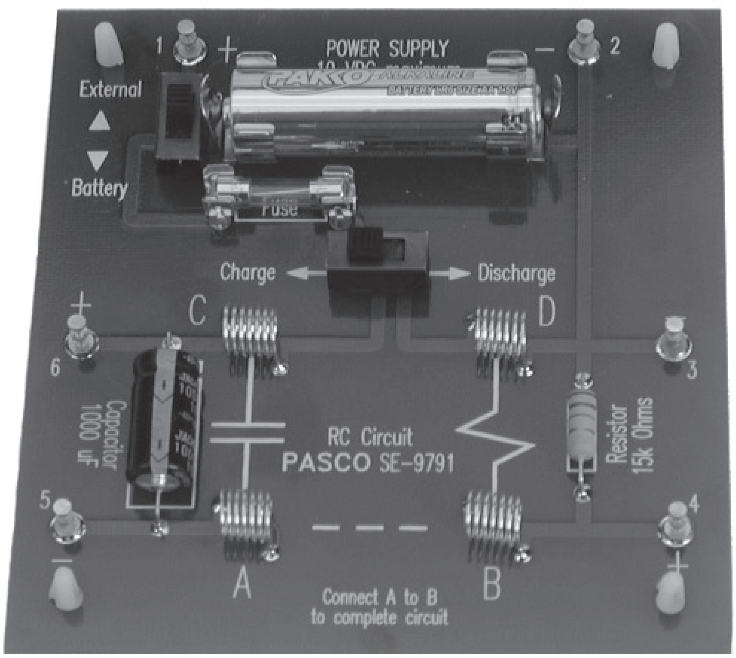
Includes Teacher's Notes and Typical Experiment Results

Instruction Manual and Experiment Guide for the PASCO scientific Model SE-9791

012-08795A

RESISTOR-CAPACITOR CIRCUIT



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Parts List:

The following are the contents of the RC Circuit package:

- Resistor-Capacitor Circuit Board with
  1.5 volt AA Battery and .315 Amp fuse mounted on the circuit board
- Jumper wire (to complete the circuit between springs A and B)
- Additional 1000 μF capacitor and 15 kΩ resistor
- User's Manual (this document)

If there are any parts missing, please contact:
PASCO® scientific
10101 Foothills Blvd.
Roseville, CA 95747-7100
Telephone: 1 (800) 772-8700 or (916) 786-3800

Additional Equipment Required:

- Either a computer interface unit and appropriate software
  (Examples: PASCO's DataStudio® or *ScienceWorkshop*® software)

Or

- A digital volt/ohm meter and stopwatch

Optional Equipment or Components:

- An external power supply can be used instead of the battery on the circuit board
- Additional resistors and capacitors of various values can be used with the RC Circuit Board.

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Developers: The Resistor-Capacitor Circuit was developed by Steve Skinner and John Rogers of LabNet, Inc.

Resistor-Capacitor Circuit Apparatus

Table of Contents

Introduction

The Resistor-Capacitor Circuit apparatus was designed by physics teachers for use in introductory physics and electronics courses at the high school and college levels. It is intended to be used in studying resistor-capacitor circuits only supplied with DC voltage. With proper care, it will provide many years of safe instructional use.

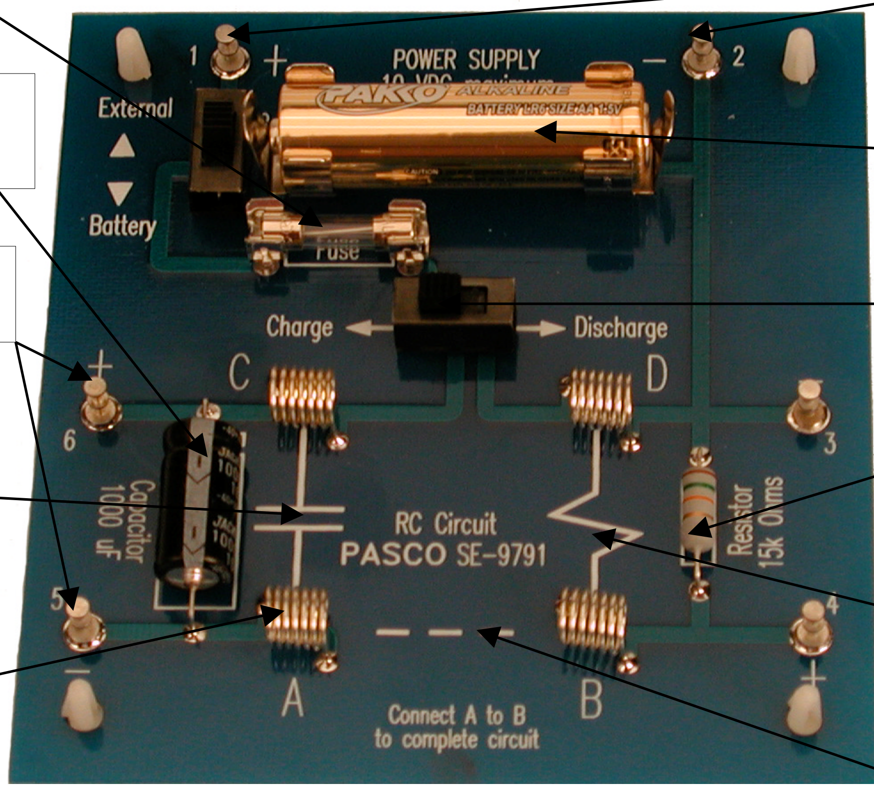
Because of its design, this circuit can be used in a wide variety of experiments, from simple circuits with single a resistor and capacitor, to more complex circuits with multiple resistors and capacitors in series and parallel. The option of using either the built in AA battery or an external power supply provides flexibility and ease of use.

A 15kΩ resistor and 1000 µF capacitor are soldered onto the circuit board and the AA battery included so that the RC Circuit Board is always ready for classroom experiments. If the jumper wire is lost, any short piece of wire, or a paper clip can be used to complete the circuit between springs A and B.

A 15kΩ resistor and 1000 µF capacitor were selected to provide a time constant of 15 seconds. This is short enough to allow full charging or discharging in 90 seconds, but long enough to allow students to think about what is happening as they watch data displaying in a graph on the computer interface. If a computer interface is not available, a 15-second time constant is also slow enough for students to record voltages from a digital voltmeter and times from a stopwatch or clock.

