Wed., 10/24 Thurs., 10/25 Fri., 10/26	**19.1-5** Capacitor Circuits **Quiz** Ch 18, **19.6-.14** Capacitor & Resistor Circuits **19.15-17,19** Meters and RC Circuits	**RE17**, **Exp** 29,30 **RE18**, **Exp** 31-34

Experiments:

Exp 19.29 –

Charging: The current starts large and decreases. There is still some current even after the light bulb stops glowing, but eventually it stops.

Discharging: The current starts large and decreases. With the long bulb (smaller "resistance"), the initial current is larger and the current doesn't flow for as long.

Exp 19.30 – Design an experiment to test the effect of the resistor on the final charge. For example, charge the capacitor through different light bulbs or pieces of Nichrome wire, but discharge it through the same light bulb. The time for discharging should be the same if the "final" charge was the same.

Intro:

We know that surface charges rearrange in nanoseconds. As long as processes take much longer, a circuit will be in "quasi-steady state." That means the current changes "slowly" (in comparison to the surface charge) as the circuit approaches static equilibrium.

Review:

Recall that back in the second chapter, Ch 15, we spent some quality time with two, oppositely charged plates, area A, separation s, and charge Q. One reason we did this was that this charge configuration constitutes a "capacitor", so named for its "capacity" to store charge. In Ch 15 we found that the electric field of a capacitor is:

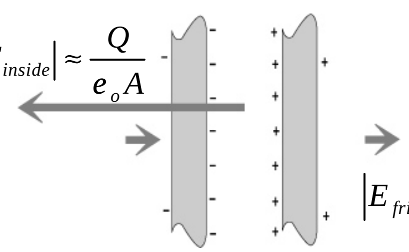
$$|E| \approx \frac{Q/A}{e_0} \quad \text{inside, not too close to edges} \;,$$

In terms of the voltage difference across the gap, which we discussed in Ch. 16,

$$|\Delta V| = |E|s \approx \frac{Q/A}{e_0}s = \frac{Qs}{e_0 A}$$

$$|E_{\text{fringe}}| \approx \frac{Q/A}{2e_0}\left(\frac{s}{R}\right) \quad \text{just outside the plates} \;.$$

$$|E_{inside}| \approx \frac{Q}{e_o A}$$



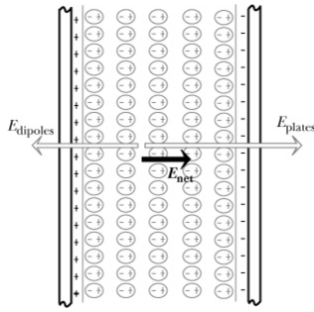
$$|E_{fringe}| \approx \frac{Q}{2e_o A}\left(\frac{s}{R}\right)$$

$$|\Delta V| = |E|s \approx \frac{Qs}{e_0 A}$$

Imagine for a moment that you have a capacitor wired up across a battery. In steady state, considering the voltage drops across the leads to be negligible, the voltage drop across the capacitor must be equal to the voltage gain across the battery $|\Delta V| = |\Delta V_{batt}|$. Thus the charge on a plate must equal

$$Q \approx \frac{e_0 A}{s} |\Delta V_{batt}|$$

Dielectrics
Then in Ch 16 we introduced the idea of sandwiching a polarizable insulator between these plates. An insulator (dielectric) inside will reduce the electric field inside by a factor of *K*, the dielectric constant of the material.



$$\vec{E}_{insulator} = \frac{\vec{E}_{empty}}{K} \text{ where K = dielectric constant}$$

(varies from 1 for empty to 310 for strontium titanate)

$$|E| \approx \frac{Q/A}{e_0 K} \quad \text{inside, not too close to edges}$$

$$\text{Similarly, } \Delta V_{insulator} = \frac{\Delta V_{empty}}{K}$$

$$|\Delta V| \approx \frac{Qs}{e_0 KA}$$

Now return to our capacitor plugged into a battery. Say we slide an insulator inside it. For the given amount of charge on the plates, that reduces the voltage drop across the plates by a factor of 1/K. Now the voltage drop is less across the plates than across the battery – *more* charge flows onto the plates until the capacitor's voltage drop again equals that of the battery:

$$Q \approx \frac{e_0 KA}{s} |\Delta V_{batt}|$$

Thus including the insulator allows the capacitor to hold a factor of *K* more charge for the same voltage drop.

