A "capacitor" is two electrical conductors separated by an insulator. The conductors are called "plates" because they are sometimes flat. If electrons are removed somehow from one of the plates and deposited on the other one then the first plate will have a _____tive charge and the second will have a ____tive charge, because electrons are ____tively charged. There is no way for the electrons to return without leaving the capacitor, travelling through an external circuit, and then re-entering.

1. Imagine an uncharged capacitor with plates labelled "A" and "B":
   What happens if we remove some electrons from A and deposit them on B?
   a. Electron pressure in A will __crease.
   b. Electron pressure in B will __crease.
   c. The pressure difference between A and B will __crease.
   d. The potential difference between A and B will __crease.

2. If the plates are initially neutral (as in #1) the process of removing electrons from one plate and depositing electrons on the other plate is called "charging" the capacitor.
   a. In 1c you figured out that charging a capacitor causes its voltage to ___crease.
   b. When we *discharge* a capacitor its voltage must __crease. (Recorded in # __ on RS __.)

3. Capacitors can be constructed by placing a thin layer of insulating material such as plastic or aluminum sulfide between two sheets of aluminum foil.
   a. In circuit diagrams a capacitor's plates are represented by two straight, parallel lines with equal lengths, drawn close together. *Draw such a pair in the space at the right.*
   b. The wires connecting those two plates to the rest of the circuit are called "leads" and are represented by straight lines outward from the centers of those two plates. *Label the plates and leads clearly in your diagram at the right.*

4. In the space at the right, draw a resistor and a capacitor connected in series to a battery.
   a. Draw arrows *on the capacitor leads* in your diagram to indicate the expected direction of electron flow in them if the capacitor is initially *uncharged*.
   b. We expect this capacitor voltage to ___crease gradually, as in part __ of #2.
   c. How must the three voltages in this circuit be related? ___ = ____ + ____
      (Use page 83 or 83R or Review Sheet VIII.)
   d. Define the symbols in equation 4c.
   e. Do you expect the battery's emf to change during the charging process? ____
   f. Do you expect the resistor voltage to change? ___ -If so, which way? ______ (Use 4b, 4c & 4e.)
   g. If you answered 4e or 4f with a "yes", please explain why, starting with 4b & 4c.

5. Suppose we want the charging process in #4 to be very slow:
   a. We must then choose a resistor with very ________ resistance. (small, great) (See #2 on RS IX.)
   b. Which device below could be used as a resistor to satisfy that requirement best?

ammeter	voltmeter	wire	spring scale
light bulb	capacitor	branch point	battery

6. Use #4 and #5 to make a prediction about the *slope* of the *capacitor voltage vs time* graph for the circuit in #5. Use the special "rate" symbol on RS V, as originally explained on page 54. Also remember to put a subscript into your statement so that you will know which voltage it describes.

   "___ is ____tive when the capacitor is ________ing"

7. In one kind of capacitor the insulator is a very thin film of an aluminum compound deposited electrolytically onto one of the foil sheets. If such an "electrolytic" capacitor is charged with the wrong polarity, that chemical process is reversed, and the capacitor is damaged. *WHEN USING AN ELECTROLYTIC CAPACITOR, AVOID GIVING THE "PLUS" PLATE A NEGATIVE CHARGE.* (That's the "**sign rule** for electrolytic capacitors".)

8. Copies of #2, 4, 5, 6, and 7 have been saved on RS ___. *You'll need them on pages 97 and 98.*

* 1. Draw a voltmeter and a capacitor connected in series to a power supply, as in #4 & 5 on p. 96. Put signs on the capacitor and voltmeter terminals. After your diagram has been approved, find out if your predictions about increasing and decreasing voltages were correct. *Watch the voltmeter after you complete the circuit.* Write three sentences beside your diagram describing what happens to each of the three voltages in this circuit. (Use #5 on RS IX, as we did in #4 on p. 96.) Then do #2.

2. Replace the voltmeter in your circuit with a flashlight bulb, diagram the new circuit and then do #3.

* 3. Unplug circuit #2 from the power supply. Connect the two plugs together so that electrons can flow through the light bulb from one capacitor plate to the other. Then plug it in again, as in #2.
   a. Repeat both steps several times and describe what you see. Also try it with a voltmeter, as in #1.
   b. Illustrate both of your descriptions with circuit diagrams. Make the capacitor leads *more than one centimeter long* in these diagrams and *label* them as you did in 3b on p. 96. *Use the sign rule.*
   c. Electrons always flow from regions with ____ pressure into regions with ___ pressure, if they can.
   d. Put *signs* on the capacitor plates and put *arrows* on the capacitor leads in the diagrams in 3b & 4, showing the directions of electron flow in both circuits. Don't contradict 3c.

