

PHYS 1441 – Section 002

Lecture #12

Monday, Oct. 12, 2020

Dr. Jaehoon Yu

- CH24

- Electric Energy Storage
- Effect of Dielectric
- Molecular description of Dielectric Material



Announcements

- Online Mid-term comprehensive exam on Quest
 - In class Monday, Oct. 19
 - Covers: CH21.1 through what we finish Wednesday, Oct. 14 + math refresher
 - BYOF: You may bring a one 8.5x11.5 sheet (front and back) of handwritten formulae and values of constants for the exam
 - No derivations, word definitions, setups or solutions of any problems, figures, pictures, diagrams or arrows, etc!
 - No additional formulae or values of constants will be provided!
 - Must send me the photos of front and back of the formula sheet, including the blank, no later than 11am the day of the exam
 - Once submitted, you cannot change, unless I ask you to delete some part of the sheet!
- Quiz 2 results
 - Class average: 35.5/60 → equivalent to 58.8/100 (Q1: 80.3/100)
 - Top score: 60/60
- Special seminar on COVID – 19: 3:30pm Sunday, Oct. 25
 - Dr. Linda Lee
 - Extra credit for participating in the seminar and asking a relevant question

Monday, Oct. 12, 2020



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Reminder: SP#3 – Civic Duty I: Voter Registration

- **Voter registration in Texas ends on Monday, Oct. 5, 2020**
 - Registration can be done: <https://www.votetexas.gov/register/index.html>
 - Check your registration: <https://teamrv-mvp.sos.texas.gov/MVP/mvp.do>
- For those who are legal to take part in the election
 - Your own registration to vote: 10 points
 - Include the screen shot your own voter registration check
 - You can have up to 3 more people who are not registered to register: 5 points each
 - Must include before and after the registration screen shots of the same person next to each other to show these are newly registered
- For those who are not legal to take part in the election
 - You can have up to 5 people who are not registered to register: 5 points each
 - Must include before and after the registration screen shots of the same person next to each other to show these are newly registered
- **Deadline: 1pm Wednesday, Oct. 14, 2020 ← Note extended deadline**
- Put all screen shots in one pdf file following the naming convention – SP3-LastName-FirstName-Fall20.pdf and upload to the CANVAS assignment

Monday, Oct. 12, 2020



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SP#3 – Civic Duty I: Voter Registration – 2

TEXAS SECRETARY OF STATE



AM I REGISTERED?
TEXAS ELECTIONET ADMINISTRATION SYSTEM

Voter Information

Name: JAEHOON YU



Gender: MALE

Valid From: 01/01/2020

Effective Date of Registration: 05/20/2004

Voter Status: ACTIVE

County: TARRANT

Precinct: 2266

VUID: 1050748339

[Change your Address](#)

Upcoming Elections (Select Election for available polling information)

11/03/2020--2020 NOVEMBER 3RD GENERAL ELECTION

***Eligibility is determined by Effective Date of Registration (Must be on or before Election Day)

Monday, Oct. 12, 2020



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SP#5 – Civic Duty II: Election Participation

- Election on Nov. 3 with early voting Tue. Oct. 13 – Fri. Oct. 30
- For those with legal voting rights: You can submit three access code green sheet for 20 points total – one your own and two others who voted, 5 points each. Any additional ones will earn 2 points each
- For those without legal voting rights: You can submit for the first four access code green sheets for 20 points total, 5 points each and any additional combinations 2 points each.
- Be sure to tape one side of the stickers on a sheet of paper with your name on it.
 - Write the full name of the person next to the corresponding access code sheet
- None of the stickers can be from the same person on someone else's extra credit or on your own. All of those with any of the identical persons on your extra credit sheet will get 0 credit.
- Deadline: Beginning of the class **Monday, Nov. 9**



