PHY294H

- Professor: Joey Huston
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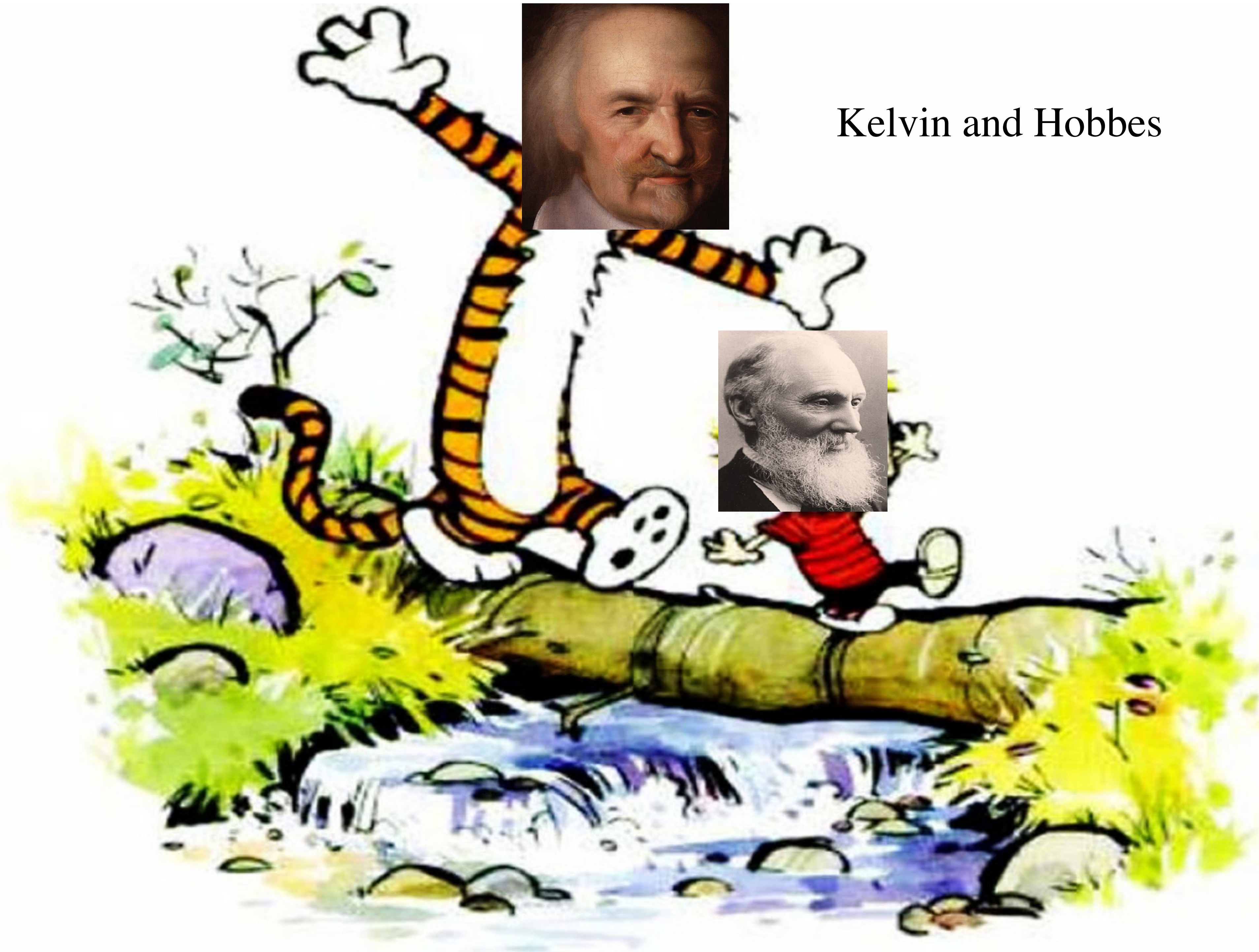
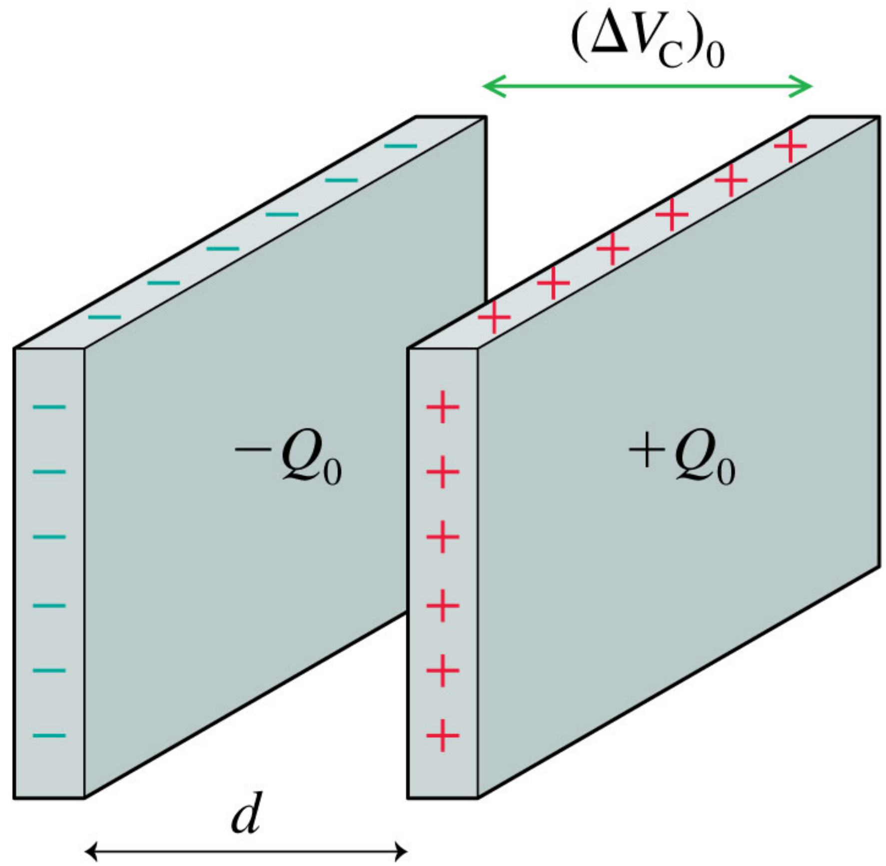
- Homework will be with Mastering Physics (and an average of 1 hand-written problem per week)
  - **Problem 29.78 (already assigned) will be the hand-in problem for 4th MP assignment (due Wed Feb. 10)**
  - **Help-room hours: 12:40-2:40 Tues; 3:00-4:00 PM Friday**
- Quizzes by iclicker (sometimes hand-written)
- Exam next Thursday: bring 1(-sided) 8.5X11" sheet of notes
  - practice exam available today
- Course website: www.pa.msu.edu/~huston/phy294h/index.html
  - lectures will be posted frequently, mostly every day if I can remember to do so