The RC Circuit is rated at a maximum of 10 volts DC to keep the voltage in a safe range for students and computer interfaces. The 1.5 volts supplied by a new AA battery is sufficient for experiments described in this manual.

Description of the RC Circuit Board Components



Test Points or Springs	Description
Test Points 1 and 2	Points 1 and 2 are for attaching an external power supply. **Caution:** Voltage from the external power supply must never exceed 10 volts DC or AC. Exceeding 10 volts will damage the circuit. Test Point 1 is for the positive lead and Test Point 2 is for the negative lead.
Test Points 3 and 4	Points 3 and 4 are for measuring the voltage across the resistor. Test Point 3 is for the negative lead and Test Point 4 is for the positive lead.
Test Points 5 and 6	Points 5 and 6 are for measuring the voltage across the capacitor. Test Point 5 is for the negative lead and Test Point 6 is for the positive lead.
Springs A and B	There is an open circuit between springs A and B. This allows for additional components to be included in the circuit in series with the components soldered on the circuit board. See page 14 for series and parallel formulas for resistance or capacitance. To operate the circuit, a component or jumper must be inserted between springs A and B.
Springs A and C	Springs A and C allow an additional capacitor to be placed in parallel to the capacitor. See page 14 for parallel capacitor formulas.
Springs Soldered	The soldered springs allow an additional resistor to be placed in parallel to resistor B and C on the circuit board. See page 14 for parallel resistor formulas.

Equipment Notes and Cautions

1. Cautions

A. The voltage applied to the RC Circuit must never exceed 10 volts DC or AC. Some of the components supplied with the RC apparatus are rated at 10 volts maximum. Exceeding 10 volts will damage the components and/or circuitry.

B. The capacitor soldered to the circuit board is an electrolytic capacitor and is therefore polarity sensitive. The voltage from the battery or the external power supply must not be reversed. When replacing the battery, insert the new one with its polarity matching the polarity marked on the circuit board by the battery holder clips. If using an external power supply, always attach the positive lead of the power supply to the positive terminal (1) on the circuit board. Attach the negative lead to the negative terminal (2).

C. Because the additional capacitor supplied with the RC Circuit is an electrolytic capacitor, it is polarity sensitive. Insert this capacitor, or any other electrolytic capacitor, in the circuit so that the polarity of the capacitor matches the polarity of the circuit where the capacitor is being added.

2. Power Supplies

There are three options for providing power to the RC Circuit. They are as follows:

1. The 1.5 volt AA-battery included on the circuit board.
2. A stand-alone external power supply adjusted to 10 volts or less.
3. A computer interface, such as the PASCO *ScienceWorkshop* 700 (with an optional Power Amplifier), or PASCO *ScienceWorkshop* 750 interface.

The AA battery or external power supply is selected by the switch (S2) near the positive (+) terminal of the battery. This prevents an external power supply from charging the AA battery, which could cause the battery to burst. To use power from a computer interface, refer to the interface manual for instructions on how to provide power safely. The PASCO *ScienceWorkshop* 700 requires the additional Power Amplifier unit. The PASCO *ScienceWorkshop* 750 interface can supply the necessary power directly from the interface.

3. Jumper Wire and Storage of Components

CAUTION: Do not allow the jumper, or any conductor, to connect the terminals of the battery holder to each other. This will cause a short across the battery or external power supply, will rapidly discharge the battery, and may cause an excessive amount of heat from either the battery or the external power supply. When the Resistor-Capacitor Circuit apparatus is not in use, the jumper wire and additional capacitors and resistors should be kept in a plastic bag separate from the RC Circuit.

4. Adding Components to the Resistor-Capacitor Circuit

CAUTION: This Resistor-Capacitor Circuit apparatus is designed to have both a resistor and a capacitor in the circuit at all times. The resistor and capacitor that are soldered to the circuit board should never have a jumper wire placed across either of them at any time. Placing a jumper wire across either the resistor or capacitor may drain the battery or blow the fuse on an external power supply.

The fuse in the circuit will not allow a current greater than 0.315 Amps. It is recommended that the total circuit resistance be greater than 1000 ohms and the total capacitance less than 50,000 **µ**F.

Additional components can be added in series or parallel to the resistor and capacitor that are soldered to the circuit board. This allows the values of the resistor and the capacitor on the circuit board to be increased or decreased. Resistors added in series increase the total resistance; resistors in parallel decrease the total resistance. Capacitors in series decrease the total capacitance; capacitors in parallel increase the total capacitance. Refer to page 14 of this manual for information about series and parallel addition of components.

Experiment 1

Charging an RC Circuit and Determining its Capacitance

When a capacitor is placed in series with a battery and a resistor, the capacitor charges up to the voltage of the battery. This kind of circuit is called a RC Circuit because the only two components besides a power supply are a resistor and a capacitor. The resistor limits the electrical current so that the charging takes place over an extended time. This allows students time to think about what must be happening as the circuit charges up to the applied voltage of the battery. After the simple voltage-time data for the charging is collected, fundamental electrical quantities of charge, current, and capacitance can be calculated via a spreadsheet. At the end of the experiment, you will be able to understand how the charge, voltage, and current change as the capacitor charges.

OBJECTIVES

- Collect voltage-time data for a capacitor in a RC circuit and curve fit the data.
- Calculate the capacitance of the capacitor in a RC circuit.
- Develop a mental image of what is happening to electrons during an RC circuit charging cycle.

MATERIALS

- PASCO *ScienceWorkshop* 500 or 750 computer interface, with *ScienceWorkshop* or DataStudio software
- RC Circuit Board and components
- Hand-held digital volt/ohm meter

PROCEDURE

1. Use a hand-held digital volt/ohm meter to measure the voltage of the battery. Record this value in the space to the right. _____________volts
2. Use a digital volt/ohm meter to measure the resistance of the resistor on the RC Circuit Board with no power supplied to the circuit. Record this value in the space to the right. __________ohms
3. Set the Battery/External power switch on the RC Circuit Board to “Battery.”
4. Set the Charge/Discharge switch on the RC Circuit Board to “Discharge.”
5. Connect a wire between points A and B on the RC Circuit Board.
6. Connect the red lead of a computer interface voltage probe to the positive (+) side of the capacitor. Connect the black lead of the computer interface voltage probe to the negative (-) side of the capacitor.
7. Connect the DIN end of the voltage probe to port 1 of the computer interface.
8. Use a pre-made template for collecting data or make your own data collection file. Collect data for 90 seconds at 1-second intervals.
9. Start the collection file and immediately move the Charge/Discharge switch on the RC Circuit Board to “Charge.”
10. After you have watched the circuit charge, read page 10 of this manual. This will help you develop a picture of what electrons are doing as the circuit charges.

