

Demonstration 3: Capacitance and Dielectrics

Equipment Required:	
Electrometer (ES-9078)	Faraday Ice Pail (ES-9042A)
Charge Producers (ES-9057B)	Proof Planes (ES-9057B)
Electrostatic Voltage Source (ES-9077)	Test leads
13 cm Conductive Spheres (2) (ES-9059B)	Variable Capacitor (Parallel Plates) (ES-9079)
Capacitor (about 30 pF) (ES-9043)	Sheet of dielectric material (See Table 3.1 for options)

Introduction

The purpose of this series of demonstrations is to investigate the relationship between charge, voltage and capacitance for a parallel plate capacitor. Each one of the variables will be held constant in turn, varying one of the others while measuring the third. The capacitance of

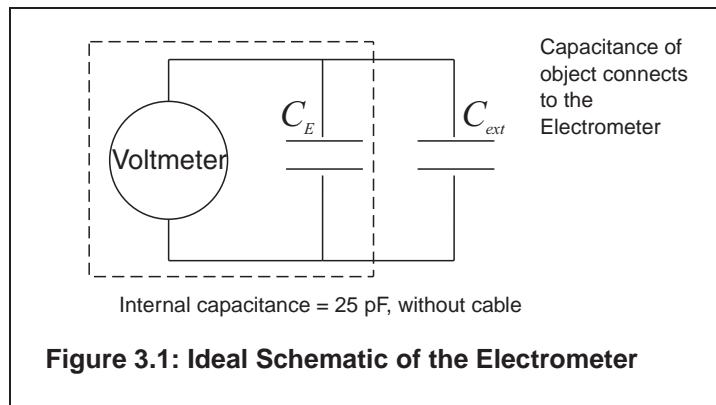
a parallel plate capacitor is given by $C = \frac{\epsilon A}{d}$, where ϵ is the dielectric coefficient, A is the plate area, and d is the plate separation. Various materials can be inserted between the plates to measure the dielectric coefficient of the materials.

NOTE: At this point, the students should understand the theory of capacitors connected in parallel. If not, go to Procedure D of this demonstration.

For all experiments, the electrometer can be thought of as an infinite impedance voltmeter in parallel with a capacitor, as shown in Figure 3.1. The capacitor C_E represents the internal capacitance of the electrometer, plus the capacitance of the leads.

Whenever you want quantitative measurements of charge, voltage or capacitance, you need to consider the effect of the internal capacitance of the electrometer, unless you are certain that the capacitor you are using has a high enough capacitance to disregard C_E . The capacitors in the PASCO RC Network (ES-9053), for example, are high enough that

C_E need not be considered. This is not true, however, when using the Basic Variable Capacitor (ES-9079).



Procedure 3A: Measuring the Electrometer's Capacitance

Use this procedure to measure a precise value of the capacitance provided by the electrometer and all cables connected to it. If you are interested in qualitative, rather than quantitative experiments, this procedure is not necessary.

When a capacitor of known capacitance C is charged by a known voltage V , the charge in it is given by $Q=CV$.

If the known charged capacitor is connected across the leads of the electrometer, it is connected in parallel with the internal capacitance of the electrometer, C_E . The total capacitance becomes $C + C_E$.

The known capacitor will discharge across the electrometer and a voltage, V_E , will be read. Since the total charge in the system is still just the charge of the known capacitor, we know that $CV=(C + C_E)V_E$.

1. Obtain a low leakage (polypropylene, or air dielectric) capacitor of known value, C , around 30 pF.
2. Charge the capacitor with a known voltage V , not higher than 100 V (the limit of the electrometer).
3. Remove the charged capacitor from the power supply used to charge it, being careful not to ground it in any way, to avoid removing the charge.
4. Connect the charged capacitor across the electrometer input leads. Note the voltage V_E indicated by the electrometer.
5. Calculate the internal capacitance of the electrometer.

$$CE = \frac{(V - V_E)}{V} \cdot C$$

Procedure 3B: Measuring C , V and Q for a Parallel Plate Capacitor

The purpose of the experiments listed in this part is to qualitatively study the relationship between C , V , and Q for the parallel plate capacitor. Values read by the electrometer are to be used as relative, comparative measurements. The electrometer can be connected to a computer and used with a *PASCO*[®] interface to obtain a graphical display of information.

