ScienceSchoolHouse™
Discover! Science Library

Laboratory Physics

for the
3D Virtual Laboratory

Part A: Mechanics

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Introduction to the 3D Virtual Laboratory

Summary Introduction

The labs in Version 2 of the ***ScienceSchoolHouse 3D Virtual Lab*** developed by EOA Scientific Systems cover several key experiments in the foundations of physics and physical science at a level that is appropriate for both middle school and high school students. We recommend that you use this Lab with the interactive multimedia tutorials, exercises and videos found in the ***Discover! Science Physical Science: Basic Concepts*** CD and/or Units of our Online Library. See below for further information.

This version of the Lab allows students and teachers to perform realistic experiments that encourage inquiry and constructive discovery of the following fundamental concepts of physical science, specifically mechanics and dynamics:

- Weight
- Mass
- Volume
- Density
- Distance
- Velocity
- Acceleration
- Buoyancy
- Gravity

Version 2.0 compared with Version 1.0

Version 2.0 has many improvements over the first version:

1. There are extensive Getting Started exercises that slowly guide you in learning how to use the many features of the Lab. We suggest that you follow these instructions, even if you are a hot-shot game player. While the Lab plays in a similar fashion to a computer game, we do many things that games do not generally do.
2. The inside Lab Bench and the Lab room itself are larger, so you have more room to move around. You could perform the new cannon trajectory experiment on the floor of the Lab, although you will find going outside with it much better.
3. You can go outside to perform the cannon trajectory experiments--at least on Earth. In a very soon to be released Version 2.1 you will also be able to perform these experiments on the moon, Mars and Jupiter. You can already perform the other experiments in these other global settings, since you don't have to leave the Lab.
4. The single experiment of the first version has been broken up into three separate experiments.

5. There is an extensive help guide on how to use the Lab, instructions in performing the experiments, and the physics of the experiments. For middle school, some of the physics discussion may be advanced (and unless you are proficient in algebra, you may not be able to follow the math), but teachers, advanced middle school students and high school physics students will benefit.
6. The analysis section has been significantly expanded, including printing capability, saving and loading of data files, graphing and export of data to files that can be imported into a spreadsheet such as Microsoft Excel. Once in Excel, students can perform many more analysis and graphing functions.
7. You can view the lab in full-screen, and you can also hide the interface (the menus, tabs, instructions and other functions) to make the Lab scene itself fill the entire screen. This is quite cool, and more similar to a computer game.

Make sure you do the Getting Started Exercises, and refer to the Help Guide to find out all about all the features of the Lab. It would be a shame for you to go through all the experiments without taking advantage of all that you can do with the Lab.

Please feel free to provide feedback to us to improve our product. Our goal is to provide the best educational experience possible.

Format of this Manual

For each of the experiments, we include here

(1) the Lab instructions (also found elsewhere in the Help guide and in the Lab itself as well).
(2) These are followed by a section that discusses the physics of the experiment and more details about the data analysis of measurements. Included is information about precision and accuracy, and many formulas that explain the physics. The formulas for the first three labs require a modest amount of algebraic mathematical ability to use symbols for variables and to manipulate simple equations. The trajectory experiment uses some trigonometry, much more involved algebra, and hints at calculus without really using it.

A large portion of the physics explanations relate to measurements and data analysis. These are fundamental to any physical science appreciation. The idea is to get students involved in taking measurements to solve problems. Our instructions suggest that you get students to prepare hypotheses before taking measurements, and we strongly suggest that you weave this into your lesson process.

Experiment 1: Weight, Mass, Volume, Density

Lab Instructions

Objectives
To weigh different samples in different gravity conditions to learn about weight, mass, volume and density. To work with measurements, recording data, making tables and comparing data. Make tables and graphs. Start a Lab Record Book, export data and import it into a spreadsheet. You will be weighing balls of different materials and sizes on different planets and on our moon.

Resources
Instruments: digital scale
Samples: balls
Global settings: all
Tools: none
Local settings: one

Hypothesis
You will weigh different balls of different sizes on different planets and the moon.

A hypothesis includes two things: (1) the numbers or answers to the question; and (2) your best explanation why those numbers or answers are correct.

Note that in Version 2 of the Lab, the sizes for the samples are 8, 4 and 2 inches. For metric, you will need to convert to centimeters by multiplying by 2.54. We kept the sizes the same so you can compare metric and Imperial unit measurements.

Formulate a hypothesis to give relative weights to the following samples under the shown conditions. Assign special units, so that the 8" granite ball on Earth weighs1000 of your special units. Make your best guess for the weights of the other samples and/or global settings. Explain your answers.

8" diameter granite ball on Earth
4" diameter granite ball on Earth
2" diameter granite ball on Earth
8" diameter wooden ball on Earth
8" diameter plastic balloon on Earth
8" diameter granite ball on the Moon
8" diameter granite ball on Jupiter
8" diameter granite ball on the space station
8" diameter granite ball on Mars

Detailed Instructions

Select the digital scale from the Instruments tab, put it aside on the bench, and then select a sample. Open the Property Inspector to see the composition and size of the sample. Make note of it on a piece of paper.

Select Earth on the Global Setting tab.

Put the sample on the scale. Note the weight shown in the Data window, and record the weight by selecting the Record button.

Use the Property Inspector to change the sample composition and/or size, and weigh and record your data for each new sample. For these instructions, we use only some of the samples, but you may use other variations and change the questions that we ask according to your own measurements.

Make sure you Record the data for each measurement before you make any further measurements.

Change the Global Setting to the moon, and weigh the 8” granite sample. Record your data. Then go to Jupiter and Mars and repeat.

Go to the Analysis section by selecting Experiment and Analyze Data from the Menu.

Analysis
Order the table of data by different parameters, such as sample size, composition and global setting. Print out each table. If you do not wish to print the tables or you do not have access to a printer, you can save your data for further analysis.

Now you will formulate hypotheses to answer questions about the ratios of different weights.