ANALYSIS

Part A: Best Fit the Data

10. Best fit the data with a curve fit available in the collection program. The voltage changes in an exponential way from zero to the ceiling voltage of the battery according to an equation which looks something like: y=yo (1-e-kx). Print a copy of this graph including the best fit equation.

Part B: Calculate the Capacitance

11. Use the suggested spreadsheet in Appendix D to calculate the actual capacitance of the capacitor in the RC Circuit.

12. Using your collected voltage-time data, calculate the percent error in the capacitance printed on the capacitor compared to the actual capacitance determined by the spreadsheet. Tolerances for capacitors are often ± 20%.

Part C: Graphing

13. Make a graph of charge vs. voltage for the charging capacitor. Compare the slope of the best fit line to the value of the capacitance printed on the capacitor.

14. Make a graph of current vs. time for the charging capacitor.

15. Make a graph of charge vs. time for the charging capacitor.

EXTENSION

1. Use the extra capacitor supplied with the RC Circuit Board so that the capacitors sit side by side on the RC Circuit Board. Make sure both positive (+) ends of the capacitors are facing the same direction. What capacitance does this parallel capacitor have compared to the single capacitor? Refer to Appendix B, RC Circuit Theory.

2. Replace the wire from A to B on the RC Circuit Board with the external capacitor supplied with the RC Circuit Board. Make sure that the positive (+) end of the extra capacitor feeds into the negative (-) end of the fixed capacitor on the circuit board. What capacitance does this series capacitor have compared to the single capacitor? Refer to Appendix B, RC Circuit Theory.

Experiment 2

Discharging a RC Circuit
and Determining its Time Constant

When a fully charged capacitor discharges through a resistor, the amount of charge which flows in the first instant is large. However, as more and more charge is transferred, coulombic repulsion starts to slow down the flow. Finally, when the capacitor is fully discharged, each plate of the capacitor is electrically neutral. The shape of the graph for this discharge is a classical definition for exponential decay.

OBJECTIVES

- Collect voltage-time data for a discharging capacitor in the RC Circuit and curve fit the data.
- Calculate the time constant of the RC Circuit.

MATERIALS

- PASCO *ScienceWorkshop* 500 or 750 computer interface with *ScienceWorkshop* or DataStudio software.
- RC Circuit Board and components

PROCEDURE

1. From experiment 1, record the values for the voltage of the AA battery, and the resistance of the resistor on the RC Circuit Board.
   voltage =_______________ resistance = ________________.
2. Record the calculated capacitance from experiment 1 ___________________F or
   record the capacitance stamped on the capacitor itself ___________________F.
3. Set the Battery/External power switch on the RC Circuit Board to "Battery."
4. Connect a wire between points A and B on the RC Circuit Board.
5. Set the Charge/Discharge switch on the RC Circuit Board to "Charge."
6. Connect the red lead of a voltage probe to the positive (+) side of the capacitor. Connect the black lead of the voltage probe to the negative (-) side of the capacitor.
7. Connect the DIN end of the voltage probe to port 1 of the computer interface.
8. Use a pre-made template for collecting data or make your own data collection file. Collect data for 90 seconds at 1-second intervals.
9. Start the collection file and immediately move the Charge/Discharge switch on the RC Circuit Board to "Discharge."

ANALYSIS
Part A: Best Fit the Data

10. Best fit the data with a curve fit available in the collection program. The voltage changes in an exponential way from the ceiling voltage of the battery to zero according to an equation which looks something like: y=yo*e-kx. Print a copy of this graph including the best fit equation.

Part B: Calculate Tau (τ), the Time Constant for the RC Circuit

11. Look at the data table in the collection program to find the time when the voltage across the capacitor is 0.3679 of its starting value. This time is called the time constant for the RC Circuit.

12. Check to see whether the voltage drop is 0.3679 of its previous value for each unit of time, constant time.

13. Compare the time constant found in 11 above to the product of the resistance in ohms and the capacitance in farads.

14. Check the units of R x C to see if the units are seconds.

Part C: Graphing

15. Make a graph of charge vs. voltage for the discharging capacitor, using the suggested spreadsheet in Appendix D, page 19, to calculate the charge.

16. Compare the slope of the best-fit line to the capacitance of the capacitor.

17. Using the spreadsheet, make a graph of current vs. time for the discharging capacitor.

18. Using the spreadsheet, make a graph of charge vs. time for the discharging capacitor.

EXTENSION

1. Use the extra resistor supplied with the RC Circuit Board so that the resistors sit side by side on the RC Circuit Board. What effect does parallel resistance have on **τ**, the time constant?

2. Replace the wire from A to B on the RC Circuit Board with the external resistor supplied with the RC Circuit Board. Use the extra resistor supplied with the RC Circuit Board so that the resistors sit one flowing into another on the RC Circuit Board. What effect does this series resistance have on **τ**, the time constant?

3. Get an unknown resistor from your instructor, and place it in the circuit. Use the time constant of the circuit to find the value of the unknown resistance.

4. Try different combinations of resistance and capacitance to see if you can predict **τ**, the time constant for the RC circuit.

Conservation of Energy and Charge in an RC Circuit

Conservation laws are important in physics because there are so few of them and because we have found no exceptions. These laws are difficult to show experimentally because they demand a change of zero, which always is at odds with any real experiment. This simple RC circuit does a good job of providing data which support zero change in energy or charge when a charging cycle is compared to a discharge cycle.

OBJECTIVES

- Compare the energy required to charge the RC Circuit to the energy delivered when the RC Circuit discharges.

- Compare the charge transferred when the RC Circuit charges to the charge transferred when the RC Circuit discharges.

MATERIALS

- PASCO *ScienceWorkshop* 500 or 750 computer interface with *ScienceWorkshop* or DataStudio software.

- RC Circuit Board and components

- Spreadsheet template like the one shown in Appendix D

PROCEDURE

1. Record the values for the battery voltage and RC Circuit resistance, from experiment 1.

   voltage =_______________ resistance = ________________.

