MILLIKAN OIL DROP EXPERIMENT
(MS-DOS® Version)

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User's Manual

Teacher's Guide

Appendixes

Vernier Software
8565 S.W. Beaverton-Hillsdale Hwy.
Portland, Oregon 97225-2429
(503) 297-5317
FAX (503) 297-1760
Internet: dvernier@vernier.com

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MILLIKAN OIL DROP EXPERIMENT

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Using This Manual

This manual is divided into two parts. The first part, the *User's Manual*, is intended both for teacher and student use. It contains a brief introduction, an explanation of how to use the program, and instructions on how to perform the experiments. This portion of the manual may be duplicated for student use.

The second section, the *Teacher's Guide*, is for teacher use. It contains an explanation of the *control menus*, which allow the teacher to modify the program to add complexities to the MILLIKAN OIL DROP EXPERIMENT. In this way, the teacher can make the experiment more difficult (and realistic) to match the ability level of the class. The *Teacher's Guide* also explains three different methods of conducting the experiment, including explanations of how to set up the program for each experimental method, and sample data taken using the program. A section is included with hints to help your Millikan oil drop experiment proceed smoothly. In the back of the teacher's guide is a section that answers some questions commonly asked by students and instructors. For those interested, this part of the manual also contains design notes on some of the details involved in writing this program.

The appendixes include a bibliography listing books and other materials about the Millikan oil drop experiment, and a listing of other Vernier Software products.

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Portland, Oregon 97225-2429
(503) 297-5317

MILLIKAN OIL DROP EXPERIMENT
USER'S MANUAL

This part of the manual includes background information on the Millikan oil drop experiment, an explanation of how to use the program, and instructions on how to conduct the experiments. You should read through the manual and try out the program following the instructions in the section entitled "A Little Practice" before you begin the experiment itself.

Introduction

HISTORICAL

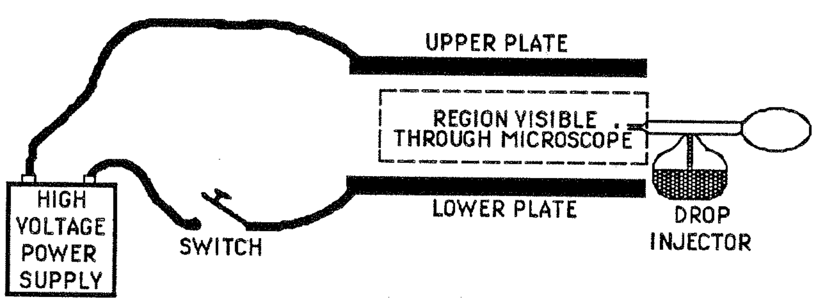
Robert Andrews Millikan was an important person in the development of physics. Best known for his oil drop experiment, Robert Millikan also verified experimentally the Einstein equation for the photoelectric effect. For these two investigations, he was presented the Nobel Prize in 1923.

Born March 22, 1868 in Morrison, Illinois, Millikan received his early schooling in Maquoketa, Iowa. In 1886 he enrolled in Oberlin College, and began his physics teaching career while still a student there. Oberlin retained him as a physics teacher after he graduated in 1891.

Seeking to increase Millikan's academic training, his Oberlin faculty friends applied for, and received a graduate fellowship at Columbia University in his name. Millikan completed his Ph.D. from Columbia in 1895 with a major in physics and minors in electrical engineering and chemistry. After finishing at Columbia, Millikan spent most of the following academic year in Germany, only to return to the United States when more teaching positions became available in 1896. Research opportunities drew him to the University of Chicago, and it was there that he carried out a brilliant series of investigations during the period 1909-1913. This was a fertile time for physics, considering the work of Rutherford, Bohr, and Einstein during the same time period. Millikan not only demonstrated conclusively the discrete nature of electric charge, but was also able to measure the charge of an individual electron.[1]

DESCRIPTION

Millikan's oil drop experiment is one of the classic physics experiments of this century. His apparatus included a fine-mist atomizer (to create the tiny drops of oil needed), a three-windowed metal box with two separate metal plates connected to a voltage supply, a microscope, and an electric light. The diagram below is a simplified diagram of the physical apparatus used:



Small drops of oil are injected into the area between the plates using an atomizer. Due to gravity they begin to fall slowly downward. If the voltage supply is turned on, the drops may begin to move at a different speed or even to move upward. The drops are usually electrically charged and the electric field between the plates exerts a force on them. By controlling the voltage between the plates, the experimenter can make the drops move up or down and control their speed. By studying the relationships between the voltage and the velocities of the various drops, much can be learned about

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[1]Several biographies (and an autobiography) of Robert Millikan are listed in *Appendix A* of this manual.

the nature of electrical charges. Using apparatus similar to this, Millikan demonstrated that charge comes in finite units. He also was able to measure the smallest electrical charge—the charge on one electron.

Too often this fascinating experiment is passed over by high school and college classes because it is simply too difficult to do. Even if the students are lucky enough to get the atomizer working properly, the entry tube clear, and the plates properly aligned, they still may spend the entire lab period just trying to capture a drop in the field of view. Ultimately, it is a major frustration for students at all levels using the relatively crude equipment available at many schools. This computer program enables you to circumvent the frustrations normally associated with this experiment and still collect analyzable data and get a feeling for the Millikan oil drop experiment.

Getting Started

This section of the manual explains how to start up the program and will help you become comfortable with the main screen and the commands used in this program.

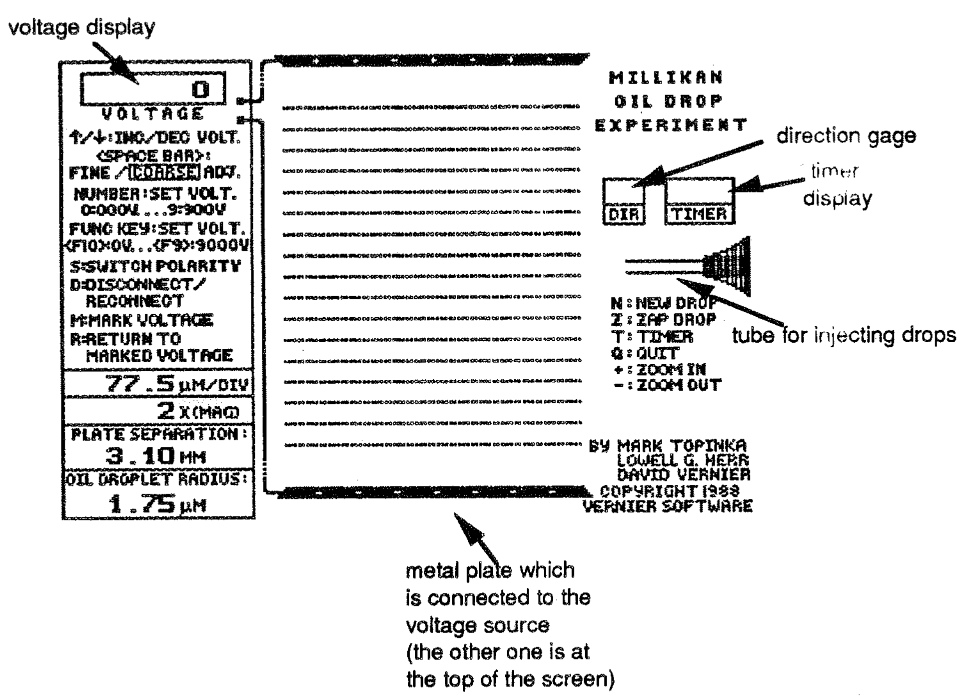
> Before you start using the MILLIKAN OIL DROP EXPERIMENT, you should make a back-up copy of the MILLIKAN OIL DROP EXPERIMENT disk. Place the original disk in a safe place and use only back-up copies. Instructions for making back-up copies and for installing the MILLIKAN OIL DROP EXPERIMENT on a hard disk are included in the *Teacher's Guide*.

STARTING THE PROGRAM

To start the MILLIKAN OIL DROP EXPERIMENT, make sure the disk (or directory) containing the program is selected as the active disk, then type MILLIKAN and press <ENTER>.

THE SCREEN

When you first start MILLIKAN OIL DROP EXPERIMENT you will be presented with the title screen. Press <ENTER> to go on to the main experimenting screen. The screen should now look similar to this:[2]



[2]This is the screen as displayed on a color graphics (CGA) monitor. If you are using Hercules graphics, the screen will be similar, but you will notice some minor differences.

Drops are injected from the nozzle at the right side of the screen. Only one drop will be displayed at a time.

The two bars at the top and bottom are the charged metal plates between which the drop will be suspended. The pluses and minuses indicate the sign of the electrical charge on that plate. It is important to understand that because of the magnification from the microscope, the viewing area often represents only a small portion of the area between the plates. Thus a drop can move below the bottom of the screen without hitting the bottom plate. The actual plates may be far above or below the edges of the screen. Wires connect the plates to the power source.[3]

The box on the left of the screen represents the high-voltage power supply. The display at the top of the box shows the voltage across the two plates. A positive voltage means that the top plate is positively charged and the bottom plate is negatively charged. A negative voltage means that the top plate is negatively charged and the bottom plate is positively charged. Whenever this display reads XXXXX, the power source is disconnected from the plates and no electric field exists. A quick summary of all the commands used to regulate the voltage to the plates appears in the power source box.

The horizontal dotted lines between the plates mark the *divisions* used to measure the distance moved by a drop when measuring velocity. In real life they are tiny etched lines on the microscope lens.

The lower left-hand corner of the screen contains information that will be necessary to complete the experiment. *Plate separation* is the distance in millimeters (mm) between the plates. *µm/div* is the distance in micrometers (µm) between each division on the screen. A micrometer is 1×10^{-6} meters. The radius display will show the current drop's radius in µm.[4]

The direction gauge and timer display are on the right side of the screen. Whenever a drop is between the plates, this direction gauge will indicate what direction the drop is moving. This is useful whenever the drop is moving so slowly that it appears to be still. It is also useful if for some reason your drop has drifted above or below the edges of the screen and you are trying to bring it back onto the screen. Whenever you have reached the voltage that comes as close as possible to balancing the drop, the direction gauge will read "0". The interval timer display reads the number of seconds since the timer was started. It is blank until you use the interval timer to measure the velocity of a drop. When you start the timer, it will begin at 0 and count up to 10 seconds.[5] This is described further in the next section.

The screen below shows the program in use. The XXXXX in the voltage display indicates that the voltage to the plates has been temporarily disconnected. A drop is shown on the screen. The direction gauge points down, indicating that the drop is falling, and the timer has been counting for 3 seconds.

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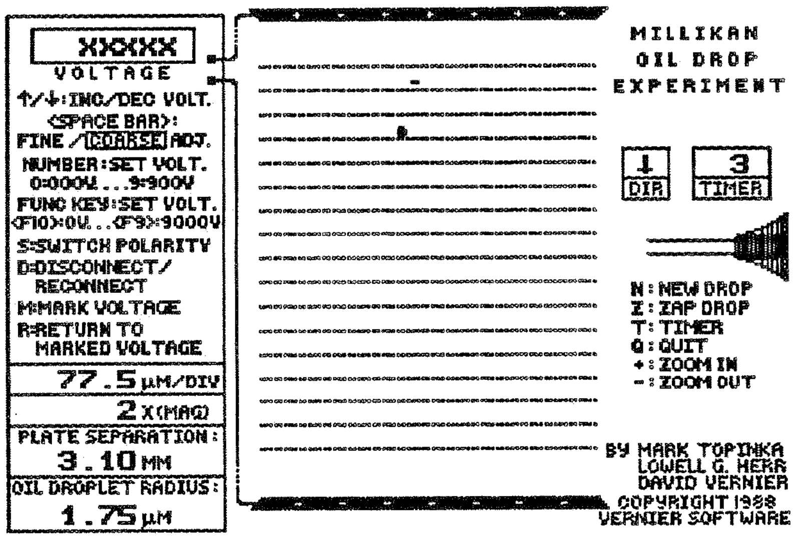
[3]These wires are normally dotted, indicating that the screen represents only a portion of the area between the plates, and the drop may move above and below the edges of the screen. If these wires are solid, the screen represents the exact setup, and the drop may not leave the screen.

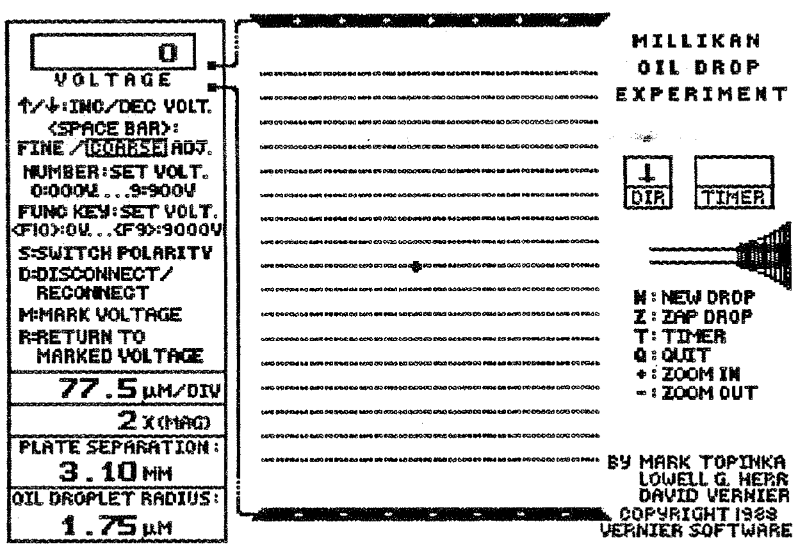
[4]Some variations of the program may not display the radius of the drop. The program can be customized to eliminate several options on the display. This customization is explained in the *Teacher's Guide*.

[5]The interval timer can be adjusted to count for a different time period. Changing the interval timer period is explained later in this section of the manual.