Kelvin and Hobbes



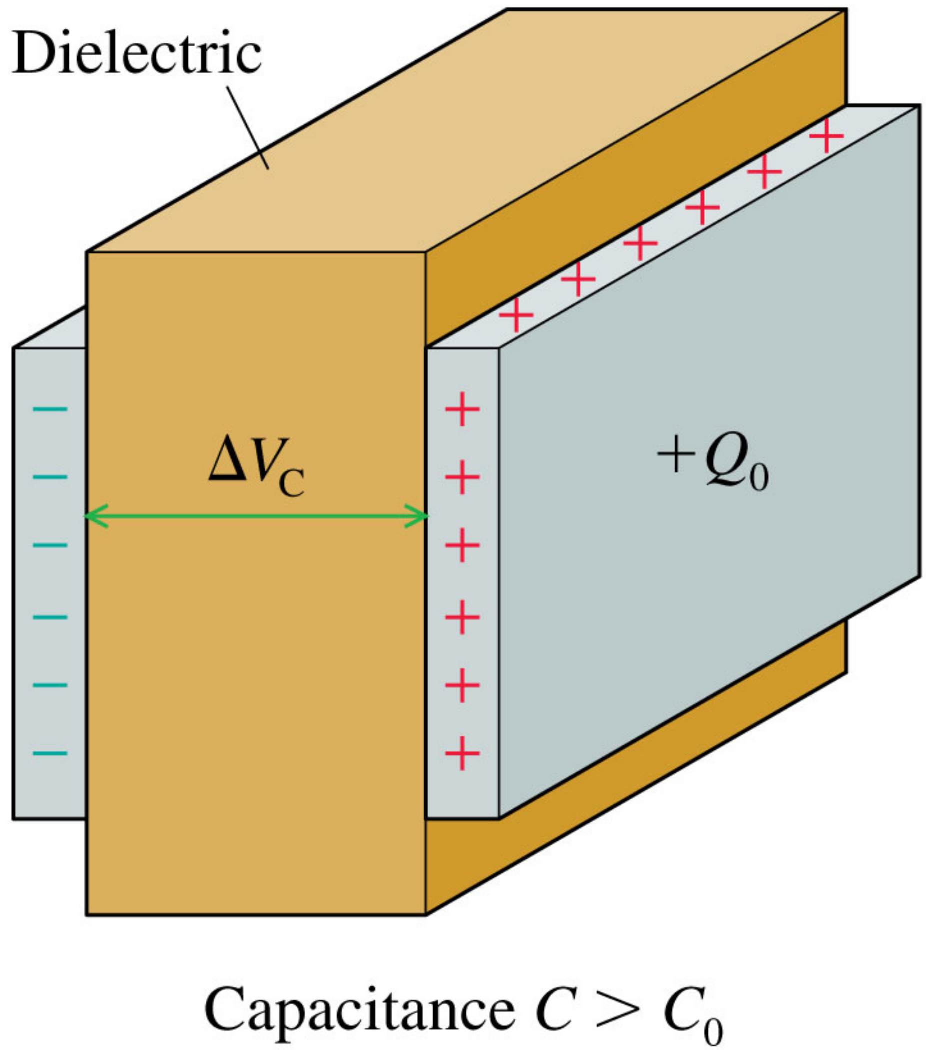
- The figure shows a parallel-plate capacitor with the plates separated by a vacuum.
- When the capacitor is fully charged to voltage $(\Delta V_C)_0$, the charge on the plates will be $\pm Q_0$, where $Q_0 = C_0(\Delta V_C)_0$.
- In this section the subscript 0 refers to a vacuum-filled capacitor.



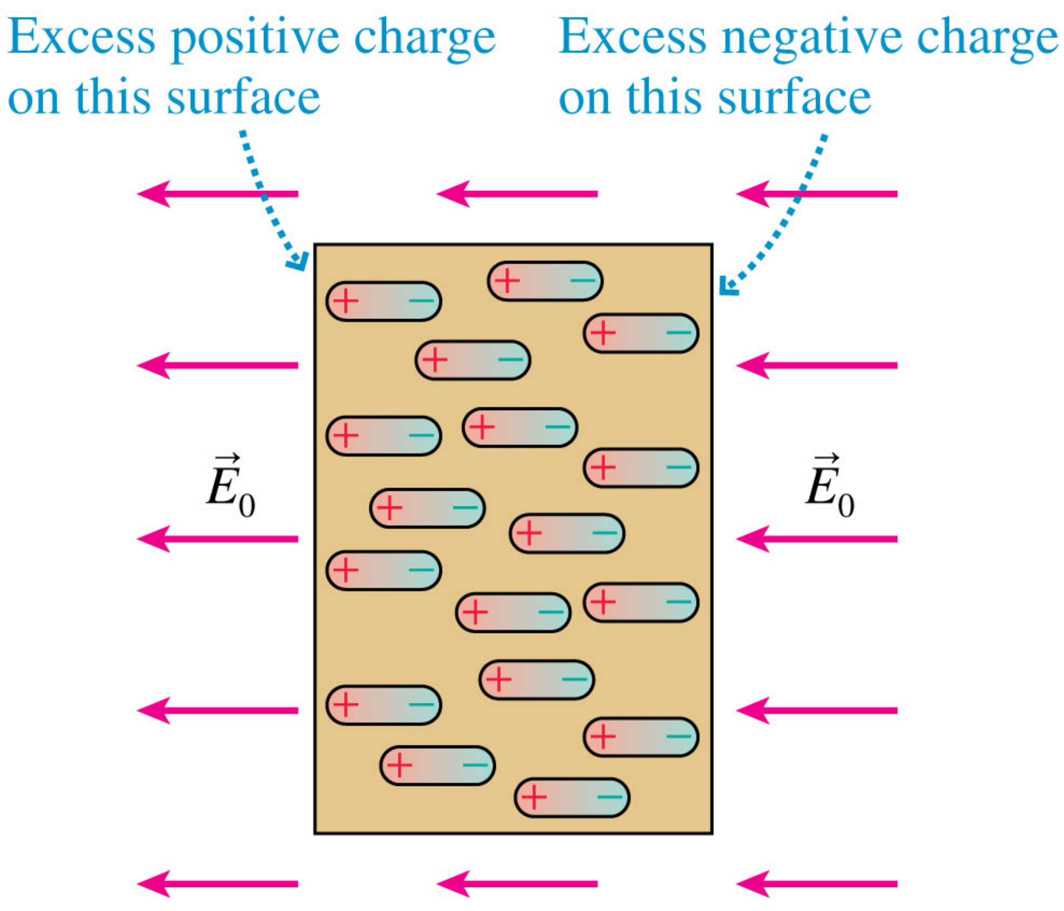
Capacitance C_0 in vacuum

- Now an insulating material is slipped between the capacitor plates.
- An insulator in an electric field is called a dielectric.
- The charge on the capacitor plates does not change ($Q = Q_0$).
- However, the voltage has *decreased*:

$$\Delta V_C < (\Delta V_C)_0$$

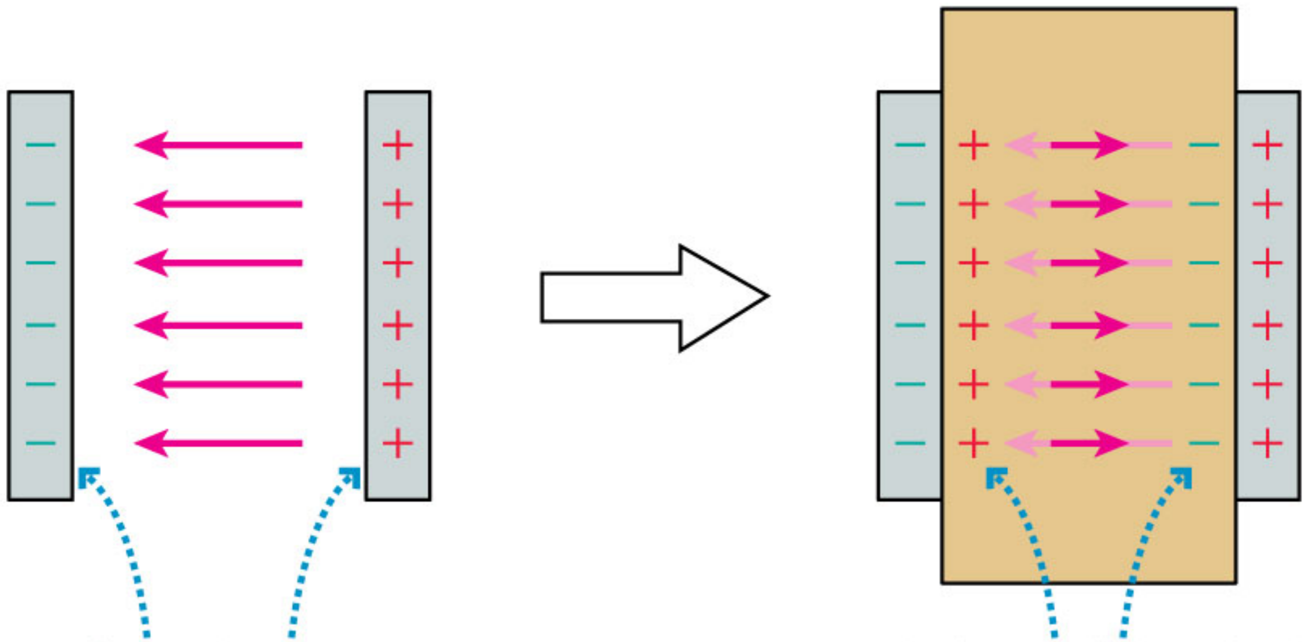


- The figure shows how an insulating material becomes polarized in an external electric field.
- The insulator as a whole is still neutral, but the external electric field separates positive and negative charge.