Before you calculate, what you think the ratios of the weights of the following samples are:

The 8” diameter granite to that of the 4” diameter granite, both on Earth?
The 8” diameter granite to that of the 2” diameter granite, both on Earth?
The 8” diameter wood to the 4” diameter wood, both on Earth?
The 8” diameter granite on Earth to the 8” diameter granite on the Moon?
The 8” diameter granite on Earth to the 8” diameter granite on the Jupiter?
The 8” diameter granite on Earth to the 8” diameter granite on Mars?

What is the significance of each of these ratios? Can you use the answers to predict other ratios? After you have thought about it, and tried to figure out what the answer should be, then use the data you have collected to compute these answers.

Hint: compute the ratio of the radii of the balls and take the cube of that ratio (the ratio times itself and then times itself again).

Now compute the ratio of the weight to the cube of the radii for different sizes, locations and materials. What do you find? Do you know what this means?

What would it mean to make more than one change in the data for the ratios? For example, what would it mean to divide the weight of the 8” granite on Earth by the 4” granite on the moon?

What is mass, and how is it different from weight?
How do your weight measurements relate to the mass of your samples?

Make a table (using paper and pencil) of the different ratios that we suggested and others that you compute on your own. Write a report with your best answers to the questions and your best understandings of the meanings of your measurements.

Start a record book of your experiments. In it, keep the tables and graphs of all your data and the notes and analysis that you did. You will need some of the data that you collected earlier for the later experiments.

Physics of the Weight, Mass, Volume, Density *Lab*

Introduction

Reference:

Discover! Physical Science: Basic Concepts

Chapter 1: Basic Concepts, Lessons 1-14

Chapter 3: Force and Motion, Lessons 15-17

Appendix B: SI Units (International System of Units)

Make sure that you go through the chapter in the ***ScienceSchoolHouse*** **Discover!** CD or online units referenced above. Those chapters will provide you with the basics of the concepts of physical science. Especially relevant to this Lab are Discover! Physical Science: Basic Concepts Chapter 1, Lessons 12-14 on volume, mass, weight and density.

Be sure to read Appendix B, especially to learn about units, accuracy, and precision.

This Lab involves an apparently simple experiment. We take samples of different compositions and weigh them under different conditions. This discussion addresses the following concepts:

Mass
Weight and gravity
Volume
Density

Mass and Weight

"Any substance has mass." This statement is circular. The definition of mass is substance; the definition of substance is mass. To say that "any substance has mass" therefore does not add anything, and it certainly doesn't give a definition of mass. So, what is mass? We can say that mass is the "solid stuff", the "matter" of our world. Any solid object, such as a pen, computer, book, your body, air or water has mass.

What is the difference between mass and weight? Any mass that is within a gravity field will exert a force in the direction of the force of gravity. Weight is a force. Mass is matter. This difference is important to understand. When the only change in an event is that the force of gravity changes, then an object's weight changes, but its mass does not. That is why we include taking the weight measurement lab to other planets. The weight of our 8" (20.32 cm) wood ball is more on the surface of Jupiter than it is on the surface of Earth because the acceleration of gravity is more on the surface of Jupiter, even though the mass of the object is the same.

If we take the experiment to the space station, the ball has no weight. However, its matter has not changed, so its mass does not change.

Mathematically, we say that:

Weight = mass *multiplied times* the acceleration of gravity
or
W = mg

Where
W = weight
m = mass
g = the acceleration of gravity

If we want to put numbers to these, we have to choose our units. **The use of units for mass and weight is probably the most confusing of all units in all of physics.**

SI Units

Science uses *SI Units (International System of Units)*. Our Lab offers a choice of SI (or metric) units and American units (oddly called "Imperial"). Imperial units are our familiar miles, yards, feet and inches; tons, pounds and ounces. SI units are kilometers, meters and centimeters; metric tons, kilograms, and grams. In SI units, distance, area and volume use meters and multiples of meters, while mass uses grams and multiples of grams (a metric ton is 1000 kilograms).

There are *approximately* (more exact figures in parentheses):

1.6 kilometers per mile	(1.621)
0.6 miles per kilometer	(0.609)
2.54 centimeters per inch	(2.54)
3.3 feet per meter	(3.281)
1.1 yards per meter	(1.094)
39 inches per meter	(39.37)
454 grams per pound	(453.6)
2.2 pounds per kilogram	(2.205)

If you memorize the approximate values, it will help you communicate scientifically.

Kilo means 1,000, so kilogram is 1,000 grams and a kilometer is 1,000 meters.
Centi means 1/100, so there are 100 centimeters in a meter.

See Appendix B in the CD or Online Unit for more on these prefixes.

Weight, Mass and Acceleration Units

If we use kilograms for mass, meters for distance and seconds for time, then we are using the MKS version of the SI unit system (M for meters, K for kilograms, S for seconds).

If we use grams for mass, centimeters for distance and seconds for time, then we are using the CGS version of the SI unit system (C for centimeters, G for grams, S for seconds). Formally, the SI unit system refers to the MKS version, but the CGS system is still used. Clearly, the CGS is for measuring things that are much smaller than things we want to use the MKS system for, since there are 100 centimeters in a meter and 1,000 grams in a kilogram, the CGS system is 100,000 times smaller than the MKS system.

The unit for mass in MKS SI is the kilogram. However, when we put a mass on a MKS metric scale to weigh it, it will measure in kilograms, even though weight is a force, not a mass. The unit for weight and force in the MKS system is the *Newton* (N), but when we weigh heavy things on a metric scale, it is never shown in Newtons; it is shown in kilograms! If you weigh 120 pounds, then you would *weigh 110 divided by 2.2 = 50 kilograms.* We would never say that you weigh 50 Newtons. However, that is exactly what most textbooks show, and that is what scientists do. If you want to learn the precision of quantitative physics, you have to learn to talk and think like scientists.

Similarly, the unit for mass in the CGS SI system is the gram, but when we put a mass on a CGS metric scale it will show grams as the weight. The unit for weight and force in the CGS system is the *dyne*.

In the Imperial system, the unit for mass is the *poundal*, and the unit for weight and force is the *pound*.

A Newton as a weight is mass times the acceleration of gravity, so

1 N = 1 kg *multiplied times* 1 m/sec^2
Hence,

A Newton is a kilogram-meter-per-second-squared.
A dyne is a gram-centimeter-per-second-squared.
A pound is a poundal-foot-per-second-squared.