* 4. Make circuit 1 again. Without unplugging anything, connect a bulb in parallel with the voltmeter. (Hold its leads in your hands.) Then connect the bulb across the capacitor. Repeat both steps several times, observing what happens. Draw ***two*** circuit diagrams showing what you did. *Make both capacitor leads and both voltmeter leads long and straight.* Describe what happens to *each* voltage in *each* case. Use "increases", "decreases", or "remains unchanged" as in #1.

5. A "significant" current is enough to light a flashlight bulb. An "insignificant" current can make the voltmeter needle move, but is *not* enough to light the bulb. The current in the leads of the ______ was *insignificant* at all times in #4, because that device has a very _____ resistance. (See #2 on RS IX.) Using what you said about input and output currents in #3 on RS IX, make *dots* on *EACH wire* which carries insignificant current in the two diagrams for #4. *A branch point is not a wire.*

6. In 3 & 4 we discovered that the capacitor *charges* rapidly when the light bulb is connected across the __________, and it *discharges* rapidly when the bulb is connected across the __________.
   a. When you stop charging the capacitor and begin discharging it, the *direction* of electron flow in the capacitor leads is ___________ed. -Does this contradict # 3 or 4 above? ___
   b. Using those clues, indicate the direction of electron flow in the capacitor leads *AND* in the light bulb in *BOTH* diagrams in #4. *DO NOT put arrows on the dotted wires. Use diodes to check.*
   c. Whenever the bulb is lit, the bulb current must be almost equal to the ________ current. (Use 6b.)
   d. Does 6c contradict 6b or the branch point law? ___ Does 6b agree with #5?___
   e. Whenever the capacitor is *charging*, its voltage is __creasing. Do #1 & 4 agree with 6e? ___
   f. During the *charging* process the resistor voltage __creases, as in #4 on p. 96. Does #1 agree? ___

7. In #1 the capacitor charged very ______ly (quickly, slowly) because the voltmeter in the circuit had very great _________. *Does #5 agree?*___ The capacitor charges and discharges more ______ly in #4 because the _______ ______ has much less resistance than the _________, as we saw on pages 84 and 90. Do these answers contradict 6c?___ Do the dots in #5 agree with #7?___

8. **Sign convention for currents:** The current in the capacitor leads is in the ***"positive"*** direction when the capacitor is *charging*. The capacitor current is in the ____tive direction when the capacitor is *discharging*. That rule is in #__ on RS __. Do #3 and 6a agree with it? __ -Does 6b? _

9. In #4, the capacitor and light bulb currents changed at the moment when the light bulb was connected. Did they change suddenly? ___ -Did they change gradually? __ *Explain on the back.*

10. Unplugging a light bulb makes it stop glowing *suddenly*. In #2, 3 and 4 the bulb dimmed out _________ly. (suddenly, gradually) This shows that the currents ________ly approached ___ as the light dimmed, so all of the graphs must approach constant "asymptotic" values as the light dims.
   a. If the current-time graph approaches that value from below, it must be "concave ____ward".
   b. If it approaches that same value from above, it must be "concave ____ward".
   c. Sketch graphs with *reasonable* initial values to illustrate answers 10a and 10b. Label them clearly.

11. After the light went out in #4 it was disconnected in preparation for the next experiment. Did that action cause any sudden changes in voltage or current? ___ *If so, please explain and illustrate.*

C. A Closer Look at the First Capacitor Experiment

1. In #3 on page 97 you saw how a capacitor can be used instead of a battery to supply energy to a light bulb. Sketch a diagram of that circuit in the space at the right. Put signs on the capacitor plates.
   a. Copy the beginner's definition of "voltage" from RS IX: _________ _________ __________
   b. Will there be any voltage between the bulb terminals if the capacitor is charged? ___
   c. Will that voltage cause a current through the light bulb? ___ (Use # 14 on RS IX.)
   d. Electrons are attracted by the ______tive plate and repelled by the ______tive plate. (#9 on RS IX)
   e. Draw arrows in your diagram showing which way electrons must flow through the light bulb.
   f. The capacitor voltage ___creases during this process.
   g. The bulb voltage must __crease at the same time, so the bulb current __creases. (See #1 on RS X)
   h. Some light came out of the bulb. Where was that energy stored before the circuit was completed?