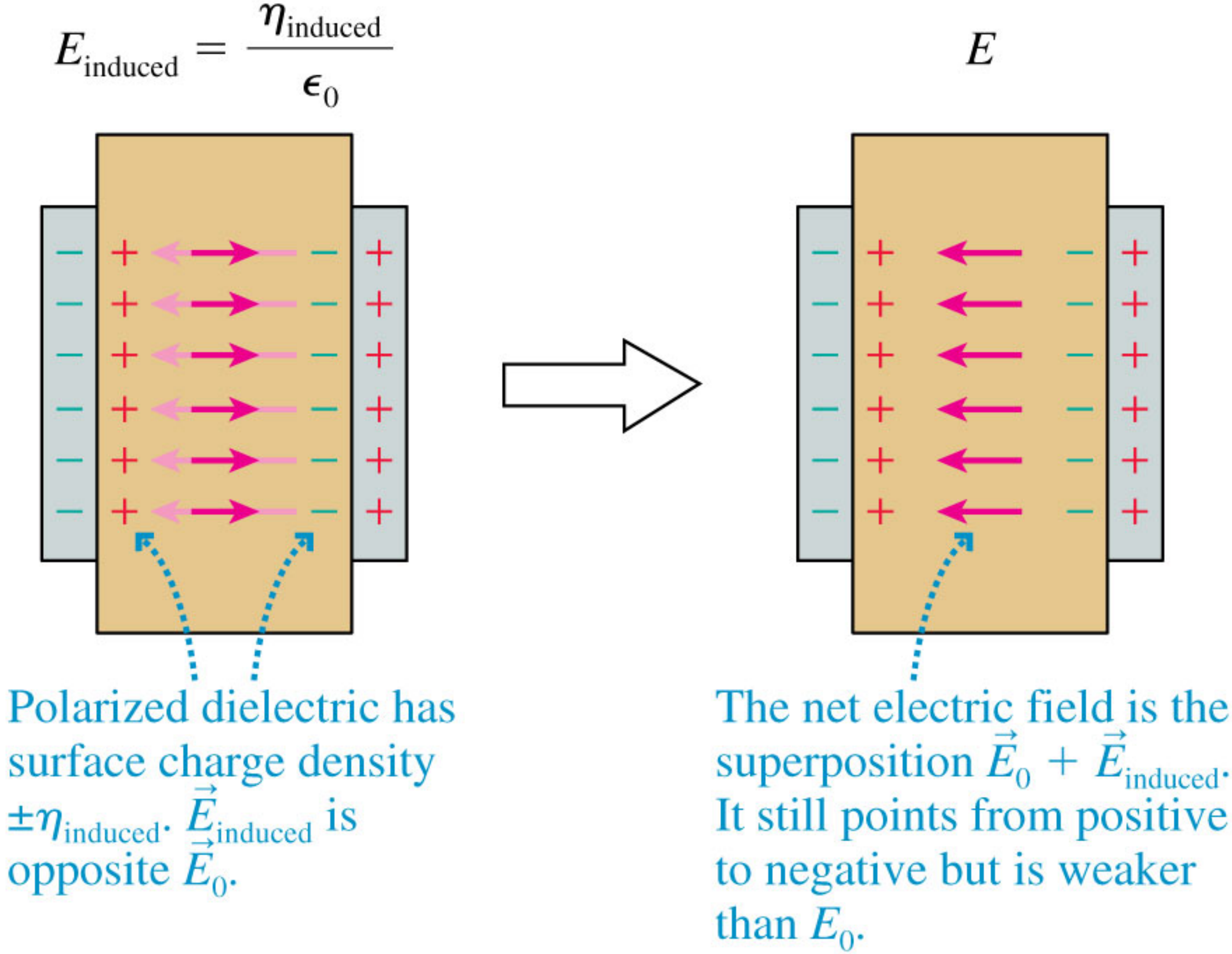
$$E_0 = \frac{\eta_0}{\epsilon_0}$$

$$E_{\text{induced}} = \frac{\eta_{\text{induced}}}{\epsilon_0}$$



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

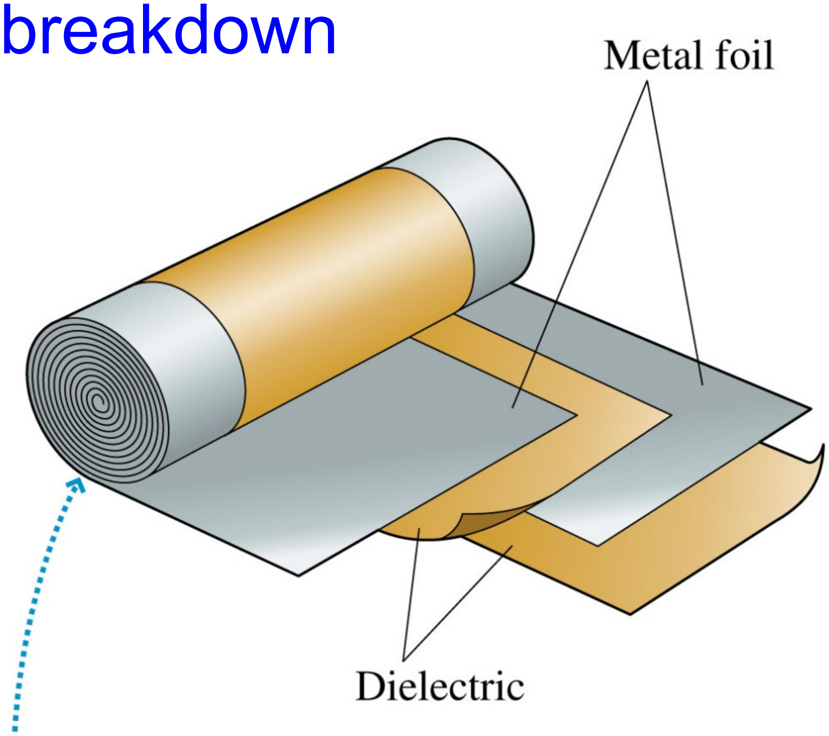
Polarized dielectric has surface charge density $\pm\eta_{\text{induced}}$. $\vec{E}_{\text{induced}}$ is opposite $\vec{E}_0$.


$E_{\text{induced}} = \frac{\eta_{\text{induced}}}{\epsilon_0}$
E
Polarized dielectric has surface charge density $\pm\eta_{\text{induced}}$. $\vec{E}_{\text{induced}}$ is opposite $\vec{E}_0$.
The net electric field is the superposition $\vec{E}_0 + \vec{E}_{\text{induced}}$. It still points from positive to negative but is weaker than E_0.

- We define the **dielectric constant**: $\kappa \equiv \dfrac{E_0}{E}$
- 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:**

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

- The production of a practical capacitor, as shown, almost always involves the use of a solid or liquid dielectric.
- All materials have a maximum electric field they can sustain without breakdown —the production of a spark.
- The breakdown electric field of air is about 3×10^6 V/m.
- A material's maximum sustainable electric field is called its **dielectric strength.**



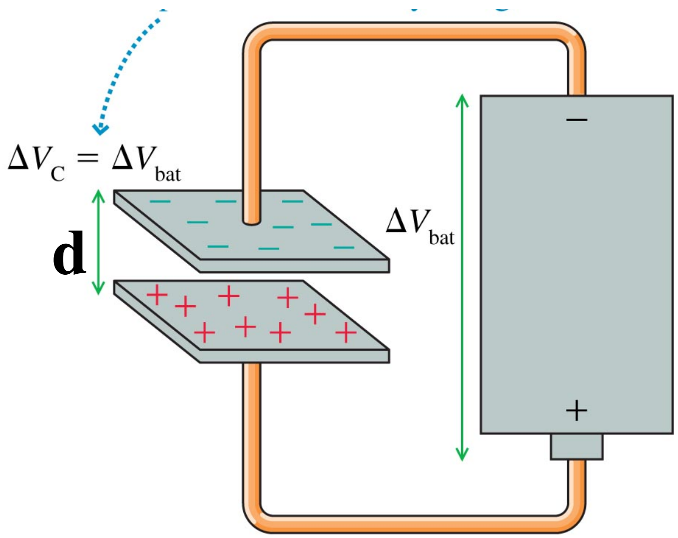
Many real capacitors are a rolled-up sandwich of metal foils and thin, insulating dielectrics.

TABLE 29.1 Properties of dielectrics

Material	Dielectric constant κ	Dielectric strength E_{max} (10^6 V/m)
Vacuum	1	—
Air (1 atm)	1.0006	3
Teflon	2.1	60
Polystyrene plastic	2.6	24
Mylar	3.1	7
Paper	3.7	16
Pyrex glass	4.7	14
Pure water (20°C)	80	—
Titanium dioxide	110	6
Strontium titanate	300	8

Clicker Question

- A parallel-plate capacitor (with area A and distance d between its plates) and is **connected to a battery**. What happens to the capacitor's charge, Q, if a glass plate is then inserted between the plates?

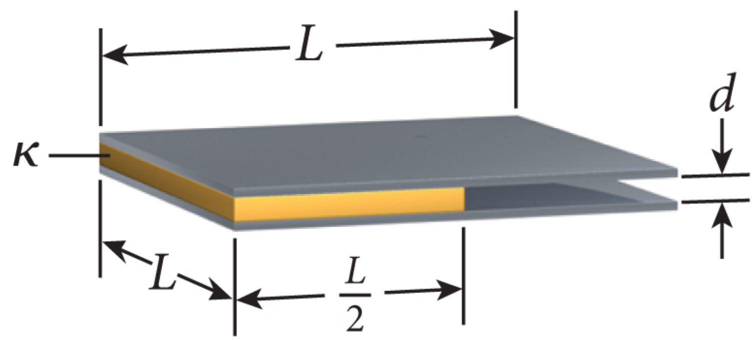


A. Q decreases
B. Q increases
C. Q stays the same
D. Q = 0

Answer: B, Battery is connected so ΔV_C stays constant but adding a dielectric increases the capacitance so Q must increase. The capacitor needs to draw more charge from the battery to keep the potential constant.