Why is it so confusing?

It is confusing because the systems grew up in history over time as we changed our understanding of the underlying physics. Mass units are the most confusing part of understanding mass, and if you can't understand mass then you will have a hard time understanding physics. So give this some thought.

It may help to understand that weight is a force—the force that gravity exerts on a mass. That's what we call the "force of gravity".

Weight in the Lab

In the Lab, we have reported that the 8" (20.32 cm) wooden ball on Earth weighs 3952 "grams". Actually this is 3952 dynes. We used grams as an abbreviation for *gram-weights*, which is the weight used when the mass is in CGS units, with grams as the unit of mass. We did this because no scale will show you the weight of something in dynes, and we wanted to be realistic.

The key point to realize is that scales on Earth that weigh objects do so with the convention that mass (on Earth) equals weight (on Earth). Hence, a one kilogram mass would show on a scale as weighing one kilogram. This is, of course, false, since we know that Weight on Earth = mass times the acceleration of gravity on Earth, and in the MKS units the acceleration of gravity is 9.8 m/sec^2 (see below for more). (Remember, mass never changes, no matter where you are!) Therefore, the weight of a 1 kg mass on Earth is 9.8 Newtons. However, we have a *convention* that a 1 kg mass on Earth weighs 1 kg-weight. We shorten the "kg-weight" (which means 9.8 Newtons) to kilograms.

Thoroughly confused yet? There is more.

Acceleration in the Lab

Acceleration is change in velocity over time.
Velocity is the change in distance over time.
Hence, acceleration is the change in distance for each time-squared, or time-per-time.

If the units of

distance are in meters (m),
velocity is in meters-per-second (m/sec), and
acceleration is in meters-per-second-per-second, or meters-per-second-squared (m/sec^2).

The acceleration of gravity on Earth in MKS units is 9.81 m/sec^2. That means that the velocity is changing 9.8044 meters-per second every second, or 9.81 m/sec^2.

In CGS units it is 980.44 cm/sec^2.

In Imperial it is 32 ft/sec^2 (more exactly, it is 31.49).

For more about acceleration, do the ***Distance, Velocity and Acceleration*** Lab. For now, all you need to know is the use of the acceleration of gravity in the calculation of weight, W = mg, to calculate the mass.

Mass in the Lab

When you measure the weight of the 8" (20.32 cm) wooden ball in the Lab, you get 3.9904 "kilograms" (which is 3990.4 'grams'). The first thing to recognize is that you are in the MKS unit system, and that "kilograms" is a mass unit, not a weight unit. Hence, what do we mean? We mean "kilogram-weight". By convention, a single "kilogram-weight" is really equal to 9.8044 Newtons. Hence, the weight is really 3.9904 x 9.8044 = 39.15 Newtons (rounded off).

So, here is our convention: the actual mass of our sample is 3.9904 **kilograms**, and the **weight** *ON EARTH* is 3.9904 **kilograms of weight**, which is really 39.15 Newtons.

W = mg
W = 3.9904 kg x 9.81 m/sec^2 = 39.15 Newtons

Now, what happens when we take the experiment to the moon, Mars and Jupiter? The acceleration of gravity in the global settings available in our Lab is:

On the moon: 1.68 m/sec^2
On Mars: 3.74 m/sec^2
On Earth: 9.81 m/sec^2
On Jupiter: 26.01 m/sec^2

When you weigh the 8" wooden ball on the Moon, you get 0.659 "kilograms", which is 659 "grams", but these are kilogram-weight and gram-weight, not mass.

How did we know that, since we didn't really go to the moon? We took the kilogram-weight of the ball on Earth, and multiplied by the ratio of the acceleration of gravity on the Moon divided by the acceleration of gravity on Earth:

$W_m = W_e \times (g_m / g_e) = 3.9904 \times (1.62 / 9.8044) = 0.659$

The big question now is what is the "actual" weight in Newtons that we calculate from this measurement? If we were on Earth the convention would be that the kilogram-weight is the same number as the kilogram-mass, and the actual-weight in Newtons is 9.81 times the kilogram-weight. But will that also work on the moon?

We know that the mass of our ball does not change just because we moved it. Mass is the same as the "amount of stuff", and we haven't changed that.

Here is our formula:

W = mg

For our 8" wooden ball, mass = 3.9904 kg.
On the Moon, g = 1.62 m/sec^2.
So the actual weight W = 3.9904 x 1.62 = 6.46 Newtons.

What is the ratio of the convention-weight, the kilogram-weight, to the actual weight?

R = 6.46/0.659 = 9.8044

OK, so now we know that if we have made a convention, a special definition, on Earth, that the convention stays with us. The convention is that the amount of "kilogram-weight" we have on a scale on Earth is the same as its kilogram-mass, and the actual weight in Newtons is 9.8044 times its kilogram-weight. We still use that convention even if we are on the moon, or anywhere else.

Acceleration of gravity on different planets

Once you have the mass, and weigh the samples on different planets and the moon, you can then calculate the acceleration of gravity on those different global settings. Since

$W_p = mg_p$, for any planet P

and you know the mass and measure the weight, it is a simple matter to measure the acceleration g_p for each different planet, p. Since the mass is the same, the acceleration of gravity on planet P can be calculated like this:

$W_{earth} = mg_{earth}$
$W_{moon} = mg_{moon}$

$W_{moon} \ / \ W_{earth} \ = \ mg_{moon} / mg_{earth}$

The masses cancel, and rearranging the terms gives:

$g_{moon} = g_{earth} \times W_{moon} / W_{earth}$

For the 8" (20.16 cm) diameter oak ball, we get

$$\begin{aligned} g_{moon} &= 980.44 \text{ cm/sec}^2 \text{ x } 68.23 \text{ gram-weight} / 399.04 \text{ gram-weight} \\ &= 980.44 \text{ cm/sec}^2 \text{ x } 0.171 \\ &= 167.66 \text{ cm/sec}^2 \\ &= 1.68 \text{ m/ sec}^2 \end{aligned}$$

and similarly for the other planets.

