## Experiment # 8

# Circuit Analysis - 1
# The Crunching Technique: (b) Capacitors

## Principles

### Defining Circuit & Circuit Analysis

An electrical circuit, in general, consists of a number of electrical components that may be connected to one or more sources of electricity. Electrical components are of two types: *(i) passive*: resistors, capacitors and inductors, and *(ii) active*: diodes, transistors and integrated circuits. Similarly the sources of electricity are of two types: (i) DC, and (ii) AC. Both, the components and the sources may be combined in three different modes: (i) series, (ii) parallel, and (iii) series-parallel. A circuit may have any number of components of the three types and any number of sources of either type, connected together in any of the three possible modes.

> *The purpose of circuit analysis is to determine (i) the voltages across each component of a given circuit, (ii) the currents that pass through each one of them, (iii) potential differences between any two given points in the circuit, and (iv) the terminal voltages of all sources.*

For our experiment, we impose the constraint that: we shall leave out active components and deal only with the passive ones. Whatever rationale we develop here, however, will be equally applicable to all types of components and sources. Again, by imposing these constraints, we have not put any limit on the number of components or sources or on the modes of their combination.

Next we state some basic rules that help us to reach the above mentioned objectives. However, their applicability is limited to basic circuits. These rules are:

(1) Components connected together in *series* share a common current (or charge) that passes through (or gets deposited on) them but each has its own characteristic voltage.

(2) Components connected together in *parallel* share a common voltage but each has its own characteristic current (or charge) that passes through (or gets deposited on) it.

(3) Equivalent resistances and equivalent capacitances, in series or parallel configurations, are given by following formulae:

$$R_{eq,\,series} = \sum_n R_n \qquad \frac{1}{R_{eq,\,parallel}} = \sum_n \frac{1}{R_n} \qquad \text{..........(1)}$$

$$\frac{1}{C_{eq,\,series}} = \sum_n \frac{1}{C_n} \qquad C_{eq,\,parallel} = \sum_n C_n \qquad \text{..........(2)}$$

(4) The battery equations for circuits with (i) resistors only, and (ii) capacitors only, are:

$$V_S = R_{eq}\, I_S \qquad \text{and} \qquad Q_S = C_{eq}\, V_S$$

(5) For an AC voltage supply ($V_S$ at frequency $\omega$, a pseudo current $i_S$ develops in capacitor-circuits. The applicable equation is:

$$V_S = \chi_{C,\,eq}\, I_S \qquad \text{..........(3)}$$

## Junctions, Strings & Loops

A junction is a point in a circuit where a set of parallel-connected components are connected to other parts of the circuit. Thus, a junction is a point where at least 3 wires meet.

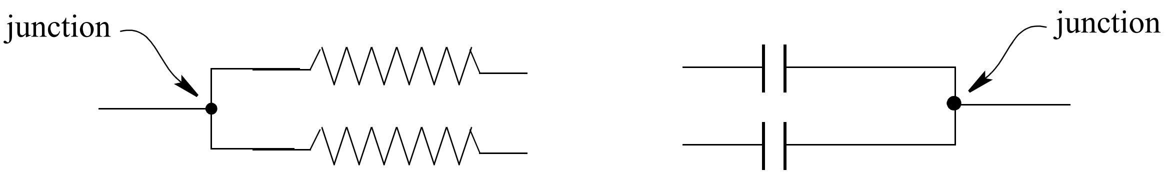


*Fig (1) Junctions; A Minimum of Three Wires Meet*

A string is an aggregate of components that are all connected in series to one another. We find strings in between a pair of junctions.

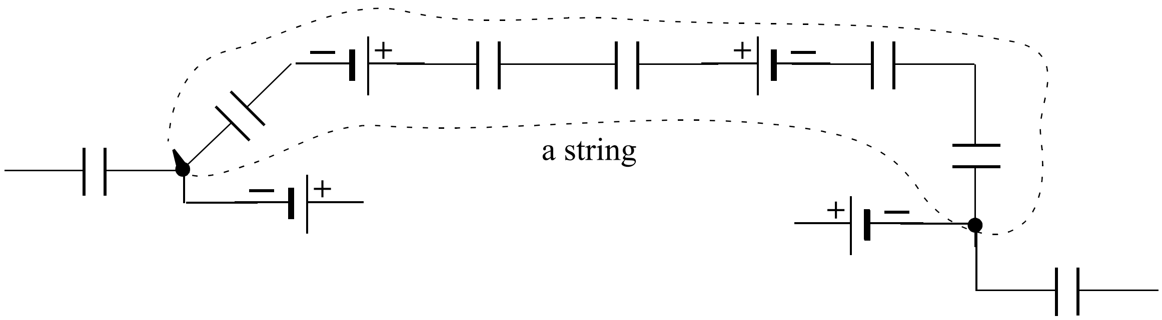
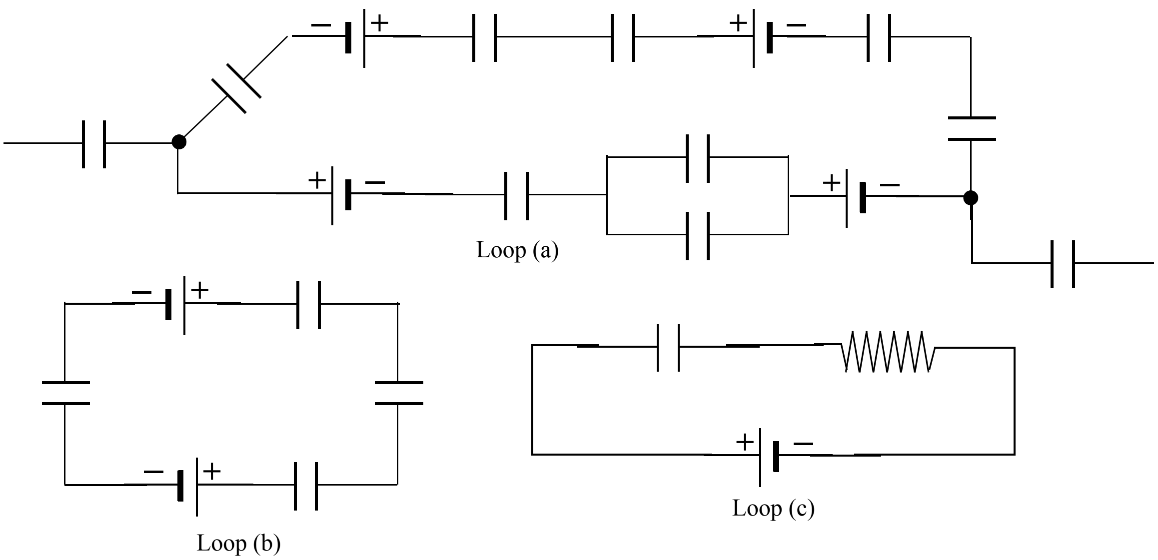


*Fig (2) A string; A Series of Components in Between a Pair of Junctions*

A loop is a closed configuration of components. It is made up of two strings in between a pair of junctions. It may also be a single string, folded around to make a closed configuration



Loop (a)

Loop (b)

Loop (c)

*Fig (3) Examples of Loop*

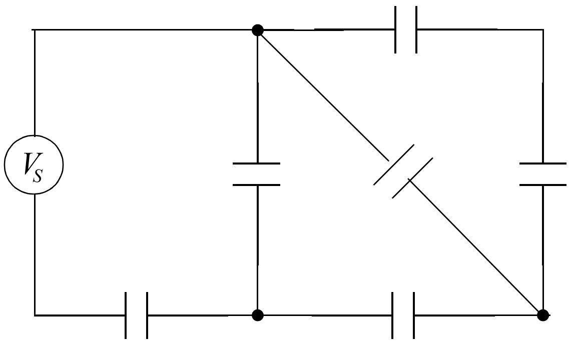
## Basics of Crunching

Crunching technique can be applied to multi-loop circuits with two constraints (conditions): (i) all batteries should be in one string only, and (ii) there should be at least one pair of series-connected or parallel-connected components. In Fig (3), loop (a) is ineligible for crunching but loops (b) and (c) can be crunched. Loops (b) and (c) do not have junctions. There is only one string that has been made into a closed configuration.