2. Draw a resistor and capacitor connected in series to a battery. Let "V_r" represent the resistor voltage, let "V_c" represent the capacitor voltage, and let "V_b" represent the battery voltage.
   a. How must those voltages be related in *this* circuit? (Use #5 on RS IX.) ___ + ___ = ___
   b. According to the charge conservation law, (#3 on RS IX) how must the input and output currents be related for *any* electrical component? _______ *That's a clue for #2c!*
   c. What can we conclude about the number of electrons in this capacitor? ________ (Increasing? -Decreasing? -Remaining constant? -Converted into joules?)
   d. The ____tive terminal of the battery pulls electrons in. -Which one *emits* electrons? ________
   e. We cannot alter the battery. But we *can* increase the current in this circuit by reducing the ________ of the _______ *or* by increasing the _______ across the ________. (See #2 & 5 on RS X.)
   f. Connecting a light bulb in parallel with the resistor is equivalent to ___creasing the resistance of the resistor, as in 2e. -Does this agree with #4 on page 90? ____
   g. When we made that change (in #5 on page 97) the capacitor's charging rate must have __creased. Does this contradict 2e? ___ *If so, explain why you have not corrected that blunder.*
   h. A capacitor's "charging rate" is the slope of its ________ vs. _____ graph. (Saved in #__ on RS XI.)
   i. *By definition* that rate is equivalent to the _________ _______. (Check units and see 1b on page 88.)
   * j. Why do the resistor voltage and current *always* decrease during the charging process, *regardless* of whether the bulb is present or absent? *Answer with a statement that is always true.* (Use 2a.)

3. Let's predict the shapes of four graphs for the "charging circuit" described in #2: "Charge vs. Time", "Capacitor Voltage vs. Time", "Resistor Voltage vs. Time", and "Current vs. Time". The capacitor's "charge" means the charge *on one plate.* (The other plate has an equal but opposite amount, as you showed in #2c above.) Draw and label axes for the four graphs on the back of this paper.
   a. If the capacitor is initially uncharged then the initial value of the capacitor voltage must be ____ ___.
   b. Using 2a, we see that the resistor voltage graph must begin ______ the origin. (at, above, below)
   c. Ohm's equation then tells us that the current graph must begin _______ the origin.
   d. Using 3a-c, make a dot on each graph's vertical axis to indicate its initial value.
   e. According to 2h, the initial slope of the first graph must be ______tive.
   f. In #1 on RS XI (#2 on page 96) you said the capacitor's voltage depends on its _______. The initial slope of the capacitor voltage graph must be ____tive. *Illustrate 3e & 3f with short line segments.*
   g. According to 2j and 3f, the initial slope of the third graph must be _____tive.
   h. The familiar equation mentioned in 3c relates the third and fourth graphs: (________ = ________)
   i. Eq. 3h tells us that the initial slope of the fourth graph must be ______tive. Make short line segments on the 3rd & 4th graphs to illustrate 3g and 3i. -Do they contradict 3d or 3e? ___
   j. What definition mentioned in 2h & 2i relates the fourth graph to the *first* graph? ___ = ______
   k. 3i and 3j tell us that the first graph must be *concave* ____*ward*. With 3f we see that the second graph must be concave ____ward. *Illustrate by extending the first two graphs.* (See #10 on p. 98.)
   l. The third and fourth graphs must be concave ___ward to satisfy 2a. After a long time has passed, each graph must resemble a _______al line. *Use those facts to finish sketching the four graphs.*

4. Copy the two circuit diagrams that you drew for #4 on page 97. Label one as the "charging" circuit and the other as "discharging". For each one sketch graphs of *Capacitor Voltage vs Time, Light Bulb Current vs Time,* and *Capacitor Current vs Time.* Label all *ALL SIX* graphs clearly, using these clues:
   a. ***Clue 1:*** Each graph must have *THREE SECTIONS,* showing conditions *before, during, and after t*he flash. *Make vertical dotted lines to indicate the boundaries between those sections.*
   b. ***Clue 2:*** Descriptions of those graphs were written on pages 96 and 97. ***Clue 3:*** In #2 on RS XI there is a sign convention for capacitor currents. ***Clue 4:*** Don't contradict 1e, 1f, 1g, or 3 on this page.