2. Record the calculated capacitance from experiment 1 ___________F or
   record the capacitance stamped on the capacitor itself ___________F.

3. Enter the values above into the proper cells of a spreadsheet, like the example in Appendix D.

ANALYSIS

Part A: Compare the Charge Transferred as the Capacitor Charges

4. Compare the value in cell D11 of the discharging spreadsheet to the value in cell D110 of the charging spreadsheet. The discharge cycle *starts with* the maximum separated charge, and the charge cycle *ends with* the maximum separated charge. If these two values are the same within experimental error, the charge separated in the charging cycle must be equal to the charge returned in the discharge cycle.

5. Make a graph of current vs. time for both charging and discharging cycles. Integrate each graph from 0 to 100 seconds to find the charge transferred, and compare results.

Part B: Compare the Energy Output to the Energy Input

6. Compare the value in cell F11 of the discharging spreadsheet to the value in cell F110 of the charging spreadsheet. The discharge cycle *starts with* the maximum energy, and the charge cycle *ends with* the maximum energy. If these two values are the same within experimental error, the energy input during the charging cycle must be equal to the energy output during the discharge cycle.

7. Make a graph of voltage times current vs. time for both the charging and discharging cycles. Integrate each graph from 0 to 100 seconds to find the energy transferred during the charging and discharging cycles, and compare the results.

Part C: Capacitor Analogy

8. Based on how both energy and charge flow during charge and discharge cycles of a RC circuit, what simple mechanical device behaves like a capacitor in a RC circuit?

EXTENSION

1. Use the extra resistor supplied with the RC Circuit Board so that the resistors sit side by side on the RC Circuit Board. What effect does parallel resistance have on the amount of charge separated during the charging cycle?

2. Replace the wire from A to B on the RC Circuit Board with the external resistor supplied with the RC Circuit Board. Use the extra resistor supplied with the RC Circuit Board so that the resistors sit one flowing into another on the RC Circuit Board. What effect does this series resistance have on the energy required to charge the capacitor in the RC Circuit?

Charging and Discharging a Capacitor: An Analogy

Capacitors are certainly mysterious components in an electrical circuit. Made from two conductive plates with an insulator in between, this "insulator sandwich" will not let any electricity flow through it, yet it is part of a conducting pathway. How? An analogy will help explain.

Consider a typical high school basketball game.

- Fans arrive at the game as either home team or visitors, but mixed randomly as they enter the building (just like positive (+) and negative (-) charge mixed randomly in a capacitor).
- The number of fans per minute admitted to the game depends on the number of ticket takers (just like the resistor in the RC Circuit limits the number of electrons per second which move toward the capacitor).
- Just prior to the start of the game, fans come into the gym in large numbers and sit on certain sides of the gym, visitors on one side and home team fans on the other (just like charges separating negative on one plate of the capacitor and positive on the other). Like the capacitor charging, the fans per second coming into the gym is large just prior to the game, and slows to a trickle as the game starts and the available seats are filled.)
- Each fan brings energy to the game in the form of cheering, and what fans on one side say or do influences what the fans on the other side do, even though fans do not cross from one side to the other side. This "action" happens at a distance (just like the effect felt on one charged side of the capacitor due to the opposite charge on the other side of the capacitor). The electric field exerts an influence through the insulator without charge flowing through the insulator.
- The number of fans divided by the average energy per fan is the "spirit" of the crowd (just like the charge in coulombs divided by the energy per coulomb is the capacitance of the circuit).
- When the game is over, a large amount of energy, emotional and physical, is released quickly as the crowd leaves in large numbers per minute (just like the rapid change in current and the quick release of energy in a short of a capacitor).
- As the fans exit, they once again form a random mixture (just like the separated charges reuniting after the capacitor is discharged).

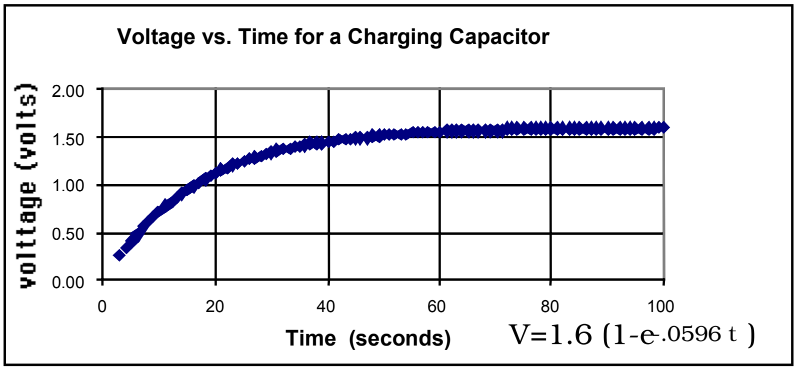
Like all analogies or models, the idea is not to provide the exact explanation of an event, but rather to provide a useful comparison to help understand how the real phenomenon behaves, and to predict new behaviors based on the comparison.

Appendix A: Answers to Questions

Experiment 1: Charging an RC Circuit and Determining its Capacitance

Part A

10.



11. The actual capacitance was .00110 Farads compared to .00100 Farads printed on the capacitor.
12. This is a + 10 % error, which is common for electrolytic capacitors.
13. The slope of a graph of Q vs. V gives .00110 Farads compared to .00100 Farads printed on the capacitor.
14. See graphs on page 17.
15. See graphs on page 17.

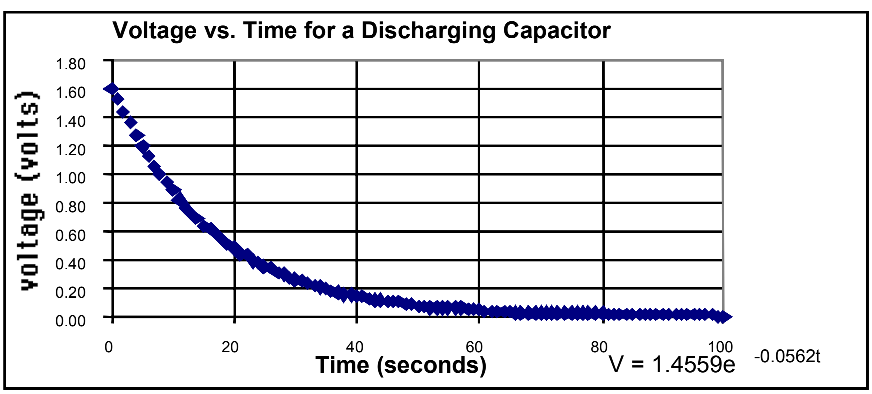
Extension Questions for Experiment 1

1. The parallel capacitor arrangement gives twice the capacitance or about .00220 Farads.
2. The series capacitor arrangement gives one half the capacitance or about .00055 Farads.