New Stuff

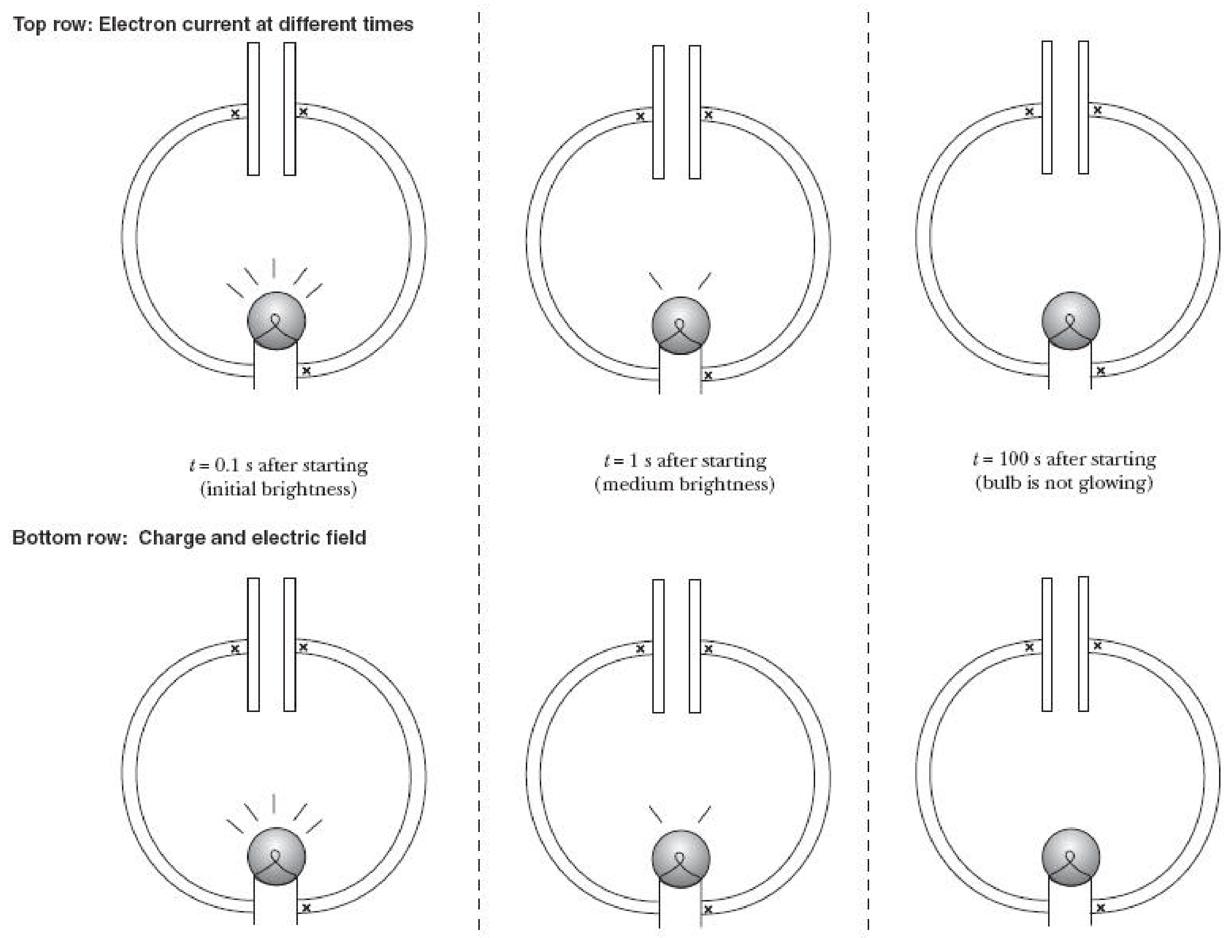
That's all stuff we could have figured out by chapter 16. Chapter 18 got us thinking about the flow of charges, currents, so now let's think about how capacitors interact with currents.

<u>Discharging a Capacitor</u>:

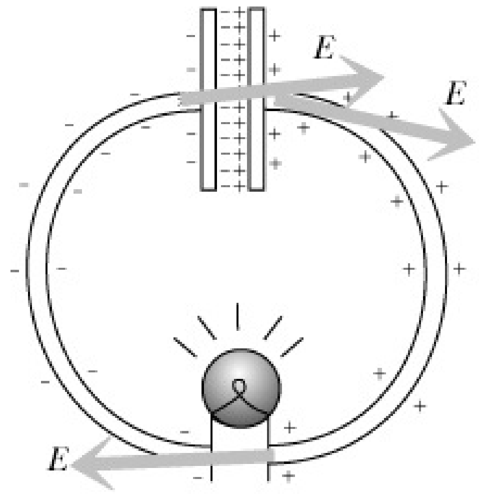
For the above, we just considered what the steady-state situation would look like, but often capacitors take a non-negligible time to get into steady-state; in fact, that's one of their virtues - that they take time to adjust. Now let's think about the process of charging and discharging the plates.

Discharging first:

In Experiment 29, when you *discharged* the capacitor, this is what you saw the light bulb do. Let's deduce from that what the current, field, and charges were doing: (see CapacitorLectureWorksheet.pdf) (say right plate positive)

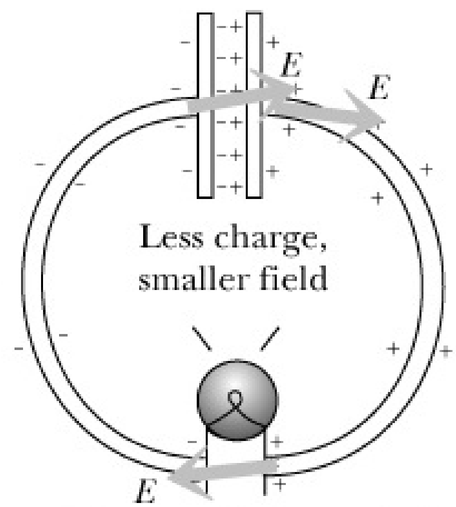


Suppose a capacitor is initially charged with the right plate positive. The fringe electric field (outside the capacitor) points away from the positive plate and toward the negative one. Soon after the capacitor is connected to a light bulb (on the scale of nanoseconds), the miniscule amount of surface charge required has been deposited, setting up a charge gradient and producing a constant magnitude field throughout the wire (though not in the bulb itself). If this *weren't* the case, the proportionality of field and current would cause charge to continue to accumulate / deplete.



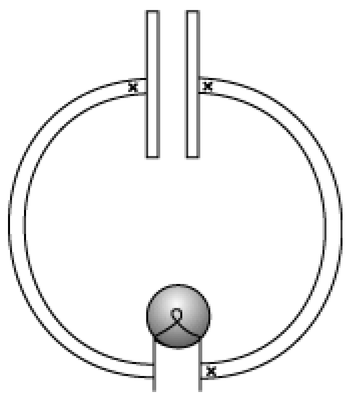
This causes an electron current to flow in the counterclockwise direction.

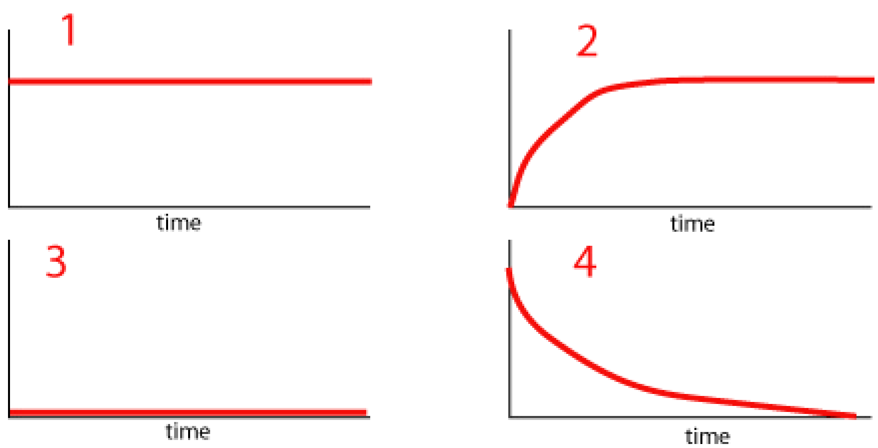
The current reduces the charge on the plates and thus reduces the electric field, which, in turn, causes the current to decrease.