Volume and Density

Another way of looking at mass, and how it always stays the same even when you move a sample to a different global setting, is to realize that the density of what a solid sample is composed of is the same. Therefore, our wooden sample (which is actually oak) has a certain "density", which is its unit mass per unit volume. That density does not change. Oak has the same density wherever it is. For a given volume sample, say our 8" ball, the volume is always the same, and the mass of our ball is always the same, and the density is always the same, no matter where you are. (This will not work with liquids and gases, since their volumes change with different pressures around them.)

Once you gather the weights, and calculate the masses, of the samples, you will be able to calculate density.

Calculate the ratio of the masses of the 8" wooden ball and the 4" wooden ball. The mass of the 8" wooden ball is (rounding off) 4 grams, and the mass of the 4" wooden ball is 0.5 grams. The ratio is exactly 8. The ratio of the diameters of the two samples is 2. Eight is 2 x 2 x 2, which is the cube of 2, or 2 raised to the 3rd power, 2^3. Test this ratio with the 4" and the 2" wooden ball, and the granite balls of different sizes and the plastic (balloon) air-filled balls of different sizes. Convince yourself that the ratios of masses are always the cube of the ratio of the diameters.

What you have determined is that the volume of a spherical sample is dependent on the cube of its diameter. The formula is usually given as a function of the radius, however, which is one-half of the diameter:

V = 4/3 *times* PI *times* R^3, or just V = (4/3) PI R^3

Where R = radius of a perfectly spherical sample, and
PI = the ratio of the diameter of a circle to its circumference.
PI = approximately 3.14157

But we could just as easily put it in terms of the diameter, since R = D/2:

V = (4/3) *times* PI *times* $(D/2)^3$, or just V = (4/3) PI (D^3/8) = (1/6) PI D^3

They are both correct.

PI is also shown in its Greek letter form, as π.

Hence, $V = 4/3\ \pi\ R^3 = (1/6)\ \pi\ D^3$

Density has two meanings, corresponding to mass and weight. The mass-density is the mass per unit volume = m/V. This is the scientific definition of density.

Density is usually given in CGS units, so we should use grams for mass, and cubic centimeters (cc) for volume. Hence, for our 8” (20.32 cm) wooden ball, with mass 3990.4 grams, we must compute the volume to get the density. The radius is 10.16 cm. The volume is V = 1.33 x 3.14 x $(10.16)^3$ = 4391 cubic centimeters (cc).

The mass density, therefore = m/V = 3990.4 grams / 4391 cc = 0.909 gm/cc.

As you should know, the density of water is defined is 1 gram per cubic centimeter. This is actually a definition of gram. Therefore, our oak ball is slightly less dense than water. This means that it will float. We have found that wood floats! Amazing!

To demonstrate again how “unscientific” our weight and mass conventions are, we can use the known mass-density of water, 1 g/cc. A liter is defined as 1,000 cubic centimeters. A liter is slightly more (1.07) than a quart. A liter of water should have a mass of 1,000 grams. If you weigh a liter of water, you will get one kilogram, which is 1,000 grams, but this is its weight, not its mass. (It will also be 2.2 pounds.) So, again, we see how this convention works: to get the actual weight in Newtons, we multiply the mass, which equals the kilogram-weight (one kg) by 9.81, and get 9.81 Newtons as the actual weight.

Experiment 2: Gravity, Velocity and Acceleration in Air

Lab Instructions

Objectives
To learn about the force of gravity, and about velocity and acceleration. To find out if all samples fall at the same rate of speed under different conditions. You will be dropping different kinds and sizes of balls on different planets and our moon.

Resources
Instruments: digital scale, laser lab stand
Samples: balls
Global settings: all
Tools: drop stage
Local setting: one

Instructions
Perform the Weight, Volume and Density experiments before doing this one. You may choose the same samples for this experiment. If you choose different ones, make sure you find the weight of the sample in the same Global Setting as you perform this experiment.

Bring a sample ball onto the bench, and then the Laser Lab Stand. Bring in the digital scale if you need it to weigh samples. Put the Drop Stage on the Lab Stand. (Hint: touch the drop stage anywhere on the Lab Stand.) The default height of the drop stage is 3' in Imperial and 1 meter in metric units. The Lab Stand properties can be changed to different heights with the Property Inspector.

Weigh a sample, record the measurement (or get the data from your previous experiment, though it is easier to just repeat it here), and then put the ball on the drop stage. This will require that you know well how to use the navigation controls for the Lab. Review the Getting Started experiments if you need to learn the fine motor control of navigating with samples well enough to get the ball on the drop stage.

Once on the drop stage, drop the ball with the button marked "Release". Note the time in the Data window and Record that measurement. This is the total time to drop that distance. Change the Global Setting to the Moon and repeat the measurement.

Before you repeat the experiment, write down how you think things will change with different size and compositions. Will a rock fall faster than wood? How about the balloon/plastic ball? Should they all fall at the same rate? Give it some thought before you test your thoughts.

Now repeat the experiment with different balls and on different planets and the moon for different gravity conditions. Make sure you do the experiment with the 8" granite rock ball and the 8" plastic ball, and compare these. Also test other sizes and the wood ball.

Go to the Analysis section by selecting Experiment and Analyze Data from the Menu.

Analysis

To see the kind of data you are collecting, select Analyze Data from the Experiment menu. Select Make Table to show the total fall times. Then select Incremental Fall Time. Note that times are given in this table for each small distance that the ball fell until it reached the bottom of the stand.

Now select Graph Data, and select the two data sets that you have collected. Graph the distance, then the velocity, then the acceleration. Note the differences. This is the kind of data you are collecting. Now go back and collect more data for different ball sizes and compositions, and different Global Settings. Then come back to the Analysis section. Make different tables, print them, and make more graphs of different data sets, compare them, and print them. Make sure you include the plastic "balloon" sample.

What is velocity?
What is acceleration?
What is the meaning of the acceleration results?
Why is the acceleration different on different Global Settings?
What is unique in the data about the plastic balloon? Why is it different? How would you test your answers?