Experiment 2: Discharging a RC Circuit and Determining the Time Constant

Part A

10.



Part B

11. In 17 seconds, the voltage dropped to 0.58 volts, which is 0.3679 of the starting value.
12. Each successive 17 seconds, the voltage drops to 0.3679 of the previous value.
13. The time constant is 17 seconds, and the product of the actual capacitance and actual resistance is .00110 farads x 14, 960 ohms x 16.5 seconds = 17 seconds to two significant figures.
14. Farads x ohms = coulomb/volt x volt/amp. These units do equal seconds.

(Answers to Questions - Continued)

Experiment 2: Discharging a RC Circuit and Determining the Time Constant:

Part C

15. Refer to page 17 for a graph of charge vs. time for the discharge. The total charge transferred is 1.76 E-3 coulombs.
16. The slope of the voltage vs. time graph for the discharge gives a slope of .0011 Farads, which is close to .00100 Farads, the value printed on the body of the capacitor.
17. Refer to page 17.
18. Refer to page 17.

Extension Questions for Experiment 2

1. If two resistors are positioned in parallel, the time constant is half as large.
2. If the resistance is in series, the time constant is twice as large.
3. When the voltage is 0.3679 of the starting voltage, the circuit has reached one time constant. Set this number equal to R*.00110 Farads. Solve for R to find the resistance of the unknown resistor in ohms.
4. Various results.

Experiment 3: Conservation of Energy and Charge in a RC Circuit

Part A

4. The value of the initial charge for the discharge cycle and the final charge for the charge cycle are the same, within experimental error. Discharge=1.76 E-3 coulombs and charge =1.75 E-3.
5. The graphs are shown on page 17. Usually the discharge integration is > 99% of the charging integration. The very small difference is due to leakage.
6. For both the charging cycle and the discharging cycle, the energy transferred is 1.4E -3 joules. The energy is conserved.
7. The graphs are on page 17. Although the time it takes for the energy to be transferred is not the same, the graphs show that charging and discharging both involve the same amount of energy.
8. Capacitors are comparable to springs in mechanical systems.

Extensions Questions for Experiment 3.

1. The charge transferred will be the same. Changing the resistors will affect how long it takes to transfer charge, but not how much charge is transferred.
2. The resistor will dissipate some heat, so a little of the energy is lost when more resistance is placed in the circuit, however this loss is probably not observable, especially when the resistance is 30,000 ohms. Data will show that the energy required to charge the circuit will be the same with one or two resistors in series, but that it will take longer to transfer the energy with two resistors in series.

Appendix B: RC Circuit Theory

Useful Formulas and Theory of Resistor-Capacitor Circuits

1. Capacitance is defined as:
   $C = Q / V$ where:
   C = the capacitance in Farads
   Q = the charge in Coulombs
   V = the voltage in volts

   Because of the difficulty in directly measuring the charge, the voltage is generally measured in RC Circuit experiments. From the formula above, it can be see that the voltage is directly proportional to the charge.

   $V \infty Q$ or $V = (1/C) \bullet Q$ with $(1/C)$ = the proportionality constant

2. The time constant for exponential growth or decay, (the Greek letter tau), is the time in seconds for the capacitor to charge or discharge to a certain percent of its final voltage. For the charging cycle, when the voltage across the capacitor gets to 63.2 % of its maximum value, one time constant, t seconds, has passed. For the discharge cycle, when the voltage across the capacitor gets to 36.8 % of its starting maximum value, one time constant, **t** seconds, has passed. For resistor-capacitor circuits, the time constant, τ, is calculated by:
   $\tau = R \bullet C$
   t = time in seconds
   R = resistance in Ohms
   C = capacitance in farads (not microfarads)

3. Formula for Exponential Decay and Discharge of a Capacitor
   $V = Vo \bullet e\ (-t/R \bullet C)$
   V = voltage at any time
   Vo = initial voltage
   $R \bullet C$ = the time constant, τ
   t = any time after to

4. Formula for Exponential Growth to a Ceiling Value (the applied voltage)
   $V = Vo\ (1 - e\ (-t / R \bullet C)$
   V = voltage at any time
   Vo = initial voltage
   $R \bullet C$ = the time constant, τ
   t = any time after to

5. Formula for Half-life of Charging and Discharging
   $t1/2 = (R \bullet C) \ln(2)$
   $t1/2$ = time to reach half of maximum voltage (charge or discharge)
   $R \times C$ = the time constant, τ
   $\ln(2)$ = natural log of 2

6. Formula for resistors in parallel

$$R_{total} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}}$$

Formula for resistors in series

$$R_{total} = R_1 + R_2$$

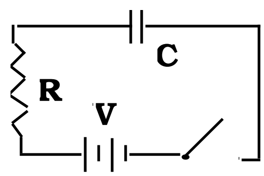
Formula for capacitors in parallel

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

Formula for capacitors in series

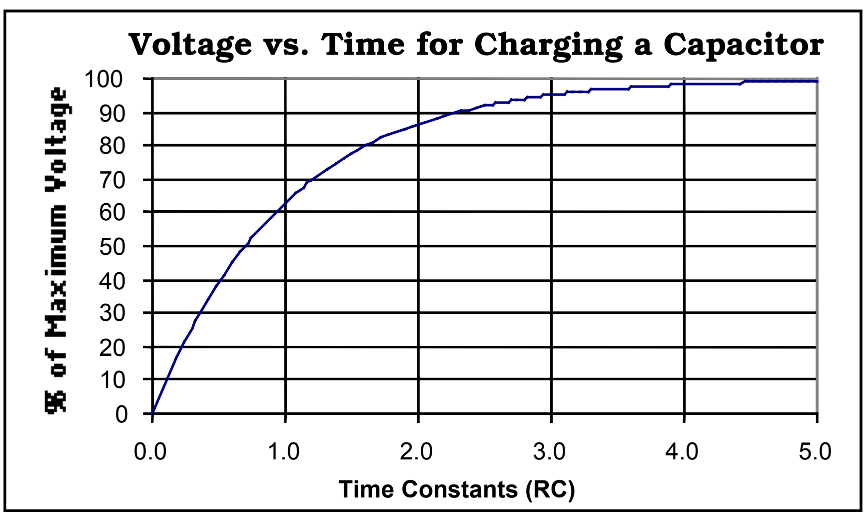
$$C_{total} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}}$$