CONTROLS

The controls used in this program are described below. In each case, both the lower and upper case of the letter will work. This section can be used as a reference guide to the commands when practicing and when actually performing the experiment. Read through the list once to get a feel for the available commands, then proceed to the "A Little Practice" section.



The <↑> and <↓> keys: Increasing or decreasing the voltage
The arrow keys allow you to adjust the voltage up or down in small steps. The <↑> key will increase the voltage, while the <↓> key will decrease it. The amount that the voltage changes at each keystroke depends upon what you have set using the <SPACE BAR>.

<SPACE BAR>: FINE/COARSE voltage adjustment
This key allows you to toggle between fine and coarse voltage adjustment. You can tell which mode you are in by which word is boxed just below the voltage display. A FINE setting will allow you to change the voltage (using the arrow keys) in 1-volt increments. The COARSE setting jumps by 10-volt increments.

The number keys (<0> through <9>): Set 100's voltage
Number keys are used to set the **hundreds** place of the voltage. They provide a quick way of making large voltage changes. The tens place and the units place are set to "0". The number keys have no effect upon the thousands place of the voltage. Here are some examples:

VOLTAGE BEFORE	KEY PRESSED	VOLTAGE AFTER
0 volts	<3>	300 volts
783 volts	<0>	0 volts
1000 volts	<8>	1800 volts
56 volts	<4>	400 volts
5934 volts	<0>	5000 volts
-1988 volts	<7>	-1700 volts

The function keys (<F1> through <F10>): Set 1000's voltage
The function keys are used to set the **thousands** place of the voltage. They will not be used very often. Whenever you press one of the function keys, the last three digits of voltage are always set to 000. For example, in order to enter in a voltage of 5400 quickly and easily, you need only type <F5> and <4>. Pressing <F10> sets the voltage to 0 volts. Here are some examples:

VOLTAGE BEFORE	KEY PRESSED	VOLTAGE AFTER
0 volts	<F3>	3000 volts
9873 volts	<F10>	0 volts
-2000 volts	<F1>	-1000 volts

<S>: Switch plate polarity
Pressing <S> switches the charge on the plates. To make the real-world analogy, this is the same as switching the leads on the power supply.

<D>: Disconnect/reconnect power source
Pressing <D> will disconnect the power source if it is currently connected, or reconnect it if it has been disconnected. Whenever the power source is disconnected, the voltage display will read XXXXX and there will be no electrical field between the plates.

<M>: Mark voltage
This key is used to record a voltage so that it can be quickly restored at a later time. When you mark a voltage, you may return to that voltage at any time by pressing <R>.

<R>: Return to voltage
When this key is pressed, you return to the voltage that you have previously marked using the <M> key. This key is often used to return to a standard voltage quickly and easily.

<N>: New drop
When this key is pressed, any drop currently in use will be destroyed, and a new drop will come out of the tube on the right side of the screen. In about a second, air friction will stop the drop's leftward movement and you will be ready to start the experiment.

<Z>: Zap drop
Pressing <Z> exposes the current drop to a dose of X rays that may cause it to gain or lose electrical charge.

<T>: Start timer
This command causes the *interval timer* to start. When you press <T> a small mark appears immediately to the right of the current drop and the box labeled TIMER begins to count up from 0. When the timer reaches 10 seconds, a second mark is placed next to the drop.[6] This allows you to estimate the distance the drop traveled in the 10 seconds and calculate the drop's velocity during this period. (The amount of time passed between markers will remain in the timer box even after the timer has completed the timing).

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[6] The interval timer can be adjusted to count for a different time period. Changing the interval timer period is explained later in the next paragraph.

<Tab> and <Shift> <Tab>: Control interval timer period
The interval timer normally counts for 10 seconds. In some situations, you may want to have the timer count for a different time period. To increase the timer period press the <Tab> key. When you do this you will see the new timer period flashed briefly just above the timer display. The period will increase by one second each time you press the <Tab> key. To decrease the period of the timer press both the <Shift> and the <Tab> keys at the same time. The interval timer may range from 1 to 90 seconds.

<+>: Zoom in
This command changes the magnification of the viewing area. Each press will increase the magnification. The maximum magnification is 100 times. Changing the magnification changes the µm per division setting. Due to the limitations in graphics, the size of the drop on the computer screen will not change when you change the magnification.

<->: Zoom out
This command is the opposite of the zoom out command. It decreases the magnification of the viewing area. The minimum magnification is 1x. Changing the magnification changes the µm per division setting.

<B>: Control the beeping sound
The program normally makes a beeping sound once a second. This sound can be helpful in determining the speed of the drops. It can sometimes be irritating. Pressing the <B> key turns off the sound if it is on or on if it is off.

<Q>: Quit the program

A LITTLE PRACTICE

Now that you have had an introduction to the screen and the commands used to perform the experiment, it is time to get a little practice. Follow the step-by-step instructions below, taking as much time as necessary at each step. If you go though these practice steps, you should have all the skills necessary to perform the MILLIKAN OIL DROP EXPERIMENT.

Getting a New Drop

1. Press <N> to get a new drop between the plates. Do this a few times to see how it works. Each time you press <N>, the current drop will be destroyed, and a new drop will come out of the tube on the right side of the screen.

Adjusting the Voltage

1. Press the <↑> and <↓> keys to get a feel for how they change the voltage.
2. Press <SPACE BAR> to switch to FINE voltage adjustment and now experiment with the arrow keys.
3. Notice that pressing <SPACE BAR> again will return you to COARSE voltage adjustment. The space bar *toggles* between FINE and COARSE.
4. Adjust the voltage to 173 volts using the arrow keys and <SPACE BAR> for practice. Pick some other values and try to reach them as quickly as you can.

Switching Plate Polarity

1. Press the <S> key. Notice that the sign on the voltage changed, as did the signs on the plates.
2. Experiment with the arrow keys after you have switched the polarity using the <S> key.

Setting the Voltage with Number Keys and Function Keys

1. Experiment with the keys from <0> to <9> and get a feel for how they control the voltage by 100-volt increments.
2. Switch the plate polarity so that you have a negative voltage. Notice that the voltage remains negative when you press any of the number keys. To return to positive voltage, you must switch the plate polarity with the <S> key.

3. Notice that after you have set the voltage above 999 volts (or below -999 volts), pressing a number key **only sets the hundreds place** of the voltage. In order to quickly return to 0 volts, you can press the <F10> key.
4. Set the voltage to 344 as quickly as possible using both the number keys and the arrow keys. Choose a few other values and practice with them until you get the hang of it.

Disconnecting the Power Source

1. Press <D> a couple of times. Whenever the voltage display reads XXXXX, this means the power source is disconnected and therefore the plates have no charge.
2. Notice that while the power source is disconnected, the computer reminds you with a beep whenever you adjust the voltage.

Balancing a Drop

You should now be fairly comfortable with adjusting the voltage. To balance a drop you must adjust the voltage until electrical force up on the drop just balances gravity pulling down on the drop. When a drop is perfectly balanced, the direction gauge should read "0". Note that most drops are positively charged, but a few are negatively charged and a few have no charge.

1. Set the voltage to 0. (Press <F10>).
2. Press <N> to get a new drop.
3. Increase the voltage rapidly using first the number keys, then the arrows, until the drop slows down. If you lose the drop, try again with a new one.
4. Finally, adjust the voltage using the arrow keys (remember that <SPACE BAR> toggles between FINE and COARSE adjustment) until the drop comes to rest. The direction gage should display "0".
5. Repeat the whole process a number of times with new drops until you get good at it. Notice that different drops take different voltages to balance. This is because they have different electrical charges. You may notice that some drops do not respond, no matter what voltage you use. These drops are electrically neutral, and therefore unaffected by electric fields.

Marking and Returning to a Balancing Voltage

1. If you have a drop balanced, press <M> to mark the balancing voltage. Now adjust the voltage to a different setting using the arrow keys, number keys, or the function keys.
2. Press <R> and notice how the voltage returns to the marked voltage and the drop is balanced again.

Dragging a Drop

The term *dragging a drop* refers to moving a drop to a desired place on the screen. If the drop is at the bottom of the screen and you want it at the top, you must *drag* it up the screen. You do this by varying the voltage in the manner explained below:

1. First of all, get a new drop and balance it using the method detailed above.
2. Press <D> to disconnect the battery from the plates and let the drop begin to fall down the screen.
3. Reconnect the power source (by pressing <D> again) when the drop is close to the bottom of the screen. You are now ready to "drag" the drop up the screen.
4. Press <M> to mark the current balancing voltage.
5. Increase the voltage until the drop is slowly moving up the screen.
6. When the drop has reached the top of the screen, press <R> to return to the balancing voltage (which you marked with the <M> key). The drop should now be stationary near the top of the screen.

Measuring the Velocity of a Drop

In all but the simplest of the experiments, it will be necessary to measure the velocity of a drop as it moves up and down the screen. The example below shows how to measure the velocity of a drop falling under gravity with no electric field present (v_g).

1. Balance a drop.
2. Mark the balancing voltage (by pressing <M>).
3. Drag the drop up to the top of the screen.
4. Turn off the voltage (using the <F10> or the <D> key).
5. Quickly press <T> to start the interval timer. A mark will appear to the right of the drop.

6. After 10 seconds, another mark will appear and the timer will stop incrementing.
7. Rebalance the drop using the <R> key.
8. You now have all the information you need to compute the velocity of the drop. To do this, you must count the divisions between the starting mark and ending mark. This gives you the distance traveled by the drop. The time it took the drop to fall that distance is shown in the timer display. It is now a simple matter to compute the drop's velocity using the formula: velocity = distance traveled/time. If you use the distance measured in divisions when you calculate velocity, the result will be in units of divisions/sec. This may be adequate for some experiments. If necessary, you can convert the velocity to µm/sec (micrometers/second) by multiplying the result by the µm/div value displayed in the box on the lower left side of the screen.
9. Practice taking the velocity for a few more drops. Pay particular attention to how the interval timer works.

Changing the Charge on a Drop

1. Balance a drop.
2. Press <Z> to simulate exposing the drop to X rays. This will usually, but not always, cause the charge of the drop to change.
3. The drop should start moving. If it doesn't, try zapping it again. The reason it is no longer balanced is that when the charge on the drop changed, the electrical force on the drop also changed.

"Zooming" In and Out

1. Balance a drop close to the center of the screen.
2. Increase magnification by pressing <+> several times.
3. Change the voltage and notice how the drop moves more quickly across the viewing area. This is because you are now at a higher magnification, and are therefore examining a smaller portion of the viewing area.
4. Allow the drop to drift towards the bottom or top of the screen. Now press <+>. The drop should appear to move away from the center of the viewing area, or if it was close to the top or bottom of the screen it should disappear out of the viewing area altogether. This is because the microscope in this simulation is fixed on the spot exactly in the middle between the two plates, and if the drop isn't close to this spot, you won't be able to see it through the microscope at high powers. Note: you will be able to see <u>any</u> drop that is between the plates when the magnification is set to 1x.
5. By decreasing the magnification (using the <-> key), you can bring a drop that is off the screen (but still between the plates) back into the viewing area.
6 Changing the magnification is often useful because with higher magnifications the drop drifts more quickly across the screen, so a more accurate reading of velocity is possible in a shorter amount of time. (Another way to get a more accurate reading of velocity is to use a low magnification and simply allow the drop to drift for a longer period of time.)

If you have worked your way through all of these procedures, you should now be ready to begin the actual experimentation.

Performing the Experiment

MILLIKAN OIL DROP EXPERIMENT - METHOD 1:

Objective:

This experiment is a simplified version of the Millikan oil drop experiment. You are to use the computer simulation to determine as much as possible about the electrical charges on the drops. You will do this by balancing the force of gravity with the force on the drop due to the electric field.

Theory:

When an electrically charged object is placed in an electric field, an electrical force is exerted on it. This force is given by:

$$F_e = E\,q$$

Since the electric field strength is equal to the voltage between the plates (V) divided by the distance between the plates (d), we can also write:

$$F_e = (V/d)\,q$$

In this simulation, oil drops are injected into an electrical field between two plates. You can control the voltage between the plates and therefore the electric field strength.

The oil drop is also in the earth's gravitational field, so it also has the following force acting on it:

$$F_g = m\,g$$

One way of studying the charge on the oil drops is to adjust the voltage between the plates until the electrical forces acting up on the drop exactly balance the pull of gravity down. In this case:

$$F_g = F_e$$
$$m\,g = (V/d)\,q$$
$$q = m\,g\,d/V$$

The charge on the drop is inversely proportional to the voltage required to balance the drop. Also, if the mass of the drop and the distance between the plates are known, you can calculate the actual charge on the drop.

Procedure:

Determine the voltage necessary to balance the oil drops in 20 to 40 different trials. Between each trial, change the charge of the drop. You can do this by either using the <Z> key to simulate exposing the drop to X rays (which causes ionization of the drop) or by getting a new drop (which will have a random charge).

Make a new list of all of the balancing voltages in numerical order. Plot a histogram of the balancing voltages and see if you can observe obvious groupings of the voltages.

Experiment Extension: Calculating Actual Charges

In this simplified version of the experiment, the radius of the drop is displayed at the bottom of the screen. The density of the drop is known (plastic density = 128 kg/m^3). The mass of the drop can therefore be calculated:

$$m = \text{volume} * \text{density}$$
$$m = 4/3\,\pi\,r^3 * \text{density}$$

Calculate the charge on the drop for each of the balance voltages measured above.

Plot a new histogram of the calculated charges for each balancing voltage.

Questions:

1. Why are some of the drops not affected by electrical fields?
2. Why do some of the drops require a negative rather than a positive balancing voltage?
3. Do the balancing voltage numbers seem to clump together in groups rather than spread out evenly over the range of values? What does this mean about the charges on the drops?
4. As you look at the voltage histogram, the "steps" are not all the same. Why is this?

Experiment Extension Questions:

5. Why are the steps on the charge histogram even, while the steps on the balancing voltage histogram were uneven?
6. What is the smallest charge that you measured?
7. What is the average step size on the charge histogram?
8. What is your best estimate of the minimum electrical charge?
9. Does your experiment support the idea of a quantized electrical charge?
10. In what ways is this simulation a simplification of Millikan's original experiment?