Access code sheet

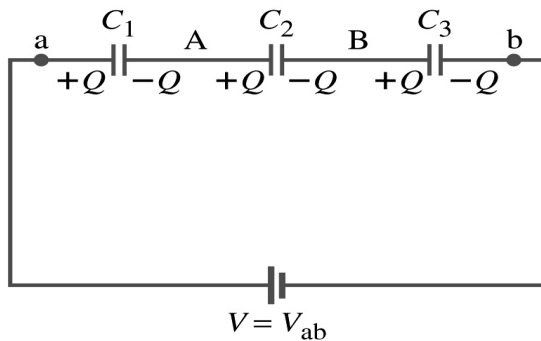


Recap: Capacitor Combinations

- Capacitance

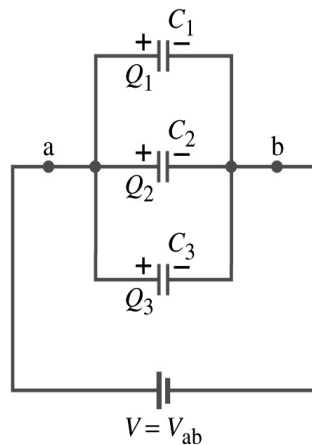
$$C = \frac{Q}{V_{ba}} = \frac{Q}{Qd/\epsilon_0 A} = \frac{\epsilon_0 A}{d}$$

- Series Combinations



$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

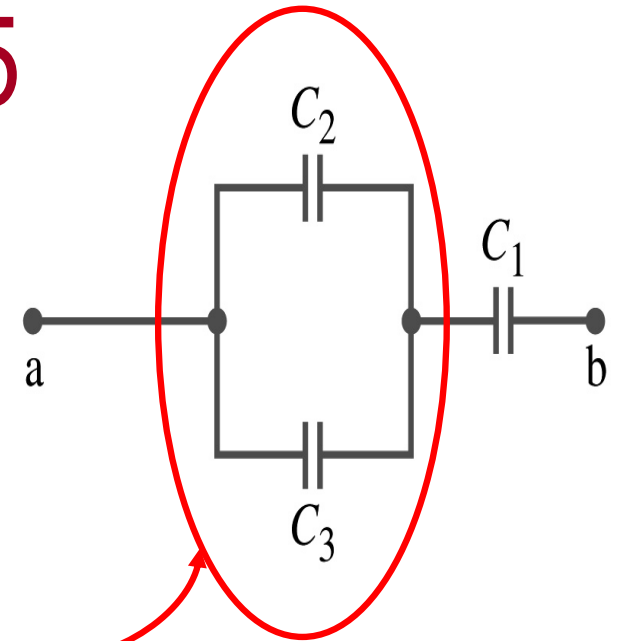
- Parallel Combinations



$$C_{eq} = C_1 + C_2 + C_3$$

Example 24 – 5

Equivalent Capacitor: Determine the capacitance of a single capacitor that will have the same effect as the combination shown in the figure. Take $C_1 = C_2 = C_3 = C$.



We should do these first!!

How? These are in parallel so the equivalent capacitance is:

$$C_{eq1} = C_1 + C_2 = 2C$$

Now the equivalent capacitor is in series with C_1 .

$$\frac{1}{C_{eq}} = \frac{1}{C_{eq1}} + \frac{1}{C_2} = \frac{1}{2C} + \frac{1}{C} = \frac{3}{2C} \quad \xrightarrow{\text{Solve for } C_{eq}} \quad C_{eq} = \frac{2C}{3}$$

Electric Energy Storage

- A charged capacitor stores energy.
 - The stored energy is the amount of the work done to charge it.
- The net effect of charging a capacitor is removing one type of charge from one plate and putting them on to the other.
 - Battery does this when it is connected to a capacitor.
- Capacitors do not get charged immediately.
 - Initially when the capacitor is uncharged, no work is necessary to move the first bit of charge. Why?
 - Since there is no charge, there is no field that the external work needs to overcome.
 - When some charge is on each plate, it requires work to add more charge due to the electric repulsion.

Electric Energy Storage

- The work needed to add a small amount of charge, dq , when a potential difference across the plates is V : $dW=Vdq$.
- Since $V=q/C$, the work needed to store total charge Q is

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

- Thus, the energy stored in a capacitor when the capacitor carries the charges $+Q$ and $-Q$ is

$$U = \frac{Q^2}{2C}$$

- Since $Q=CV$, we can rewrite

$$U = \frac{Q^2}{2C} = \frac{1}{2} CV^2 = \frac{1}{2} QV$$

Example 24 – 8

Energy store in a capacitor: A camera flash unit stores energy in a $150\mu\text{F}$ capacitor at 200V . How much electric energy can be stored?

Using the formula for stored energy. Umm.. Which one?