To crunch, one seeks out a set of components that are either all in series or all in parallel. These are combined using either the series combination equation or the parallel combination equation. These are then replaced by one component. In what follows, we shall talk of capacitors only but the same will equally apply to resistors also. The starting set of components must be as far away from the battery as possible. The ones in the vicinity of the battery must be crunched at the very end.

## Objectives of the Experiment

*To study the crunching technique as applied to the following circuit;*



*(i) directly, by comparing the calculated and the measured values of currents and voltages for all six capacitors in the circuit and for the source, ((the circuit being fed by an AC supply at circular frequency ω)*

*(ii) indirectly, by plotting a suitable graph.*

## Setting Up

We shall proceed with the crunching process. The circuit consists of a function generator and a total of 6 capacitors. The circuit is reproduced in Fig (4a). As can be seen, it has 3 junctions, (labeled *A*, *B* and *C*.), 5 strings and 5 loops. The states of the circuit during different stages of crunching are also shown in Fig (4).

In Fig (4a), the two capacitors at the top left hand corner are found to be in series. This is our starting point. We promptly call them $C_1$ and $C_2$. We calculate their series combination as:

$$C_{1,2})_S = (C_1^{-1} + C_2^{-1})^{-1} = C_{12}$$

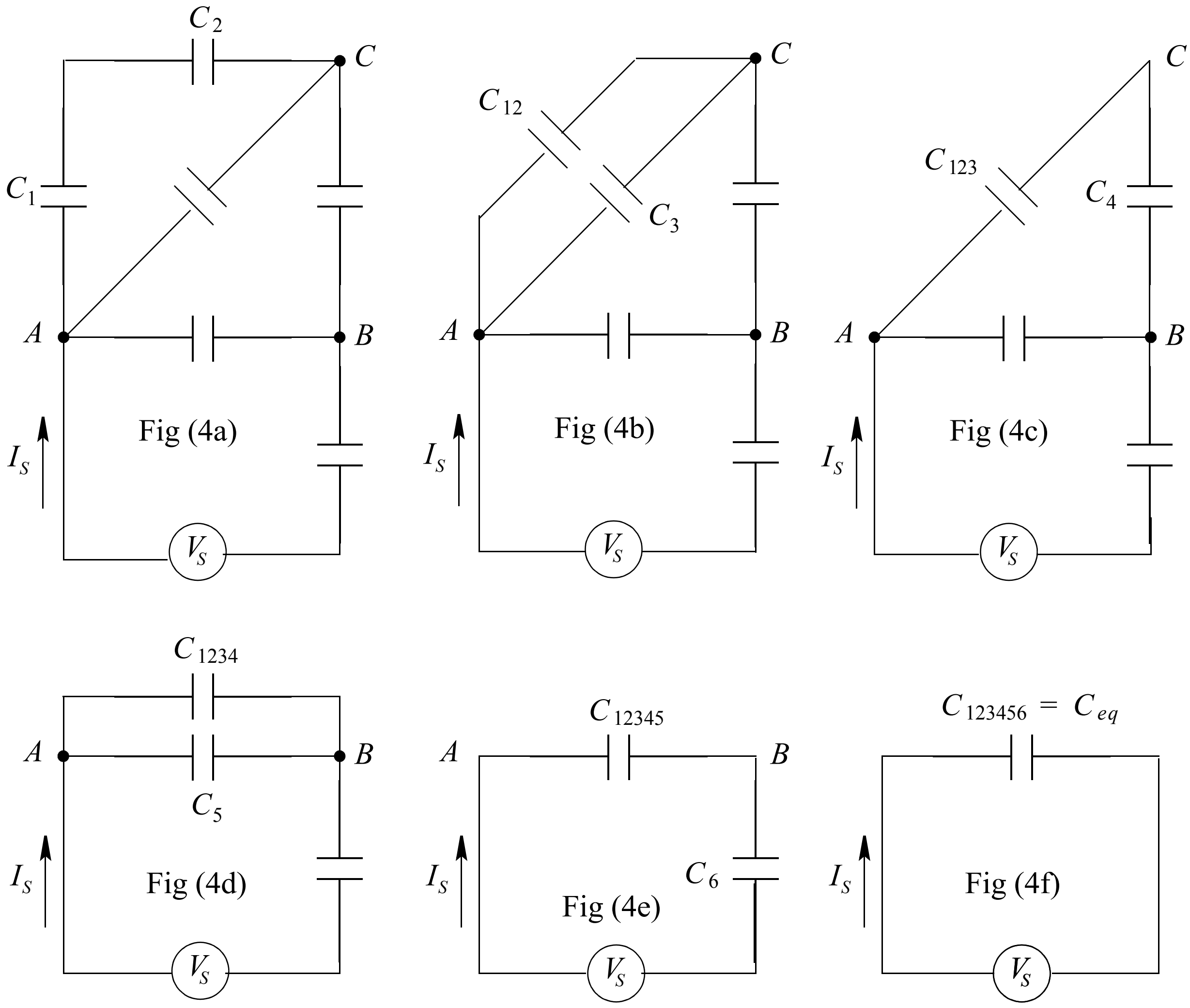


*Fig (4) Steps of Crunching*

In Fig (4b), the two capacitors, $C_1$ and $C_2$ are replaced by one capacitor: $C_{12}$. Capacitor $C_{12}$ is found to be in parallel with another capacitor which we name $C_3$. We calculate their parallel combination as:

$$C_{12,3})_P = C_{12} + C_3 = C_{123}$$

In Fig (4c), the two capacitors $C_{12}$ and $C_3$ are replaced by one capacitor: $C_{123}$. We find that junction $C$ has disappeared and capacitor $C_{123}$ is now in series with another capacitor which we name $C_4$. We calculate their series combination as:

$$C_{123,4})_S = (C_{123}^{-1} + C_4^{-1})^{-1} = C_{1234}$$

In Fig (4d), the two capacitors $C_{123}$ and $C_4$ are replaced by one capacitor: $C_{1234}$. Capacitor $C_{1234}$ is found to be in parallel with another capacitor which we name $C_5$. We calculate their parallel combination as:

$$C_{1234,5})_P = C_{1234} + C_5 = C_{12345}$$

In Fig (4e), the two capacitors $C_{1234}$ and $C_5$ are replaced by one capacitor $C_{12345}$. We find that junctions $B$ and $C$ both have disappeared and capacitor $C_{12345}$ is now in series with the last capacitor, to be named $C_6$. We calculate their series combination as:

$$C_{12345,\,6})_S = (C_{12345}^{-1} + C_6^{-1})^{-1} = C_{123456} = C_{eq}$$

In Fig (4f) the two capacitors $C_{12345}$ and $C_6$ have been replaced by one capacitor, $C_{123456}$ or $C_{eq}$. This completes the crunching process. The whole circuit is replaced by one capacitor and one voltage source, $V_S$. For $V_S$ to be an AC supply, a (pseudo) current $I_S$ will develop in the circuit, given by:

$$I_S = \frac{V_S}{\chi_{C,\,eq}} \qquad \textit{where} \qquad \chi_{C,\,eq} = \frac{1}{\omega C_{eq}} \qquad \textit{and} \qquad \omega = 2\pi f$$

We find:

$$I_S = \omega C_{eq} V_S$$

But

$$C_{eq} V_S = Q_S .$$

This allows us to write:

$$I_S = \omega Q_S$$

Using reactances of capacitors to calculate currents would have been a terribly messy proposition. It turns out that we can bypass reactances altogether and work with charges $Q$ and currents $I$. To convert charges to to currents, we shall multiply charges by $\omega$. To convert currents to charges, we shall divide currents by $\omega$.