MILLIKAN OIL DROP EXPERIMENT - METHOD 2:

Objective:

This experiment is a slightly simplified version of the original Millikan oil drop experiment. You are to use the computer simulation to determine as much as possible about the electrical charges on the drops. You will do this by determining the drift velocities of the drops under various conditions.

Theory:

When an electrically charged object is placed in an electric field, an electrical force is exerted on it. This force is given by:

$$F_e = E\,q$$

Since the electric field strength is given by the voltage between the plates (V) divided by the distance between the plates (d), we can also write:

$$F_e = (V/d)\,q$$

$$F_e = V\,q/d$$

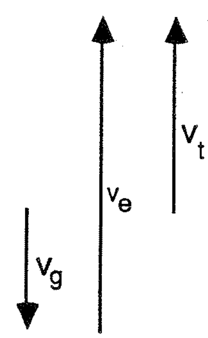
Notice that if the voltage is held constant, the electrical force on the drop is proportional to the charge on the drop.

The drop is also in the earth's gravitational field, so it also has the following force acting on it:

$$F_g = -m\,g$$

The total force acting on the drop is the vector sum of these two forces.

For small objects moving through air under the influence of a constant force (like these drops), the drift velocity is proportional to the force. Therefore, by measuring the drift velocity, you can indirectly get a measure of the force acting. With this simulation, you can easily measure drift velocities; in fact, you can measure both the drift velocity of the drop under the influence of gravity alone (v_g) and the drift velocity of the drop under the influence of both gravity and the electric field. By vector subtraction, you can then determine the force due to the electric field alone (v_e). This quantity is proportional to the charge on the drop.



Procedure:

In this version of the experiment, the velocity of a drop is measured in a constant electrical field as its charge is changed. A standard voltage should be chosen; it can be any voltage between 100 volts and 400 volts. Your instructor may have a suggestion. The voltage will need to be changed temporarily to drag a drop up and down the screen, but when measuring velocities, the voltage should always be returned to this standard voltage. Before injecting the first drop, set the voltage to the standard value and press <M> to mark this voltage. After you do this, you can instantly set the voltage to the standard value by pressing the <R> key.

A. Determine the drift velocity of the drop under the influence of gravity alone: Inject a new drop by pressing <N>. Adjust the voltage to get control of the drop. Drag the drop to the top of the grid. With the drop slightly above the top line of the grid, press <D> so that the plates are disconnected. The drop will start to fall slowly downward. As the drop crosses the top line of the grid, press <T> to start the timer. After a specified time period the second mark will appear on the screen. Now adjust the voltage to keep the drop on the screen. You can now count how many divisions the drop has fallen in the specified time interval. Record this value. This distance is used to calculate the drift velocity due to gravity alone (v_g). Write down both the number of divisions (use a negative number since the motion is downward) and the division spacing.

B. Determine the drift velocity under the influence of both gravity and the standard voltage (v_t):
Press <R> to restore the standard voltage and measure the velocity of the drop under the influence of both gravity and the standard electric field (v_t). Note that if you lose a drop, you can inject a new one without causing any problems, because in this version of the experiment all of the drops are identical in mass.

You should now repeat the measurement of the velocity of the drop under the influence of both gravity and the standard electric field (v_t) many more times with different charges on the drop. You can change the charge on the drop by pressing the <Z> key. This simulates exposing the drop to X rays which cause ionization. You also can change the charge by injecting another drop. In each case, calculate the velocity due to the electric field only (v_e) by vector subtraction. Some drops will move down and some will move up, so be sure to set up a notation to note the directions. Record all downward motions as negative. Use the zoom in <+> and zoom out <-> keys if you wish. Note both the number of divisions that the drop moves and the division spacing. For best results, record from twenty to forty readings. Millikan and his co-workers measured the charges of thousands of drops of oil. In one case, Millikan kept one drop in the field of view for over four hours. Let that be a challenge!

C. Analyze the data:
For each trial, you should have determined the velocity due to the electric field only (v_e). Remember to treat the velocities as vectors. Sort the v_e values in numerical order and plot a histogram of them. Think about what this histogram indicates about the charges on the drops.

Experiment Extension: Calculating Actual Charges

The *velocity due to electric field* data can be used to calculate the actual charge on each drop. If you know the radius of the drop, this calculation is fairly simple. For small drops moving through air, the terminal velocity is proportional to the force acting on the drop. Using this relationship to compare the velocity of the drop when the electric field is off (v_g) and when the electric field is on (v_t):

$$\frac{v_t}{v_g} = \frac{Eq - mg}{-mg}$$

$$\frac{v_t}{v_g} = \frac{(V/d)\,q - mg}{-mg}$$

$$\frac{v_t}{v_g} = \frac{(V/d)\,q}{-mg} - 1$$

$$q = (v_t/v_g - 1)\,(-mgd/V)$$

Notice that you need to know only the two velocities, the mass of the drop, the voltage, and the plate separation to calculate the charge. Downward velocities are negative, upward velocities are positive. In this experiment, the quantity (mgd/V) is constant for all of the trials and only needs to be calculated once. The radius of the drop is known (displayed on the bottom of the screen). You also know the density of the material used (plastic density = 128 kg/m^3), so you can calculate the mass of the drop.

Use the equation above to calculate the charge on the drop in each trial. Notice that in this case all velocities must be in units of meters/second if the charges are to come out in standard units (coulombs). Make a data table of your calculations. Sort the charges in order and plot a histogram of the values.

Questions:

1. Why are some of the drops not affected by electrical fields?
2. Why do some of the drops move downward with the standard field applied?
3. Do the v_e values seem to clump together in groups rather than spread out evenly over the range of values? What does this mean about the charges on the drops?
4. What is the average step size on the v_e histogram? What electrical charge difference does this correspond to?
5. Are there any forces acting on the drop which were not considered in the discussion of the experiment?

Experiment Extension Questions:

6. What is the smallest charge that you measured?
7. What is the average step size on the charge histogram?
8. What is your best estimate of the minimum electrical charge?
9. Does your experiment support the idea of a quantized electrical charge?

MILLIKAN OIL DROP EXPERIMENT - METHOD 3:

Objective:

This experiment closely approximates the original Millikan oil drop experiment. You will use the computer simulation to determine as much as possible about the electrical charges on the drops. You will do this by determining the drift velocities of the drops under various conditions.

Theory:

When an electrically charged object is placed in an electric field, an electrical force is exerted on it. This force is given by:

$$F_e = E\,q \qquad \text{(eq. 1)}$$

The electric field strength (E) can be calculated from the voltage between the plates divided by the distance between the plates.

The drop is also in the earth's gravitational field, so it also has the following force acting on it:

$$F_g = -m\,g \qquad \text{(eq. 2)}$$

To be completely correct, the equation for the downward force on the drop (F_g) should use the apparent mass of the drop. This is the mass corrected for the buoyant (upward) force of the air. The buoyant force is equal to the weight of the air displaced by the drop—a very minor correction. The apparent mass is given by the equation:

$$m_a = 4/3\,\pi\,r^3\,(\text{density}_{drop} - \text{density}_{air}) \qquad \text{(eq. 3)}$$

The total force acting on the drop when the electric field is on is the vector sum of these forces:

$$F_t = E\,q - 4/3\,\pi\,r^3\,(\text{density}_{drop} - \text{density}_{air})\,g \qquad \text{(eq. 4)}$$

For small drops moving through air, the terminal velocity is proportional to the force acting on the drop. Using this relationship to compare the velocity of the drop when the electric field is off (v_g) and when the electric field is on (v_t):

$$\frac{v_t}{v_g} = \frac{E\,q - 4/3\,\pi\,r^3\,g\,(\text{density}_{drop} - \text{density}_{air})}{-4/3\,\pi\,r^3\,g\,(\text{density}_{drop} - \text{density}_{air})} \qquad \text{(eq. 5)}$$

solving for q:

$$q = \frac{4\,\pi\,r^3\,g\,(\text{density}_{drop} - \text{density}_{air})}{3\,E}\;\frac{(v_g - v_t)}{v_g} \qquad \text{(eq. 6)}$$

Notice that you need know only the two velocities, the radius (r) of the drop, the voltage, and the electric field strength to calculate the charge. You will use this equation to calculate the charge on a drop in a number of different trials. In this experiment the quantities E, d and g will be constant throughout. The radius of the drop and v_g will change only if you lose the drop and have to start with a new one. When using this equation, downward velocities should be negative and upward velocities positive.

Each time you do start with a new drop, you will have to determine its radius. The viscous force on a drop of radius r, moving with a velocity v, through a fluid of viscosity μ, is given by Stoke's law:

$$f = -6\,\pi\,\mu\,r\,v \qquad \text{(eq. 7)}$$

where v is the terminal velocity and r is the radius of the drop.

If Stoke's law holds, then for a drop falling with no electric field the frictional force must be equal in magnitude to the gravitational force.

$$f = m_a g$$

$$-6 \pi \mu r v_g = 4/3 \pi r^3 (density_{drop} - density_{air}) g$$

$$r = 3\left(\frac{-\mu v}{2 g(density_{drop} - density_{air})}\right)^{\frac{1}{2}} \qquad \text{(eq. 8)}$$

By measuring the drift velocity of a drop with the electric field off and knowing the density of air ($density_{air} = 1.29$ kg/m^3) and the viscosity of air ($\mu = 1.81 \times 10^{-5}$ N-sec/m^2), you can determine the radius of the drop. Again, enter the downward velocity of the drop as a negative number. Once the radius is calculated, the effective mass of the drop can also be calculated using equation 6 above.

Procedure:

In this version of the experiment, the velocity of a drop is measured in a constant electrical field as its charge is changed. A standard voltage should be chosen; it can be any voltage between 100 volts and 400 volts. Your instructor may have a suggestion. The voltage will need to be changed temporarily to drag a drop up and down the screen, but when measuring velocities, the voltage should always be returned to this standard voltage. Before injecting the first drop, set the voltage to the standard value and press <M> to mark this voltage. After you do this you can instantly set the voltage to the standard value by pressing the <R> key.

Brownian motion of the drop is noticeable in this experiment. Brownian motion is the result of the thousands of random collisions between the drop and air molecules. The drop is deflected slightly by each collision. Brownian motion will add a slight randomness to your experimental data.

A. Determine the drift velocity under the influence of gravity alone:
Inject a new drop by pressing <N>. Adjust the voltage to get control of the drop. Drag the drop to near the top of the grid and measure the drift velocity due to gravity alone (v_g). It is essential to calculate the velocity in units of m/sec. As you proceed with the experiment, you must repeat the determination of v_g each time you introduce a new drop, since each drop has a different size.

B. Determine the drift velocity under the influence of both gravity and the standard voltage (v_t):
Move the drop into the central area of the grid before making the next change to reduce the probability of losing the drop. Press <R> to restore this standard voltage and measure the velocity of the drop under the influence of both gravity and the standard electric field (v_t). Use the zoom in <+> and zoom out <-> keys if you wish. Note both the number of divisions that the drop moves and the division spacing. Calculate the velocity in units of m/sec.

You now should repeat the measurement of the velocity of the drop under the influence of both gravity and the standard electric field (v_t) many more times with different charges on the drop. Record downward velocities as negative numbers and upward velocities as positive numbers. You can change the charge on the drop by pressing the <Z> key. This simulates exposing the drop to X rays which cause ionization. If you lose a drop, you can get a new one, but you will need to determine its radius by measuring its v_g. For best results, record from twenty to forty readings. Millikan and his co-workers measured the charges of thousands of drops of oil. In one case, Millikan kept one drop in the field of view for over four hours. Let that be a challenge!

C. Analyze the data:
Make a data table listing v_g and v_t for each trial. Calculate the radius of each drop used. Finally calculate the charge in coulombs for each trial. Sort the charges in order and plot a histogram of the values.

Questions:

1. Why are some of the drops not affected by electrical fields?
2. Why do some of the drops require a negative rather than a positive balancing voltage?
3. What is the percentage difference between the mass of the drop and the apparent mass of the same drop?
4. Derive equation 6 from equation 5.
5. Each time a new drop is injected, the radius can vary over a range of 20%. How much possible change can this cause in the mass of the drop?
6. What is the smallest charge that you measured?
7. What is the average step size on the charge histogram?
8. What is your best estimate of the minimum electrical charge?
9. Does your experiment support the idea of a quantized electrical charge?
10. If we had neglected the buoyancy of the air, how big an error would have been introduced into the calculation of the charge?

MILLIKAN OIL DROP EXPERIMENT
TEACHER'S GUIDE

This section of the manual is not meant for student use. It includes background information for teachers, information on how to back up and configure the program on your computer, and suggestions for conducting a successful experiment. The *Teacher's Guide* also contains sample experimental results and program design notes.

Background Information

Rare is the high school class that performs the Millikan oil drop experiment. Even where it is done on the college or university level, it is considered a very difficult experiment. Teachers trained in the Physical Science Study Committee (PSSC) mold know well the importance of this experiment, but few of these teachers have their students carry out the actual experiment. Instead, most PSSC teachers have their students view the PSSC film, *Millikan Experiment.*

There are numerous reasons why teachers have chosen not to have students perform the Millikan oil drop experiment :

- Equipment cost – Even the least expensive apparatus is too expensive for many schools.
- Image inversion – The small microscope inverts the image, so falling particles appear to move up as students view the field. This confuses students.
- Particle randomness – Not all particles are identical in radius or mass, so they will fall at different rates. This makes a "simple version" of the experiment impossible.
- Safety – In order to change charge, a new particle must be introduced into the field of view, because bombarding the particle with X rays requires health and safety standards most schools cannot meet. There may also be safety concerns about using the high voltages necessary.
- Equipment problems – Ultimately, it is difficult to keep the apparatus necessary for the oil drop experiment functioning in an introductory laboratory situation.

This program is designed to circumvent these frustrations, and provide a way for physics teachers to introduce their students to this experiment.