What do we know from the problem? C and V

So we use the one with C and V: $U = \frac{1}{2}CV^2$

$$U = \frac{1}{2}CV^2 = \frac{1}{2}(150 \times 10^{-6} \text{ F})(200\text{V})^2 = 3.0\text{J}$$

How do we get J from FV^2 ? $FV^2 = \left(\frac{C}{V}\right)V^2 = CV = C\left(\frac{J}{C}\right) = J$

Electric Energy Density

- The energy stored in a capacitor can be considered as being stored in the electric field between the two plates
- For a uniform field **E** between two plates, **V=Ed** and **C=ε₀A/d**
- Thus the stored energy is

$$U = \frac{1}{2} CV^2 = \frac{1}{2} \left(\frac{\epsilon_0 A}{d} \right) (Ed)^2 = \frac{1}{2} \epsilon_0 E^2 \textcolor{red}{Ad}$$

- Since *Ad* is the gap volume **V**, we can obtain the energy density, stored energy per unit volume, as

$$u = \frac{1}{2} \epsilon_0 E^2$$

**Valid for any space
that is vacuum**

Electric energy stored per unit volume in any region of space is proportional to the square of E in that region.

Dielectrics

- Capacitors have an insulating sheet of material, called the dielectric, between the plates to
 - Increase breakdown voltage greater than that in air (**3MV/m**)
 - Apply higher voltage to the gap without the charge passing across
 - Allow the plates get closer together without touching
 - Increases capacitance (recall **$C = \epsilon_0 A/d$**)
 - Increase the capacitance by the dielectric constant
$$C = KC_0$$
 - Where **C_0** is the intrinsic capacitance when the gap is vacuum

Dielectrics

- The value of dielectric constant K varies depending on the material (Table 24 – 1)
 - K for vacuum is 1.0000
 - K for air is 1.0006 (this is why the permittivity of air and vacuum are used interchangeably.)
 - K for paper is 3.7
- Maximum electric field before breakdown occurs is called the dielectric strength. What is its unit? (poll3)
 - V/m
- The capacitance of a parallel plate capacitor with a dielectric (K) filling the gap is

$$C = KC_0 = K\epsilon_0 \frac{A}{d}$$

Dielectrics

- A new quantity of the permittivity of a dielectric material is defined as $\epsilon = K\epsilon_0$
- The capacitance of a parallel plate capacitor with a dielectric medium filling the gap is