Capacitor Partially Filled with a Dielectric

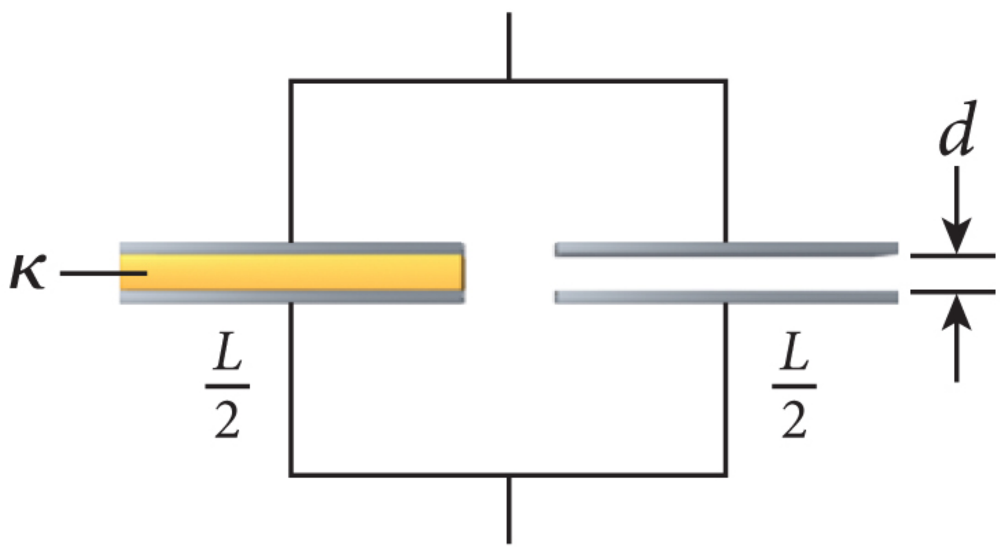
- A parallel plate capacitor is constructed of two square conducting plates with side length L = 10.0 cm.



- The distance between the plates is d = 0.250 cm.
- A dielectric with dielectric constant κ =15.0 and thickness 0.250 cm is inserted between the plates.
- The dielectric is L = 10.0 cm wide and L/2 = 5.00 cm long.
- What is the capacitance of this capacitor?

Capacitor Partially Filled with a Dielectric

- We have a capacitor partially filled with a dielectric.
- We can treat this capacitor as two capacitors in parallel.
- One capacitor is a parallel plate capacitor with plate area $A = L(L/2)$ and air between the plates.
- The second capacitor is a parallel plate capacitor with plate area $A = L(L/2)$ and a dielectric between the plates.



Capacitor Partially Filled with a Dielectric

- The capacitance of a parallel place capacitor is:

$$C_1 = \frac{\varepsilon_0 A}{d}$$

- If a dielectric is placed between the plates we have:

$$C_2 = \kappa \frac{\varepsilon_0 A}{d}$$

- The capacitance of two capacitors in parallel is:

$$C_{12} = C_1 + C_2$$

Simplify

- Putting our equations together gives us:

$$C_{12} = C_1 = \frac{\varepsilon_0 A}{d} + \kappa \frac{\varepsilon_0 A}{d} = (\kappa + 1)\frac{\varepsilon_0 A}{d}$$

Capacitor Partially Filled with a Dielectric

- The area of the plates for each capacitor is:

$$A = L\left(L/2\right) = L^2/2$$

- Putting our expressions together gives us:

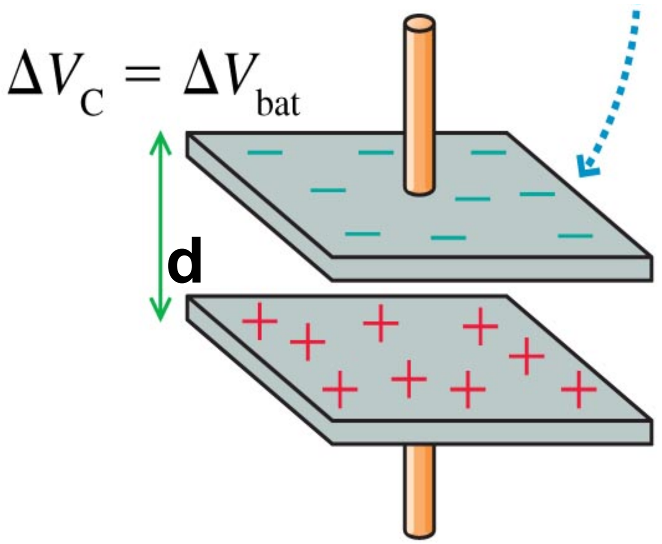
$$C_{12} = \left(\kappa + 1\right)\frac{\varepsilon_0\left(L^2/2\right)}{d} = \frac{\left(\kappa + 1\right)\varepsilon_0 L^2}{2d}$$

- Putting in our numerical values:

$$C_{12} = \frac{\left(15.0 + 1\right)\left(8.85 \cdot 10^{-12}\ \text{F/m}\right)\left(0.100\ \text{m}\right)^2}{2\left(0.00250\ \text{m}\right)} = 2.832 \cdot 10^{-10}\ \text{F} = 283\ \text{pF}$$

Clicker Question

A parallel-plate capacitor (area A and distance d between its plates) is filled by a glass plate (dielectric constant K) and is charged up by a battery **which is then disconnected.** What happens to the capacitor's stored energy if the glass plate is pulled out?

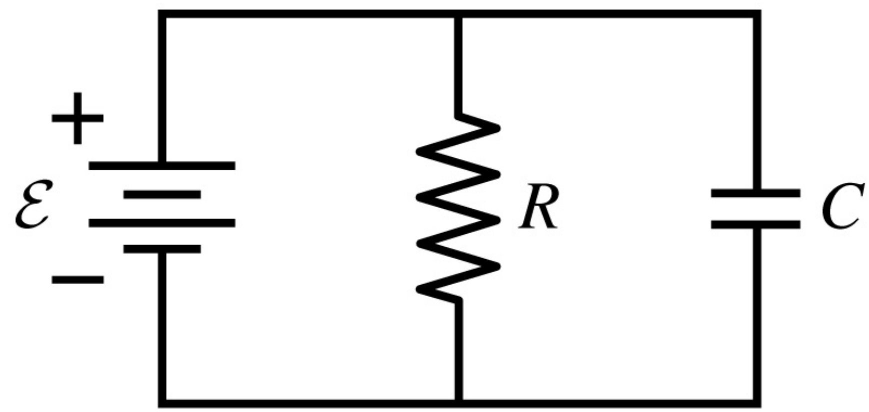


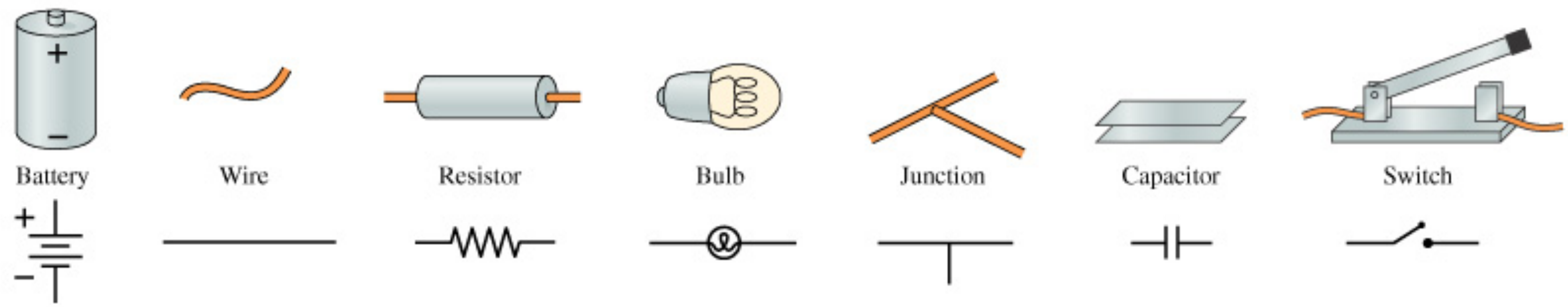
A. Increases
B. Decreases
C. Stays the same

Answer: A, Removing the glass plate reduces the capacitor's capacitance and Q stays constant so the energy increases.