3B.1: V Measured, Q Variable, C Constant

- Figure 3.2 below shows the equipment set up. The Parallel Plate capacitor is connected to the electrometer. The electrometer is grounded to earth. One of the spheres is connected to the voltage source, set at 2000 VDC. Take care to place the capacitor sufficiently far away from the sphere and the voltage source, to prevent it from being charged by induction.

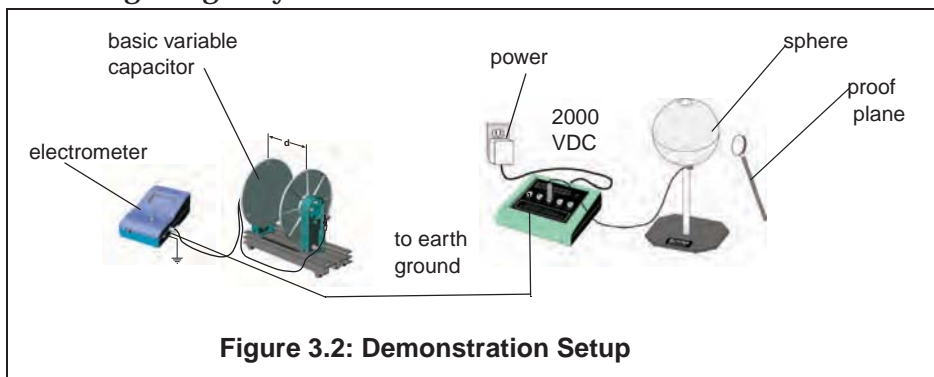
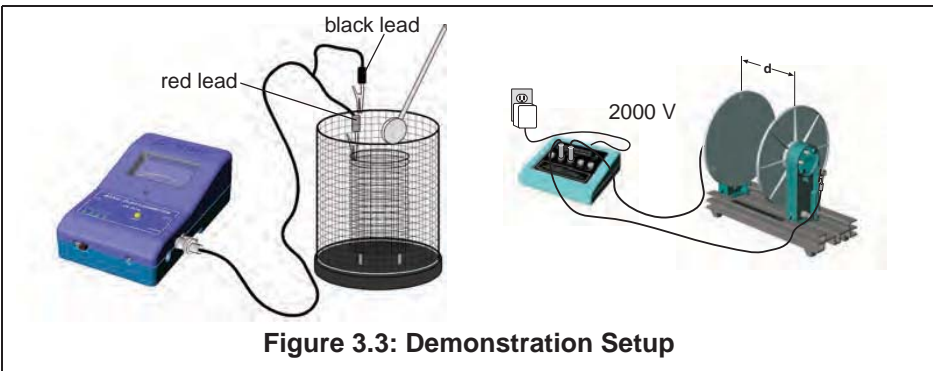


Figure 3.2: Demonstration Setup

- Press the **ZERO** button to remove any residual charge from the electrometer and the plates of the capacitor.
- Set the plate separation to about 2 mm. Use a proof plane to transfer charge from the charged sphere to the capacitor plates. The charge is transferred merely by touching the proof plane to the sphere and then to one capacitor plate. If you always touch the sphere and the capacitor plate at the same place, equal amounts of charge will be transferred each time.

Question: Why is it sufficient to touch only one plate of the capacitor?

4. Observe how the potential difference reading from the electrometer varies as more charge is put in the capacitor.
5. Double the plate separation and repeat the experience. What happens to the potential now? Compare the values to the previous case.



3B.2: Q Measured, C Variable, V Constant

1. Figure 3.3 above shows the equipment set up. The Parallel Plate capacitor has an initial plate separation of 6 cm and is connected to the voltage source, set at 2000 VDC. The Faraday Ice Pail is connected to the electrometer, and the electrometer is grounded to earth.
2. Momentarily ground a proof plane and then use it to examine the charge density of the capacitor, using the ice pail to measure the charge. Investigate the charge density at various points on the plates — both on the inner and the outer surfaces. How does the charge density vary over the plate?
3. Choose a point near the center of one capacitor plate and measure charge density in this area at different plate separations. (Keep in mind whether you are increasing or decreasing the capacitance by moving the plates.) How does the charge vary with capacitance?