Physics and Data Analysis of the Gravity, Velocity and Acceleration in Air *Lab*

Introduction

Reference:
Discover! Physical Science: Basic Concepts
Chapter 1: Basic Concepts, Lessons 1-14, esp. the exercise in Lesson 13
Chapter 3: Force and Motion, Lessons 1-5 and Lesson 22
Appendix B: SI Units (International System of Units)
Discover! Astronomy: Astronomy and the Universe
Chapters 1-4, especially Chapter 2, Lesson 4 Exercise

In the previous Lab, *Weight, Mass, Volume and Density*, you learned a little about gravity. In this lab you will learn more about gravity and the relationships between distance, velocity and acceleration.

When you open the *drop stage* of the *lab stand* on Earth, the ball falls. That is because the mass of Earth is attracting the mass of the ball. The direction of attraction is towards the center of Earth, and that direction we call "down", by convention. Its opposite, we call "up".

Actually, as you can learn from the references listed above, and especially from the exercise in the Astronomy unit, any mass attracts any other mass in the entire universe. So the sample ball is also attracting the Earth and causing it to move! But it moves so little that you do not notice it.

Now let's learn about distance, velocity and acceleration. In the process we will learn about measurement accuracy and precision, and statistical data analysis.

The *Discover! Physical Science Basic Concepts* and Appendix B Reference materials will help. Please review them.

Data analysis: accuracy and precision

Teachers: This data analysis section has several activities for students that are not found in the Lab itself.

The ball drops a certain distance, say 1 meter. Our lab stand has a few different height levels. One is 36", which is about 91 cm. Our lab stand also has a built-in laser that marks the ball's passage from the drop stage to the platform of the lab stand. It takes a measurement every tenth of a second. Here is a sample of the first data points in a data set that might be collected, where the "distance" is from the drop stage downwards. The time measurement is collected every centimeter down.

Let's start with the 8" oak ball on Earth.

Data Point	Time (sec)	Distance (cm)
1	0	0
2	0.01	0.049
3	0.02	0.196
4	0.03	0.441
5	0.04	0.784
6	0.05	1.224
7	0.06	1.763
8	0.07	2.400
10	0.08	3.107

We also offer the option to present a table of velocity and acceleration data also, but these are calculated, and you should perform the calculations yourself on some of the data. We will go over that formula here.

Velocity = change in distance *divided by* change in time = change v / change t

Look at the first two data points:

Data point 1:
Time = 0 sec
Distance = 0 cm

Data point 2:
Time = 0.01 sec
Distance = 0.049 cm

The change is calculated (by convention) as the *later point minus the former point*.

Velocity = (Distance for data point 2 – Distance for data point 1)
divided by
(Time for data point 2 – Time for data point 1)

This is summarized with subscripts or parentheses.

With parentheses:

$$v(2,1) = \frac{d(2) - d(1)}{t(2) - t(1)}$$

Where
v = velocity
d = distance
t = time

With subscripts:

$$v_{2,1} = \frac{d_2 - d_1}{t_2 - t_1}$$

> Note: Mathematics is all just shorthand for long sentences! There is no mystery. To master math (the language of science) all you need to do is master the shorthand language.

For our two data points,

$$v_{2,1} = \frac{0.049\ \text{cm} - 0\ \text{cm}}{0.01\ \text{sec} - 0\ \text{sec}}$$

$$v_{2,1} = \frac{0.049}{0.01}\frac{\text{cm}}{\text{sec}} = 4.9\ \text{cm/sec}$$

The average velocity between those two points is 4.9 cm/sec.

Note what we did with the units. When you subtract 1 cm from 2 cm you get 1 cm. **You can't forget the units!**

Now do the same thing for the next data point:

$$v_{3,2} = \frac{0.196\ \text{cm} - 0.049\ \text{cm}}{0.02\ \text{sec} - 0.01\ \text{sec}}$$

$$v_{3,2} = \frac{0.147}{0.01}\frac{\text{cm}}{\text{sec}} = 14.7\ \text{cm/sec}$$

Note that the velocity increases every centimeter. The velocity for the first 0.01 second time interval is 4.9 cm/sec, and for the next 0.01 second time interval it is 14.5 cm/sec.

Now we ask, what is the change in velocity? The change in velocity is called the acceleration. We do that calculation the same way. We use "a" as the acceleration, but we must now take the differences in the velocities, and span them over 3 data points:

$$a_{3,2} = \frac{v_{3,2} - v_{2,1}}{t_{3,2} - t_{2,1}}$$

$$a_{3,2} = \frac{14.7 - 4.9}{0.02 - 0.01}\ \frac{(\text{cm/sec})}{\text{sec}} = 980\ \text{cm/sec/sec} = 980\ \text{cm/sec}^2$$

Now do it for the next data point, #3:

$$v_{4,3} = \frac{0.441\text{ cm} - 0.196\text{ cm}}{0.02\text{ sec} - 0.01\text{ sec}}$$

$$v_{4,3} = \frac{0.245\text{ cm}}{0.01\text{ sec}} = 24.5\text{ cm/sec}$$

$$a_{4,3} = \frac{24.5 - 14.7}{0.02 - 0.01} \frac{(\text{cm/sec})}{\text{sec}} = 980\text{ cm/sec/sec} = 980\text{ cm/sec}^2$$

This exercise gives several lessons in real physics and real measurements.

Round-off Errors

Note first that the number we get for acceleration is 980, while if you peeked at the acceleration table in the Lab you saw 979.02. Why are they different? 980 is not a good round-off for 979.02; that would be 979. But if you look closely at the distance and time numbers, you will see that the best precision we can get is in tens. The distance has 3 decimals of precision, and we divide by two decimals (0.01) of time to get velocity, so the velocity has only 1 decimal of precision. Then, we divide again by the two decimals of time to get acceleration, so the precision is moved over two more places to the tens. As you will see, some of the numbers we get are 970, not 980.

Look at the velocity for the next two points, and the acceleration from those:

$v_{5,4} = 34.3$ cm/sec
$v_{6,5} = 44.0$ cm/sec
$a_{6,5} = 970$ cm/sec^2

There are two things happening: The largest difference is due to **measurement error** from the level of precision that we are using for our display. **This is a very important lesson for understanding real physics experiments.** Make sure you read the Appendix B Lessons 12 -17 in the **Discover! *Physical Science: Basic Concepts*** CD or Online Unit.