We shall now proceed backward and calculate (pseudo) currents and voltages for each capacitor. This can be done easily by following the scheme shown in Table # 1 below.

**Table #1 Calculating Voltages and Currents for Each Capacitor**

| | $C$ | V | Q | I |
|---|---|---|---|---|
| | | First: $V_S = Q_S/C_{eq}$,<br>Subsequent: $V_C = Q_C/C$ | First: $Q_S = C_{eq}V_S$ ,<br>Subsequent: $Q_C = C\,V_C$ | First: $I_S = \omega Q_S$<br>Subsequent: $I = \omega Q_C$ |
| | $C_{eq} =$<br>$C_{123456}$ | $V_S =$<br>(given) | $Q_S = (C_{123456})(V_S) =$ | $I_S = (\omega)(Q_S) =$ |
| S | $C_6 =$ | $V_6 = \frac{Q_6}{C_6} =$ | $Q_6 = Q_S$ | $I_6 = I_S$ |
| | $C_{12345} =$ | $V_{12345} = \frac{Q_{12345}}{C_{12345}} =$ | $Q_{12345} = Q_S$ | $I_{12345} = I_S$ |
| P | $C_5 =$ | $V_5 = V_{12345}$ | $Q_5 = (C_5)(V_5) =$ | $I_5 = (\omega)(Q_3) =$ |
| | $C_{1234} =$ | $V_{1234} = V_{12345}$ | $Q_{1234} = (C_{1234})(V_{1234}) =$ | $I_{1234} = (\omega)(Q_{1234}) =$ |

## Table #1 Calculating Voltages and Currents for Each Capacitor

| | $C$ | V | Q | I |
|---|---|---|---|---|
| | | First: $V_S = Q_S/C_{eq}$,<br>Subsequent: $V_C = Q_C/C$ | First: $Q_S = C_{eq}V_S$ ,<br>Subsequent: $Q_C = C\,V_C$ | First: $I_S = \omega Q_S$<br>Subsequent: $I = \omega Q_C$ |
| S | $C_4 =$ | $V_4 = \frac{Q_{1234}}{(C_4)} =$ | $Q_4 = Q_{1234}$ | $I_4 = I_{1234}$ |
| | $C_{123} =$ | $V_{123} = \frac{Q_{1234}}{(C_{123})} =$ | $Q_{123} = Q_{1234}$ | $I_{123} = I_{1234}$ |
| P | $C_3 =$ | $V_3 = V_{123}$ | $Q_3 = (C_3)(V_3) =$ | $I_3 = (\omega)(Q_3) =$ |
| | $C_{12} =$ | $V_{12} = V_{123}$ | $Q_{12} = (C_{12})(V_{12}) =$ | $I_{12} = (\omega)(Q_{12}) =$ |
| S | $C_2 =$ | $V_2 = \frac{Q_2}{C_2} =$ | $Q_2 = Q_{12}$ | $I_2 = I_{12}$ |
| | $C_1 =$ | $V_1 = \frac{Q_1}{C_1} =$ | $Q_1 = Q_{12}$ | $I_1 = I_{12}$ |

## Table #2: Preparing to Develop an Equation for a Straight Line

| to combine | process of combination | combined |
|---|---|---|
| $C_{1,2})_S$ | $\frac{C_1\,C_2}{C_1 + C_2}$ | $C_{12}$ |
| $C_{12,3})_P$ | $\frac{C_1\,C_2}{C_1 + C_2} + C_3 =$<br>$\frac{C_1\,C_2 + C_2C_3 + C_3\,C_1}{C_1 + C_2} = \frac{A}{B}$ | $C_{123}$ |
| | Where $A = C_1\,C_2 + C_2C_3 + C_3\,C_1$<br>and $B = C_1 + C_2$ | |
| $C_{123,4})_S$ | $\left(\frac{B}{A} + \frac{1}{C_4}\right)^{-1} = \frac{A\,C_4}{A + BC_4}$ | $C_{1234}$ |

**Table #2: Preparing to Develop an Equation for a Straight Line**

| to combine | process of combination | combined |
|---|---|---|
| $C_{1234,\,5})_P$ | $\frac{A\,C_4}{A+BC_4} + C_5 = \frac{(A\,C_4)+(BC_4+A)(C_5)}{A+BC_4}$<br>$= \frac{A\,C_4 + D\,C_5}{D}$ | $C_{12345}$ |
| | where $D = A + BC_4$ | |
| $C_{12345,\,6})_S$ | $\left(\frac{D}{A\,C_4 + D\,C_5} + \frac{1}{C_6}\right)^{-1}$<br>$= \left(\frac{DC_6 + A\,C_4 + D\,C_5}{(A\,C_4 + D\,C_5)(C_6)}\right)^{-1}$<br>$= \frac{(A\,C_4 + D\,C_5)(C_6)}{AC_4 + D(C_5 + C_6)}$ | $C_{123456} = C_{eq}$ |

## (A) Direct Verification

The circuit can be set up on a circuit board, such as the one shown in Fig (5). An AC supply of 5 volts (rms) at 1.00 kHz should feed the circuit. One can measure all seven voltages and all seven currents using an AC voltmeter and an AC ammeter. These can then be compared with the calculated ones. These calculations are shown in Table #1 above, but necessary tables for these calculations for the experiment appear just before the Data Sheets

## (B) Indirect Verification

Recall the source equation:

$$V_S = \chi_{C,\,eq}\, I_S = \left(\frac{1}{\omega C_{eq}}\right) I_S \qquad \text{..........(4)}$$

Using the value of $C_{eq}$ from last row of Table (2), we get:

$$V_S = \frac{1}{\omega\left(\frac{D}{A\,C_4 + D\,C_5} + \frac{1}{C_6}\right)^{-1}}(I_S)$$

$$\omega\, V_S = \left(\frac{D}{A\,C_4 + D\,C_5} + \frac{1}{C_6}\right) I_S$$

Rearranging:

$$\frac{\omega}{I_S} = \left(\frac{1}{V_S}\right)\left(\frac{D}{A\,C_4 + D\,C_5} + \frac{1}{C_6}\right)$$

Expanding the right hand side, we get:

$$\frac{\omega}{I_S} = \left(\frac{1}{V_S}\right)\left(\frac{D}{A\,C_4 + D\,C_5}\right) + \left(\frac{1}{V_S}\right)\left(\frac{1}{C_6}\right) \qquad \text{..........}(5)$$

One can measure source current $I_S$ for a number of values of values of $C_6$. A graph of $\omega/I_S$ against $1/C_6$, will yield a straight line. The reciprocal of the slope of this straight line will reproduce $V_S$ . The intercept represents the value of $\omega/I_S$ for the case when $1/C_6$ vanishes.

## *Procedure*

### *(1) Direct Verification*

(1) The circuit board, to be used in this experiment, is shown in Fig (5). The top and bottom lines of holes contain 20 holes each. These are arranged in 4 groups of 5 holes each. All 20 holes in the top line are internally electrically connected together. The 20 holes in the bottom line are also similarly connected. But the holes in the top line are not connected to the holes in the bottom line. In between the top and bottom lines, we have two sets of $23 \times 5$ holes. All 5 holes in one column are connected together but holes in one column are not connected to the holes of any other column. The 5 holes in the upper part of the circuit board are not connected to the 5 holes in the lower part.