3B.3 Q Measured, V Variable, C Constant

1. Figure 3.3 shows the equipment set up, which is identical to the setup for B2. The Parallel Plate capacitor has an initial plate separation of 6 cm and is connected to the voltage source, set initially at 3000 VDC. The Faraday Ice Pail is connected to the electrometer and the electrometer is grounded to earth.
2. Keep the plate separation constant and change the potential across the plates by changing the setting of the voltage source. You have

to move the connecting cable from the 3000 V to the 2000 V slot. Examine the charge density near the center of one capacitor plate. How does the charge vary with the voltage? Repeat with 1000 VDC.

3B.4: V Measured, C Variable, Q Constant

1. Figure 3.4 shows the equipment set up. The Parallel Plate capacitor is connected to the electrometer and the electrometer is grounded to earth. The voltage source will be used to only momentarily charge the capacitor.



Figure 3.4: Demonstration Setup

2. With the plate separation at 2 mm, charge the plates by momentarily connecting them across the voltage source, set at 30 V. Adjust the scale sensitivity of the electrometer so that the initially charged plates represent a meter reading of about 1/5 scale.
3. Increase the plate separation and note the electrometer's readings at various separations. How does the potential vary with capacitance?

NOTE: An alternative method is to charge one of the spheres and then transfer some charge to the capacitor. The charge, however, will not be as high.

Procedure 3C: Dielectric Coefficients

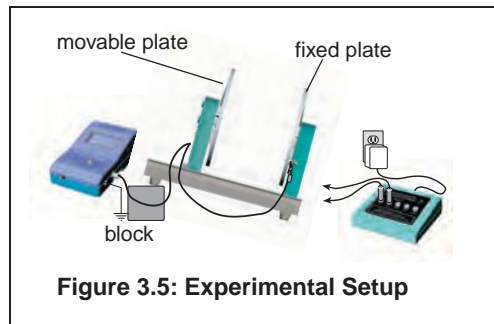
The dielectric coefficient κ is the dimensionless factor by which the capacitance increases (relative to the value of capacitance before the dielectric) when a dielectric is inserted between the plates. It is a fundamental property of the dielectric material and is independent of the size or shape of the capacitor. Table 3.1 on page 28 lists the dielectric coefficients of some common materials.

The ideal procedure to measure κ would be to simply slip a piece of dielectric material between a set of charged capacitor plates and then note the changes in potential. However, sliding a dielectric between the plates of the capacitor when they are too close together can generate a significant static charge that will alter the measurements. Hence, it is best to proceed as follows:

NOTE: Depending on the model of parallel plate capacitor you have, there may be only one plate that is movable. If your model allows both plates to be moved, choose one to keep fixed and the other to be the movable one.

1. Connect the electrometer across the plates of the capacitor and set the separation between the plates to about 3 mm.
2. Raise the side of the set up nearest the movable plate by setting a block about 3 cm high below it, as shown in Figure 3.5.

3. Use the voltage source to momentarily touch the plates and charge them to about 4/5 full scale. Record the voltage reading of the electrometer, V_i .



4. Carefully increase the separation of the plates until it is enough to insert the dielectric without forcing it. It should be enough so that you can simply lean the dielectric sheet against the stationary plate. Make sure the dielectric you are using is free of residual charge before inserting it.
5. After inserting the dielectric, return the plates to the original 3 mm separation and record the new electrometer reading, V_f .
6. Pull the plates apart again, and lift and carefully remove the dielectric sheet.
7. Return the plates to the original 3 mm separation and check that the electrometer reading agrees with the original V_i reading.

Analysis:

The calculations needed to determine the dielectric constant are long, but straight forward:

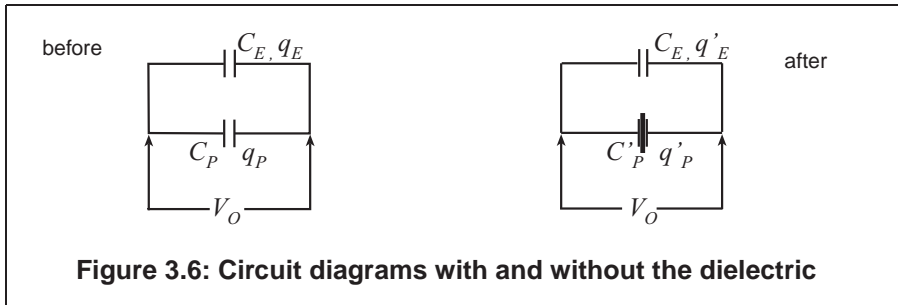


Figure 3.6: Circuit diagrams with and without the dielectric

Before inserting the dielectric...