Again, note that our distance measurements were to a precision of 3 decimal points of centimeters. That is *thousandths* of a centimeter, which is 10 micrometers, which is pretty good precision. However, since our time interval is in *hundredths* of seconds, and we divide distance by time, we get less precision in the velocity. The velocity now has a precision of only *tenths* of a centimeter-per-second. When we divide again by the time interval to get acceleration, we get a precision of only *tens* of cm/sec^2.

But there is more to get from this data. We can now take the average of our many accelerations to get the more precise value.

In this experiment, the ball dropped from 36", which is 91 cm, and took a total time of 0.4339 seconds to fall. That is the number you recorded when you took the measurement.

When we have the full list of accelerations for this experiment, from time zero to time 0.43, we get 42 acceleration data points. The range of all of them is from 970 to 990. The **average** is the sum of these divided by the number of them.

Average = sum of the numbers / number of numbers.

Our average of the 42 accelerations is 979.048 cm/sec^2.

However, we know that the acceleration of gravity on the surface of Earth is about 9.8 meters/sec^2. We use a more exact figure, and converted to CGS units, which is 980.44 cm/sec^2. The difference is almost 1.4 cm/sec^2. It doesn't seem like a lot, but if you were calculating the acceleration of a flight to Mars, you may end up on the sun instead!

Is this a measurement error? That could be. But there is another possibility.

Here is the first set of data points as calculated for velocity and acceleration with the better precision of the Lab, beyond what is displayed in the tables. These were obtained from the data analysis section by exporting the separate distance, velocity and acceleration data tables to Excel, and then merging them into one table.

time	distance	velocity	acceleration
-	0	0	0
0.01	0.049	4.90	0
0.02	0.196	14.69	979.02
0.03	0.441	24.48	979.02
0.04	0.783	34.27	979.02
0.05	1.224	44.06	979.02
0.06	1.762	53.85	979.02
0.07	2.399	63.64	979.02
0.08	3.133	73.43	979.02
0.09	3.965	83.22	979.02
0.10	4.895	93.01	979.02

So our manual calculation of the average of our acceleration data is different from the data shown on the Lab tables. Part of this is data error, but if that's all there is, both should be closer to 980.44? Why aren't they?

The reason is buoyancy.

Buoyancy

The reason we have three different samples for you to drop, and different sizes, and also the reason we have the next experiment (you put the lab stand and samples under a bell jar which functions as a vacuum chamber) is so that you can drop the samples in a vacuum. We know full well that feathers do not drop as fast as rocks. The reason is buoyancy, which is the same reason that our oak ball floats on water.

When you have a sample with a density that is significantly different from its surroundings, there is a buoyancy force pushing up. This buoyancy force essentially reduces the gravity force pulling down. For a fluid as dense as water, and a sample that is far less dense than water, such as oak, the buoyancy force is even more than the gravity force. Similarly, a helium balloon that is less dense than air floats up to the altitude where its density matches the density of the air.

The density of air is 0.0013 gm/cm^3 (which is 1.3 gm/liter) and the density of our oak is 0.9 gm/cm^3 . The ratio is 0.00144, or 1.44 parts per thousand. So we would expect that the difference between the net forces of gravity and buoyancy and the expected force of gravity without buoyancy would be about 1.44 parts per thousand. Since our theoretical gravity acceleration is 980.44 cm/sec^2, that would be slightly more than 1 cm/sec^2 difference.

The formula is

Acceleration = acceleration due to gravity times (the difference between the densities of the sample and its surroundings divided by the density of the sample).

a = g * [(density of ball – density of air) / density of ball]

a = g * B, where everything in the [ ] brackets is the buoyancy factor, B; g is the acceleration of gravity; and a is the sample's final acceleration.

The density of the oak ball is 0.9 gm/cc.
The density of air is 0.0013 gm/cc.
Therefore, B = .998555, which, by the way, = 1 – 0.001444.
Note that B is a unit-less factor.

The new acceleration a = g * B = 981.44 * 0.99855 cm/sec^2 = 979.024 cm/sec^2.

This value is much closer to our 979.048 average. So our measurements showed some error in the data and we also discovered something new: buoyancy.

The buoyancy factor is small for the oak sample. However, when you use the plastic ball filled with air, which is like a balloon, the difference is much larger. The density of an 8" balloon filled with air is 0.0017 g/cc, which is much closer to the density of air (0.0013 g/cc). You would think that would be the case, since it is a balloon filled with air. The buoyancy factor is about 0.24, and the final acceleration is around 230 cm/sec^2.

As you know, a balloon falls much slower than a rock. Now confirm this with your own data analysis.

The granite sample, has a density 3 times that of oak, and the acceleration is much closer to 980.44 cm/sec^2.

We have ignored the drag of air pressure in this experiment. That is a much more complicated variation.

Experiment 3: Gravity, Velocity and Acceleration in a Vacuum

Lab Instructions

Objectives
To learn why objects fall at different rates of speed even in the same gravity conditions. You will drop different objects inside a relative vacuum and compare it with dropping in air.

Resources
Instruments: digital scale, laser light stand
Samples: balls
Global settings: all
Tools: drop stage, bell jar
Local settings: any one

Instructions
This experiment is a repeat of the previous one on Gravity, Velocity and Acceleration, but with a twist: you will drop balls in a vacuum! To do this, you will need to include the bell jar in your tool kit. The bell jar fits over the laser lab stand. Make sure that the ball is on the drop stage first, since you will not be able to get it with the bell jar covering it up.

You will follow the same basic procedure of weighing and dropping samples and recording your measurements, but this time you will evacuate the bell jar and let the objects fall in the relative vacuum that is produced.

The key difference is that you will want to select the heaviest sample and the lightest sample. These are the granite rock and the plastic "balloon". The plastic ball is just like a balloon, except that the "rubber" has been replaced by a thin plastic that will not expand further than the set diameter. Why do you think we did this? What will happen to a balloon in the bell jar when the air is evacuated?