Circuit elements

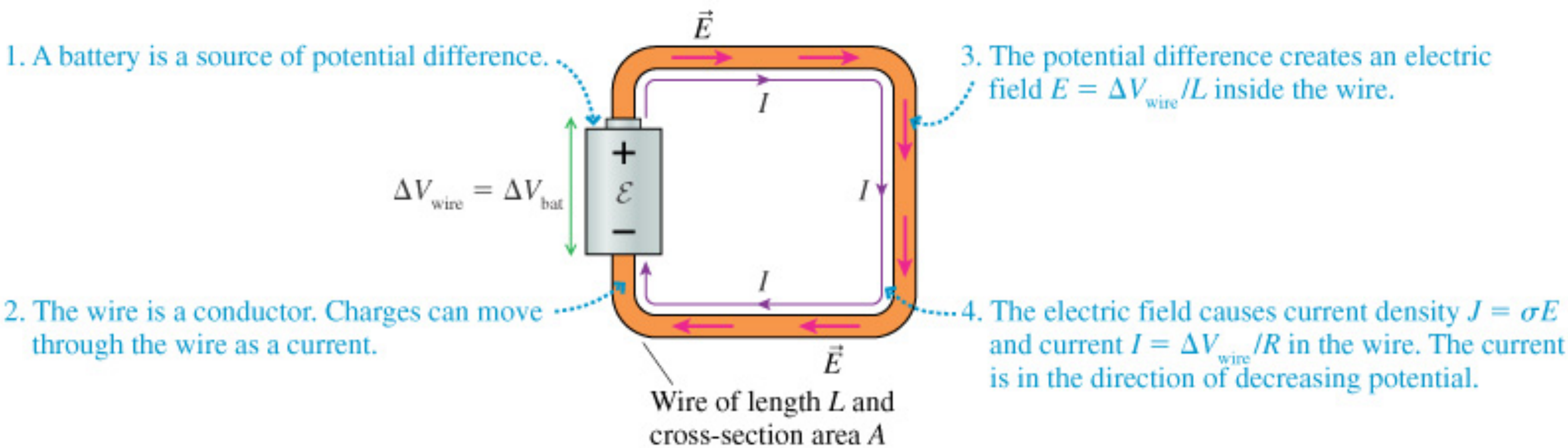
- We' ll encounter each of the circuit elements shown below (with their accompanying symbols)





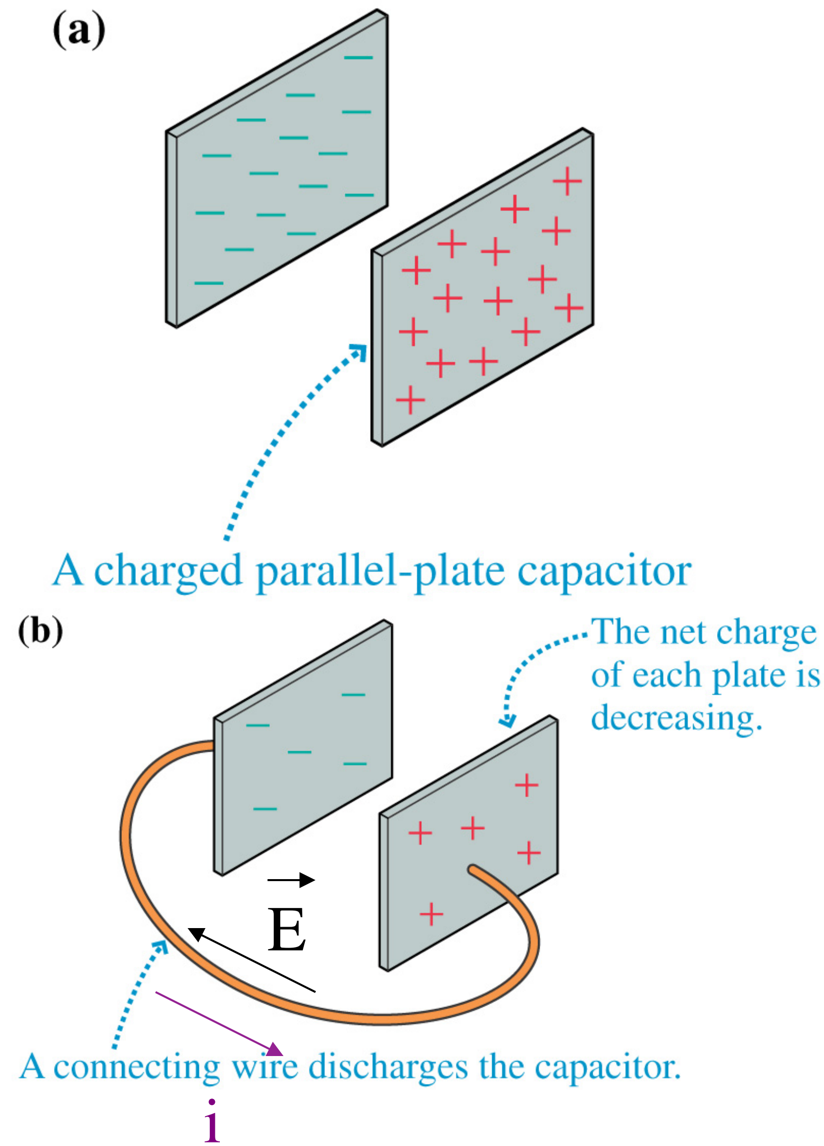
DC circuits

- DC=direct current, as opposed to AC (=alternating current)