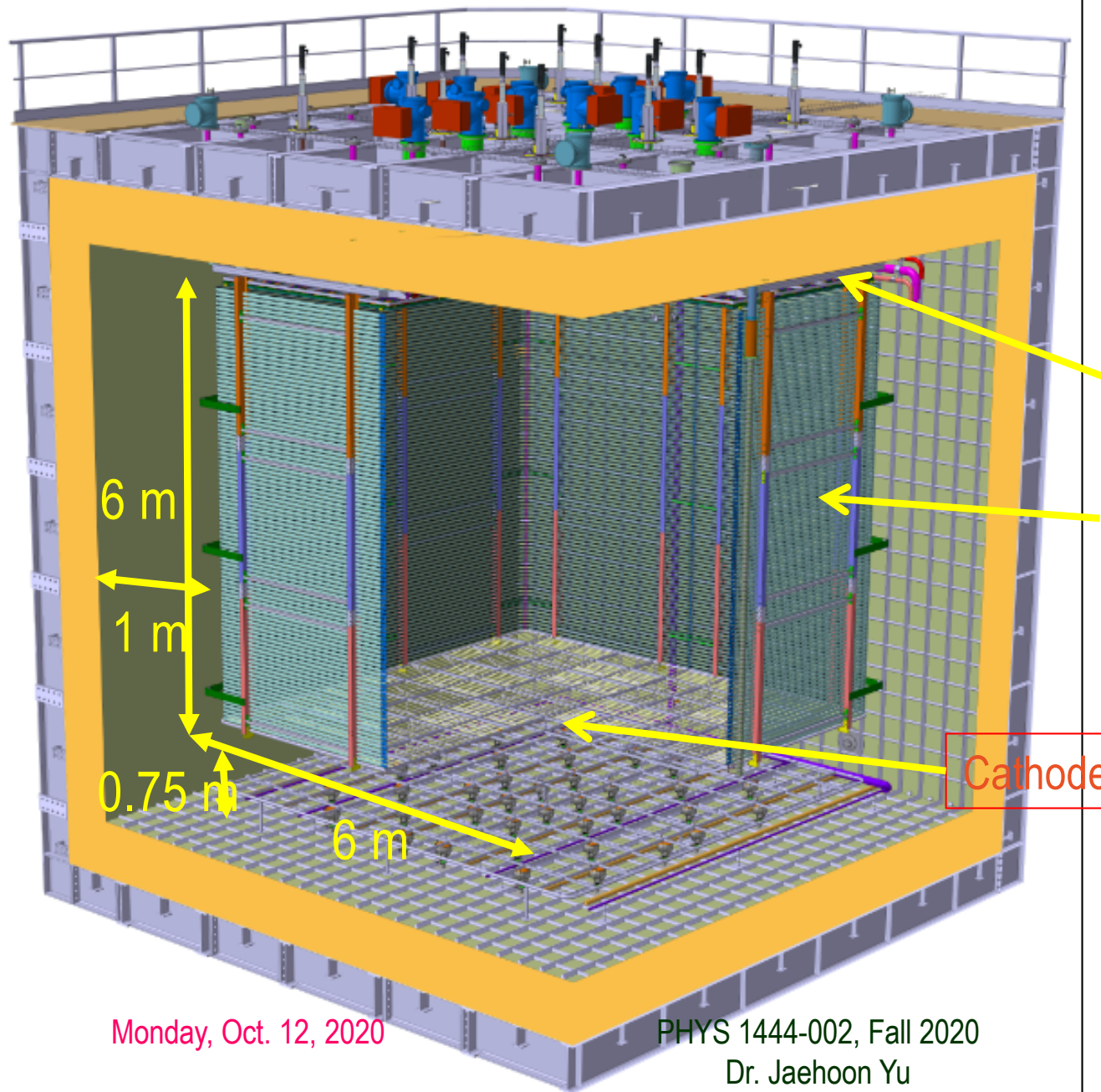
$$C = \epsilon \frac{A}{d}$$

- The energy density stored in an electric field E in a dielectric is

$$u = \frac{1}{2} K \epsilon_0 E^2 = \frac{1}{2} \epsilon E^2$$

Valid for any space w/ dielectric w/ permittivity ϵ .

ProtoDUNE Dual Phase

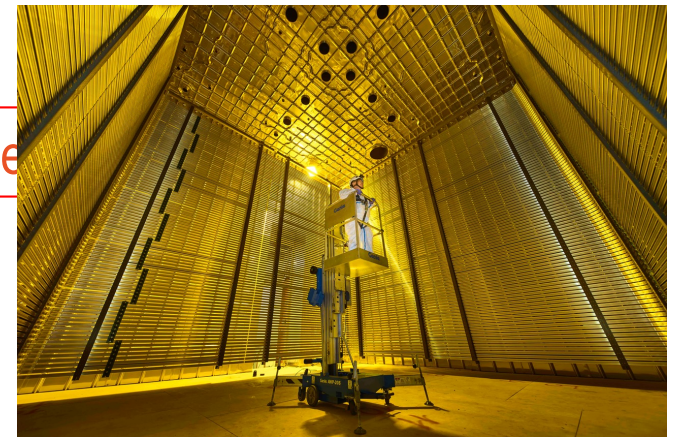


- Calculate the capacitance between each of the side wall to the FC & the cathode to the ground grid
- Calculate the total energy stored in the capacitors
- $\epsilon_{\text{LAr}} = 1.4 \epsilon_0$

Charge Readout Planes

Field Cage (common structural elements with SP)

Cathode



Monday, Oct. 12, 2020

PHYS 1444-002, Fall 2020
Dr. Jaehoon Yu

Effect of a Dielectric Material on Capacitance

- Let's consider the two cases below:

Case #1 :
constant V

$$V_0 \begin{array}{|c|} \hline \text{no dielectric} \\ \hline \end{array} \begin{array}{l} +Q_0 \\ -Q_0 \end{array} C_0 = \frac{Q_0}{V_0} \longrightarrow V_0 \begin{array}{|c|} \hline \text{with dielectric} \\ \hline \end{array} \begin{array}{l} +Q_0 = +KQ_0 \\ -Q_0 = -KQ_0 \end{array} C = \frac{Q}{V_0} = KC_0$$

(a) Voltage constant

Case #2 :
constant Q

$$V_0 \begin{array}{|c|} \hline \text{no dielectric} \\ \hline \end{array} \begin{array}{l} +Q_0 \\ -Q_0 \end{array} C_0 = \frac{Q_0}{V_0} \longrightarrow \begin{array}{l} +Q_0 \\ -Q_0 \end{array} \Big| V_0, C_0 = \frac{Q_0}{V_0} \longrightarrow \begin{array}{l} +Q_0 \\ -Q_0 \end{array} \Big| V = \frac{V_0}{K} \quad C = KC_0$$

