_0 L} \ln \frac{b}{a} \]

\[ Q = C \Delta V \]

\[ \Rightarrow C = \frac{2\pi \varepsilon_0 L}{\ln(b/a)} \quad \text{(in vacuum or air)} \]

\[ \Rightarrow C = \frac{2\pi \kappa \varepsilon_0 L}{\ln(b/a)} \quad \text{(dielectric medium)} \]
Capacitor usage in energy storage:

http://www.mpoweruk.com/alternatives.htm
Questions about usefulness of electric fields outside of physics class.

Example: ipad touch screen (from HowThingsWork web page)
Electrical circuits using capacitors and voltage source

Capacitor symbol

Battery symbol

Switch symbol

Wire connection

\[ \Delta V = \frac{Q}{C} \]
More complicated circuits –
Capacitors connected in parallel

\[ \Delta V = \frac{Q_1}{C_1} = \frac{Q_2}{C_2} \equiv \frac{Q_{tot}}{C_{eq}} \]

\[ Q_{tot} = Q_1 + Q_2 = C_1 \Delta V + C_2 \Delta V \]

\[ (C_1 + C_2) \Delta V \]

\[ \Rightarrow C_{eq} = C_1 + C_2 \]
More complicated circuits – Capacitors connected in series

\[ \Delta V = \frac{Q_1}{C_1} + \frac{Q_2}{C_2} \equiv \frac{Q_{tot}}{C_{eq}} \]

\[ Q_{tot} = Q_1 = Q_2 = C_{eq} \Delta V \]

\[ C_{eq} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}} \]
Equivalent capacitance circuits

Parallel connections: \( C_{eq} = C_1 + C_2 + C_3 + \cdots \)

Series connections: \( C_{eq} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots} \)
i-clicker question
Consider the circuit diagrams shown below. In each the voltage is $\Delta V=100V$ and $C_1=C_2=1\mu F$. Which circuit can store the most total charge?

A. 

```
  +---+  +---+
  |  |   |  |
  +---+  +---+
```

B. 

```
  +---+  +---+  +---+
  |  |   |  |   |  |
  +---+  +---+  +---+
```

$\Delta V$
Energy storage within a capacitor

Electrons move from the plate to the wire, leaving the plate positively charged.

Separation of charges represents potential energy.

Electrons move from the wire to the plate.

Electric field in wire

Electric field between plates

Chemical potential energy in the battery is reduced.

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

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

$U = \frac{1}{2} C (\Delta V)^2$
Effects of dielectric materials in capacitors

The charged edges of the dielectric can be modeled as an additional pair of parallel plates establishing an electric field $\vec{E}_{\text{ind}}$ in the direction opposite that of $\vec{E}_0$.

\[ E_{\text{total}} = E_0 - E_{\text{ind}} \]
\[ E_{\text{ind}} = \kappa E_{\text{total}} \]
\[ E_{\text{total}} = \frac{1}{1 + \chi} E_0 \equiv \frac{1}{\kappa} E_0 \]
\[ \Delta V_{\text{total}} = \frac{1}{\kappa} \Delta V_0 = \frac{Q}{\kappa C_0} \]
\[ \Rightarrow C = \kappa C_0 \]
A tubular capacitor whose plates are separated by paper and then rolled into a cylinder.

A high-voltage capacitor consisting of many parallel plates separated by insulating oil.

An electrolytic capacitor.

- Plates
- Oil
- Metallic foil + oxide layer
- Case
- Electrolyte
- Contacts
Example:

Find equivalent capacitance:

\[ C_{eq} = \frac{1}{\frac{1}{8} + \frac{1}{6+2} + \frac{1}{8}} \mu F = \frac{8}{3} \mu F \]

Find total charge:

\[ Q = C_{eq} \Delta V = \frac{8}{3} \times 10^{-6} \cdot 9 \text{ Coul} = 2.4 \times 10^{-5} \text{ Coul} \]
### Table 26.1: Approximate Dielectric Constants and Dielectric Strengths of Various Materials at Room Temperature

<table>
<thead>
<tr>
<th>Material</th>
<th>Dielectric Constant $\kappa$</th>
<th>Dielectric Strength$^a$ (10$^6$ V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air (dry)</td>
<td>1.000 59</td>
<td>3</td>
</tr>
<tr>
<td>Bakelite</td>
<td>4.9</td>
<td>24</td>
</tr>
<tr>
<td>Fused quartz</td>
<td>3.78</td>
<td>8</td>
</tr>
<tr>
<td>Mylar</td>
<td>3.2</td>
<td>7</td>
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<tr>
<td>Neoprene rubber</td>
<td>6.7</td>
<td>12</td>
</tr>
<tr>
<td>Nylon</td>
<td>3.4</td>
<td>14</td>
</tr>
<tr>
<td>Paper</td>
<td>3.7</td>
<td>16</td>
</tr>
<tr>
<td>Paraffin-impregnated paper</td>
<td>3.5</td>
<td>11</td>
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<tr>
<td>Polystyrene</td>
<td>2.56</td>
<td>24</td>
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<tr>
<td>Polyvinyl chloride</td>
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<td>Porcelain</td>
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<td>Pyrex glass</td>
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<td>Silicone oil</td>
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<td>Strontium titanate</td>
<td>233</td>
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<td>Teflon</td>
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<tr>
<td>Vacuum</td>
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<tr>
<td>Water</td>
<td>80</td>
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</table>

$^a$The dielectric strength equals the maximum electric field that can exist in a dielectric without electrical breakdown. These values depend strongly on the presence of impurities and flaws in the materials.