Charging a Capacitor



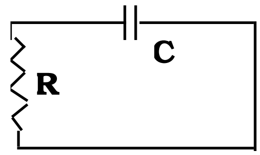
When a capacitor is being charged in a circuit such as that shown above, at any moment the voltage, Q/C, across the capacitor has the opposite sign compared to the battery voltage,V, and thus tends to oppose the flow of additional charge. For this reason, a capacitor does not acquire its final charge the instant it is connected to a battery or other source of emf. The net potential difference when the charge on the capacitor is Q is V - Q/C, and the current is then $I = \Delta Q/\Delta t = (V-Q/C)/R$. Look at the graphs in Appendix C to compare how charge, voltage and current change for the charging cycle of a RC circuit. The equation for charging a capacitor and a graph of voltage vs. time are shown below.
$Q = Q_o (1 - e^{-t/RC})$ where

Qo = the final charge
t = any time during the charge cycle
RC = the time constant
e = 2.718 and is often found in equations in engineering and science



A quantity that consists of **e** raised to a power is called exponential. To find the value of e^x or e^{-x}, an electronic calculator can be used. It is easy to see why Q reaches 63 percent of Qo in time RC. When t = RC, t/RC = 1 and $Q = Q_o(1 - e^{-1}) = (1 - 1/e) = Q_0(1 - .368) = .632\ Q_0$

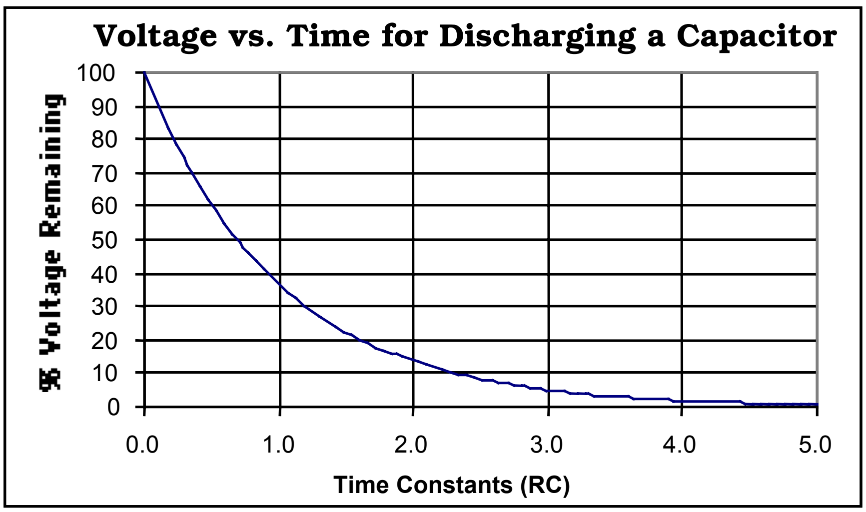
Discharging a Capacitor



When a charged capacitor is discharged through a resistor, the decrease in the charge is governed by the formula:

$$Q = Qoe\text{-}t/RC$$

where again RC is the time constant. The charge will fall to 36.8 percent of its original value after time RC. The smaller the time constant, the more rapidly a capacitor can be charged or discharged. The graph below shows voltage vs. time constant for a discharging capacitor. After five time constants, any capacitor is over 99% discharged.



Appendix C: Sample Graphs

Five Pairs of Graphs

1. **Charge vs. Voltage Graph**
   Charge separated in the capacitor is directly proportional to the voltage applied across the capacitor. As the voltage across the capacitor increases, more charge can be separated. The slope of this graph is the capacitance. The charging graph gives a cleaner result for the capacitance because the charging starts from a clear cut zero and ends with a clear cut maximum voltage, the voltage of the battery.

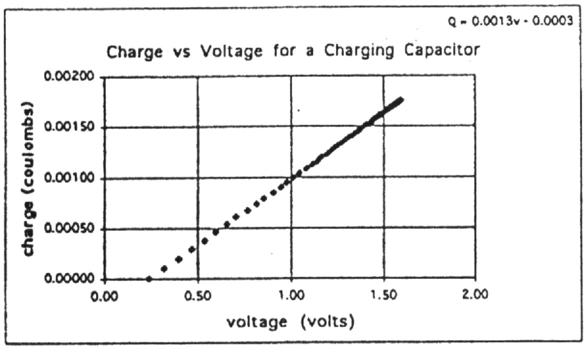
2. **Voltage vs. Time Graph**
   The charging graph represents exponential growth to a ceiling. Tau, the time constant for the circuit, is the time it takes to reach 63.2% of the final voltage. The discharging graph represents classical exponential decay. Tau, the time constant, is the time it takes to fall to 36.8% of the starting voltage. Tau is the same time regardless of the charge or discharge cycle.

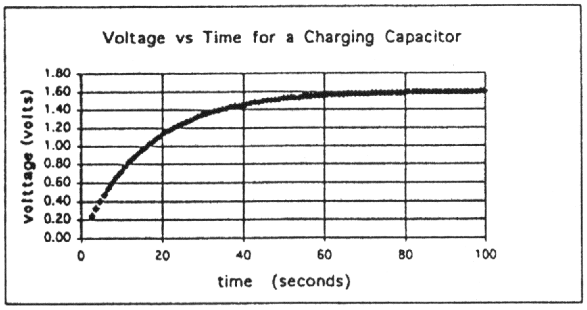
3. **Current vs. Time Graph**
   Note that regardless whether the capacitor is charging or discharging, the current starts high and falls to zero. None of the other capacitor graphs are like this. The integral of the charging current graph and the integral of the discharging current graph give the total charge separated and the total charge returned to ground respectively. This shows the conservation of charge.