The MILLIKAN OIL DROP EXPERIMENT program allows students to execute this experiment on several levels. It can be arranged to simulate the frustrating experiment known to most physics majors or options can be selected allowing students to come away with analyzable data in one class period.

This is not a program for demonstration purposes, but is rather designed for students to perform the "actual" experiment. The Millikan experiment has been relegated to a mere footnote in many current physics texts even though it is considered to be one of the all-time classic experiments. Not only does this experiment show that charges come in discrete units, but it forms the backbone for the concepts of potential difference and acceleration of charges in an electric field, and it is a natural bridge into magnetic field lines. This computerized version of the Millikan oil drop experiment gives physics instructors the opportunity to have students discover that charges come in integer units, determine the elementary charge, and re-enact a famous experiment.

HARDWARE REQUIREMENTS

To run this version of MILLIKAN OIL DROP EXPERIMENT, you will need an IBM-compatible computer (PC, PC-XT, PC-AT, PS/2 or equivalent) with the following:

- At least 256K of RAM memory
- A CGA or Hercules compatible graphics card
- MS-DOS version 2.0 or higher

It is also recommended that you have two disk drives for creating back-up copies, but this is not absolutely necessary.

MAKING BACK-UP COPIES

Before you start using MILLIKAN OIL DROP EXPERIMENT, you should make a back-up disk. To do this you will need a blank disk and a copy of MS-DOS version 2.0 or higher. Once you have created your backup(s), store your original disk in a safe place.

Floppy Drive Systems:

1. Format a blank disk using the MS-DOS command FORMAT/S. This disk will become your working copy.
2. Place the original of MILLIKAN OIL DROP EXPERIMENT in drive A:
3. Place the formatted disk in drive B:
4. From the regular MS-DOS prompt, enter: `COPY A:*.* B:*.*`
5. Label your new working copy clearly.
6. You now have a working copy of MILLIKAN OIL DROP EXPERIMENT that can be run by simply placing it in drive A: and turning the computer on. If you prefer, you can start up the computer using another disk, then change the active directory to the MILLIKAN OIL DROP EXPERIMENT disk, and enter `MILLIKAN` to start the program.

Hard Drive Systems:

1. Boot up on the hard disk and make sure you are in the root directory (usually C:\).
2. Enter: `MD MILL`. This creates a subdirectory called \MILL that will hold all the necessary MILLIKAN OIL DROP EXPERIMENT files.
3. Enter: `CD MILL`. You should now be in the newly created \MILL subdirectory of your hard drive.
4. Place the MILLIKAN OIL DROP EXPERIMENT original disk in drive A:
5. Enter: `COPY A:*.* C:*.*`
6. You now have all the files you need copied into directory C:\MILL. To start up the program at any time, follow this procedure:
   a. Change the active directory to the C:\MILL directory (use the MS-DOS CD command).
   b. Enter: `MILLIKAN`

Control Menus

The capabilities of the MILLIKAN OIL DROP EXPERIMENT go beyond simulating the simple version of the experiment described in the *User's Manual*. Using the control menus, you can change a number of factors which make the experiment more challenging for students. You can change the program to simulate Millikan's actual experiment, or you can design experiments of your own. You might prefer to let your more interested students use the control menus also. You access the control menus by pressing the <CONTROL> key followed by a two letter "secret code." When the MILLIKAN OIL DROP EXPERIMENT disk is shipped, the code is "OP". To access the control panel you hold down the <CONTROL> key while you quickly press the <O> key and then the <P> key.

You can change the code letters used to gain access to the control panel if you wish. This will make it more difficult for students to use the control panel to change the experimental conditions. To change the code letters follow this procedure: (1) Load the file DEFAULTS.DAT into your standard word processor or text editor. (2) Examine the last two lines of the file. Normally they will be the letters "O" and "P". (3) Use your word processing program to change these two letters to the code letters you want to use. (4) Save the DEFAULTS.DAT file back on the disk with the same name. If you ever forget the code letters and are unable to access the control panel, remember that you can always determine the code by examining the last two lines of the file DEFAULTS.DAT on your working copy of the MILLIKAN OIL DROP EXPERIMENT.

The Master Options Menu offers the following choices:

```
T - Timing options
D - Difficulty options
M - Miscellaneous control options
S - Save current options
X - Return to experiment
```

The first three choices allow you to change the various aspects of the program. The *Timing Options* control the interval timer. The *Difficulty Options* allow you to add (or remove) features to the program to make it more challenging for your students. The *Miscellaneous Control Options* provide a way to change the experimental apparatus (plate separation, type of drops, etc.). When you have all of the options set as you want them, you can select "Save Current Options" to save the current conditions on the disk for later use.

All of the options that can be changed in the program are explained in detail in the sections below.

USING THE CONTROL MENUS:

Making a Selection from the Menus: Menus are used in this program as they are in other Vernier Software programs. You make a selection in a menu by moving the highlighted bar over the desired choice and pressing <ENTER>. You can move the bar up and down the menu by pressing the arrow keys. The <↑ > and <↓> keys move the bar up and down the menu. Often a quicker way to move the bar to the desired selection is simply to press the letter in front of the choice. Remember that a choice will not be activated until you press <ENTER>.

Entering Values: To change a selection that is a *toggle* (a choice that is either *On* or *Off*), you highlight the selection and press <ENTER>. This will cause the value to toggle to the opposite setting (*On* goes to *Off*, and *Off* goes to *On*). For some selections you will need to enter a new numeric value. A standard format is used in these situations. A default entry is displayed. This entry is usually the most reasonable or likely choice. If you simply press <ENTER>, the default entry will be used. If you wish to enter something different, type in the correct entry. If your first keystroke is a number key or a letter, the default entry is wiped out and your new value can be entered. If your first keystroke is one of the editing keystrokes below, you can begin editing the default entry. Whenever you are entering information, the following keystrokes can be used:

KEY	ACTION
<→>	moves cursor right
<←>	moves cursor left
<BACKSPACE>	deletes character to the left of the cursor
<Delete>	deletes character that the cursor is on
<Insert>	toggles between the normal "type over" mode and the "insert" mode
<Home>	moves the cursor to the left end of the entry
<End>	moves the cursor to the right end of the entry
<CONTROL><X>	deletes all characters (start over from scratch)
<CONTROL><Z>	restores the default entry (start over from the default entry)
<CONTROL><Y>	deletes from cursor to end of line
<ESC>	exits what you are doing and returns to the previous menu (escape)

To use one of the "control" commands, hold the <CONTROL> key down while pressing the other (letter) key. The number of characters allowed is limited in some cases, and if you try to enter too many characters the computer will beep. When you have the entry the way you want it, press <ENTER>. Pressing the <ESC> key will cause the program to return to the Main Menu or to a previous menu.

TIMING OPTIONS MENU

The Timing Options Menu allows you to adjust the timing of the program and control the interval timer. The options in this menu, with the original defaults (as the program was sold), are as follows:

```
M - Timer correction delay                                      128
A - Automatic setting of timer correction delay at startup      On
T - Ticking sound on/off                                        On
C - Number of seconds in interval timer                         10
X - Return to Master Options Menu
```

M - Timer correction delay
This option allows you to manually change the speed of the program. The timer correction delay is usually correctly set when the program begins, so most people will never need to use this option. If you find that the program is running too slow or fast (the ticks of the clock are not one second apart), you can enter a different correction delay. A larger number for the timer correction delay will make the program run slower. A smaller number will make the program run faster. See "Timing" under "Program Design Notes" for more details.

A - Automatic setting of timer correction delay at startup
With this option on when the program starts, it will automatically set the "timer correction delay" to match the speed of your computer. If you want to control the timer correction delay you can choose to turn this option off. See "Timing" under "Program Design Notes" for more details.

T - Ticking sound on/off
Turns the ticking sound (one tick per second) on or off. The ticking sound can also be turned on or off using the <B> key during the experiment.

C - Number of seconds in interval timer
This value is the number of seconds between the time that the first marker is put on the screen and the time of the second. The period of the interval timer can also be adjusted using <Tab> and <Shift> <Tab> keys during the experiment. The number of seconds in the interval timer may vary from 1 to 90 seconds.

X - Return to Master Options Menu
Returns you to the Master Options Menu. Pressing <ESC> will get you back to the Master Options Menu also.

DIFFICULTY OPTIONS MENU

This menu is used to adjust the skill level of the experiment. The options in this menu, with the original defaults (as the program was sold), are as follows:

```
R - Random drop radii                   Off
D - Display of radius                   On
L - Intermittent loss of charges        Off
M - Movement direction gauge            On
B - 90-V battery simulation             Off
C - Interval timer                      On
A - Charge loss alarm                   On
Z - Brownian motion                     Off
S - Skill level                         Low
X - Return to Master Options Menu
```

Changing the skill level settings (*Low*, *Medium* and *High*) automatically adjusts all eight of the other settings on this menu. These eight options can also be adjusted individually. Setting an option to *On* is not necessarily the more difficult setting.

R - Random drop radii

If this option is off, each drop is exactly the same in radius. Therefore, the experimenter can get a new drop at any time with little penalty. If this option is on, each new drop will have a different radius and mass. Drops may vary by 20%. This is what would happen if you were doing a "real life" oil drop experiment. In this case, students must be more cautious when moving a drop up and down the grid, because losing a drop means they will almost surely get a drop of different mass. If they are doing a controlled experiment in which the mass is to remain constant, they may need to start the experiment over.

D - Display of radius

This option determines whether or not the radius of the current drop is to be displayed. Not displaying the radius makes calculation of the exact charge on a drop much more difficult, since it means that the mass of the drop must be determined from the drift velocity due to gravity alone (v_g) and Stoke's equation.

L - Intermittent loss of charges

When this option is on, drops will occasionally lose a charge. This makes the experiment more realistic, and was really a factor in Millikan's experiment. The average time between the loss of a charge is about ten minutes—after all, students can suffer only so much frustration!

M - Movement direction gauge

This option controls the direction indicator on the main screen. When on, you have a helpful indicator as to when the drop is in balance and if not balanced, which way it is moving. Experimental results using Method 1 will be improved if it is on, as it is a more accurate indicator than the human eye when viewing very slowly moving particles. In fact, experimental results might be too perfect if this option is on. This is definitely a good option to have on while students are learning to use the program. Turning it off makes the experiment more realistic.

B - 90-V battery simulation

This option will allow the experimenter to control the voltages only by 90-volt increments. This option more nearly simulates the way early experimenters did this experiment. They could change the voltage only by adding or removing batteries. Turning this option on makes the experiment more difficult.

C - Interval timer

When this option is on, the interval timer is available and displayed on the screen. If this is off, the experimenter will need to use sóme external timing system as was required of Millikan. If you don't want "too perfect" lab results, then this might be a good option to turn off.

A - Charge loss alarm

This setting is associated with the "L - Intermittent loss of charges" option. When this option is on, the computer will alert the user with a beep whenever a particle loses a charge. If this option is off, the drop can lose a charge and the student will have to notice it or else faulty data may be collected.

Z - Brownian motion

This option allows you to add Brownian motion to the experiment. Brownian motion is the motion that the droplet undergoes as the air molecules randomly collide with it. This will add a random "jiggle" to the droplet's movement. Brownian motion makes this simulation more like the real world experiment. It adds a small amount of experimental uncertainty to the experiment.

S - Skill level

There are three pre-programmed skill levels: *Low*, *Medium* and *High*. Selecting one of these three skill levels automatically adjusts all of the difficulty options described above. The various settings for the different levels are as follows:

Skill Level	Random R	Display R	Ch. Loss.	Dir Gauge	90V	Timer	Alarm	Brownian
Low	OFF	ON	OFF	ON	OFF	ON	ON	OFF
Medium	ON	ON	ON	OFF	OFF	ON	ON	OFF
High	ON	OFF	ON	OFF	OFF	ON	OFF	ON
Custom	???	???	???	???	???	???	???	???

Selecting this option will cause the skill level to change to the next setting. This means that if the skill level is currently *Low* and you move to the "Skill level" option and press <ENTER>, the level will change to *Medium*. In a similar way, each time you press <ENTER>, the program will step through the possible skill levels. Whenever this indicator reads *Custom*, it means that the current difficulty setup is a custom setup and is different than any of the three pre-programmed settings. If you adjust the various options so that they happen to fit into one of the skill settings, the skill level will change to the appropriate setting.

This choice provides a quick way of setting all of the difficulty options.

X - Return to Master Options Menu
Choosing option X or pressing <ESC> will get you back to the Master Options Menu.

MISCELLANEOUS CONTROL OPTIONS

This menu allows you to modify such things as the substance used (usually oil drops or plastic drops), the separation between plates, and the magnification of the microscope to be used.

The options in this menu, with the original defaults (as the program was sold), are as follows:

T - Random plate separation at startup	Off
P - Plate separation	3.10 mm
R - Average radius of drop	1.75 µm
D - Density of drop	128 kg/m³
M - Magnification	2X
S - Miscellaneous sounds	On
C - Substance type	Plastic
X - Return to Master Options Menu	

T - Random plate separation at startup
If this option is on, each time you start the program you will have a different plate separation. This ensures that every lab group collects their own data, because different plate separations produce different data. If this option is off, then plate separation is set according to the "P - Plate separation" option loaded at startup.

P - Plate separation
This allows you to set the plate separation. If option "T - Random plate separation at startup" is on, then this value will be assigned randomly each time the program starts.

R - Average radius of drop
This option lets you have control over the average drop radius. If the "R - Random drop radii" option (under Difficulty Options) is off, then this value will be the radius of every drop. Otherwise, the drop radii will vary by about 20% around this average value. The default values for average radii are: oil = 1.40 µm and plastic = 1.75 µm.

D - Density of drop
This allows the instructor to control the density of the drop. The default value for an oil drop is around 850 kg/m^3. For a plastic drop, as used in the PSSC Millikan experiment, the default value is 128 kg/m^3. Practically any substance imaginable can be simulated using this option, even substances with densities less than air.