(b) Charge constant

- Constant voltage: Experimentally observed that the total charge on each plate of the capacitor increases by **K** as a dielectric material is inserted between the gap $\rightarrow Q = KQ_0$
 - The capacitance increased to $C = Q/V_0 = KQ_0/V_0 = KC_0$
- Constant charge: Voltage found to drop by a factor **K** $\rightarrow V = V_0/K$
 - The capacitance increased to $C = Q_0/V = KQ_0/V_0 = KC_0$

Effect of a Dielectric Material on Field

- What happens to the electric field within a dielectric?
- Without a dielectric, the field is
 - What are V_0 and d ?
 - V_0 : Potential difference between the two plates
 - d : separation between the two plates
- For the constant voltage, the electric field remains the same
- For the constant charge: the voltage drops to **$V=V_0/K$** , thus the field in the dielectric is
 - The field in the dielectric is reduced.

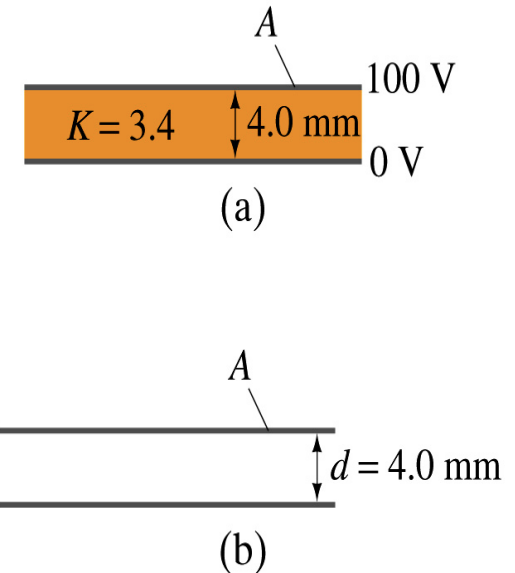
$$E_0 = \frac{V_0}{d}$$

$$E = E_D = \frac{V}{d} = \frac{V_0}{dK} = \frac{E_0}{K}$$

$$E_D = \frac{E_0}{K}$$

Example 24 – 11

Dielectric Removal: A parallel-plate capacitor, filled with the dielectric of $K=3.4$, is connected to a 100-V battery. After the capacitor is fully charged, the battery is disconnected. The plates have area $A=4.0\text{m}^2$, and are separated by $d=4.0\text{mm}$. (a) Find the capacitance, the charge on the capacitor, the electric field strength, and the energy stored in the capacitor. (b) The dielectric is carefully removed, without changing the plate separation nor does any charge leaving the capacitor. Find the new value of capacitance, electric field strength, voltage between the plates and the energy stored in the capacitor.



$$(a) \quad C = \frac{\epsilon A}{d} = \frac{K \epsilon_0 A}{d} = \left(3.4 \times 8.85 \times 10^{-12} \text{ C}^2 / \text{N} \cdot \text{m}^2\right) \frac{4.0 \text{ m}^2}{4.0 \times 10^{-3} \text{ m}} = 3.0 \times 10^{-8} \text{ F} = 30 \text{ nF}$$

$$Q = CV = (3.0 \times 10^{-8} \text{ F}) \times 100 \text{ V} = 3.0 \times 10^{-6} \text{ C} = 3.0 \mu\text{C}$$

$$E = \frac{V}{d} = \frac{100 \text{ V}}{4.0 \times 10^{-3} \text{ m}} = 2.5 \times 10^4 \text{ V/m}$$

$$U = \frac{1}{2} CV^2 = \frac{1}{2} (3.0 \times 10^{-8} \text{ F}) (100 \text{ V})^2 = 1.5 \times 10^{-4} \text{ J}$$

Example 24 – 11 cont'd

- (b) Since the dielectric has been removed, the effect of dielectric constant must be removed as well.

$$C_0 = \frac{C}{K} = \left(8.85 \times 10^{-12} \text{ C}^2 / \text{N} \cdot \text{m}^2\right) \frac{4.0 \text{ m}^2}{4.0 \times 10^{-3} \text{ m}} = 8.8 \times 10^{-9} \text{ F} = 8.8 \text{ nF}$$