Make sure that you have collected data in the previous experiment (Gravity, Velocity and Acceleration, without the bell jar) for the samples that you use here. If you haven't, then do that one again. You want to compare the same samples in the same gravity conditions and change only the air pressure. This is called holding all variables as constant except one. This gives you the capability to test how that one variable affects the previously measured data.

Go to the Analysis section by selecting Experiment and Analyze Data from the Menu.

Analysis
Analysis of this data is important in comparison to the analysis of data collected in the previous experiment (Gravity, Velocity and Acceleration). Print tables and graphs in the same way as you did for that experiment, and compare the results for the same size and

composition sample ball. What information can you conclude from this data? Look especially at a heavy sample (a granite ball) and the 8” plastic balloon. What happened and how do you explain it?

Physics and Mathematics of the Gravity, Velocity and Acceleration in a Vacuum *Lab*

The physics and data analysis for this experiment are exactly the same as for the previous experiment where samples were dropped in air. The data will show an average acceleration closer to 981 cm/sec^2. That is because in a vacuum the buoyancy factor B = 1, so the acceleration of the sample is the same as just gravity.

In this experiment you will find that a balloon falls as fast as a granite ball. Recall the lunar astronaut's dropping a feather and a hammer; they fell at the same rate, since the moon has no atmosphere.

Experiment 4: Trajectories: Force and Motion in a Gravity Field

Lab Instructions

Objectives
To find out about the paths (trajectories) of balls fired from a cannon. You will find the total time, highest height, and longest range for a given impulse. You will learn about momentum.

Resources
Instruments: digital scale, cannon
Samples: balls
Global setting: Earth
Tools: none
Local setting: Sports Field

Instructions
You may conduct this experiment inside the Laboratory, or outside. Outside may be more interesting. Check the Global Setting tab and make sure you are on Earth. Choose the Sports Field in the Local Setting tab.

To go outside, click on the Hand icon on the wall next to the door of the Lab. Then click in the scene outside, shown in the doorway. This will bring you to a football field. The Lab Ship is in one end zone, and next to the Lab Ship is the landing zone for your equipment. Feel free to explore.

Bring in the cannon and a sample ball. If you have not weighed that size and type of ball on Earth before, then bring in the scale and weigh the sample.

Put the ball in the cannon. Note that the 8” balls will not fit into the cannon, so only 4” and 2” diameter samples are available. Select the cannon and then click on the Property Inspector to set the angle of the cannon and the impulse.

Impulse is the same as momentum. Momentum is the mass times the velocity of an object. Impulse is therefore the mass of an object times the initial velocity. If your ball weighs one kilogram, and your impulse is 100, the ball will have an initial velocity of 100 meters-per-second. The impulse units are therefore kilogram-meters-per-second.

Put the cannon near one goal line, under one set of goal posts, pointing towards the other set of goal posts. Place the cannon so that the ball is in line with the end zone zero-yard marker.

Click the button on the cannon, and…Fire!

Record the total distance traveled in the horizontal direction. If the distance is longer than 300 yards or 100 meters, lower the impulse. Note that the granite ball of the same size as the wood ball is about 6 times heavier, so the initial velocity for the wood ball will be 6 times higher at the same impulse setting.

You have a few tasks (make sure you record the total distance each time):

a. Find out which angle gives the highest vertical distance (the maximum height) for the same impulse, size and type of ball. This is easy to find out.

b. Find out which angle gives you the longest horizontal distance (range) using the same impulse and the same size and type of sample.

c. Try to shoot just over and between the opposite goal posts.

(If you lose a ball, you can use the V, M and W keys to go get it, or just bring in another one.)

d. Find out which combinations result in the most distance.

e. Try to throw the ball back into the cannon. Is this realistic?

f. Make tables and graphs in the Analysis section.

Analysis
You should know the drill by now. Select different ways of ordering tables, make the tables, print them. Then make different graphs and print them. Put them in your Lab Book.

Compare your results for different times and distances (vertical and horizontal) for different impulses and balls. Draw some conclusions from your data about trajectories.

Don't forget to look at the shape of the curves. What are the shapes? If you can't figure it out, go back and do an experiment at a large impulse, using the small wood ball, at a high angle (not 90 degrees).

Physics of Trajectories: Force and Motion in a Gravity Field: Vectors

Introduction

Reference:
Discover! Physical Science: Basic Concepts
Chapter 1: Basic Concepts, Lessons 1-14, esp. the exercise in Lesson 13
Chapter 3: Force and Motion, Lessons 1-5 and 18-19
Appendix B: SI Units (International System of Units)

Note to teachers and students: This section uses algebra in the equations that demonstrate the motions of our cannonballs. It also hints at how to use calculus without really using it.

The cannon imparts a given *impulse* to the samples. This impulse is a momentum. Momentum is mass times velocity. Hence, for a given mass—such as a 10.16 cm diameter (4") oak ball—when you increase the impulse you will be increasing the initial velocity.

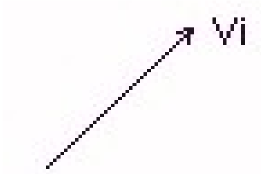
Impulse = momentum = mass *times* velocity, where we understand that this velocity is the initial velocity.

Now we must look at a further complication regarding velocity and acceleration. They have a direction attached. The speed is the value of the velocity without direction, while the velocity must have a direction. Anything that has a value and a direction is called a "vector". Acceleration also has a value and direction, and so is also a vector. The acceleration from gravity is always pointed downwards, so its value usually has a negative sign to indicate the downward direction. Whether a value is negative or positive is a convention.

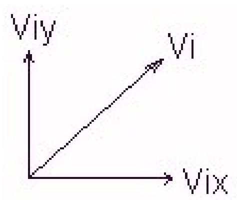
When we dropped balls in the previous experiment, the balls experienced acceleration in the downward direction due to the force of gravity, and their velocity was also in that same direction.

Now, when we fire the same sample balls from a cannon, the cannon imparts an impulse, a momentum, hence an initial velocity on the ball that is not in the same direction as the force of gravity. (When you fire it straight up, it will be opposite to the force of gravity.)