M - Magnification
This option allows you to change the microscope's power. If the magnification is set at 1X, this means there is no magnification. At this setting, the wires on the main screen connecting the plates to the power supply will be solid, indicating that the plates are shown in their actual location. If magnification is greater than 1X, then the wires will be dotted, indicating the plates are actually above and below the limits of the screen. Notice that when the magnification changes, the "mm/div" on the main screen changes accordingly. Magnification can also be changed from the main experiment screen by using the <+> and <-> keys.

S - Miscellaneous sounds
This option controls the sound emitted when you change the charge on the drop and the sound made when the drop hits the charged plates. If the experiment is performed in a room where other students require a quiet atmosphere, you can eliminate this sound.

C - Substance type
This control is much like the "S : Skill level" control found in the Difficulty Options Menu. It allows you to quickly set the average radius and the density to the default settings for both oil and plastic. If you change either the density or radius to a non-default value, then the substance type will be listed as *Custom*. Don't be afraid to try out some "custom" substances.

X - Return to Master Options Menu
Returns to Master Options Menu. Pressing <ESC> will get you back to the Master Options Menu also.

Performing the Experiment

METHOD 1: BALANCING THE DROPS

Suggested Settings:

Skill level	Low
Random plate separation at startup	Off
Plate separation	3.10 mm
Average radius of drop	1.75 µm
Density of drop	128 kg/m^3
Magnification	2X
Miscellaneous sounds	On
Substance type	Plastic

(Note: All of these settings are as the disk is delivered)

Optional Settings: If you want to make the experiment slightly more difficult, you can change the following settings using the Difficulty Options Menu:

Intermittent charge loss	*Off -> On*
Movement direction gauge	*On-> Off*
Charge loss alarm	*On-> Off*

Discussion and Sample Results:

This version of the experiment is similar to the *Project Physics Resource Book* lab "The Measurement of Elementary Charge." The simplest method for measuring the charge on a drop or particle is to determine the balancing voltage for differently charged particles. When the drop is balanced:

$$force_{up} = force_{down}$$

$$qE = mg$$

$q\ (V/d) = mg$

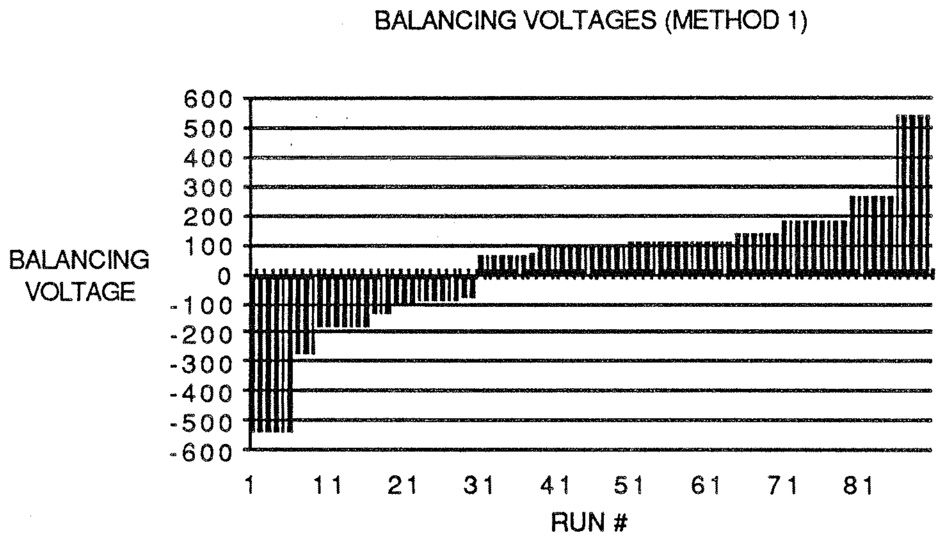
$q = mgd/V$

The charge is inversely proportional to the balancing voltage if the mass of the drops (and other factors) remain constant. The sample data below (90 trials) were collected using this method:

BALANCING VOLTAGES:

180	108	108	180	-90	-180
180	90	180	90	-90	-540
180	108	90	67	-135	-270
180	108	135	108	-540	-540
90	68	77	68	-180	-180
135	68	90	108	-180	-540
540	68	90	180	-90	270
180	108	108	-270	-108	540
90	108	135	-270	-90	180
108	270	108	-540	-135	90
90	108	90	-180	-77	135
135	108	90	-180	-90	270
270	68	108	-108	-77	270
540	90	270	-108	-135	-540
135	68	540	-90	-180	540

A histogram of this data (after sorting) is shown below. Notice that there are definite "steps" in the balancing voltages. Each bar represents one balancing voltage.



Method 1 - Experiment Extension: Calculating Actual Charges

Using the *Low* skill level, the radius of the drop is displayed at the bottom of the screen. The density of the drop is known. Unless you have changed the standard conditions, plastic drops are being used; their density is 128 kg/m^3. You can always check to determine the density of the drops being used by accessing the Miscellaneous Control Options Menu. The density of the drops is displayed on this menu.

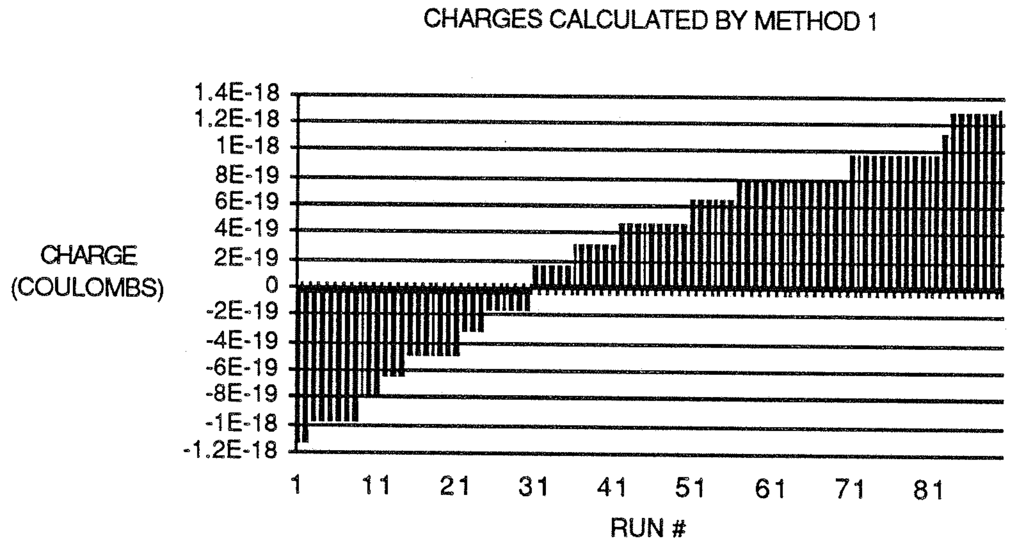
The mass of the drop can therefore be calculated:[7] $m = \text{volume} * \text{density}$

$$m = 4/3\ \pi\ r^3 * \text{density}$$

With all of this information known, the charge on each drop can then be calculated using $q = mgd/V$. If the charge on each drop is calculated, and a histogram of the calculated charges is made, you can see the distribution of charge nicely. The charges calculated from the sample data above are graphed

[7]To be completely correct, the mass calculated here and used later should be the *apparent mass*, corrected for the buoyant force of the air. Method 3 takes apparent mass into account.

below. Notice that "steps" on these histograms are evenly spaced. Each step is an elementary charge (1.6 E-19 coulombs). It is possible, of course, that some lab groups will not get every possible charge, and have "missing steps" on their histogram.



Method 1 is a very simplified and not a very realistic version of the Millikan oil drop experiment. It can be done quickly, however, and does introduce students to the experiment and allow them to "discover" that charge comes in finite units. This method totally avoids the complicating issues of vector subtraction, Stokes law and apparent mass.

Answers to Questions:

1. Why are some of the drops not affected by electrical fields? Some drops are electrically neutral.
2. Why do some of the drops require a negative rather than a positive balancing voltage? A few drops are positively charged.
3. Do the balancing voltage numbers seem to clump together in groups rather than spread out evenly over the range of values? What does this mean about the charges on the drops? The balancing voltage histogram shows definite steps which indicate that the charges are quantized.
4. As you look at the voltage histogram, the "steps" are not all the same. Why is this? This histogram shows voltages which are inversely proportional to the charge.

Experiment Extension Questions:

5. Why are the steps on the charge histogram even, while the steps on the balancing voltage histogram were uneven? The charge histogram steps are even because each step indicates a change of one elementary charge.
6. What is the smallest charge that you measured? It should be nearly 1.6×10^{-19} coulombs or some small integer times 1.6×10^{-19} coulombs.
7. What is the average step size on the charge histogram? It should be very close to 1.6×10^{-19} coulombs.
8. What is your best estimate of the minimum electrical charge? Hopefully, 1.6×10^{-19} coulombs.
9. Does your experiment support the idea of a quantized electrical charge? Yes.
10. In what ways is this simulation a simplification of Millikan's original experiment? Aside from avoiding all of the equipment problems, this method simplifies the experiment by providing uniform drops of known radius and density. Quick control of the voltage is possible, there is no ionization, and the charge can be changed whenever you wish.

METHOD 2: MEASURING VELOCITIES - RADIUS OF DROPS KNOWN

Suggested Settings:

Skill level	Low
Random plate separation at startup	Off
Plate separation	3.10 mm
Average radius of drop	1.75 µm
Density of drop	128 kg/m3
Magnification	2X
Miscellaneous sounds	On
Substance type	Plastic

(Note: All of these settings are as the disk is delivered.)

Optional settings: If you want to make the experiment slightly more difficult, you can change the skill level setting to *Medium*. This will add the following complication to the experiment:

- Each time a new drop is used, the radius (and mass) will be different. The radius will still be displayed at the bottom of the screen.
- The drops may occasionally (and randomly) lose electrical charge by ionization.
- The direction gauge is no longer functional.

Some teachers may want to increase the time interval used by the interval timer. This will generally increase the accuracy of the results. This change is made using the Timing Options Menu.

Discussion and Sample Results:

Method 2 parallels the experiment done in the PSSC Millikan Experiment film and lab book. It is recommended for most students. Instructors may wish to have their students go through Method 1 just to acquaint them with the screen and a few of the control keys. Method 2 requires a bit more dexterity on the part of the experimenter, and therefore raises the frustration level. In this version of the experiment, the velocity of a drop is measured in a constant electrical field as its charge is changed. A standard voltage should be chosen; it can be any voltage between 100 volts and 400 volts. In the PSSC film, 270 volts were used. The voltage will need to be changed temporarily to drag the drop up and down the screen, but when measuring velocities, the voltage must be returned to this standard value.

Students need only measure the drift velocity due to gravity alone (v_g) one time in this experiment, since all drops are the same. They should measure the drift velocity under the influence of gravity and the standard voltage together (v_t) at least 20 times. Forty times yields a much better histogram. You can also pool the results from several student groups if they use drops with the same radius.

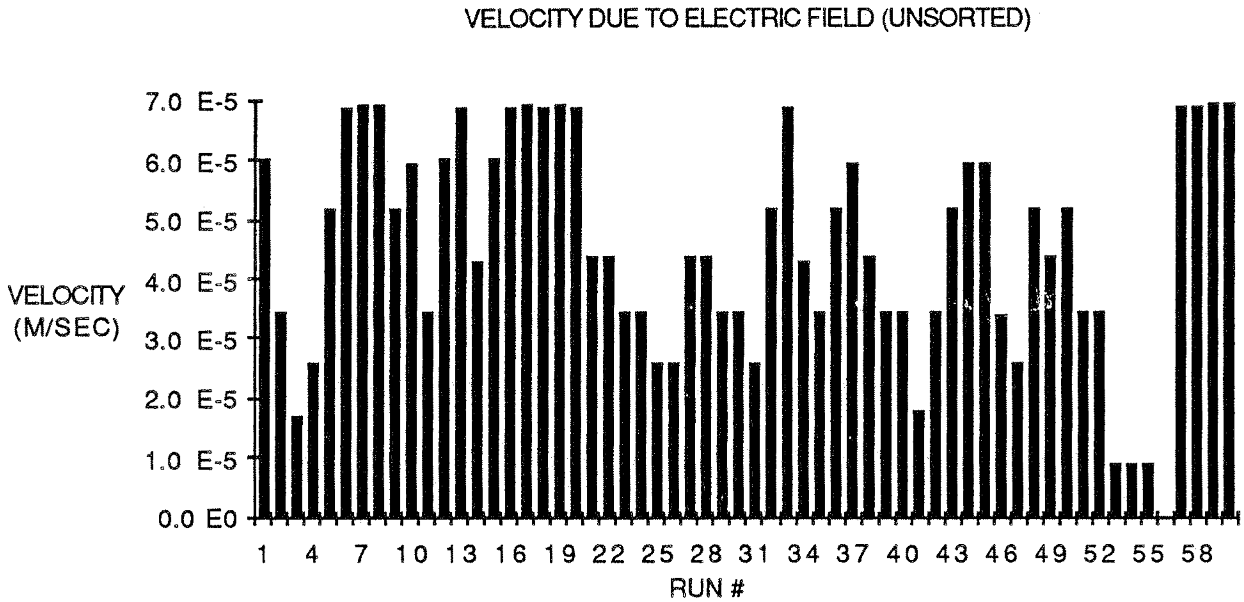
The following sample table of data was collected using this program and a standard voltage of 100 volts. In this experiment, v_g was found to be 4.65 x 10^{-5} m/sec. All data is recorded using the notation of positive up, negative down. The fourth column of numbers was calculated by vector subtraction of v_g from v_t.