Eventually, the capacitor will be discharged and the current will stop flowing. This is static equilibrium (E=0 throughout the wire).

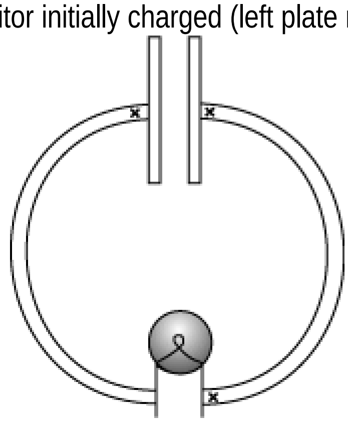
Q19.1a Capacitor initially charged. Which graph shows CURRENT vs TIME while DISCHARGING?





Q19.1b

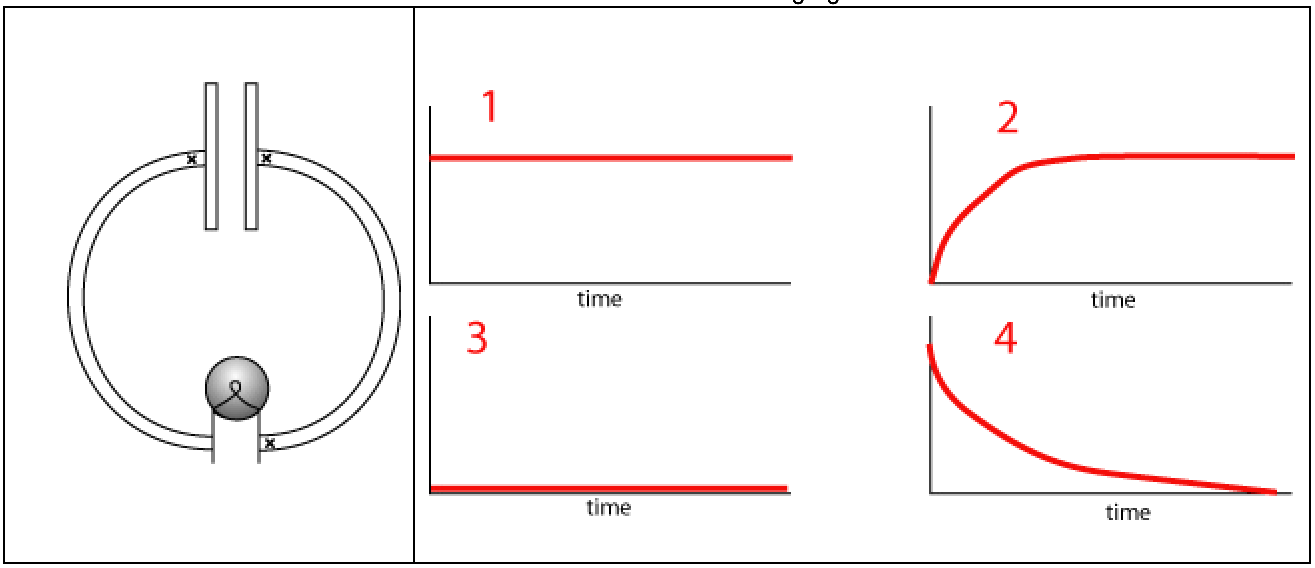
Capacitor initially charged (left plate negative)



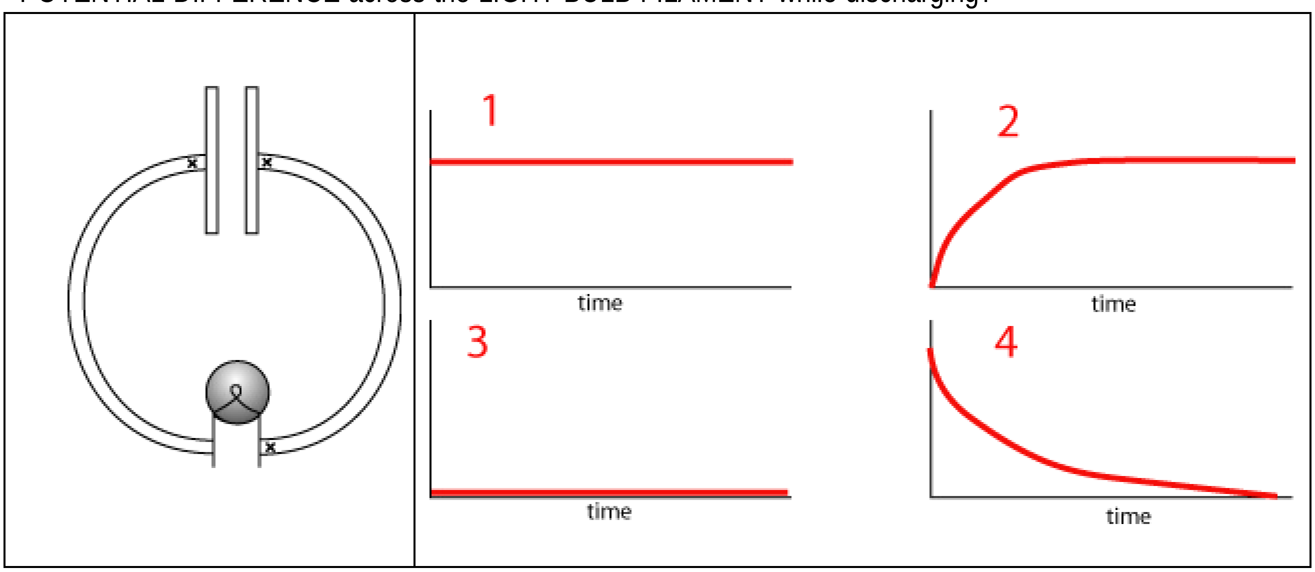
When circuit is connected:

1) Charge on the plates stays constant.
2) Left plate gets less negative.
3) Left plate gets more negative.