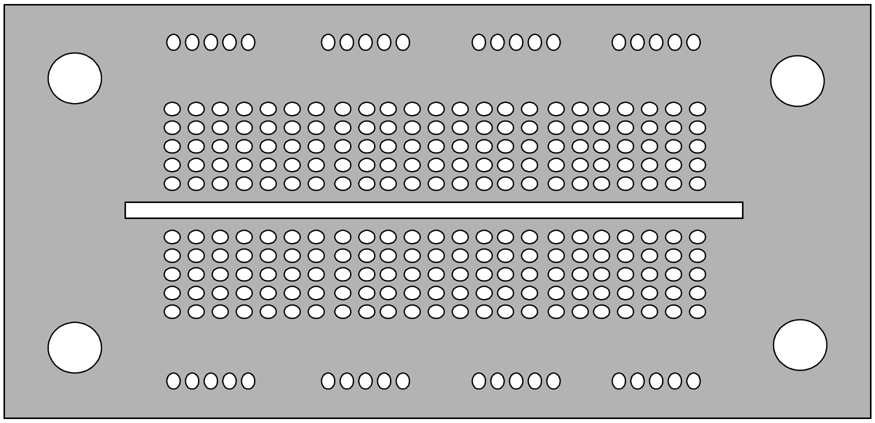


*Fig (5) The Circuit Board*

(2) The capacitors to be used in this experiment have been chosen as: $C_1$ = 1500 $pF$, $C_2 = 1800\ pF$ , $C_3 = 2200\ pF$, $C_4 = 3300\ pF$ , $C_5 = 4700\ pF$ , and $C_6 = 5600\ pF$. Find the exact values of these capacitors using the digital LCR meter and record them in Table #1 of the data sheet.

The instructor may change these resistors and suggest a different set altogether.

(3) Start assembling the circuit by inserting the connecting wires on the board. These are represented by straight solid lines, with one filled circle at each end. All necessary connections are shown in Fig (6).

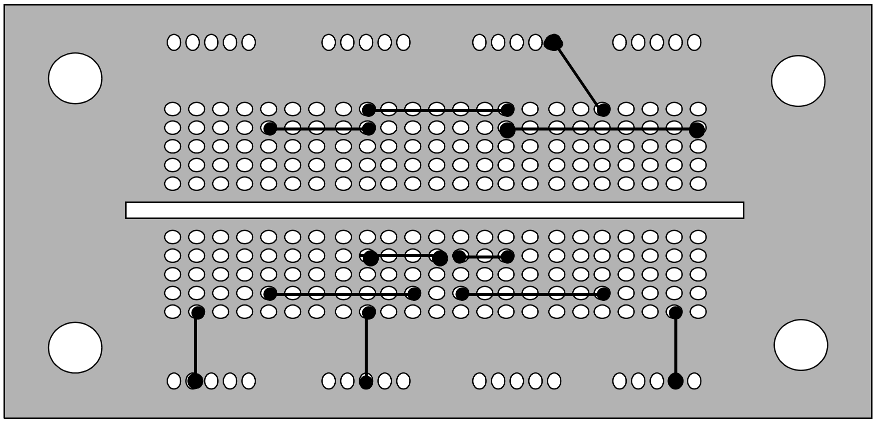


*Fig (6) Inserting the Connecting Wires on the Circuit Board*

(4) Next insert the capacitors in their proper places. These positions are shown in Fig (7) as lines with double arrows. Connecting wires, already set up, are omitted here for clarity. Use a nose pliers (provided) to straighten out the terminals of capacitors (if needed).

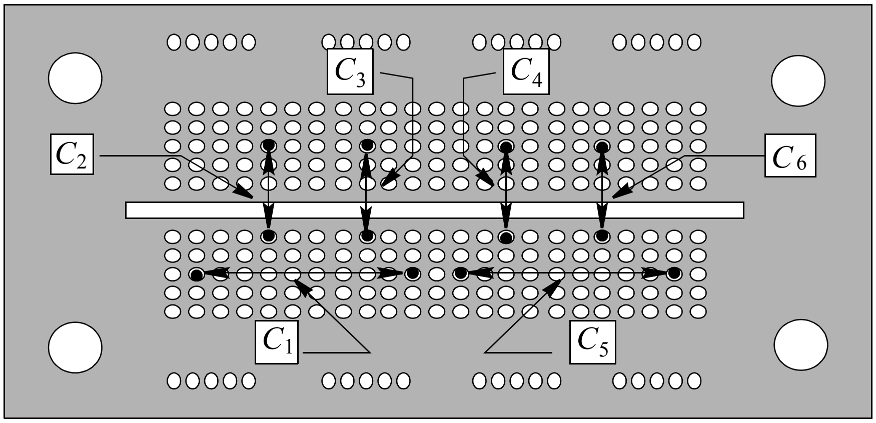


*Fig (7) Mounting Capacitors*

The completed circuit is shown in Fig (8). It will be a good idea to measure the equivalent capacitance of the circuit using an LCR meter on 20 $nF$ scale. This value should match the value (to be found later) in Table (3), last row, last column. Necessary circuit is shown in Fig (9). Make this measurement and enter in the data sheet.

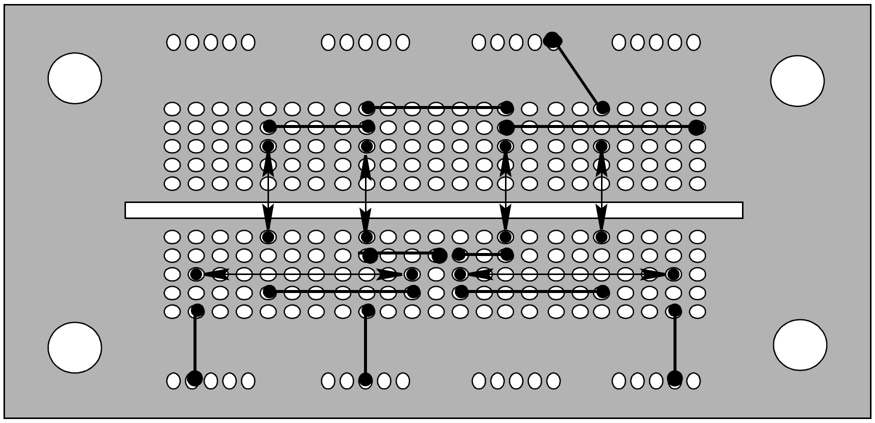


*Fig (8) The Complete Circuit*

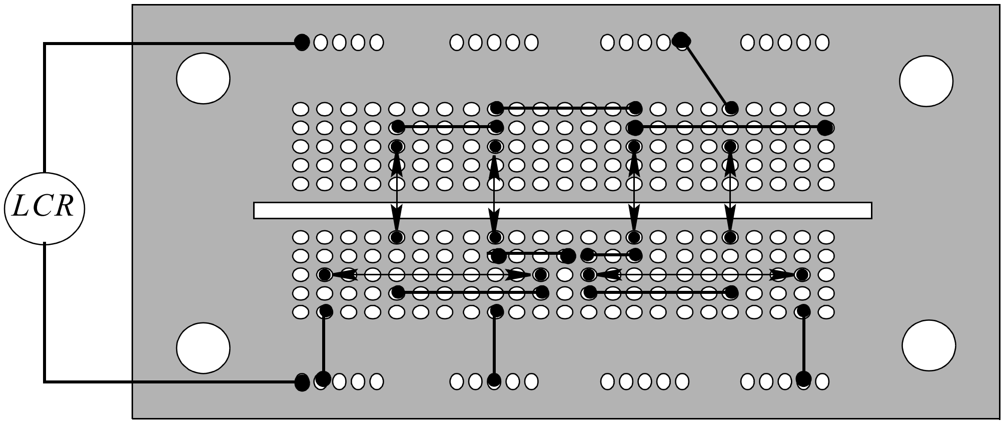


*Fig (9) Measuring the Equivalent Capacitance of the Circuit.*

We are ready to hook up to the power supply. to our circuit.