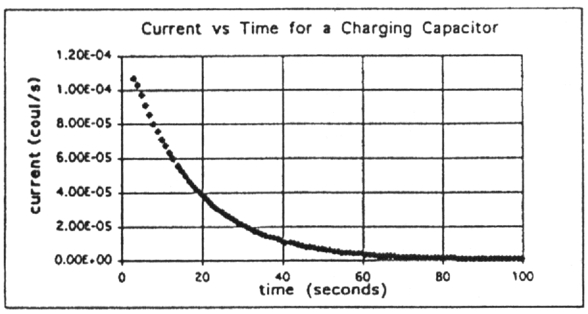
4. **Charge vs. Time Graph**
   Like the voltage, the charge accumulates to a maximum during the charge cycle and falls to zero during the discharge cycle. The charging and discharging graphs parallel the voltage graphs since $Q=CV$. Note that the charge is conserved. The maximum charge separated is equal to the charge delivered during the discharge cycle.

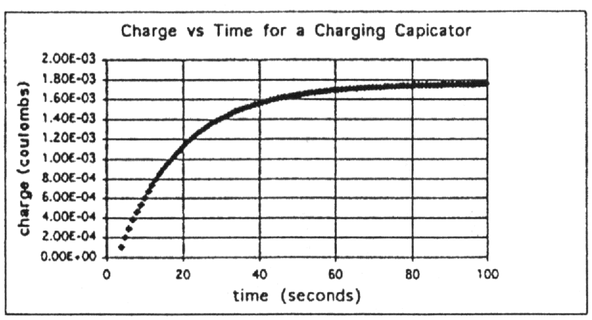
5. **Energy vs. Time Graph**
   The graphs of energy output and energy input vs. time are not the same. Note that the both cases, the energy transferred is same. Energy is conserved. The time plays no part in the energy transfer. Only the starting and ending energy is important. For the charging cycle, it takes more time to separate charge due to coulombic repulsion within the capacitor. The energy transferred during the discharge is delivered to ground, and happens faster. In the end, the energy output equals the energy input, conserving the energy.