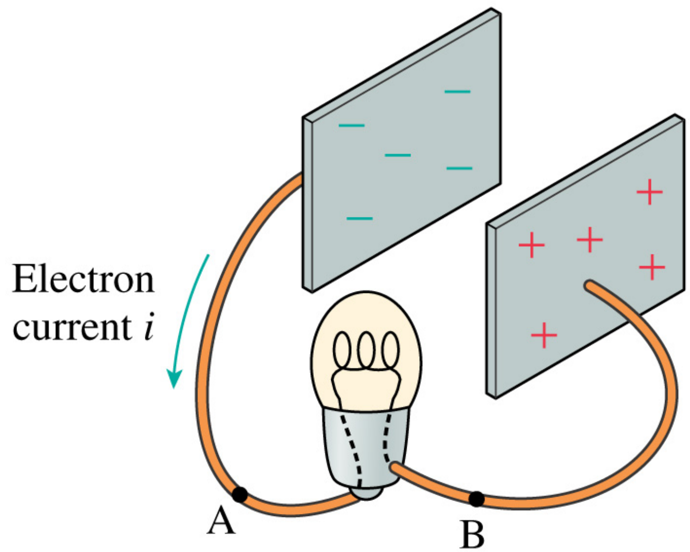
Creating an electrical current

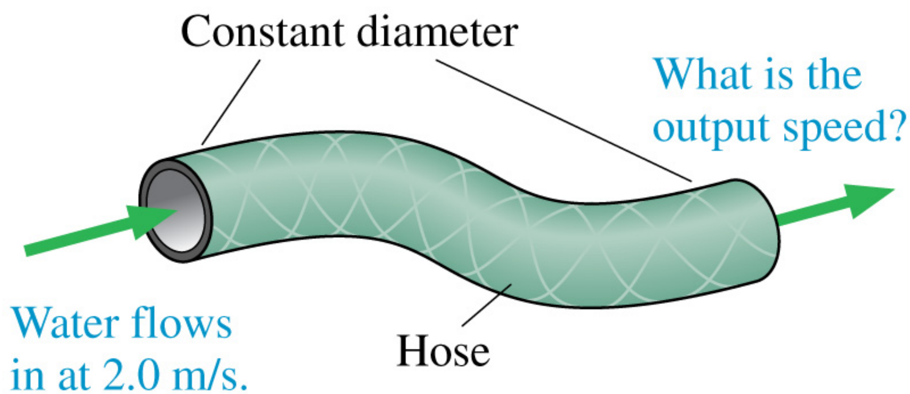
- Suppose I have a parallel plate capacitor in which I have equal and opposite charges on two separated plates
- If I connect the two plates by a conductor, then I know that the excess electrons will flow from the negative plate to the positive plate
- That would constitute an electrical current
- Why are the electrons moving from to the + plate?
  - there's an electric field in the conducting wire
  - the electric field provides the electrons with their motivation to move in a particular direction…but not very fast



Conservation of current

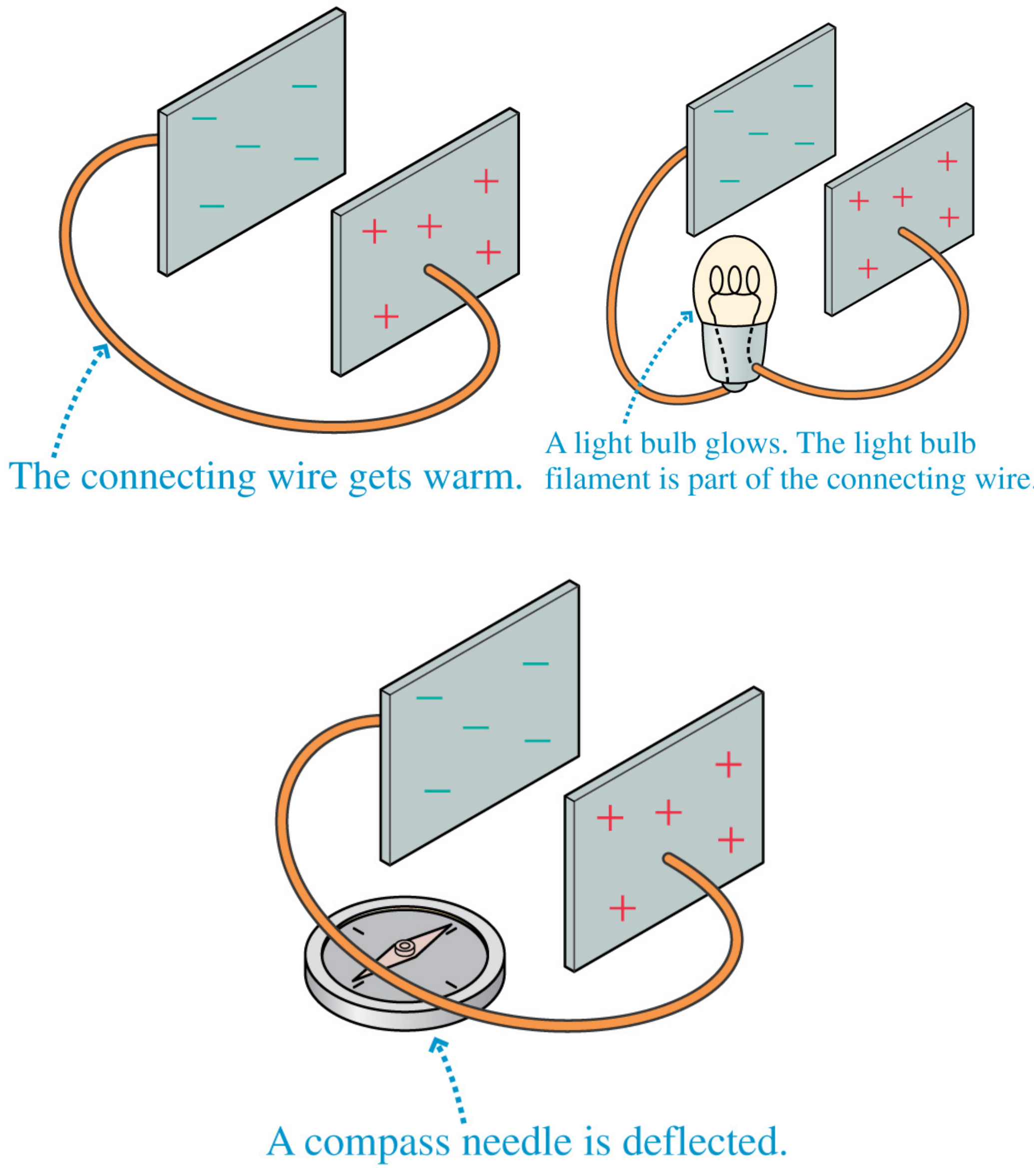
- How does the electron current leaving the - plate compare to the electron current entering the + plate?
- Electrons are conserved, so the current has to be the same
- Most common analogy is to the flow of water through a hose