(5) Connect the circuit board to the function generator (with amplifier). Adjust the frequency as close to 1 kHz as possible. One of Pasco Inc.'s elegant function generator (with amplifier), opens up with a stable frequency of 1 kHz. In this case, no further adjustment is necessary. Then using the amplitude control, adjust the output voltage as close to 5.00 V as possible. Measure all seven voltages using the given multimeter as voltmeter (set to $20V$ AC). Details of measurement are given in Fig (10), (11) and (12). Each diagram shows voltmeter connections to the circuit with proper polarities which must be set correctly. Each diagram shows several voltmeters, connected simultaneously. There is, however, only one voltmeter. Voltages are measured one after the other and not all at the same time.

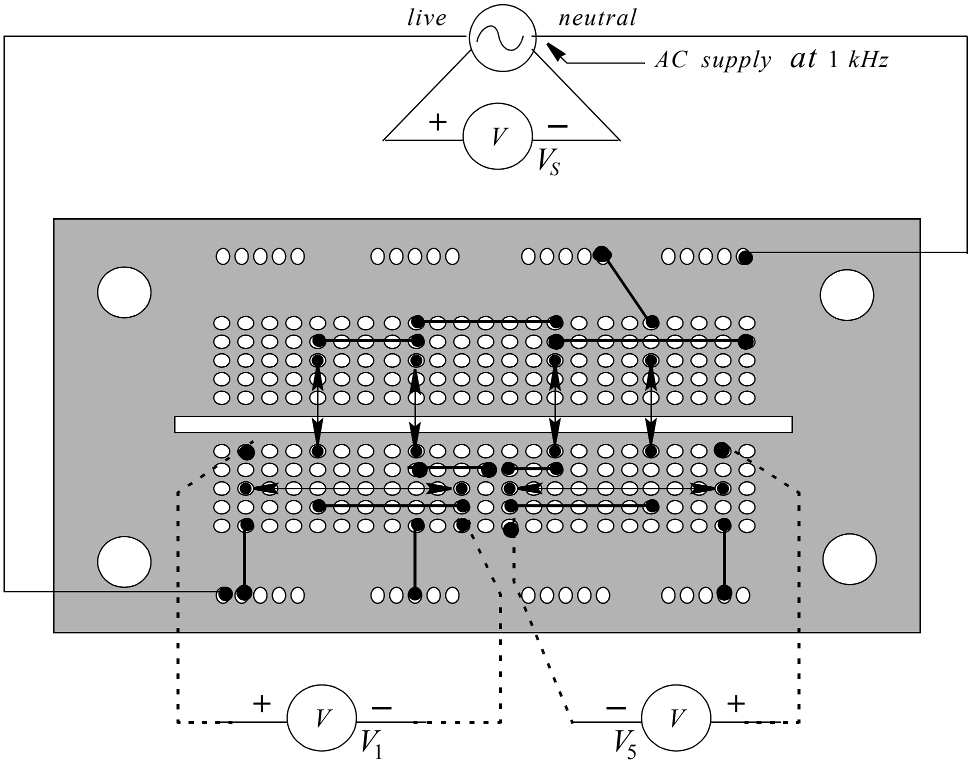


*Fig (10) Measuring Voltages Across the Power Supply and Across Capacitors $C_1$ and $C_5$*

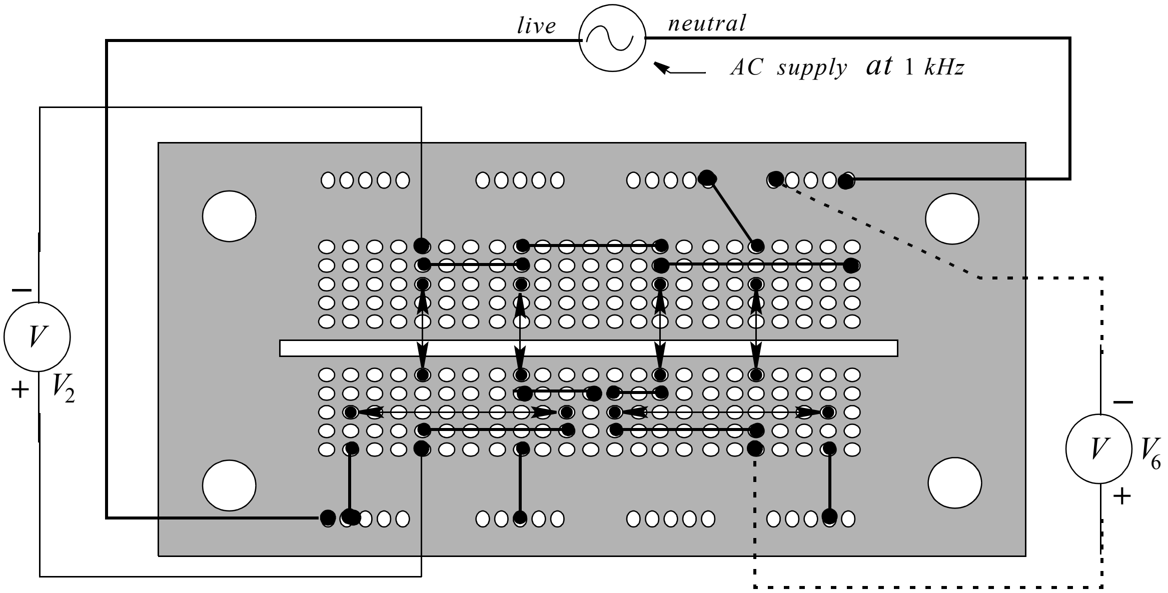


*Fig (11) M measuring Voltages Across Capacitors $C_2$ and $C_6$*

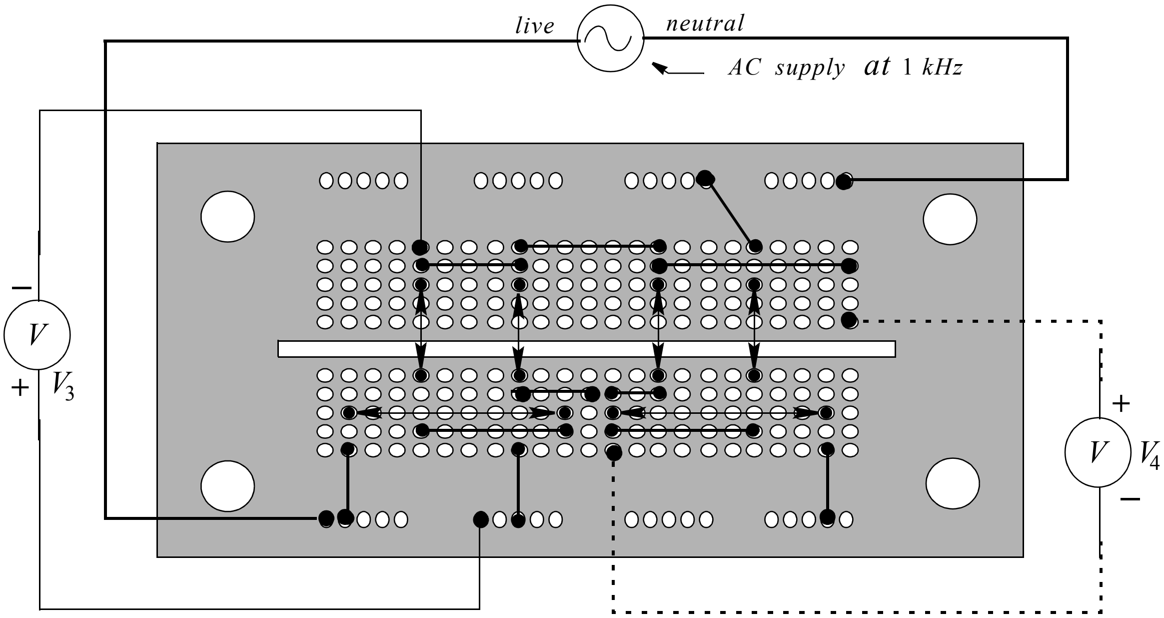


*Fig (12) Measuring Voltages Across Capacitors* $C_3$ *and* $C_4$

(6) Measure all seven currents using the given multimeter as ammeter (set to $2\ mA$, $AC$). Details of current measurement are shown in Fig (13), (14) and (15).