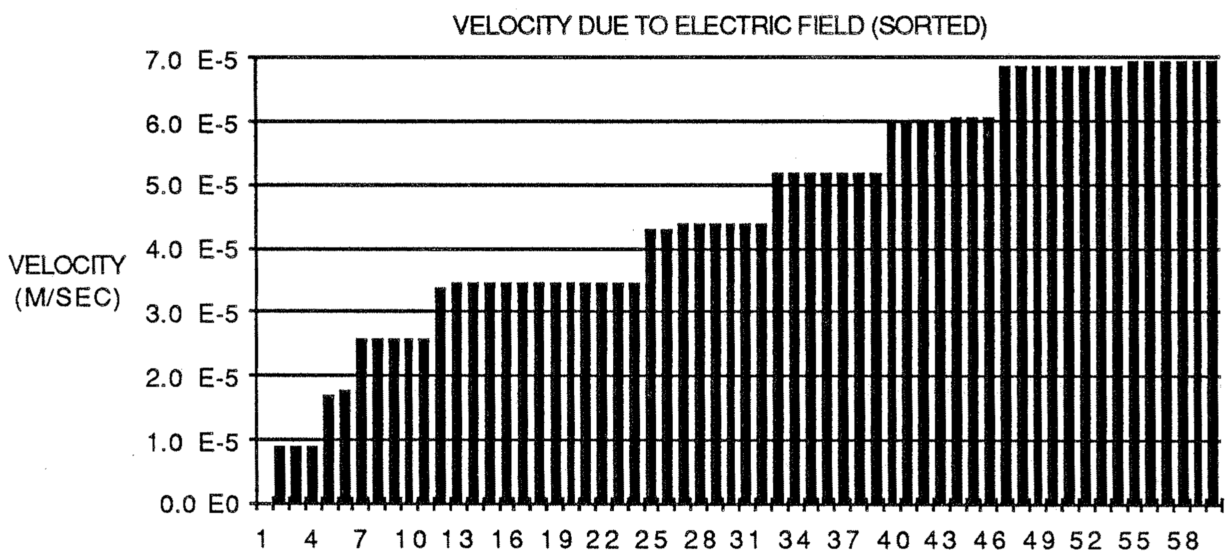
drop radius = 1.748 µm
plate separation = 0.0031m
plastic drops (density 128 kg/cubic meter)
interval timer set for 15 seconds

standard voltage = 100V
drift distance with no field = -9.0 divisions
v_g = -4.65 E-5 m/sec
distance/division = 7.75 E-5 m

RUN #	DISTANCE TRAVELED (DIVISIONS)	VELOCITY (v_t) (M/SEC)	VELOCITY (v_e) (M/SEC)	(v_t / v_g-1)	CALCULATED CHARGE (COULOMBS)	CHARGE DIVIDED BY 1.6E-19
1	2.7	1.4 E-5	6.0 E-5	-1.3	1.1E-18	7.00
2	-2.3	-1.2 E-5	3.5 E-5	-0.7	6.4E-19	4.01
3	-5.7	-2.9 E-5	1.7 E-5	-0.4	3.2E-19	1.97
4	-4.0	-2.1 E-5	2.6 E-5	-0.6	4.8E-19	2.99
5	1.0	5.2 E-6	5.2 E-5	-1.1	9.6E-19	5.98
6	4.3	2.2 E-5	6.9 E-5	-1.5	1.3E-18	7.96
7	4.5	2.3 E-5	6.9 E-5	-1.5	1.3E-18	8.05
8	4.5	2.3 E-5	6.9 E-5	-1.5	1.3E-18	8.05
9	1.0	5.2 E-6	5.2 E-5	-1.1	9.6E-19	5.98
10	2.6	1.3 E-5	6.0 E-5	-1.3	1.1E-18	6.91
11	-2.3	-1.2 E-5	3.5 E-5	-0.7	6.4E-19	4.01
12	2.7	1.4 E-5	6.0 E-5	-1.3	1.1E-18	7.00
13	4.3	2.2 E-5	6.9 E-5	-1.5	1.3E-18	7.96
14	-0.7	-3.6 E-6	4.3 E-5	-0.9	7.9E-19	4.97
15	2.7	1.4 E-5	6.0 E-5	-1.3	1.1E-18	7.00
16	4.3	2.2 E-5	6.9 E-5	-1.5	1.3E-18	7.96
17	4.5	2.3 E-5	6.9 E-5	-1.5	1.3E-18	8.05
18	4.3	2.2 E-5	6.9 E-5	-1.5	1.3E-18	7.96
19	4.5	2.3 E-5	6.9 E-5	-1.5	1.3E-18	8.05
20	4.3	2.2 E-5	6.9 E-5	-1.5	1.3E-18	7.96
21	-0.6	-2.8 E-6	4.4 E-5	-0.9	8.1E-19	5.06
22	-0.6	-2.8 E-6	4.4 E-5	-0.9	8.1E-19	5.06
23	-2.3	-1.2 E-5	3.5 E-5	-0.7	6.4E-19	4.01
24	-2.3	-1.2 E-5	3.5 E-5	-0.7	6.4E-19	4.01
25	-4.0	-2.1 E-5	2.6 E-5	-0.6	4.8E-19	2.99
26	-4.0	-2.1 E-5	2.6 E-5	-0.6	4.8E-19	2.99
27	-0.6	-2.8 E-6	4.4 E-5	-0.9	8.1E-19	5.06
28	-0.6	-2.8 E-6	4.4 E-5	-0.9	8.1E-19	5.06
29	-2.3	-1.2 E-5	3.5 E-5	-0.7	6.4E-19	4.01
30	-2.3	-1.2 E-5	3.5 E-5	-0.7	6.4E-19	4.01
31	-4.0	-2.1 E-5	2.6 E-5	-0.6	4.8E-19	2.99
32	1.0	5.2 E-6	5.2 E-5	-1.1	9.6E-19	5.98
33	4.3	2.2 E-5	6.9 E-5	-1.5	1.3E-18	7.96
34	-0.7	-3.6 E-6	4.3 E-5	-0.9	7.9E-19	4.97
35	-2.3	-1.2 E-5	3.5 E-5	-0.7	6.4E-19	4.01
36	1.0	5.2 E-6	5.2 E-5	-1.1	9.6E-19	5.98
37	2.6	1.3 E-5	6.0 E-5	-1.3	1.1E-18	6.91
38	-0.6	-2.8 E-6	4.4 E-5	-0.9	8.1E-19	5.06
39	-2.3	-1.2 E-5	3.5 E-5	-0.7	6.4E-19	4.01
40	-2.3	-1.2 E-5	3.5 E-5	-0.7	6.4E-19	4.01
41	-5.6	-2.9 E-5	1.8 E-5	-0.4	3.3E-19	2.06
42	-2.3	-1.2 E-5	3.5 E-5	-0.7	6.4E-19	4.01
43	1.0	5.2 E-6	5.2 E-5	-1.1	9.6E-19	5.98
44	2.6	1.3 E-5	6.0 E-5	-1.3	1.1E-18	6.91
45	2.6	1.3 E-5	6.0 E-5	-1.3	1.1E-18	6.91
46	-2.5	-1.3 E-5	3.4 E-5	-0.7	6.3E-19	3.92
47	-4.0	-2.1 E-5	2.6 E-5	-0.6	4.8E-19	2.99
48	1.0	5.2 E-6	5.2 E-5	-1.1	9.6E-19	2.99
49	-0.6	-2.8 E-6	4.4 E-5	-0.9	8.1E-19	5.98
50	1.0	5.2 E-6	5.2 E-5	-1.1	9.6E-19	5.06
51	-2.3	-1.2 E-5	3.5 E-5	-0.7	6.4E-19	5.98
52	-2.3	-1.2 E-5	3.5 E-5	-0.7	6.4E-19	4.01
53	-7.3	-3.8 E-5	8.8 E-6	-0.2	1.6E-19	4.01
54	-7.3	-3.8 E-5	8.8 E-6	-0.2	1.6E-19	1.02
55	-7.3	-3.8 E-5	8.8 E-6	-0.2	1.6E-19	1.02
56	-9.0	-4.7 E-5	0.0 E0	0.0	0.0E0	1.02
57	4.3	2.2 E-5	6.9 E-5	-1.5	1.3E-18	0.00
58	4.3	2.2 E-5	6.9 E-5	-1.5	1.3E-18	7.96
59	4.5	2.3 E-5	6.9 E-5	-1.5	1.3E-18	7.96
60	4.5	2.3 E-5	6.9 E-5	-1.5	1.3E-18	8.05
						8.05

The histograms that follow show the distributions of velocities in these 60 trials. Notice that the steps on the histograms are nearly equal.





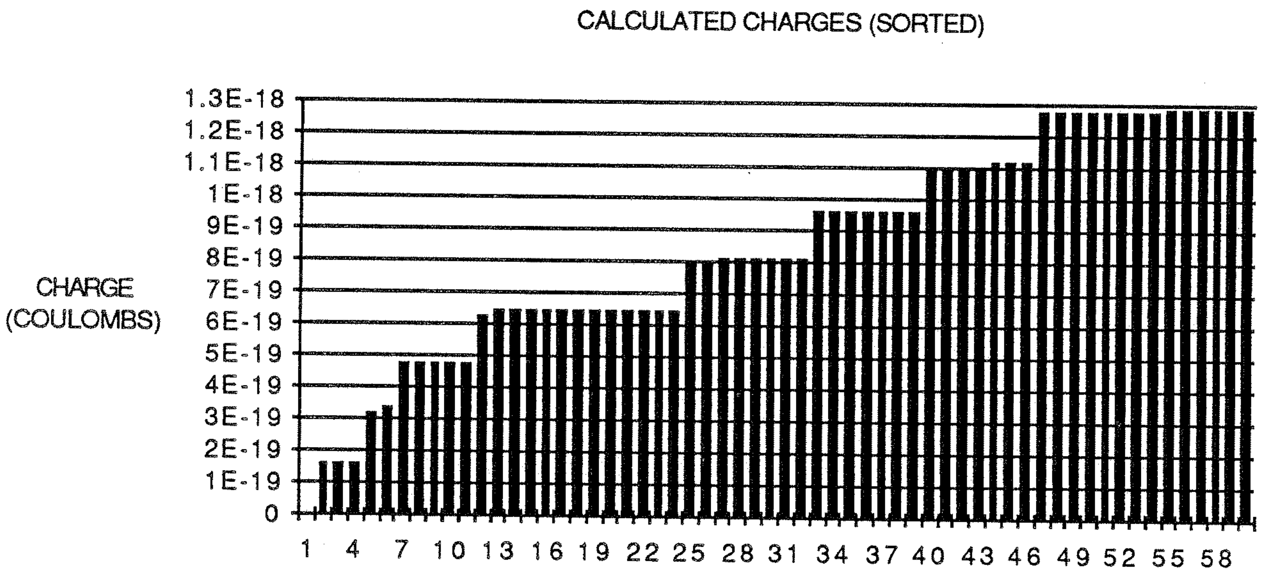
Method 2 - Experiment Extension: Calculating Actual Charges

Students can use the equation $q = (v_t/v_g-1)(-mgd/V)$ to calculate the charges from the two velocities. They need to determine the mass of the drop. Since the radius of the drops is displayed on the screen, this is not much of a problem.

$$\text{mass} = \text{density} * \text{volume} = \text{density} * 4/3\ \pi\ r^3$$

Only the two velocities, the mass of the drop, the voltage, and the plate separation are needed to calculate the charge. This equation is based on the assumption that for small objects moving through the air, the terminal velocity is proportional to the force acting on the object. This is a well-known and experimentally tested relationship. It may be new to many students.

The charges were calculated in this way in the data table above. The last column in the table shows the calculated charge divided by 1.6 E-19 coulombs. The result is approximately an integer in all cases. This is one method of analyzing the data that you may want to suggest to your students. The histogram of the sorted charges is shown below. Notice that each step on the histogram is approximately 1.6×10^{-19} coulombs.



Answers to Questions:

1. Why are some of the drops not affected by electrical fields? Some drops are electrically neutral.
2. Why do some of the drops move downward with the standard field applied? A few drops are positively charged.
3. Do the v_e values seem to clump together in groups rather than spread out evenly over the range of values? What does this mean about the charges on the drops? This indicates that charges (which are proportional to the v_e values) must come in finite units.
4. What is the average step size on the v_e histogram? What electrical charge difference does this correspond to? The v_e value depends on the experimental conditions. It should correspond to a change in charge of 1.6×10^{-19} coulombs.
5. Are there any forces acting on the drop which were not considered in the discussion of the experiment? The buoyant force of the air. Method 3 below considers the buoyant force.

Experiment Extension Questions:

6. What is the smallest charge that you measured? It should be nearly 1.6×10^{-19} coulombs or some small integer times 1.6×10^{-19} coulombs.
7. What is the average step size on the charge histogram? It should be very close to 1.6×10^{-19} coulombs.
8. What is your best estimate of the minimum electrical charge? Hopefully 1.6×10^{-19} coulombs.
9. Does your experiment support the idea of a quantized electrical charge? Yes.

METHOD 3: MEASURING VELOCITIES - RADIUS OF DROPS NOT KNOWN

Suggested Settings:

Skill level	High
Random plate separation at startup	Off
Plate separation	3.10 mm
Average radius of drop	1.75 μm
Density of drop	128 kg/m^3
Magnification	2X
Miscellaneous sound	On
Substance type	Plastic

(Note: All of these settings are as the disk is delivered, except the skill level.)

This experiment is similar to the experiment described in Method 2 with the following complications added to make the experiment more realistic and difficult:

1. The radius of the drop is not displayed on the screen and it changes each time a new drop is introduced. The students must determine the radius of each drop by using the velocity under the influence of gravity (v_g) and Stokes equation.
2. Another complication is introduced into the analysis in method 3–the buoyancy of air. The apparent mass of the drop used in the equations should be calculated from:

$$4/3\, \pi\, r^3 * (\text{density}_{drop} - \text{density}_{air})$$

3. Drops may randomly lose electrical charge due to ionization. This happens only about every 10 minutes on average.
4. The direction gauge no longer functions.
5. Brownian motion is now included, which makes the experiment more realistic.