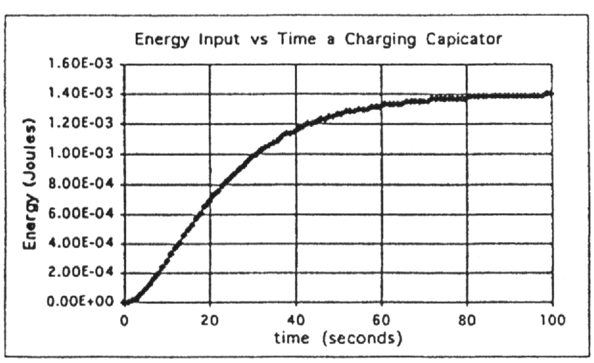
Charging



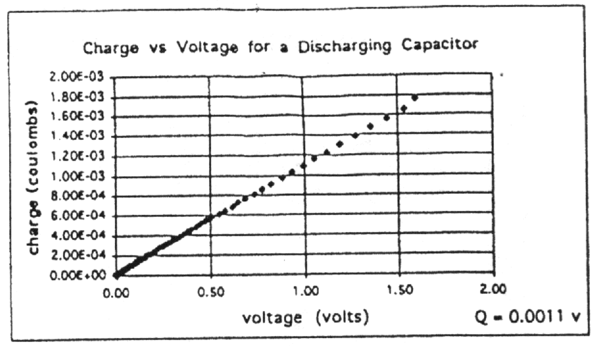


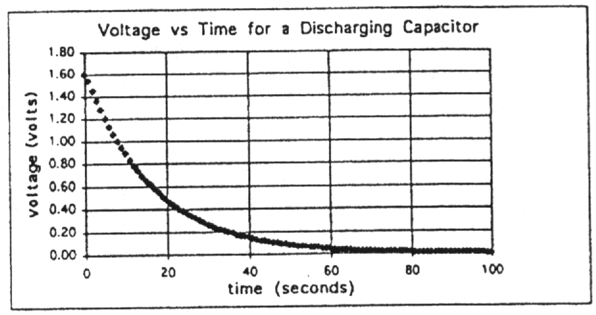


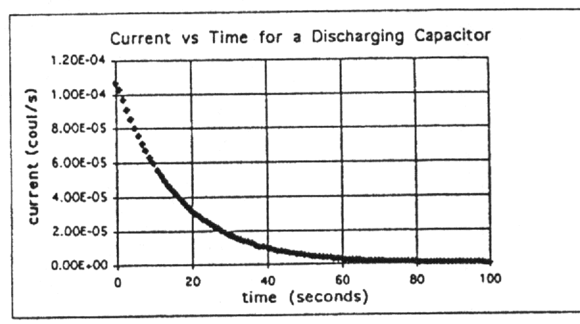


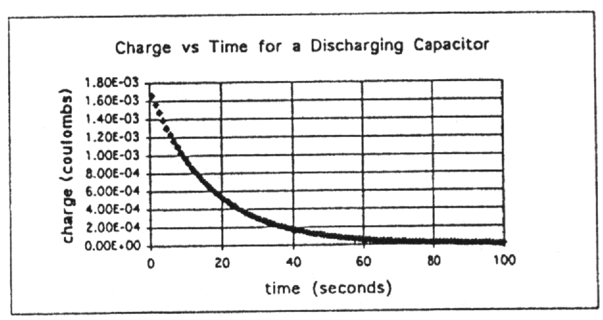


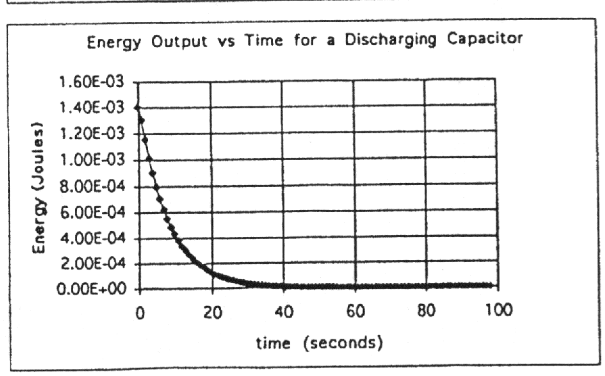
Discharging











Appendix D: Charging Spreadsheet

Instructions for Creating the Spreadsheet

Experiment 1: Charging in a Resistor – Capacitor Circuit

	A	B	C	D	E	F	G	H
1	Experiment 1: Charging in a Resistor – Capacitor Circuit							
2							Resistance =	14960
3	Time and Voltage data is copied						(from meter)	(Ohms)
4	and pasted from computer						Starting Voltage=	1.60
5	interface software data table						(from meter)	(volts)
6							Time Interval (Δt)=	1.00
7	(data)	(data)	(calculated)	(calculated)	(calculated)	(calculated)		(seconds)
8	Time	Voltage	Current	Charge	Capacitance	Energy In	Capacitance	.00110
9	(seconds)	(volts)	(Coulombs/s)	(Coulombs)	(Farads)	(Joules)	(average of)	(Farads)
10	0	0.00	1.07E-04	0.00	------	0.00E+00	(values)	
11	1	0.06	1.03E-04	1.03E-04	1.72E-03	1.97E-06	(from cells)	
12	2	0.15	9.69E-05	2.00E-04	1.33E-03	1.23E-05	(E20 to E110)	
13	3	0.24	9.09E-05	2.91E-04	1.21E-03	3.15E-05		
14	4	0.32	8.56E-05	3.76E-04	1.18E-03	5.61E-05		
108	98	1.59	6.68E-07	1.75E-03	1.10E-03	1.38E-03		
109	99	1.60	0.00E+00	1.75E-03	1.09E-03	1.40E-03		
110	100	1.60	0.00E+00	1.75E-03	1.09E-03	1.40E-03		

In each cell identified on the left, type in the data or formula shown on the right.

1. Type the text in cells exactly as shown in the picture above.
2. In cell H2: Resistance of the resistor as measured with the volt-ohm meter.
3. In cell H6: Change in time between voltage measurements.
4. In cell H8: Value of the capacitance in Farads (not **μ**F) printed on the capacitor.
5. In cell C10: =H4/H2
6. In cell C11: =($H$4/$H$2)-(B11/$H$2)
7. In cell D11: = C11/*A11
8. In cell E11: = D11/B11
9. In cell F11: =.5*E11*B11^2
10. Highlight cell C11 to F11, drag to the last of the Voltage-Time data and then "fill down."

Appendix D (continued): Discharging Spreadsheet

Instructions for Creating the Spreadsheet
Experiment 2: Discharging in a Resistor - Capacitor Circuit

	A	B	C	D	E	F	G	H
1	**Experiment: 2 Discharging in a Resistor - Capacitor Circuit**							
2							**Resistance =**	**14960**
3	Time and voltage data is copied						(from meter)	(Ohms)
4	and pasted from computer						**Starting Voltage**	**1.60**
5	interface software data table						(from meter)	volts
6							**Time interval (∆t) =**	**1**
7	data	data	(calculated)	(calculated)	(calculated)	(calculated)		(seconds)
8	**Time**	**Voltage**	**Current**	**Charge**	**Capacitance**	**Energy Out**	**Capacitance=**	**.00110**
9	(seconds)	(volts)	Coulombs/s	(Coulombs)	(Farads)	(Joules)		(Farads)
10	0	1.60	1.07E-04	1.76E-03	1.10E-03	1.41E-03		
11	1	1.54	1.03E-04	1.66E-03	1.08E-03	1.30E-03		
12	2	1.45	9.69E-05	1.56E-03	1.08E-03	1.16E-03		
13	3	1.36	9.09E-05	1.47E-03	1.08E-03	1.02E-03		
14	4	1.28	8.56E-05	1.38E-03	1.08E-03	9.01E-04		
108	98	0.01	6.68E-07	1.00E-05	1.00E-03	5.50E-08		
109	99	0.00	0.00E+00	1.00E-05	#DIV/0!	0.00E+00		
110	100	0.00	0.00E+00	1.00E-05	#DIV/0!	0.00E+00		

In each cell identified on the left, type in the data or formula shown on the right.

1. Type the text in cells exactly as shown in the picture above.
2. In cell H2: Resistance of the resistor on the RC Circuit measured with a volt-ohm-meter.
3. In cell H4: Power supply voltage as measured with a volt-ohm meter.
4. In cell H6: Change in time between voltage measurements.
5. In cell H8: =average (E20:E110) from experiment 1 spreadsheet
6. In cell C10: =$H$4/$H$2
7. In cell F10: =.5*$H$8*B10^2
8. In cell C11: = ($H$4/$H$2)-(B11/$H$2)
9. In cell D11=-C11/*A11
10. In cell E11: = D11/B11
11. In cell F11: =.5*E11*B11^2
12. Highlight cell C11 to F11, drag to the last of the Voltage-Time data and then "fill down."

Appendix E: Troubleshooting

Trouble Shooting

1. Fuse

The fuse on the RC Circuit apparatus is to protect from excessive current. If necessary, it must be replaced with a commonly available 5 mm x 20 mm fuse rated at 0.315 amp. Radio Shack stores carry a fuse of this size and current value.

2. Trouble Shooting

If the capacitor does not charge, there are a number of possible causes.

A. Check the following:

- Check for a jumper wire or other conductive component between springs A and B.
- The External/Battery switch (S2) must be set properly.
- Use a voltmeter to check the battery rating. The battery must be "good."
- Any external power supply must be turned on and set for a voltage between 0 and 10 volts.
- The Charge/Discharge switch (S1) must be set for charge.

B. Test the capacitor for damage.

The capacitor may be damaged by reverse polarity charging. Test the capacitor as follows:

1. Remove all power(battery or external) from the circuit.
2. Remove the jumper wire between springs A and B and any additional components added to the circuit.
3. Set the Charge/Discharge switch (S1) to the Charge position.
4. Using an Ohm meter (a digital is best), check the resistance through the capacitor by connecting the positive lead of the meter to the positive terminal on the capacitor and the negative lead to the negative terminal of the capacitor. Set the meter for a high range.
5. Wait a minute or more to allow the capacitor to charge. After charging, the resistance value should be from kohms to infinite resistance. Low resistance means a damaged capacitor.
6. If the capacitor is damaged, return the circuit board for repairs.

C. Test the S1 and S2 Switches.

The S1 or S2 switches might be defective. Test the switches as follows:

1. Use a jumper wire to jump over each switch and check to see if the capacitor will charge. If the circuit will charge when a switch is jumpered, but not when the switch is used normally, the switch is defective.
2. If a switch is damaged, return the circuit board for repairs.

If none of the steps above correct the RC Circuit, contact PASCO Scientific.