Since charge is the same ($Q_0 = Q$) before and after the removal of the dielectric, we obtain

$$V_0 = Q/C_0 = K Q/C = KV = 3.4 \times 100 \text{ V} = 340 \text{ V}$$

$$E_0 = \frac{V_0}{d} = \frac{340 \text{ V}}{4.0 \times 10^{-3} \text{ m}} = 8.5 \times 10^4 \text{ V/m} = 84 \text{ kV/m}$$

$$U_0 = \frac{1}{2} C_0 V_0^2 = \frac{1}{2} \frac{C}{K} (KV)^2 = \frac{1}{2} K C V^2 = KU = 3.4 \times 1.5 \times 10^{-4} \text{ J} = 5.1 \times 10^{-4} \text{ J}$$

Where did the extra energy come from?

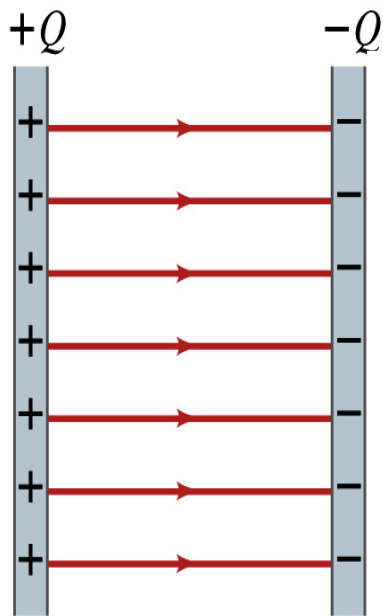
~~The energy conservation law is violated in electrostatics??~~

Wrong!
Wrong!
Wrong!

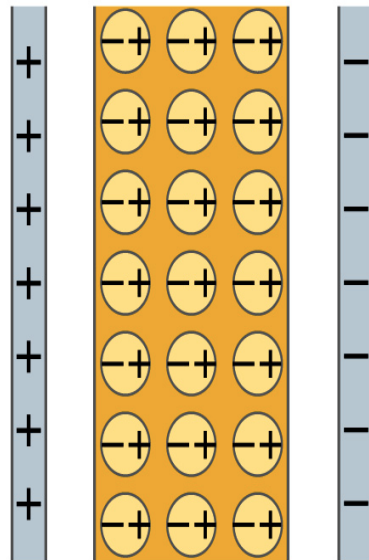
An external force has done the work of $3.6 \times 10^{-4} \text{ J}$ on the system to remove dielectric!!

Molecular Description of Dielectric

- So what in the world makes dielectrics behave the way they do?
- We need to examine this in a microscopic scale.
- Let's consider a parallel plate capacitor that is charged up $+Q(=C_0V_0)$ and $-Q$ with air in between.
 - Assume there is no way any charge can flow in or out



(a)

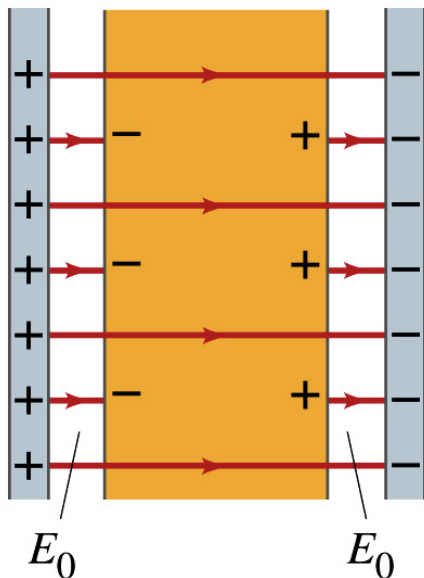


(b)

- Now insert a dielectric
 - Dielectric can be polar → could have permanent dipole moment. What will happen?
- Due to the electric field molecules will be aligned.

Molecular Description of Dielectric

- OK. Then what happens?
- Then effectively, there will be some negative charges close to the surface of the positive plate and positive charge on the negative plate
 - Some electric field do not pass through the whole dielectric but stops at the negative charge



(c)

Monday, Oct. 12, 2020



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Dr. Jaehoon Yu

- So the field inside dielectric is smaller than in air
- Since electric field is smaller, the force is smaller
 - The work need to move a test charge inside the dielectric is smaller
 - Thus the potential difference across the dielectric is smaller than across the air