From the equations explained in the theory section, students can determine the radius of each drop and calculate its charge. Brownian motion adds some "noise" to the experiment. Any two measurements of the velocity of a drop with the same charge and subject to the same voltage potential will probably be slightly different. This means that any patterns in the data collected during this experiment will be a little harder to detect since there will be a small amount of deviation from theoretical values in each reading.

The results obtained by doing the experiment using Method 3 should be very similar to the sample charge distribution histograms shown for Method 2. The table of data and the histogram below were made using Method 3. 300 volts was the standard voltage.

Millikan Data taken by D. Vernier 2/3/90:

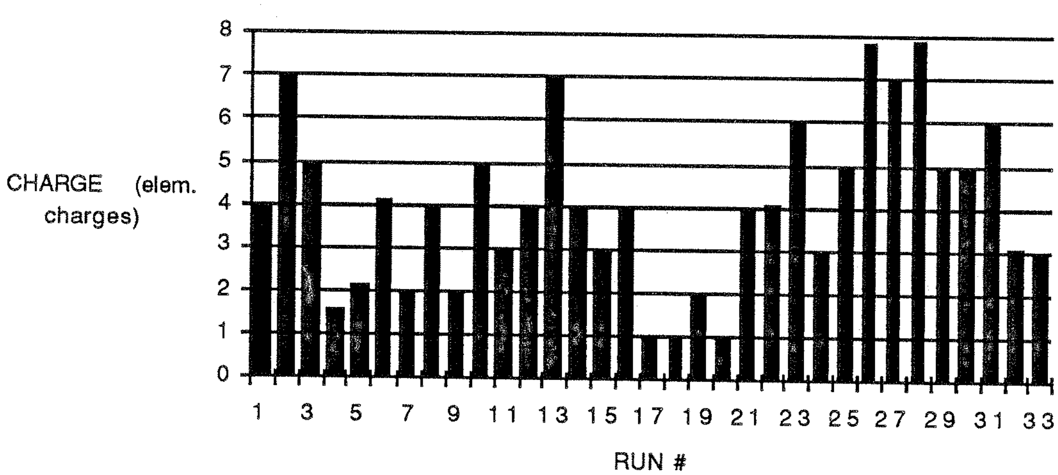
drop radius = 1.6745E-06 μm
plate separation = 0.0031m
plastic drops (density 128 kg/cubic meter)
viscosity = 1.8E-05

density of air = 1.29
standard voltage = 300V
E = 96774

Run #	**No field:** divisions	div. spacing (micrometer)	distance (μm)	speed (m/sec)
1	-5.3	77.5	-410.8	-4.108E-05
2	-11.3	38.8	-438.4	-4.384E-05
3	-11.2	38.8	-434.6	-4.346E-05
4	-11	38.8	-426.8	-4.268E-05
5	-11	38.8	-426.8	-4.268E-05
		average->	-427.47	-4.275E-05

Run #	At 300 V: divisions	div. spacing (micrometers)	distance (µm)	speed wt field (m/sec)	charge (coulombs)	q / 1.6e-19
1	17	38.8	659.6	0.00006596	6.4E-19	4.01
2	9.5	155	1472.5	0.00014725	1.1E-18	7.01
3	12	77.5	930	0.000093	8.0E-19	5.01
4	-0.1	38.8	-3.88	-3.88E-07	2.5E-19	1.56
5	3.8	38.8	147.44	1.4744E-05	3.4E-19	2.12
6	4.4	155	682	0.0000682	6.5E-19	4.09
7	2.9	38.8	112.52	1.1252E-05	3.2E-19	1.99
8	8.3	77.5	643.25	6.4325E-05	6.3E-19	3.95
9	6.1	19.4	118.34	1.1834E-05	3.2E-19	2.01
10	11.9	77.5	922.25	9.2225E-05	8.0E-19	4.98
11	10	38.8	388	0.0000388	4.8E-19	3.01
12	8.3	77.5	643.25	6.4325E-05	6.3E-19	3.95
13	9.5	155	1472.5	0.00014725	1.1E-18	7.01
14	8.5	77.5	658.75	6.5875E-05	6.4E-19	4.01
15	9.7	38.8	376.36	3.7636E-05	4.7E-19	2.97
16	8.4	77.5	651	0.0000651	6.4E-19	3.98
17	-2	77.5	-155	-0.0000155	1.6E-19	1.01
18	-8.2	19.4	-159.08	-1.591E-05	1.6E-19	0.99
19	5.8	19.4	112.52	1.1252E-05	3.2E-19	1.99
20	-8	19.4	-155.2	-1.552E-05	1.6E-19	1.00
21	8.4	77.5	651	0.0000651	6.4E-19	3.98
22	8.7	77.5	674.25	6.7425E-05	6.5E-19	4.06
23	7.7	155	1193.5	0.00011935	9.6E-19	5.98
24	4.9	77.5	379.75	3.7975E-05	4.8E-19	2.98
25	5.9	155	914.5	0.00009145	7.9E-19	4.95
26	11	155	1705	0.0001705	1.3E-18	7.87
27	9.5	155	1472.5	0.00014725	1.1E-18	7.01
28	11.1	155	1720.5	0.00017205	1.3E-18	7.92
29	11.8	77.5	914.5	0.00009145	7.9E-19	4.95
30	11.9	77.5	922.25	9.2225E-05	8.0E-19	4.98
31	7.8	155	1209	0.0001209	9.7E-19	6.04
32	5.1	77.5	395.25	3.9525E-05	4.9E-19	3.04
33	9.7	38.8	376.36	3.7636E-05	4.7E-19	2.97

Charges calculated by method 3



A good reference on these equations and the original Millikan oil drop experiment is *Great Experiments In Physics* (see *Appendix A*).

Even this method of doing the Millikan oil drop experiment does not introduce all of the real-world complexities. In the course of his experiments, Millikan discovered that Stoke's law was not completely accurate for the drops he was using. He experimentally determined that the radius given by Stokes law could be off slightly due to the inhomogeneities of the air. This can lead to a 15% error in the final charge value obtained. This complexity is not built into this simulation. For more information refer to *A Laboratory Manual of Experiments in Physics*.

Answers to Questions:

1. Why are some of the drops not affected by electrical fields? Some drops are electrically neutral.
2. Why do some of the drops require a negative rather than a positive balancing voltage? A few drops are positively charged.
3. What is the percentage difference between the mass of the drop and the apparent mass of the same drop? 1.29 / 128 * 100% = about 1%.
4. Derive equation 6 from equation 5.

$$\frac{v_t}{v_g} = \frac{E\,q - 4/3\,\pi\,r^3\,g\,(\text{density}_{drop} - \text{density}_{air})}{-4/3\,\pi\,r^3\,g\,(\text{density}_{drop} - \text{density}_{air})} \qquad \text{(eq. 5)}$$

$$\{E\,q - 4/3\,\pi\,r^3\,g\,(\text{density}_{drop} - \text{density}_{air})\}\,v_g = v_t\,\{-4/3\,\pi\,r^3\,g\,(\text{density}_{drop} - \text{density}_{air})\}$$

$$E\,q = 4/3\,\pi\,r^3\,g\,(\text{density}_{drop} - \text{density}_{air}) - \frac{v_t\,\{4/3\,\pi\,r^3\,g\,(\text{density}_{drop} - \text{density}_{air})\}}{v_g}$$

$$E\,q = \{4/3\,\pi\,r^3\,g\,(\text{density}_{drop} - \text{density}_{air})\}\,\{1 - v_t / v_g\}$$

$$q = \frac{4\,\pi\,r^3\,g\,(\text{density}_{drop} - \text{density}_{air})}{3\,E}\;\frac{(v_g - v_t)}{v_g} \qquad \text{(eq. 6)}$$

5. Each time a new drop is injected, the radius can vary over a range of 20%. How much possible change can this cause in the mass of the drop? Since the radius is cubed in the calculation of the mass, the mass can change by as much as 72%.
6. What is the smallest charge that you measured? It should be nearly 1.6×10^{-19} coulombs or some small integer times 1.6×10^{-19} coulombs.
7. What is the average step size on the charge histogram? It should be very close to 1.6×10^{-19} coulombs.
8. What is your best estimate of the minimum electrical charge? Hopefully 1.6×10^{-19} coulombs.
9. Does your experiment support the idea of a quantized electrical charge? Yes.
10. If we had neglected the buoyancy of the air, how big an error would have been introduced into the calculation of the charge? Less than 1%.

Managing a Successful Experiment

This section contains several hints that you may find helpful while running this lab and using this manual.

GROUP SIZE

The maximum size for a single lab group using this program should be about three people. If there are more than three people using the computer at one time, invariably somebody will lose interest and will let the other students in the group do all of the work (and learning). The best results are obtained with groups of two or with individuals working alone.

DISK SETUP

It is often helpful to make several copies of the MILLIKAN OIL DROP EXPERIMENT disk with different options saved on them. For example, you can have one disk with the skill level set to *Low* for groups just learning the program and another copy with the options set differently for actually performing the experiment. To do this, simply make direct copies from the original to disks and do not change any of the defaults. These disks will be your practice disks (*Low* difficulty setting). Then copy the original onto another disk and change the default settings to the setting appropriate for the experiment and the difficulty desired. Choose "Save the Current Options" from the Master Options Menu. Copy this disk as many times as needed. These disks will be your experiment disks. It is a good idea to make as many sets of working disks as you have lab groups. This is so you don't have to run around starting the program on ten different computers while lab groups throw questions at you.

Make sure that all the default settings are correctly set on all of the practice and experiment disks. Make sure the practice and experiment disks are labeled clearly.

HANDOUTS

We recommend you make copies of the "Introduction," "Getting Started," and the appropriate "Performing The Experiment" section of the *User's Manual* for each lab group. Have them read the handout the night before the experiment so that the entire period will not be spent learning the program. Of course students will have questions, since they did not have access to a computer while reading the instructions, but these questions can be resolved in a short amount of time at the beginning of class.

GETTING THE CLASS STARTED

Pass out the MILLIKAN OIL DROP EXPERIMENT working copies to each group and have them start up the practice version. They should look over the sections of the manual titled "Getting Started," "The Screen" and "Controls." After spending a couple of minutes on this, they should spend about ten minutes becoming acquainted with the program by running through the "A Little Practice" section. The remaining half hour or so should be plenty of time to collect a reasonable amount of data. The analysis of the data can be done overnight or over a weekend. You may choose to allow your students to use a computer spreadsheet/graphics program to analyze their data. All of the histograms in this manual were done using Microsoft Excel. Lotus 1-2-3, AppleWorks, and many other programs could be used.

QUESTIONS STUDENTS MAY ASK

Q: *I balanced an oil drop perfectly using the direction gauge (it showed a "0"), but when I looked at the drop a few minutes later, it had drifted down the screen one complete division. Why?*
A: The problem here lies in the understanding of the direction gauge. When it reads "0", it is telling you that the drop is *as close to stationary* as possible using one-volt increments. It is *not* guaranteeing that the drop is absolutely still. Another reason that a drop would behave in this manner is that it could have lost a charge during the interval (if the "Intermittent loss of charges" option is *On*), and would therefore no longer be balanced.

Q: *Why do some drops seem unaffected by the voltage between the plates?*
A: Once in a while you will encounter an electrically neutral drop. Such drops are not influenced by electrical fields. In real life, a large voltage could potentially induce a separation of charge on the droplet. For the purpose of this experiment, however, this interaction is negligible.

Q: *Why do some drops just move faster downwards as I increase the voltage? I thought this was how you balanced a drop!*
A: The charge on the drop (or drops) must be positive instead of negative. A small percentage of the drops will come out positively charged. Use the <S> key to switch the polarity of the plates and you can balance these drops.

Q: Sometimes the drop is destroyed (the computer beeps, the direction gauge goes blank) when it hits the plates, and at other times it seems to drift above or below the plates and can be worked back onto the screen. Why?

A: The magnification (found in the lower left hand corner of the screen) is different in the two cases. In one case it is be 1X, and in the other it is larger than 1X. When the magnification is 1X (no magnification), the setup you see on the screen is the actual experimental setup. When the magnification is greater than 1X, however, the plates are, in "real life," above and below the boundaries of the screen. Because of this, with a magnification greater than 1X, a drop can drift above or below the screen and be rescued before it hits the plates. When the program is shipped, the magnification is 2X.

Q: Why does the drop jump around, and sometimes leave or appear on the screen when I change the magnification using the <+> and <-> keys?

A: This occurs because when you change the magnification the field of view changes in size. When you zoom in, a smaller region is visible. Drops which were near the edge of the screen may disappear; they no longer fit on the screen. When you zoom out a larger region is displayed on the screen. Drops will change position on the screen. The same effect occurs as you zoom in on something using a dissecting microscope or telephoto lens. Notice that if the drop is balanced in the exact center of the screen, then zooming in or out will not change its position on the screen.

Program Design Notes

MILLIKAN OIL DROP EXPERIMENT was written on an IBM-PC using Turbo Pascal 4.0. This language was chosen for its speed, as well as source code readability over other choices such as BASIC, C, and FORTRAN. The project started out as the brainchild of Lowell G. Herr at The Catlin Gabel School in Portland, Oregon and was programmed by Mark Topinka for Vernier Software. The following sections are primarily for programmers who are interested in some of the details of how the program works.

GRAPHICS

The first thing this program does is check what type of graphics card is available. If a CGA or Hercules display adapter is found, the program automatically initializes the appropriate driver. If the answer comes back as EGA, VGA, or some other non-supported card, then the program checks the MONITOR.DAT file to see what graphics mode to default to. This file normally causes the graphics to default to CGA. If you have a card other than a regular CGA or Hercules compatible, therefore, the program will try to use CGA graphics unless you modify the MONITOR.DAT file.

To force the program to use Hercules graphics when it starts up, change the contents of the MONITOR.DAT file to the one word HERC. To force the program to use CGA graphics at startup, change the contents of the MONITOR.DAT file to read CGA. The files MONITORC.DAT and MONITORH.DAT files are of this type.