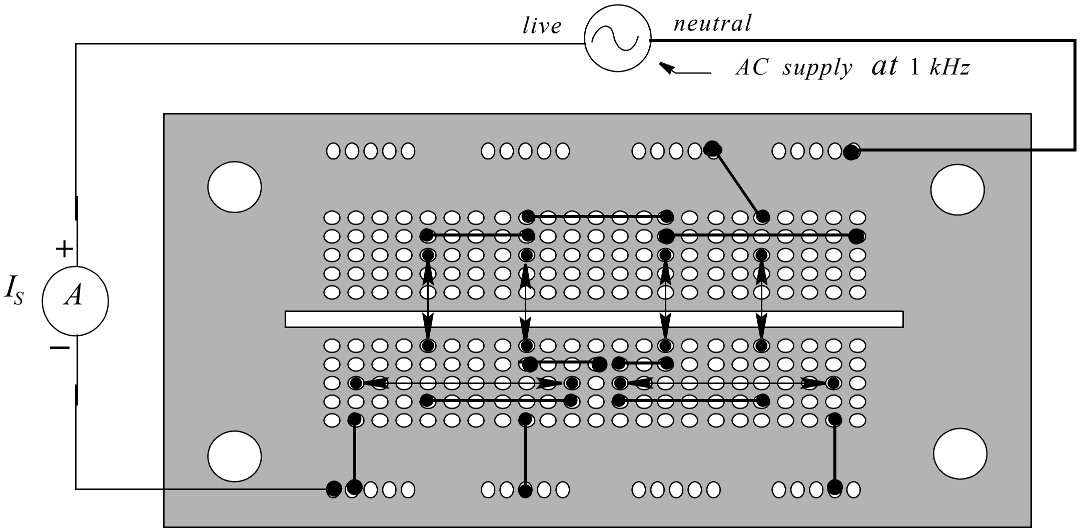


*Fig (13) Measuring Source Current* $I_S$

For measuring a current, one has to break the circuit and connect ammeter in series. To facilitate this, a *jump* wire (marked *J*) is provided for each capacitor. Thus for each current measurement there is a jump wire. One needs to pull this wire out after connecting the ammeter at points shown in the diagram. Removing jump wire, puts ammeter in series with the capacitor whose current is being measured. In Fig (13), the ammeter is measuring the supply current current $I_S$. When this value has been recorded, remove the ammeter, reconnect the wire from the live terminal of the function generator to the circuit board, as before. Note that no jump wire is needed for measuring $I_S$.

Next proceed to measure the other six currents, one at a time.

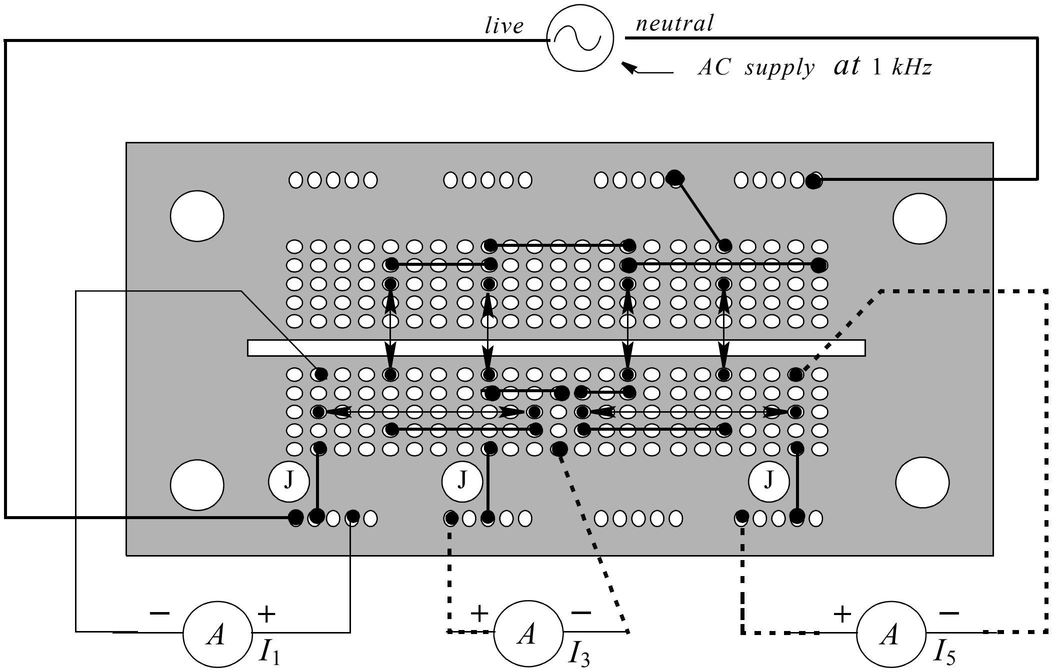


Fig (14) Measuring Currents $I_1$, $I_3$, and $I_5$

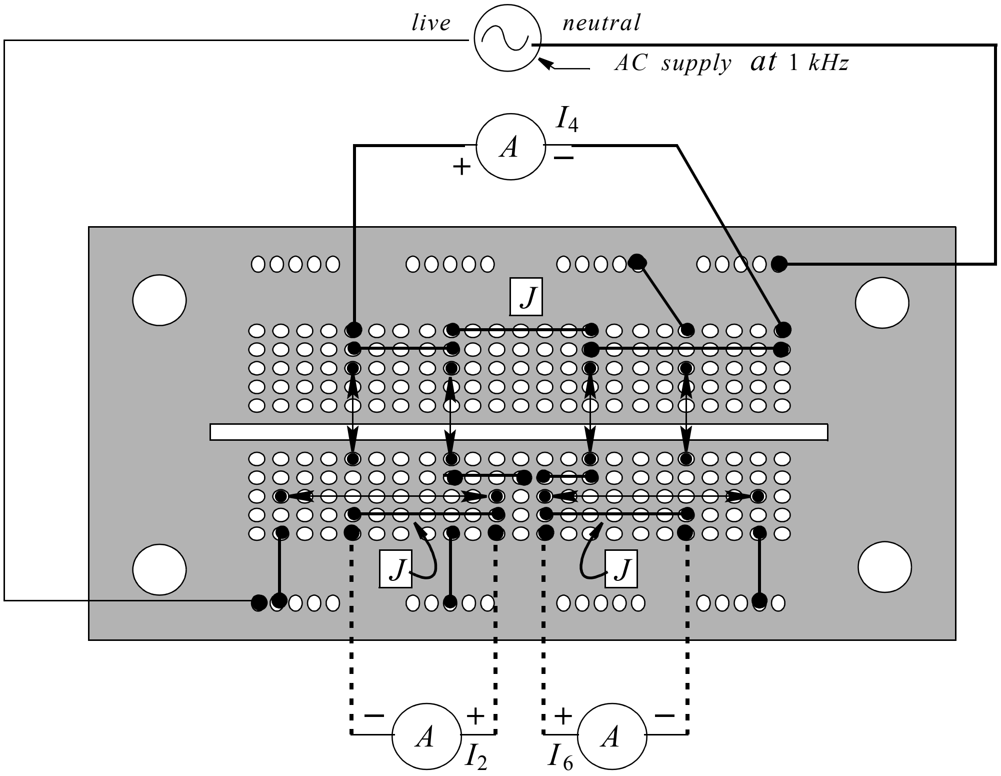


Fig (15) Measuring Currents $I_2$, $I_6$, and $I_4$

For each measurement, connect the ammeter as shown and then remove the jump (*J*) wire. When the ammeter reading has been recorded, remove the ammeter and replace the jump wire. These are shown in Figs (14) and (15).