Q19.16c Capacitor initially charged. Which graph shows the absolute value of the POTENTIAL DIFFERENCE across the CAPACITOR while discharging?

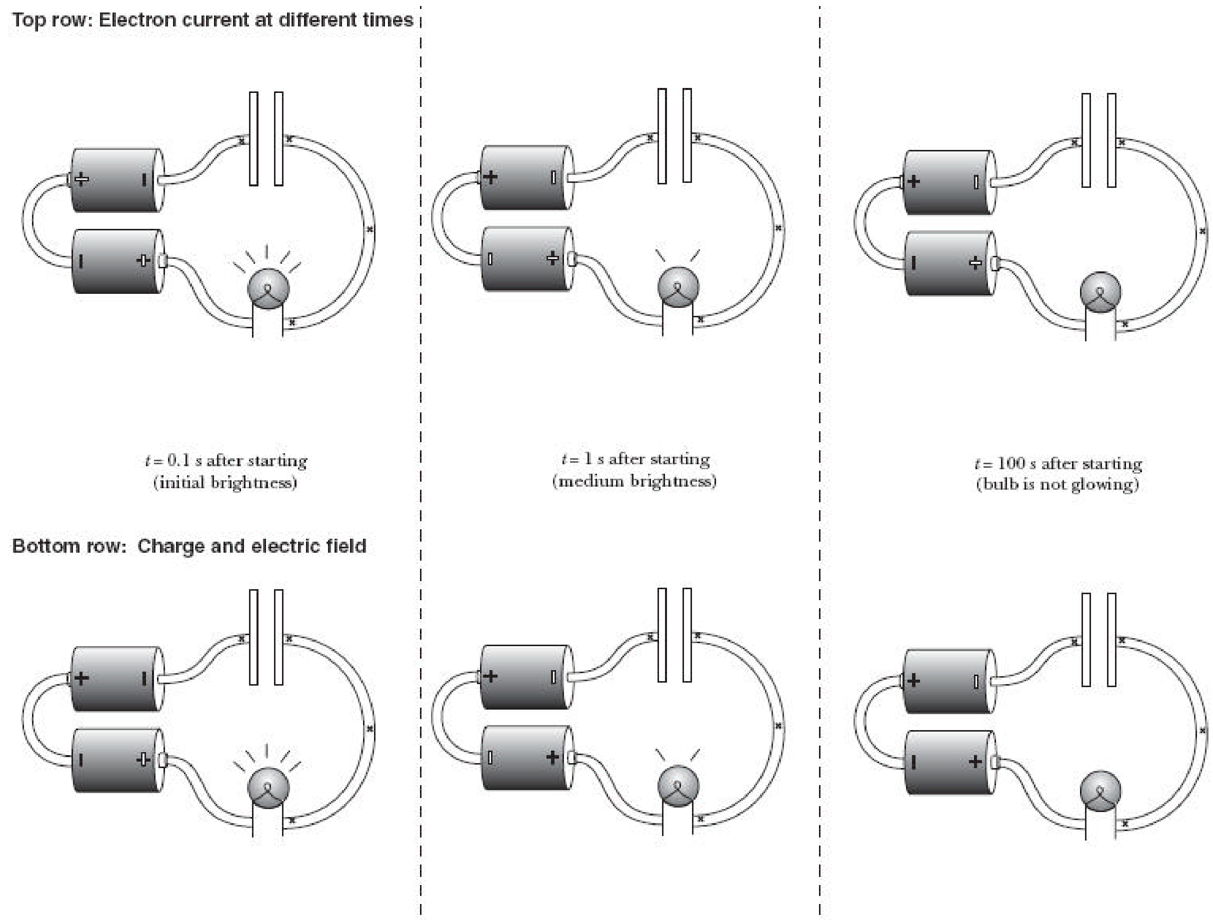


Q19.16d Capacitor initially charged. Which graph shows the absolute value of the POTENTIAL DIFFERENCE across the LIGHT BULB FILAMENT while discharging?

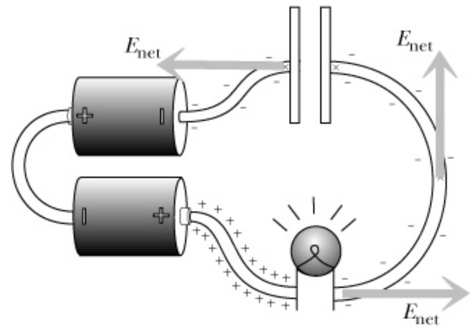


Charging a Capacitor:

In Experiment 29 when you *charged* the capacitor, *this* is what you saw the light bulb do. Now let's deduce what the current, field, and charges were doing. Now let's complete this sequence of images (see CapacitorLectureWorksheet.pdf)

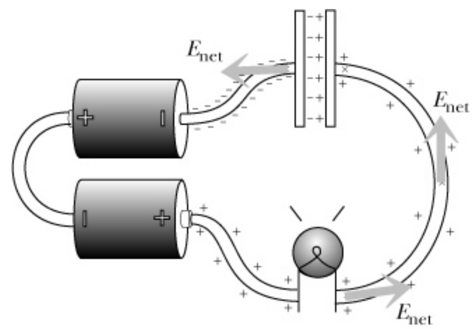


Suppose that there is initially <u>no</u> charge on the capacitor. A few nanoseconds after the capacitor is connected to a battery through a light bulb, it is almost as if the capacitor wasn't there: electrons move from the negative end of the battery onto the wire at its end, and electrons move off of the wire into the positive terminal of the battery at its other end. The charges have rearranged to produce a large electric field throughout the wire. Note that the electric field will be even larger in the light bulb, so the surface charges are as shown below. (The negative charges get more dense closer to the negative side of the battery.