TIMING

The method used to get the program to run at approximately real-time speed (the timer ticking one beep/sec) on any computer regardless of microprocessor speed is slightly complicated. We use a delay loop in each cycle through the program to slow it down to 1/10th second per cycle. Basically, it is simply a FOR NEXT loop containing the variable, DelayLoop. For slower computers, the delay variable will be small (DelayLoop = 105 for an IBM-PC 4.77 MHz), while for faster machines the delay variable will be larger (DelayLoop = 2050 for an IBM-AT 9.54 MHz). DelayLoop is directly accessible to you through the Timing Options Menu. It is the value listed after "Timer correction delay." The way that the program initially determines this value is by using the DOS clock as an absolute time base for comparison. When the program begins (if "Automatic setting of timer correction delay" is turned on) the time of day from the DOS clock is noted. The program then does 10000 mathematical calculations. When these calculations are completed, the time of day is again noted. The program then calculates an approximate "speed" for the computer and sets the timer delay appropriately. The DOS clock is only accurate to the nearest 1/18th of a second, so the value used for the timer delay can vary just slightly for a particular computer from one calibration to another. Note that whether or not the program runs at correct real-time speed makes no difference to the accuracy of the experiment, as long as you use the program's interval timer for velocity measurements.

FILES

Your MILLIKAN OIL DROP EXPERIMENT original disk contains 13 files. They are described below:

MILLIKAN.EXE	This is the main program. It contains everything, including the main experiment and the menu system.
MONITOR.DAT	The file that holds the default graphics card should a non-CGA/Hercules MGA graphics card be found. See "Graphics" section above
MONITORC.DAT	See "Graphics" section above.
MONITORH.DAT	See "Graphics" section above.
DEFAULTS.DAT	This is a text file that holds the default values. Toggles are stored as either 1's(on) or 0's(off).
MILLIKAN.BAT	The startup batch file.
AUTOEXEC.BAT	Exact same file as MILLIKAN.BAT.
CGA.BGI	The CGA graphics driver provided by the makers of Turbo Pascal, Borland, Inc. This file may not be used for any other program.
HERC.BGI	The Hercules MGA graphics driver also provided by Borland.
PICCGA.PIC	The CGA main screen.
PICHERC.PIC	The Hercules MGA main screen.
LOGOCGA.PIC	The title screen for CGA.
LOGOHERC.PIC	The title screen for Hercules MGA.

CONSTANTS

The MILLIKAN OIL DROP EXPERIMENT comes with several constants that have been fixed. It is not possible to change these within the program, but it is often useful when analyzing data to be aware of the exact constants and the number of significant figures used. The following physical constants are used in the program:

Temperature of air	=	30.0°
Viscosity of air	=	1.81×10^{-5} N-sec/m^2
Density of air	=	1.29 m/kg^3
Elementary charge	=	-1.6×10^{-19} coulomb
Gravitational constant	=	9.80 m/s^2

MISCELLANEOUS

A very similar version of this program that runs on Apple II computers (64K) is also available from Vernier Software. All of the major program functions and commands are the same as they are on this version.

If you have any problems or questions about this program, please contact us. We encourage you to fill out and return the registration card included with the MILLIKAN OIL DROP EXPERIMENT disk so that we can keep you informed of future upgrades. We publish a periodic newsletter for registered customers containing program improvements and new ideas for using this and other Vernier Software programs.

Vernier Software
8565 S.W. Beaverton-Hillsdale Hwy.
Portland, Oregon 97225-2429
(503) 297-5317

Appendix A
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Historical Information:

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Millikan Experiment, PSSC film, 30 min., B&W, 1959, MLA.

Millikan's Oil Drop Experiment, 6 min., B&W, silent, Macmillan Films.

Videotape:

Millikan's Oil-Drop Experiment, 15 min., color, Films for the Humanities & Sciences, Inc.

Appendix

Other Vernier Software Products

Vernier Software has been publishing science software since 1981. We have software and hardware for Apple II, IBM-compatible, and Macintosh computers. The following is a list of products available. If you would like to receive a complete catalog of Vernier Software products, write or call:

Vernier Software
8565 S.W. Beaverton-Hillsdale Hwy.
Portland, Oregon 97225-2429
(503) 297-5317
FAX (503) 297-1760
Internet: dvernier@vernier.com

Books on Computer Interfacing

How to Build a Better Mousetrap and 13 Other Science Projects Using the Apple® II: This 227-page book includes 14 science projects for students (or teachers) who want to learn about laboratory interfacing via the Apple II+/IIe/IIGS game port. Projects include: temperature probe, pH meter, strain gage, stepper motor, and photogate timer. $24.95

Chaos in the Laboratory and Thirteen Other Science Projects for the Apple® II: This is the sequel to *How to Build a Better Mousetrap*. It includes 14 new science projects for the Apple II+/IIe/IIGS. Projects include: A-to-D converter, barometer, light meter, magnetic field sensor, and quiz show buzzer system. $25.95

Chemistry with Computers by Dan D. Holmquist and Donald L. Volz. A collection of experiments and demonstration ideas using Vernier Software programs and probes. Both an Apple II/IBM and a Macintosh version are available. The student lab sheets are provided on disks so that teachers can edit and print them. $24.95 for the Apple II/IBM version; $35.00 for the Macintosh version.

Physical Science with Computers by Donald L. Volz and Sandy Sapatka. A collection of forty physical science experiments using Vernier Software programs and probes. Either Apple II or MS-DOS versions of our products can be used. The student lab sheets are provided on disks so that teachers can edit and print them. $35.00

Exploring Science with a Computer by John N Fox. A collection of experiment and demonstration ideas using our MPLI hardware and software. The ideas come from a series of summer workshops for high school teachers. Physics, chemistry and biology topics are included. $30.00. Also available is a videotape series called *Kids and Computers*. Contact Vernier Software for details.

Software and Hardware for IBM-Compatible Computers

MultiPurpose Lab Interface Package: Turns your computer into a three channel data recorder and storage oscilloscope. The IBM MPLI hardware-software package consists of a 12-bit, 3-input A/D board, an interface box, and program. $290.00 with the MS-DOS version of MPLI Program; $310 with the new MPLI for Windows program.

Motion Plotter: Allows measurements of motion and force to be studied using the IBM MPLI Package (MS-DOS Version), an Ultrasonic Motion Detector, and/or a force transducer. $39.95 ($90 for Motion Detector and $99 for Student Force Sensor).

Serial Box Interface: Our Serial Box Interface is the low-cost way to take data with your IBM. Plug the Serial Box Interface into the serial port of the IBM, connect your sensor(s), and graph temperature, pH, pressure, heart rate, light intensity, voltage, and more. Use with any of the standard Vernier Software sensors with 5-pin DIN connectors. May be powered by a battery pack mounted inside the box (sold separately). Serial Box Interface is $104.00. Two programs are available for use with the Serial Box: Data Logger or Serial Box Plotter. Either is $30.00.

Universal Lab Interface: The Universal Lab Interface (for IBM computers) allows a wide variety of sensors and probes to be interfaced to IBM-compatible computers. Available sensors include ultrasonic motion detectors, force sensors, radiation monitors, pH probes, pressure sensors, light sensors, magnetic field sensors, and microphones. ULI Package includes User's Manual, cable to IBM, power supply, Data Logger software, and Voltage Measurement Leads, $350.

Tufts University has now converted five of the popular Macintosh ULI programs to MS-DOS. The IBM versions of these four programs:

- **Data Logger:** For use with all Vernier Software analog sensors. $30
- **Sound:** For use with the Microphone/Amplifier. $30
- **Motion:** For use with the Ultrasonic Motion Detector and Force Probe. $30
- **Event Counter:** For use with the Radiation Monitor $30
- **Temperature:** For use with Vernier Software temperature probes. $30

Voltage Plotter: Allows the IBM PC or IBM-compatible to be used to monitor, display, graph, and print data collected using the Voltage Input Unit game-port interface with Vernier Software probes and sensors. $39.95

Temperature Plotter: Provides an accurate, inexpensive method of monitoring temperatures with your IBM. Requires a temperature probe system which connects to an IBM game port. $39.95

Precision Timer: Turns the IBM PC or the IBM-compatible computer into a laboratory timer. Requires a photogate system ($60 for a 4-Photogate Parts Kit) which connects to an IBM game port. $39.95

Frequency Meter: Allows the IBM to be used as a general purpose audio-range frequency meter. A Microphone/Amplifier ($30.00), which connects to an IBM game port, is used to deliver the signal to the game port. $39.95

Graphical Analysis: Plots graphs of experimental data and allows students to examine the data in a number of ways. $29.95

Millikan Oil Drop Experiment: A simulation of one of the classic physics experiments. $29.95

Mass Plotter: Reads Ohaus balances that have built-in digital ports. It will display the results in large digits, graph mass vs. time or do histograms. $39.95, cable to Ohaus balance $25.00.

Spectrophotometer Program: Collects, displays and graphs data from a Spectronic® 20D or Spectronic® 20. Great for plotting absorbance vs. wavelength, or doing Beer's law graphs and determining the concentration of an unknown. $39.95, cable to serial port or interface box $25.00.

Orbit: Simulates the motion of an earth satellite. $29.95

Charged Particles: Simulates the motion of various charged particles in magnetic and electric fields. $29.95

Projectiles: Allows students to experiment with projectile motion, including the effects of air resistance and wind. $29.95

Software and Hardware for the Apple II

MultiPurpose Lab Interface Package: Turns your computer into a three channel data recorder and storage oscilloscope. Package includes program, analog-to-digital board, and connector box. $290.00

GS Scope: Turns your Apple IIGS into a three channel storage oscilloscope. This program takes full advantage of the IIGS speed, graphics, and mouse. Requires our Apple II MPLI package. $39.95

Temperature Plotter III: Provides an accurate, inexpensive method of monitoring temperatures with your Apple II. Requires a temperature probe system ($25 to $70) which connects to the game port. $39.95

Voltage Plotter III: Allows the Apple II to be used as a general purpose voltmeter or chart recorder. Requires a Voltage Input Unit ($45) which connects to the game port. $39.95

Graphical Analysis III: Plots graphs of experimental data and allows students to examine the data in a number of ways. $29.95

Precision Timer III: Turns the Apple II into a laboratory timer. Requires a photogate system ($40 for a 3-Photogate Parts Kit) which connects to the game port. $39.95

Frequency Meter III: Allows the Apple II to be used as a general purpose audio-range frequency meter in the laboratory. Requires a microphone/amplifier ($30) which connects to the game port. $39.95

Mass Plotter: Reads Ohaus balances that have built-in digital ports. It will display the results in large digits, graph mass vs. time or do histograms. $39.95, cable to Ohaus balance $25.

Millikan Oil Drop Experiment: A simulation of one of the classic physics experiments. $29.95

Vector Addition III: Graphically demonstrates the head-to-tail addition of vectors. $29.95

Orbit II: Simulates the motion of an earth satellite. $24.95

Charged Particles II: Simulates the motion of various charged particles in magnetic and electric fields. $24.95

Projectiles II: Allows students to experiment with projectile motion, including the effects of air resistance and wind. $24.95

Wave Addition III: Graphically demonstrates the superposition of waves. $29.95

Products for the Macintosh

Universal Lab Interface: The Universal Lab Interface (ULI) allows a wide variety of sensors and probes to be interfaced to the Macintosh. Available sensors include ultrasonic motion detectors, force sensors, radiation detectors, photogates, pH probes, thermocouples, pressure sensors, microphone, and light sensors. The ULI is really a computer that controls and reads values from the sensors and communicates with the Macintosh using the modem port. $350.00

The following programs are used with the ULI. Data Logger and ULI Timer are included with the ULI Package.

> **Data Logger:** For use with all Vernier Software analog sensors.
> **ULI Timer:** For use with photogates or PASCO Smart Pulleys
> **Sound:** For use with the Microphone/Amplifier. $25
> **Motion:** For use with the Ultrasonic Motion Detector and Force Probe. $25
> **Event Counter:** For use with the Radiation Monitor $25
> **Temperature:** For use with Vernier Software temperature probes. $25

Serial Box Interface: Our Serial Box Interface is the low-cost way to take data with your Macintosh! Plug the Serial Box Interface into the modem port of the Mac, connect your sensor(s), and graph temperature, pH, pressure, heart rate, light intensity, voltage, and more. Use with any of the standard Vernier Software sensors with 5-pin DIN connectors. May be powered by a battery pack mounted inside the box (sold separately). Serial Box Interface is $99.00 Data Logger software for use with the Serial Box Interface $30.00.

Graphical Analysis: This program is designed for use in high school and college science classes. It plots well-labeled graphs of experimental data entered by students, following accepted scientific graphing conventions. After data is entered, modified versions of the graph (e.g., with the x-axis data squared before plotting) may be quickly drawn to help in the search for the relationship between the variables. Semi-log and log-log graphs can be made. The linear regression "best fit" line can be included on the graph. Data files collected using Vernier Software data acquisition programs for Apple II or IBM can be imported (after use of Apple File Exchange) and then graphed. $49.95

Mass Plotter: A HyperCard stack that reads Ohaus balances which have built-in digital ports. It will display the results in large digits, graph mass vs. time or do histograms. $39.95, cable to Ohaus balance $25.00.

Spectrophotometer Program: Collects, displays and graphs data from a Spectronic® 20D. Great for plotting absorbance vs. wavelength, or doing Beer's law graphs and determining the concentration of an unknown. $39.95, cable to Macintosh modem port $25.00.

Calculator-Based Laboratory (CBL)

The Calculator-Based Laboratory System (CBL) from Texas Instruments allows students to take data directly with their TI-82 or TI-85 graphing calculator. The CBL has six channels: three analog inputs, a sonic motion detector input, digital input, and a digital output. The CBL can be operated with batteries and is very portable, so it is perfect for remote data collection. Adapters are available to allow almost all of our sensors to be used with the CBL. The CBL system includes temperature, light and voltage probes. $185

Data collected using the CBL can be transferred to a Macintosh or IBM-compatible computer by using the TI-GRAPH LINK software and cable. $55.00