(7) This part of the experiment ends. Remove meter and switch off. Do not disconnect the circuit.

## *(b) Indirect Verification*

(1) Set up the circuit as shown in Fig (16)

(2) Set the given multimeter as ammeter; to measure current in the range of $2\ mA$ , $AC$.

(3) Replace $C_6$ by a capacitance box. Set it to $1000\ pF$. Record in the Data Table

(4) Switch on the circuit and the ammeter. Read and record the corresponding value of $I_S$

(5) For the next 25 trials, increase $C_6$ in steps of $300\ pF$; (last setting: $8500\ pF$). For each value of $C_6$, read and record the corresponding value of $I_S$.

(6) Now switch on *all* the capacitors in the box. We are trying to simulate $C_6 \to \infty$, by making it as big as we can. Read and record the corresponding value of $I_S$, in the special table provided at the end of the Data Sheet.

(7) This completes the experiment. Switch off and disconnect. Arrange everything neatly on the table.

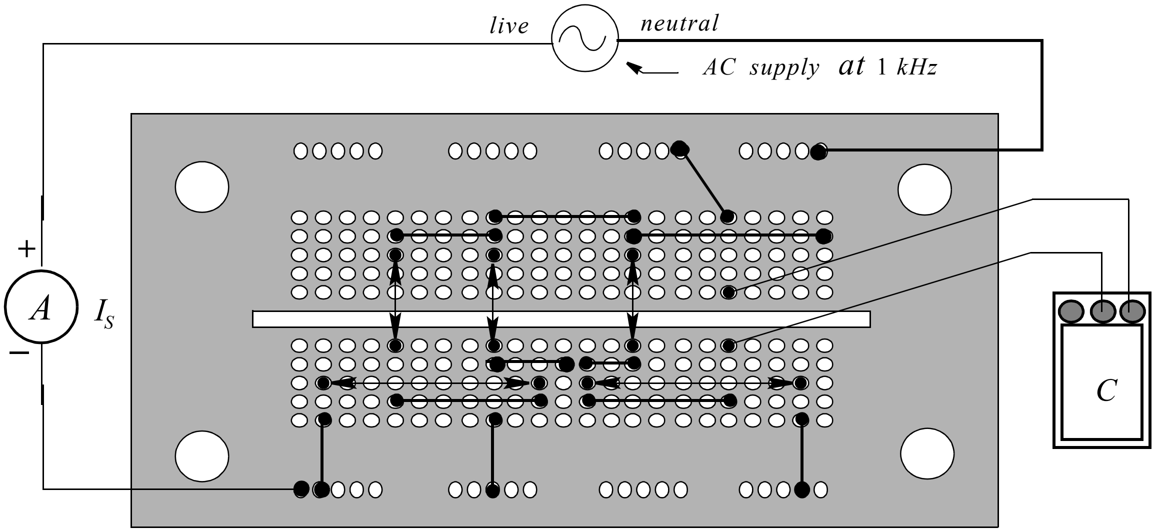


*Fig (16) Circuit for Plotting a Suitable Graph*

## Calculations & Graphs

### (A) Pre-graph Calculations

(1) Calculate $C_{eq}$ using Table #5 and then calculate currents and voltages for all six capacitors, by completing Table #6. These tables appears just after the Data Tables.

(2) Calculate the y-exits intercept $b$ using table #7.

(3) Calculate $\omega / b$ also using Table #7. This is the ***expected*** value of $I_S$ when $C_6$ is large enough for $1 / C_6$ to approach zero.

(4) Enter all 26 values of $I_S$ and $C_6$ in the computer data sheet, in *amperes* and *farads*, using scientific notation. Example: 2.234 $mA$ equals $2.234 \times 10^{-3}$ $A$, and 100 $pF$ equals $100 \times 10^{-12}$ $F$. Choose four decimal places (in the scientific notation) for display.

(5) Calculate $\omega / I_S$ on the computer using the value of $\omega$ from step (8) of Table #7.

(6) Calculate $1 / C_6$, also on the computer.

### (B) Graph

There is only one graph. Plot ( $\omega / I_S$) on the y-axis and $1 / C_6$ on the x-axis. Ask the computer to fit a straight line (or a second order polynomial). Ask the computer to print the equation of the line with 5 decimal places (preferably in scientific notation). The value of $r^2$ should also be printed out.

### (C) Post-Graph Calculations

(1) Find the reciprocal of the slope (printed out by the computer). This is the ***experimental*** *value* of $V_S$ . Compare with the actual value that was measured in step (5) of *Procedure.* Find percent error.

(2) The y-axis intercept $b$, as printed out by the computer, should match the value of $b$, found in step (2) of the pregraph calculations. But $b$ (unit $C^{-1}$) is of no particular significance. So we move on to step (3).

(3) Find the reciprocal of the y-axis intercept $b$, as printed out by the computer and multiply by $\omega$ to obtain the experimental value of $\omega / b$ (which is current in amperes). This is the ***experimental*** value of $I_S$, when $C_6 \rightarrow \infty$. Compare with its expected value found in step (3) of *Pre-graph Calculations* and find percent error. Also compare with the value found experimentally by letting $C_6 \rightarrow \infty$ (step #6 of *Indirect Verification*).

(4) Complete the report with *Results* (special *Results* sheet is provided).

## Conclusions and Discussions

Write your conclusions from the experiment and discuss them.

## ***What Did You Learn in this Experiment?.***

A hearty and thoughtful account of what you learned in this experiment by way of the principle and the techniques of experimentation, should be given

## Data & Data Tables

**Name**................................... **Date**.............................

**Instructor**............................. **Lab Section**...................

**Partner..........................** **Table #**..........................

### *(i) Direct Verification*

Supply Voltage $V_S$ : Nominal value: 5 *Volts* Actual value: *Volts*
Frequency: Nominal Value 1000 Hz
Frequency at the beginning: *Hz* at the end: *Hz*
Average frequency: *Hz*
Magnitude of $C_{eq}$, as determined in Step (4) of *Procedure:* *pF*

**Table 1: Capacitor Values**

| Capacitor | Nominal Values $(pF)$ | Actual Values $(pF)$ | Capacitor | Nominal Values $(pF)$ | Actual Values $(pF)$ |
|---|---|---|---|---|---|
| $C_1$ | | | $C_4$ | | |
| $C_2$ | | | $C_5$ | | |
| $C_3$ | | | $C_6$ | | |

**Table 2: Experimentally Measured Values of Voltages and Currents**

| Capacitor Voltages | Voltages $(V)$ | Capacitor Currents | Currents $(mA)$ | Currents $(\mu A)$ |
|---|---|---|---|---|
| $V_s$ | | $I_S$ | | |
| $V_1$ | | $I_1$ | | |
| $V_2$ | | $I_2$ | | |
| $V_3$ | | $I_3$ | | |
| $V_4$ | | $I_4$ | | |
| $V_5$ | | $I_5$ | | |
| $V_6$ | | $I_6$ | | |

## *(ii) Indirect Verification:*

**Table 3: Varying $C_6$ and Measuring $I_S$**

| Trial # | $C_6$ $(pF)$ | $I_S$ $(mA)$ | Trial # | $C_6$ $(pF)$ | $I_S$ $(mA)$ | Trial # | $C_6$ $(pF)$ | $I_S$ $(mA)$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 1000 | | 11 | 4000 | | 21 | 7000 | |
| 2 | 1300 | | 12 | 4300 | | 22 | 7300 | |
| 3 | 1600 | | 13 | 4600 | | 23 | 7600 | |
| 4 | 1900 | | 14 | 4900 | | 24 | 7900 | |
| 5 | 2200 | | 15 | 5200 | | 25 | 8200 | |
| 6 | 2500 | | 16 | 5500 | | 26 | 8500 | |
| 7 | 2800 | | 17 | 5800 | | 27 | | |
| 8 | 3100 | | 18 | 6100 | | 28 | | |
| 9 | 3400 | | 19 | 6400 | | 29 | | |
| 10 | 3700 | | 20 | 6700 | | 30 | | |