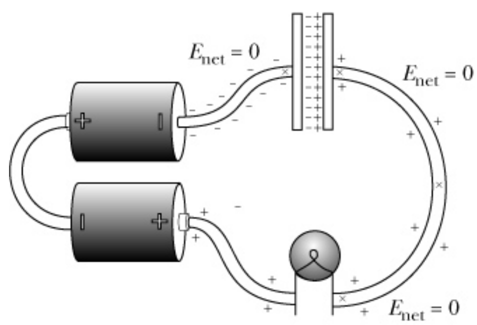
t = 0.1 s after starting
(initial brightness)

An electron current flows clockwise, so the capacitor becomes charged with positive charge on the right plate. The fringe field of the capacitor somewhat reduces the net electric field near the capacitor and it equalizes throughout the wire (because surface charges rearrange).



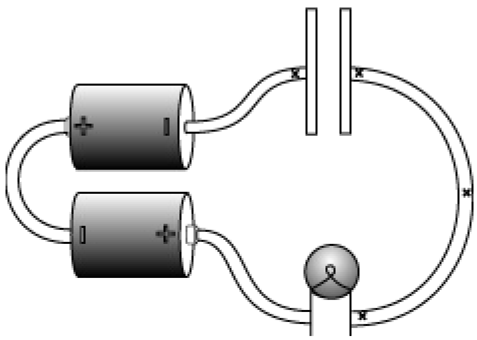
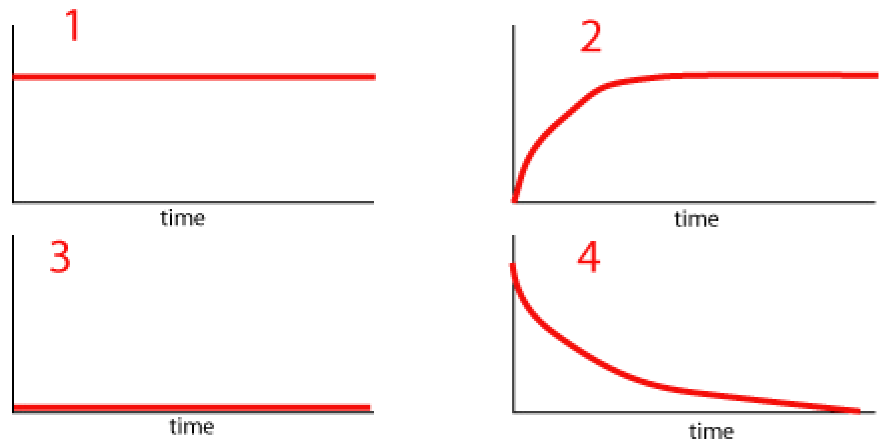
t = 1 s after starting
(medium brightness)

The current reduces gradually as the capacitor charges. Eventually the current stops flowing and the circuit is in static equilibrium (E=0 throughout the wire).

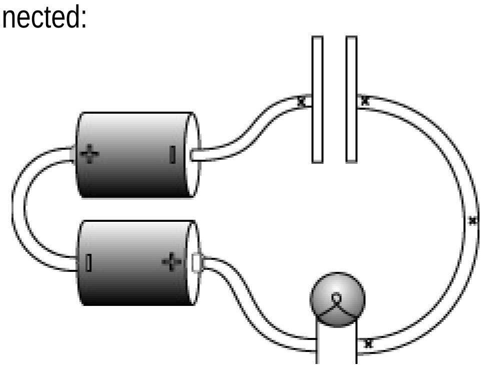


t = 100 s after starting
(bulb is not glowing)

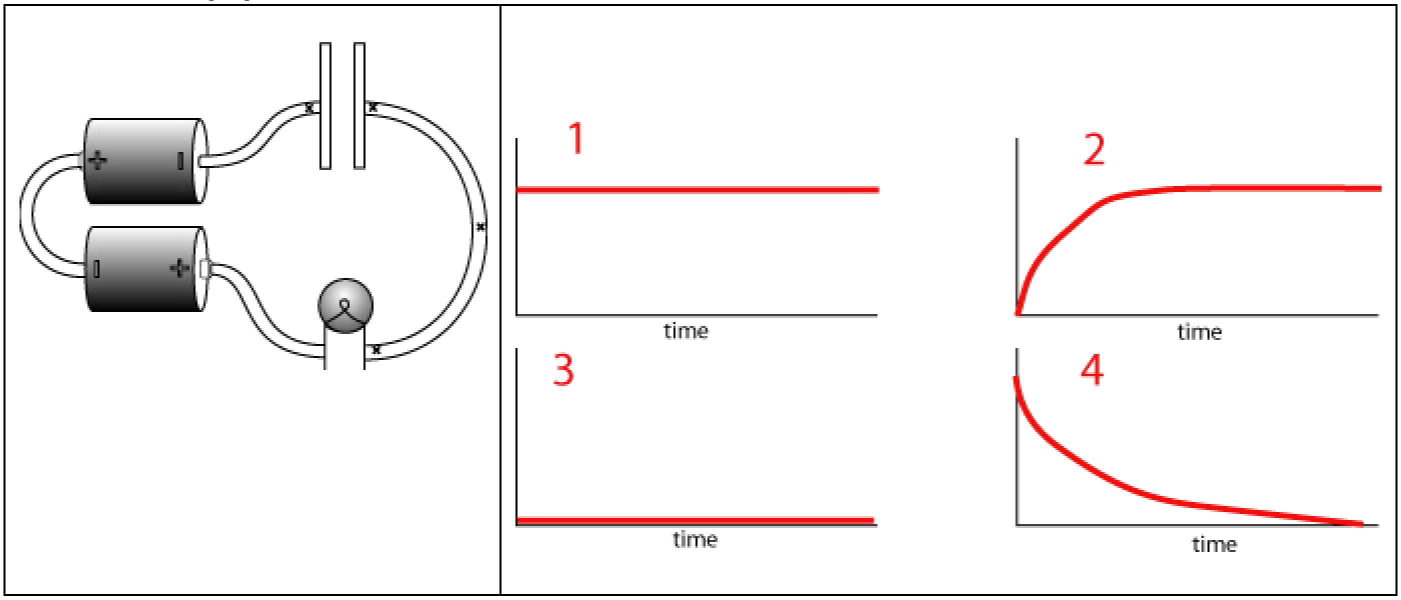
Q19.1c Which graph shows CURRENT vs TIME while CHARGING?