Let q_P be the charge on the capacitor plates, and C_P be the capacitance of the plates, without the dielectric.

Let q_E be the charge on C_E , the internal capacitance of the electrometer.

Let V_i be the initial reading of the electrometer.

The total charge in this initial system is given by

$$q_P + q_E = (C_P + C_E)V_i$$

After inserting the dielectric...

Let q'_P be the new charge on the capacitor plates; the capacitance is now C'_P .

Let q'_E be the new charge on C_E , the internal capacitance of the electrometer. Since there is no dielectric in C_E , its value is still the same.

Let V_f be the new reading of the electrometer.

The total charge in the system after inserting the dielectric is given by

$$q'_P + q'_E = (C'_P + C_E)V_f$$

Now, the total amount of charge in the system was never changed, so

$$q_P + q_E = q'_P + q'_E$$

and $(C_P + C_E)V_i = (C'_P + C'_E)V_f$

After some algebra and rearranging, you find that

$$\frac{C'_p}{C_p} = \frac{C_E(V_i - V_f) + C_p V_i}{C_p V_f}$$

where the ratio (C'_p/C_p) is the dielectric coefficient κ :

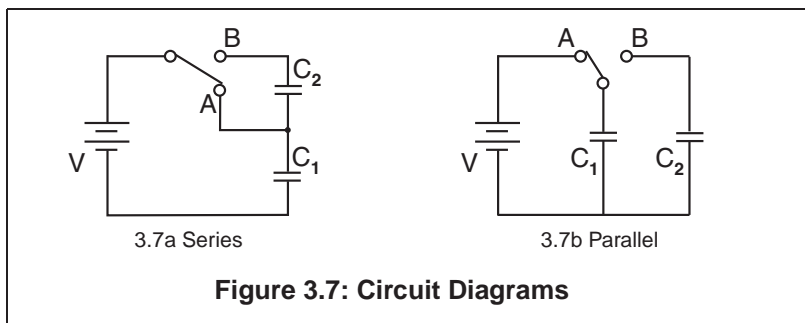
$$\kappa = \frac{\varepsilon A_d}{\varepsilon_0 A_d} = \frac{C'_p}{C_p}$$

Table 3.1: Some Dielectric Coefficients

Material	κ
Vacuum	1
Air	1.00059
Polystyrene	2.6
Paper	3.7
Pyrex	4.7
Mica	5.4
Porcelain	6.5

Procedure 3D: Capacitors in Series and in Parallel

The purpose of this demonstration is to examine the effect of placing capacitors in series and in parallel. You will need two capacitors of known value (between 200 - 400 μF , to ignore the internal capacitance of the electrometer), a DC voltage source, the electrometer, some cables, and a double throw switch.



3D.1: Capacitors in Series

Make sure all capacitors are uncharged before connecting them. (Use a short wire to momentarily short each one.)

1. Set up the series circuit, as shown in Figure 3.7a.
2. Plug in to the 30 VDC output on the Voltage Source. Close switch A to charge capacitor C1.
3. Using the known value of C_1 , calculate the initial amount of charge on C_1 . Let's call it Q_0 . (Remember $Q=CV$.)
4. Throw the switch to position B. C_1 and C_2 are now in series.
5. Use the electrometer to measure the voltage drop across each of the capacitors (V_1 and V_2).
6. Using the known values of capacitance, determine the amount of charge in each of them. (Q_1 and Q_2).
7. Questions: Can you find a relation between V_1 , V_2 and the voltage of the source? How does Q_1 and Q_2 relate to the original charge on C_1 ?

3D.2: Capacitors in Parallel

1. Make sure all capacitors are uncharged before connecting them to the circuit.
2. Set up the parallel circuit, as shown in Figure 3.7b.
3. Set the voltage source to 30 VDC. Close the switch to charge the capacitors.
4. Use the electrometer to measure the potential difference across each of the capacitors. How does it compare to the voltage of the source?
5. Use the known value of the capacitances to determine the charge in each capacitor. How are the charges related?