Next switch on ***all*** the capacitors in the Capacitance Box. Read and record the corresponding value of $I_S$ **This pair of values is not to be used in plotting the graph.**

**Table 4. Letting $C_6$ go to infinity (or as big as it can get)**

| | $C_6$ (µF) | $I_S$ $(mA)$ |
|---|---|---|
| | | |

## *Pre-Graph Calculations*

**Table 5. Finding $C_{eq}$**

| | combining | Your combination | result |
|---|---|---|---|
| 1 | $C_{1,2})_S$ | | $C_{12}$ |
| 2 | $C_{12,3})_P$ | | $C_{123}$ |
| 3 | $C_{123,4})_S$ | | $C_{1234}$ |
| 4 | $C_{1234,5})_P$ | | $C_{12345}$ |
| 5 | $C_{12345,6})_S$ | | $C_{123456} = C_{eq}$ |
| | calculate $\omega = 2\pi f$ your value: | | |

Value of ω from “Pregraph Calculations” (rad/sec)

## Table 6. Calculating Voltages and Currents for all Capacitors

| | $C$ $(pF)$ | your value of $C$ $(pF)$ | $V_C = Q/C$ $(V)$ | $Q = CV_C$ $(pC)$ | $I_C = (Q)(\omega)$ $(pA)$ |
|---|---|---|---|---|---|
| | $C_{123456} = C_{eq}$ | | $V_S$ (given) | $Q_S = C_{eq} V_S$ | $I_S = (Q_S)(\omega)$ |
| S | $C_6$ | | | | |
| | $C_{12345}$ | | | | |
| P | $C_5$ | | | | |
| | $C_{1234}$ | | | | |
| S | $C_4$ | | | | |
| | $C_{123}$ | | | | |
| P | $C_3$ | | | | |
| | $C_{12}$ | | | | |
| S | $C_2$ | | | | |
| | $C_1$ | | | | |

## *Calculating the Intercept: b*

$$b = \left(\frac{1}{V_S}\right)\left(\frac{D}{A\,C_4 + D\,C_5}\right) \qquad \text{..........(6)}$$

where

$$A = C_1C_2 + C_2C_3 + C_3C_1 \qquad D = A + (C_1 + C_2)C_4 \qquad \text{..........(7)}$$

**Table 7 Calculating the Intercept $b$**

| step # | steps of calculations | using nominal values | using actual values |
|---|---|---|---|
| $C_1 = 1500\ pF$ $C_2 = 1800\ pF$ $C_3 = 2200\ pF$ $C_4 = 3300\ pF$ <br> $C_5 = 4700\ pF$ $C_6 = 5600\ pF$ $V_S = 5.00\ V$ | | | |
| 1 | $A =$ <br> $C_1C_2 +$ <br> $C_2C_3 +$ <br> $C_3C_1$ | $(1500\times10^{-12})(1800\times10^{-12}) +$ <br> $(1800\times10^{-12})(2200\times10^{-12}) +$ <br> $(2200\times10^{-12})(1500\times10^{-12}) =$ <br> $9.960\times10^{-18}$ | |
| 2 | $D =$ <br> $A +$ <br> $(C_1 + C_2)C_4$ | $9.960\times10^{-18} +$ <br> $(1500\times10^{-12} + 1800\times10^{-12}) \times$ <br> $3300\times10^{-12} =$ <br> $2.085\times10^{-17}$ | |
| 3 | $AC_4$ | $9.960\times10^{-18} \times 3300\times10^{-12} =$ <br> $3.2868\times10^{-26}$ | |
| 4 | $DC_5$ | $2.085\times10^{-17} \times 4700\times10^{-12} =$ <br> $9.7995\times10^{-26}$ | |
| 5 | $AC_4 + DC_5$ | $3.2868\times10^{-26} + 9.7995\times10^{-26}$ <br> $1.30863\times10^{-25}$ | |

## Table 7 Calculating the Intercept $b$

| step # | steps of calculations | using nominal values | using actual values |
|---|---|---|---|
| $C_1 = 1500\ pF \quad C_2 = 1800\ pF \quad C_3 = 2200\ pF \quad C_4 = 3300\ pF \quad C_5 = 4700\ pF \quad C_6 = 5600\ pF \quad V_S = 5.00\ V$ | | | |
| 6 | $\dfrac{D}{AC_4 + DC_5}$ | $\dfrac{2.085\times10^{-17}}{1.30863\times10^{-25}} = 159.327\times10^{6}$ | |
| 7 | $b = \left(\dfrac{1}{V_S}\right)\times$<br>$\left(\dfrac{D}{AC_4+DC_5}\right)$ | $\left(\dfrac{1}{5.00}\right)\times(159.327\times10^{6}) =$<br>$31.8654\times10^{6}\ C^{-1}$ | |
| 8 | $\omega$ | $2\pi\times1000 = 6283.1853\ Hz$ | 6283.1853 rad/sec |
| 9 | $\dfrac{\omega}{b} = I_S$ | $\dfrac{6283.1853}{31.8654\times10^{6}} =$<br>$197.1790\times10^{-6}\ A$ | |

The equation printed out by the computer contains slope and intercept.

(1) Take reciprocal of slope. This is $V_S$ . Compare with the actual value and find percent error.

(2) Take reciprocal of intercept and then multiply by $\omega$ . It should match the last number in row #9 of this table. (table #7)

**Name:** **Date:** **Partner's Name**

## Results

## *Crunching A Six-Pack (of Capacitors)*

### *(i) Direct Verification*

*Verification By Direct Measurements Using a Multimeter*

**Table 4: Experimental & Expected Values of Voltages and Currents**

| Source Voltage and Capacitor Voltages $(V)$ | | | | Source Current and Capacitor Currents $(\mu A)$ | | | |
|---|---|---|---|---|---|---|---|
| | Experimental | Expected | Percent Error | | Experimental | Expected | Percent Error |
| $V_s$ | | | | $I_S$ | | | |
| $V_1$ | | | | $I_1$ | | | |
| $V_2$ | | | | $I_2$ | | | |
| $V_3$ | | | | $I_3$ | | | |
| $V_4$ | | | | $I_4$ | | | |
| $V_5$ | | | | $I_5$ | | | |
| $V_6$ | | | | $I_6$ | | | |

### *(ii) Equivalent Capacitance of the Circuit*

**Table 3. Equivalent Capacitance of the Given Circuit**

| | Expected Value (from Table 3) (pF or nF) | Experimental Value (step 4 of Procedure) (pF or nF) | % error |
|---|---|---|---|
| $C_{eq}$ | | | |

## *(iii) Indirect Verification:*

*Verification By Studying the Dependence of Source Current $I_S$ on Capacitor $C_6$*

*(a) Source Voltage $V_S$.*

| Description | Expected Value | Experimental Value | Error |
|---|---|---|---|
| source voltage | $(V)$ | $(V)$ | % |

*(b) Source Current $I_S$ when $C_6$ is very large.*
*(i) as found by using component values.*

| Description | Expected Value | Experimental Value | Error |
|---|---|---|---|
| source current as calculated using component values | $(A)$<br>(step #9 of Table #7) | $(A)$<br>(step #3 of postgraph calculations) | % |

*(b) Source Current $I_S$ when $C_6$ is very large.*
*(ii) as found by using a very large value of $C_6$, in the experiment*

| Description | Expected Value | Experimental Value | Error |
|---|---|---|---|
| source current as found by choosing a very large value of $C_6$ | $(A)$<br>(step #9 of Table #7) | $(A)$<br>(step #6 of indirect verification | % |