Capacitor initially uncharged. 	

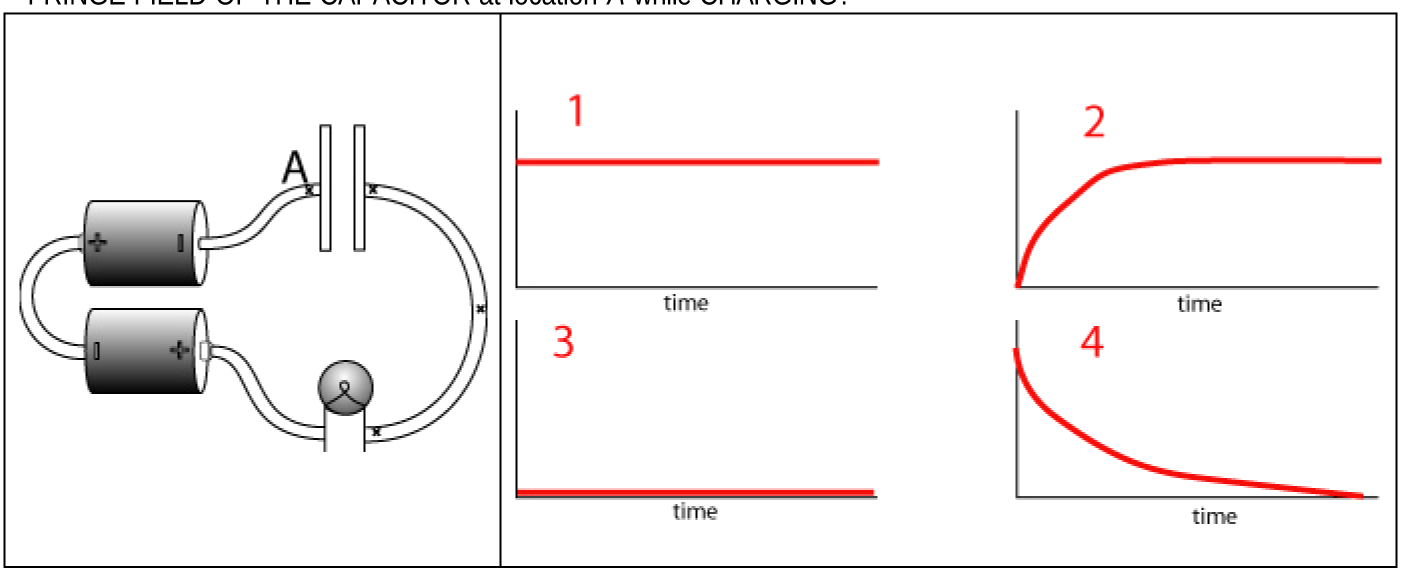
Q19.1d

Capacitor initially uncharged. When circuit is connected: 	1) Electrons jump across the gap between the plates. 2) Electrons pile up on the left plate. 3) Electrons pile up on the right plate.

Q19.1e Capacitor initially uncharged. Which graph shows MAGNITUDE of CHARGE on RIGHT PLATE vs. time while charging?

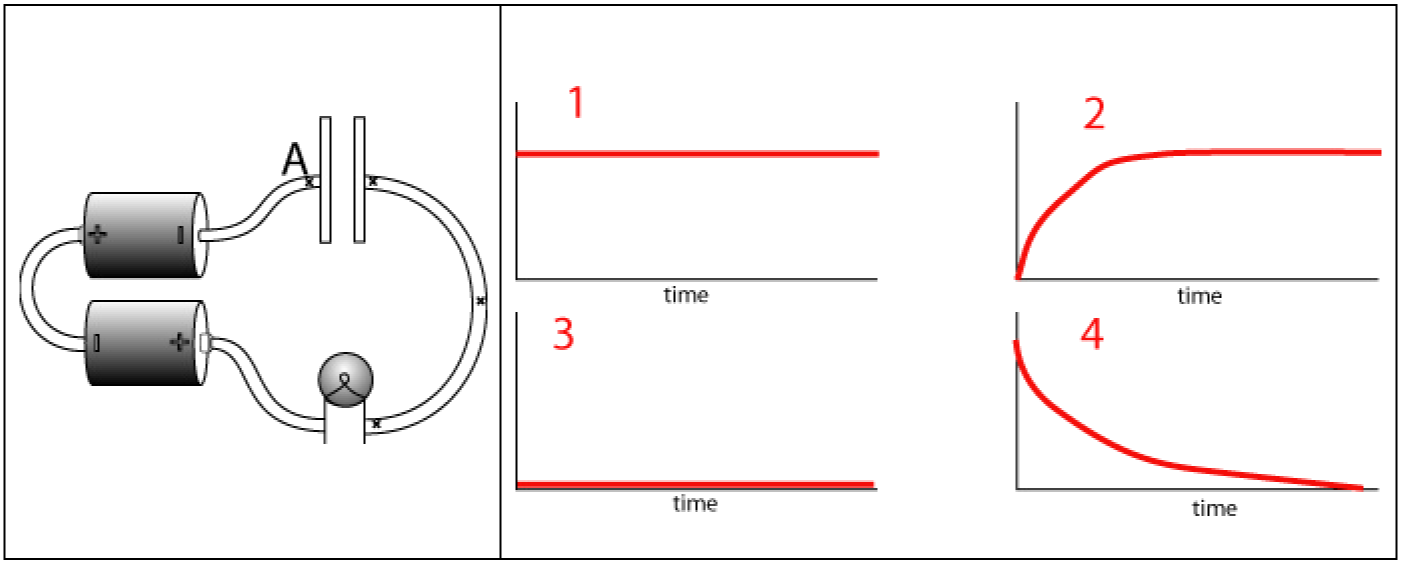


Q19.1f Capacitor initially uncharged. Which graph shows the magnitude of the FRINGE FIELD OF THE CAPACITOR at location *A* while CHARGING?