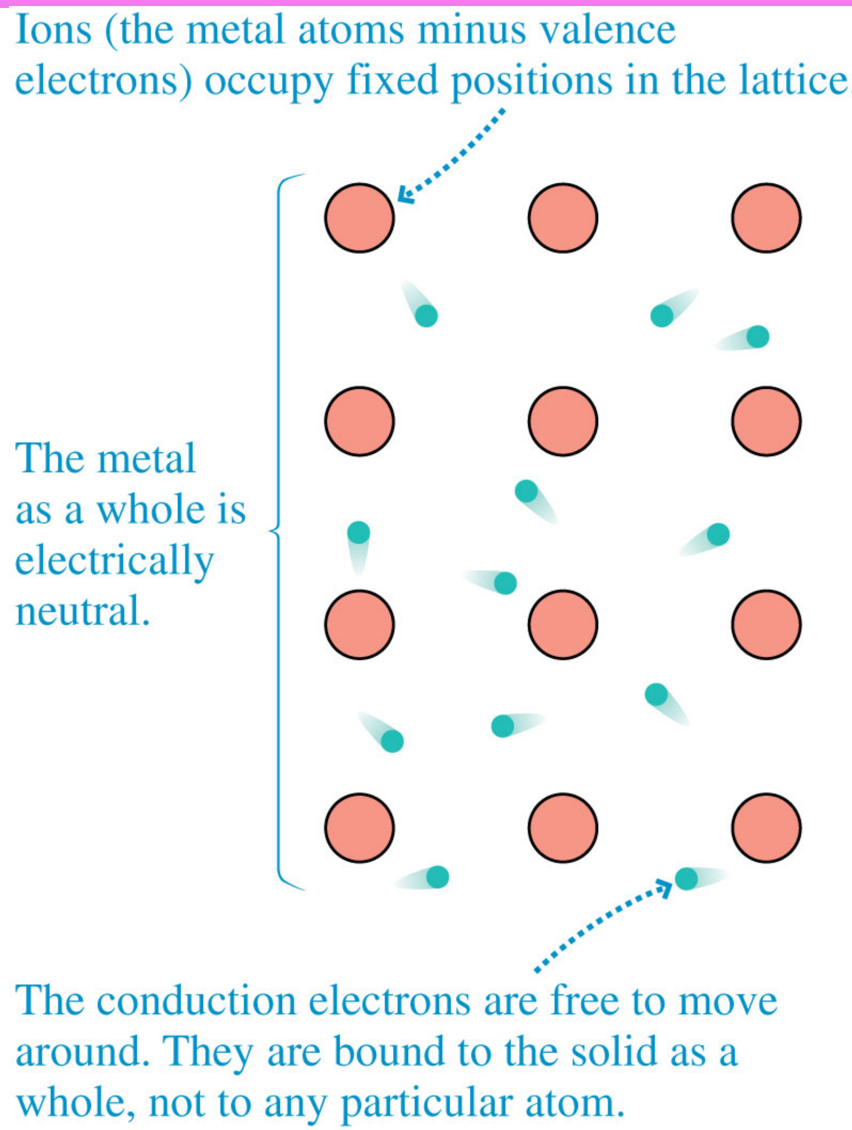
Conservation of charge

- The current is the same all the way through the conductor
- However energy is used up, for example in heating up the conductor or lighting a light bulb, etc …
- Where does the energy come from
- We know it takes energy to separate the electric charges initially



Back to conduction electrons

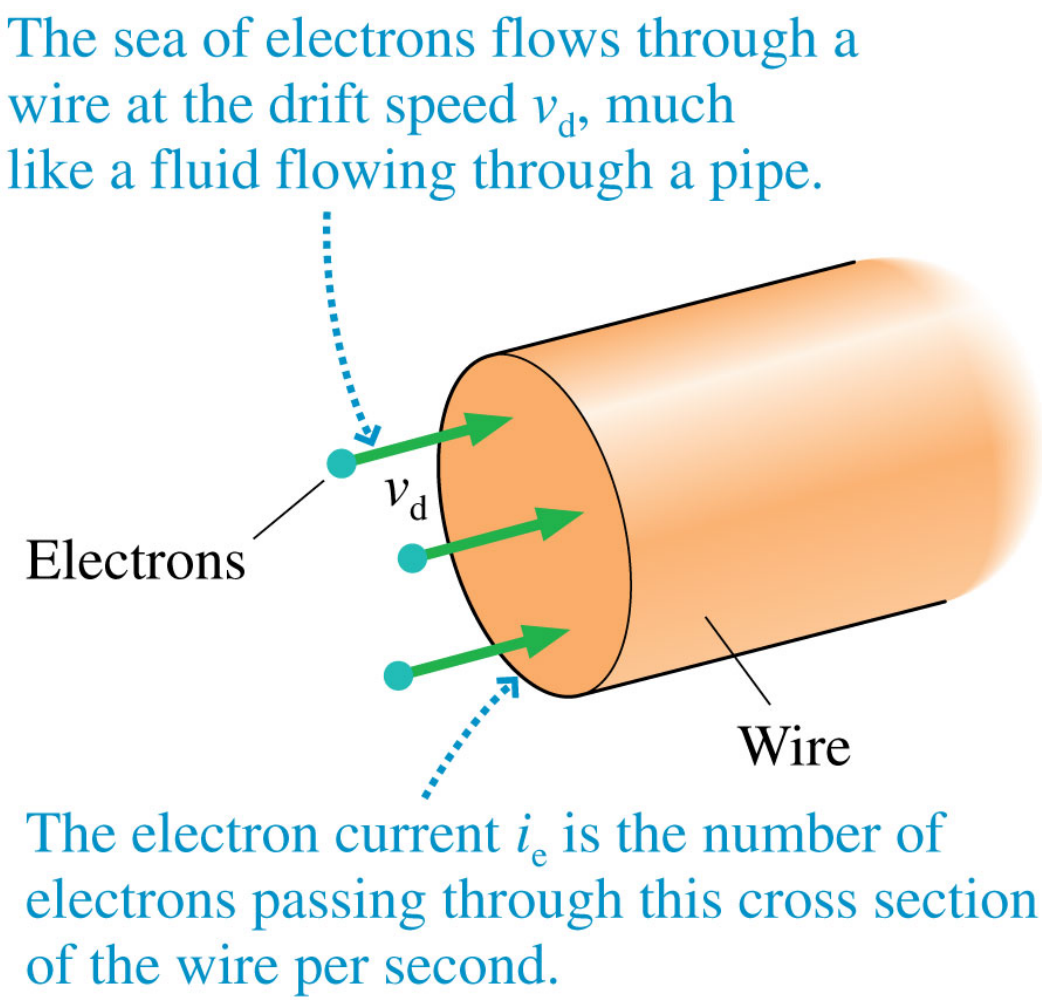
- The outer electrons of metal atoms are only weakly bound to the nuclei.
- In a metal, the outer electrons become detached from their parent nuclei to form a fluid-like *sea of electrons* that can move through the solid.
- **Electrons are the charge carriers in metals.**



Electron current

- We define the **electron current** i_e to be the number of electrons per second that pass through a cross section of the conductor.
- The number N_e of electrons that pass through the cross section during the time interval Δt is

$$N_e = i_e \Delta t$$



- If the number density of conduction electrons is n_e, then the total number of electrons in the shaded cylinder is

$$N_e = n_e V = n_e A\Delta x = n_e A v_d \Delta t$$

- So the electron current is:

$$i_e = n_e A v_d$$