Analysis:

1. Compare series and parallel capacitors in terms of charges, voltages and capacitance.

Demonstration 4: Charging and Discharging Capacitors

Equipment Required:	
Electrometer (ES-9078)	Faraday Ice Pail (ES-9042A)
Power Amplifier (CI-6552A)	Test leads
Capacitors, 200-400 μ F	Resistors, (10-90k Ω ; 10-1000 Ω)
Computer with <i>PASCO</i> interface	DataStudio [®] software

Introduction

The purpose of this demonstration is to investigate how the voltages across a capacitor and a resistor vary as the capacitor charges and discharges, and to find the capacitive time constant. When a capacitor is connected to a DC power supply, charge builds up in the capacitor and the potential difference across the capacitor increases until it equals the voltage of the source. Both the charging and the discharging of a capacitor are characterized by a quantity called the time constant, which is the product of the capacitance, C and the resistance R . That is,

$$\tau = RC.$$

Use capacitor values in the recommended range, so that the internal capacitance of the electrometer needs not be considered. You can adjust the resistance value for a convenient RC constant.

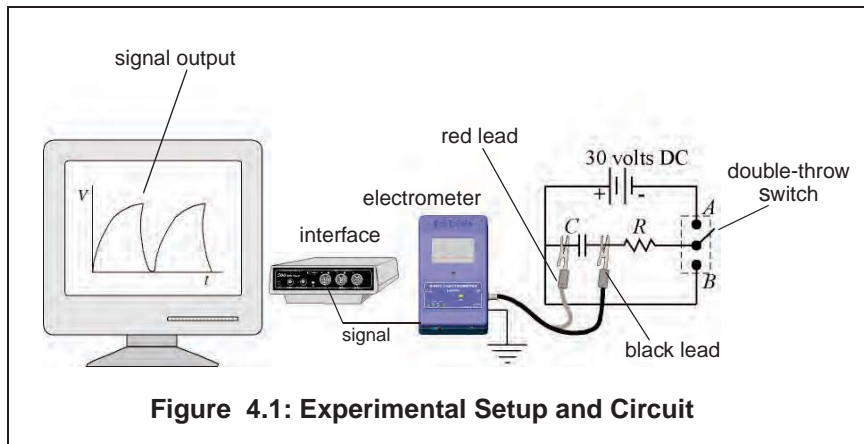
There are two variations of the same activity presented here. The first uses a direct DC voltage source and results are obtained in a voltage vs. time graph. Use higher resistances (10-90 k Ω for this method. The second uses a signal generator with a square wave to charge and discharge the capacitor. Use lower resistances (100-1000 Ω for this method.

Equipment Setup

The signal output cable of the electrometer allows it to be connected to a *PASCO* interface as an analog sensor.

1. Open the software program and select the electrometer from the list of sensors.

- Set up the circuit shown in Figure 4.1, where the resistor and the capacitor are connected in series to the voltage source, set at 30 VDC. The electrometer output goes to one of the analog channels of the PASCOS interface. Use a single-pole double-throw switch.



- Set up your experiment display in the computer to plot voltage vs. time. (Refer to the steps listed above for correcting the electrometer readings.)
- With the switch open, press start to begin collecting data. Throw the switch to position A to begin charging the capacitor. Observe the behavior of the voltage on the screen.
- When the charge in the capacitor has reached the value of the source (30 VDC), flip the switch to position B to begin discharging the capacitor. Observe the behavior of the voltage in the screen.
- You may want to try the experiment with different values of R and notice the differences in charging time.

Analysis:

When a capacitor is charged through a resistor from a DC power supply, the charge on the capacitor and the voltage across the capacitor increase with time. The voltage, V , as a function of time is given by

$$V = V_0 (1 - e^{-t/RC}) \text{ where } V_0 \text{ is the charging voltage.}$$

After a time $t = RC$ (one time constant), the voltage across the capacitor has increased to 63% its maximum value ($V = 0.63V_0$ at $t = RC$).