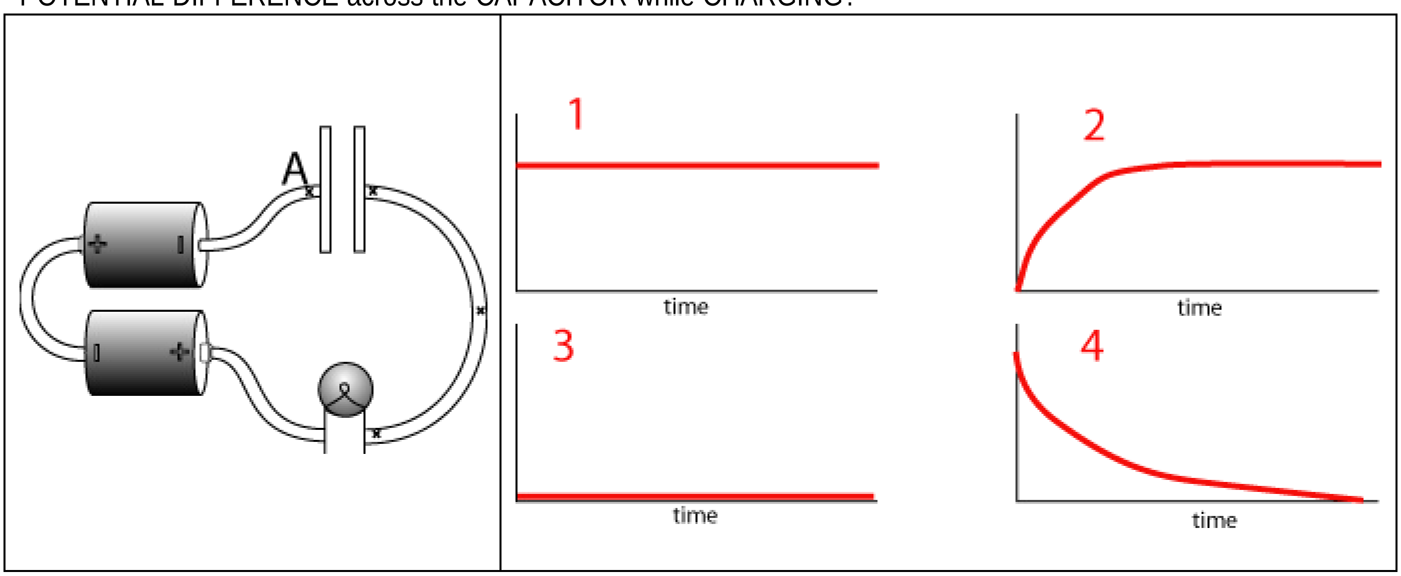


Note: when fully charged, there will be the largest fringe field, yet no current – there must be an equal and opposite field generated by the charge distribution on the wire. That's what the next question is about.

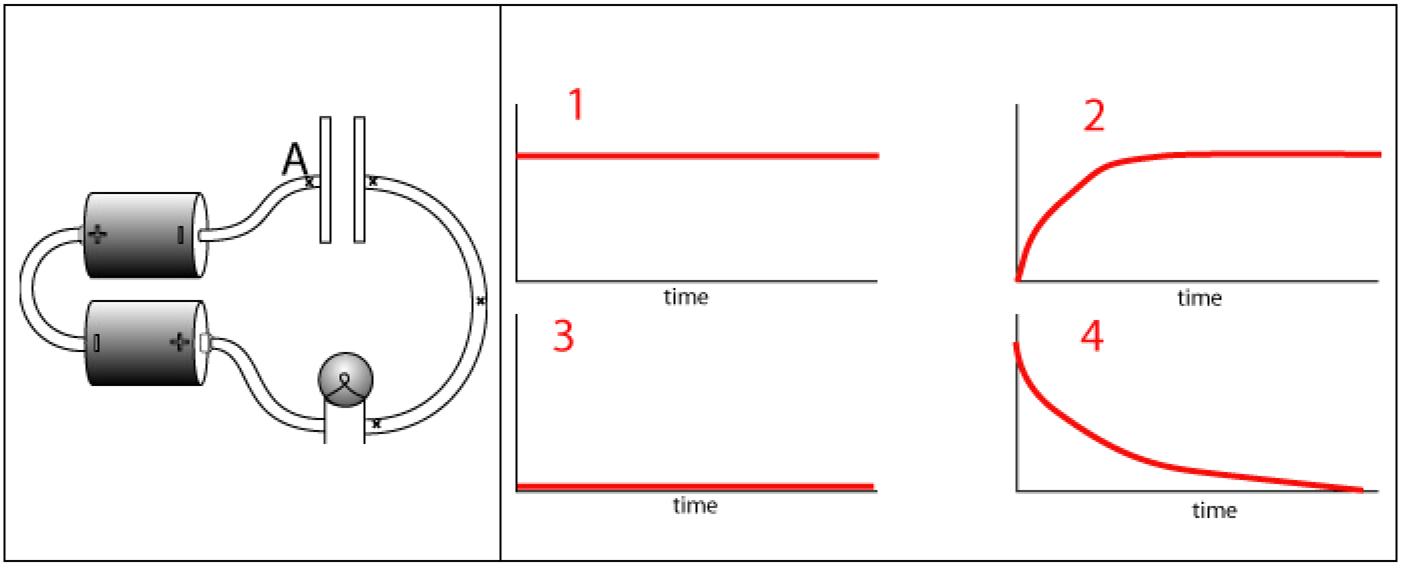
Q19.1g Capacitor initially uncharged. Which graph shows the magnitude of the NET FIELD at location *A* while CHARGING?



Q19.16a Capacitor initially uncharged. Which graph shows the magnitude of the POTENTIAL DIFFERENCE across the CAPACITOR while CHARGING?



Q19.16b Capacitor initially uncharged. Which graph shows the magnitude of the POTENTIAL DIFFERENCE across the LIGHT BULB FILAMENT while CHARGING?