Given an initial direction, say 45 degrees (45º), we can draw a diagram of the initial velocity as the first step in understanding what the trajectory—the plot of the distance and time of travel—will be:



In order to calculate our sample's trajectory we must calculate the velocity in the direction of the force of gravity—vertically—and the velocity in the direction "down-range", or horizontally. The first thing we do is draw these components of the initial velocity.



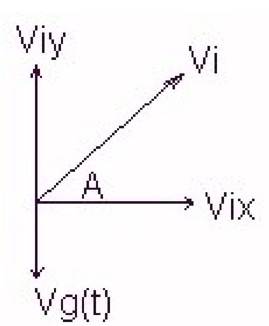
The really neat thing about vectors is that you can break them down into their components like this and then when you add vectors you just add the components separately. For our current situation, we need a velocity that will come from the acceleration of gravity. But this velocity will change depending on the length of time that the ball accelerates. The formula for velocity depending on acceleration and time is:

V_a = a times t = at

For us, the acceleration a, is just g, the acceleration of gravity, hence

$V_g = gt$

We say that V_g is a function of time by writing it like this $V_g(t)$. This shows that it will vary. So we have:



Where A is an angle.

The cool thing about vectors is that the Vg(t) subtracts from the Viy, but leaves the Vix alone. So we can completely do away with the Vi, and just deal with the x and y components.

Without friction (air resistance), which we are ignoring here, we have

$V_x = V_{ix}$

$V_y = V_{iy} – V_g(t)$

As noted before, $V_g(t) = gt$

Also, from geometry, given the angle A between the X axis and the direction of the initial velocity,

$V_{ix} = V_i$ cos(A)[initial Velocity Vi times the cosine of the angle A)

$V_{iy} = V_i \sin(A)$

So, we have

$\mathbf{V_x = V_i \cos(A)}$

$\mathbf{V_y = V_i \sin(A) – gt}$

These are our two main velocity equations.

Now our challenge is to translate this into distances. The initial horizontal distance we can call zero. The initial vertical distance is that we are calling our zero surface the height of the ball in the cannon.

We will use * for our multiplication symbol, so we don't get confused with the x for the X-axis. Letting D_x be the distance in the x-axis horizontal direction, and D_y be the vertical distance,

$\mathbf{D_x = Dx0 + t * V_i \cos(A) = t * V_i \cos(A)}$

$\mathbf{D_y = Dy0 + tV_i \sin(A) – gt^2/2 = 81cm + tV_i \sin(A) – gt^2/2}$

These are our main distance equations.

And what, you ask, happened to the gravitational acceleration term? If the velocity change is gt, why is the distance term not t times gt = gt^2? Since the velocity is changing at every time, we can't just multiply the time to get the distance change. We have to multiply the time as an average over a period of time before and after the time when we calculate the distance. This requires calculus, which we will not go into. Trust that the answer is correct.

As an example of this, in the first second of dropping a ball with zero initial velocity, and acceleration from gravity of 9.8 meters/sec^2, the ball will reach a velocity of 9.8 meters/sec, but will only fall 4.9 meters. That's because it slowly increased its velocity, and did not have a velocity of 9.8 meters/sec for the whole first second.

So, when $\mathbf{tV_i \sin(A) - gt^2/2 =}$ 0 cm, we will be back at our original starting height. What is the value of t at this height? With some algebra, we find

$$\mathbf{T = 2\ V_i \sin(A)/g}$$

This is our total time equation.

For an angle of 45^o, the sine and cosine are both = sqrt(2)/2 = 0.707. Also, g = 9.81 m/sec^2.

$$T = 2 * 0.707\ \ V_i / g$$

$$T = 0.144\ V_i \text{ seconds}$$

As we mentioned before, V_i = Impulse/mass

Remember, the mass is the weight value in mass units, as explained before. So, for example, take

Ball = 10.16 cm (4" - the maximum size for the cannon) diameter granite
Density = 2.73 gm/cc
Volume = 550 cc
Mass = 1.5 kg

Take an initial impulse of 50.
Then the V_i = 33.3 m/sec, and T = 4.8 seconds.

What is the distance travelled in this time? We could plug it into the distance formula, or get a range formula.

If we plug this total time into the distance formula we get:

$D_x = t * V_i \cos(A)$ = 4.8 sec * 33.3 m/sec * 0.707 = 113 meters, which is a bit more than the length of our football field, 100 yards (91.44 meters).

D_y = 81cm + $tV_i \sin(A) - gt^2/2$ for t = 4.8 sec

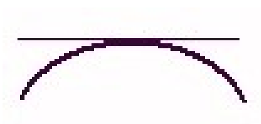
$= 0.81$ m + 4.8 sec * 33.3 m/sec * 0.707 – 9.8 m/sec^2 * 4.8 sec * 4.8 sec /2
$= 0.92$ m

which is about the original height of the ball in the cannon. This is close to 0.81 m, and we could guess that the difference is round-off errors from the approximations of the numbers, and perhaps a bit of a buoyancy factor (although that is small for a rock).

We can also derive a formula for the maximum horizontal distance:

xmax = 2* V_i * V_i * cos(A) * sin(A) / g

The maximum height formula is found from calculus, taking the vertical Y distance formula, finding the formula for the slope of this curve, and setting the slope equal to zero. A zero slope line is horizontal. So we are trying to find the point where the zero slope line intercepts the trajectory curve:



$D_y = 81\text{cm} + tV_i \sin(A) – gt^2/2$

Slope of D_y = change of D_y with time

$= V_i \sin(A) – gt$

which we set to zero. With a little algebra, we get the time for the maximum height

$T_{maxheight} = V_i \sin(A)/g$

For our particular experiment, Tmax-height = 33.3 m/sec * 0.707 / 9.8 m/sec^2 = 2.4 seconds.

Of course, this is half of the total time. We have found that the ball reaches its maximum height at half the total trajectory, or 2.4 seconds. To get the height at this time, we use the vertical distance formula again:

D_y $= 81\text{cm} + tV_i \sin(A) – gt^2/2$ for t = 2.4 sec
= 0.81m + 2.4 sec * 33.3 m/sec * 0.707 - 9.8 m/sec^2 * 2.4 * 2.4 /2
= 29.1 m