1. Calculate 63% of the voltage of the source. Locate the position in the graph where the voltage has reached this value. How long a time has passed to reach 63% of the voltage of the source? This time is RC . (Using the Smart Tool in DataStudio makes these measurements easy!)
2. Compare the measured time constant from the graph with the calculated from the known values of ϵ and R . Now, when a fully charged capacitor is discharged through a resistor, the voltage across (and the charge on) the capacitor decreases with time according to the equation $V = V_0 e^{-t/RC}$. After a time $t = RC$ (one time constant), the voltage across the capacitor decreases to 37% its maximum value.
3. Determine how much is 37% of the total voltage and locate where in the discharging plot this value has been reached. How long a time since the start of discharging did it take to reach this value? (Use the smart cursor tools!)
4. Compare this measured RC constant with the known value.

Procedure 4B: Charging/Discharging Capacitors with Signal Generator

When a positive square wave signal is applied to a capacitor in an RC circuit, the capacitor periodically charges and discharges, as shown in Figure 4.2. The period of a full charge-discharge equals the period of the wave.

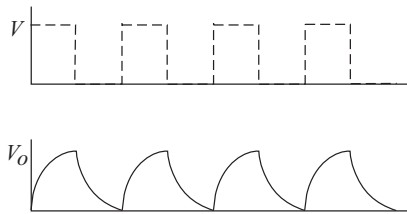
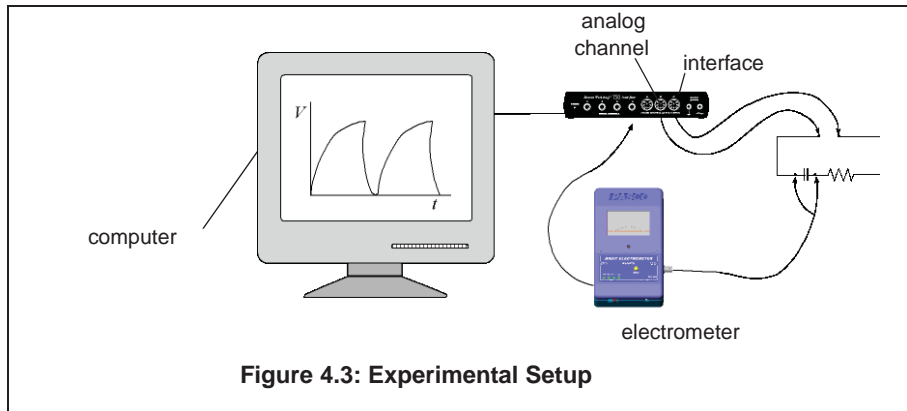


Figure 4.2: Charging and Discharging with a Square Wave Signal

Note: The procedure listed here specifies values for R , C and the frequency of the signal that work well together. If you decide to use any other R or C value, you have to adjust the frequency of the wave. Notice that the voltage has to remain constant for enough time to fully charge the capacitor before the voltage goes to zero and the capacitor is discharged. A good estimate of the time needed to fully charge a capacitor can be determined as $t = RC[\ln V_0]$.

- $\ln 0.01$], where V_0 is the voltage of the source. Choose a signal such that the period of the wave is at least double this charging time.



Experimental Setup

1. Set up the circuit shown in Figure 4.3, where the resistor and the capacitor are connected in series to the signal output generator of the PASCO 750 Interface. Use a $200\mu\text{F}$ capacitor and a resistance of $1000\ \Omega$. The electrometer is reading the voltage across the capacitor, and it is also connected to one of the analog channels of the PASCO interface.
2. With the DataStudio software, create a display of voltage vs. time for the readings of the electrometer.
3. Set the signal generator to produce a positive square wave of maximum around 4 volts and of frequency 0.45 Hz. Set the signal generator to AUTO. In this way, the signal will turn on and off as you press Start or Stop to collect data.
4. Start recording data. Observe the behavior of the voltage across the capacitor on the screen. When several cycles of charging-discharging have completed, stop the collection of data.
5. Only one full cycle is necessary to complete all the analysis. Zoom in to a full cycle of charge-discharge.

Analysis:

The analysis is similar to the analysis for Procedure A.

Extra Things to Try:

1. Check what is happening to the voltage across the resistor while the capacitor charges and discharges.

Appendix A: Copyright and Warranty Information

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Credits:

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Appendix B: Technical Support

For assistance with the Basic Electrostatics Systems equipment or any other PASCO products, contact PASCO as follows:

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Roseville, CA 95747-7100

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