<u>Effect of Different Resistors (Light Bulbs)</u>: (Relates to Ex. 30)

What did you see in Ex. 30?

The final charge (in equilibrium) of the capacitor does <u>not</u> depend on the resistance in the circuit. In equilibrium, there is no (zero) electric field in the wires or resistor. That means the potential difference across the capacitor must be the same size as the battery's emf (loop rule). The charge on the capacitor will determine the electric field in the gap. Therefore, the charge must be the same regardless of the resistance.

That said, a different, say thinner, light bulb filament will allow a lower current to flow for a given electric field – so for any snapshot of field in the circuit, the corresponding current will be slower, thus it'll take longer for charge to be rearranged on the plates.

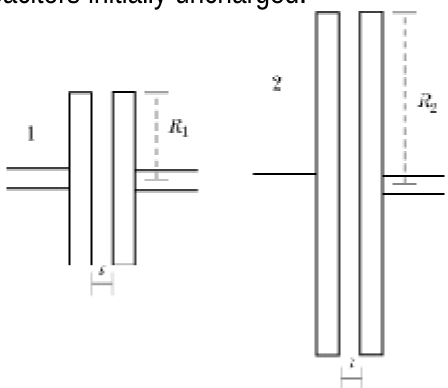
<u>EXERCISES</u>: What effects do the following changes have on the charging of a capacitor? Hint: Think about what happens in the first fraction of a second. Explain your reasoning in detail.

$$\left|E_{\text{fringe}}\right| \approx \frac{Q/A}{2e_0}\left(\frac{s}{R}\right) \quad \text{just outside the plates}$$

1. Replace the original capacitor with one that is larger.

(see Ch19 clicker – capacitor.doc question 5)

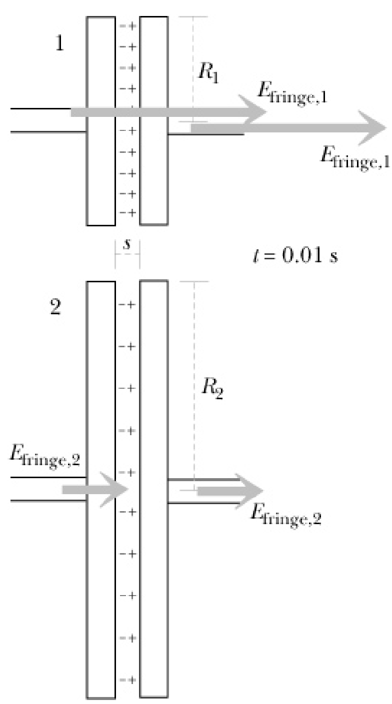
Q19.5a

<table>
<tr>
<td>Capacitors initially uncharged.


$$E_{fringe} = \frac{Q/A}{\varepsilon_0}\left(\frac{s}{2R}\right)$$</td>
<td>After 0.01 s of charging:

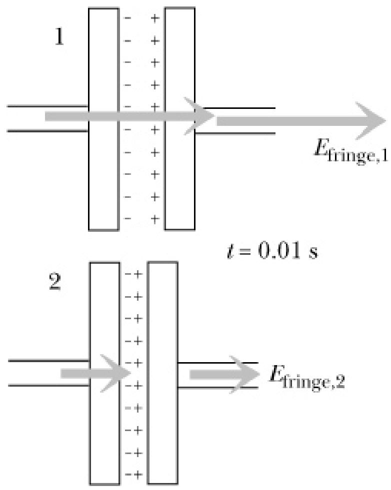
1) The fringe field of each capacitor is the same
2) The smaller capacitor (#1) has a larger fringe field
3) The larger capacitor (#2) has a larger fringe field</td>
</tr>
</table>

Initially, the capacitor is uncharged so the electric field in the wires is due to the battery. About the same charge would end up on each capacitor in the first time interval. The area of the larger capacitor is larger, so *Q*/(*AR)* is smaller and the fringe electric field it generates is smaller. So, in the process of putting charge Q on the plates, the net field in the wire has reduced less, thus the current has reduced less. So, the current dies off more slowly with the big capacitor than the small capacitor.



Replace the original capacitor with one that has a smaller gap.

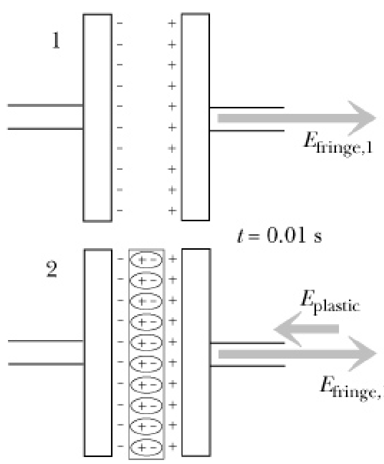
Initially, the capacitor is uncharged so the electric field in the wires is due to the battery. About the same charge would end up on each capacitor in the first time interval. The gap of the second capacitor is smaller, so its fringe electric field is smaller. That means that there is a larger net field and the current does <u>not</u> decrease as quickly.



$$E_{fringe} = \frac{Q/A}{\varepsilon_0}\left(\frac{s}{2R}\right)$$

2. Replace the original capacitor with one that has an insulating layer between the plates.

   Initially, the capacitor is uncharged so the electric field in the wires is due to the battery. About the same charge would end up on each capacitor in the first time interval. The electric field of the polarized insulator is opposite in direction to the fringe field, i.e., in the same direction as the field due to the charge gradient on the wires. That means that there is a larger net field ($\vec{E}_{wire} + \vec{E}_{plate} + \vec{E}_{insulator}$) and the current does <u>not</u> decrease as quickly.



$$E_{fringe\text{-}plastic} = \frac{Q/A}{e_0 K}\left(\frac{s}{2R}\right)$$

In all cases, more charge flows onto the capacitor. Tomorrow, we will define the *capacitance* as the ability to store charge (for a given potential difference.)

Review for Quiz 18

Start on **Experiments 19.31-34** (for tomorrow)

Thursday: Circuits Lab