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INTRODUCTION

As a TA in the laboratory, you must walk a very fine line. On one hand, you want to make sure that students complete their tasks and benefit from their experience. On the other hand, you cannot provide too much assistance or the students will refuse to work on their own and will be afraid to try out their own ideas. This instructor guide is meant to help you become a better coach to your students. This guide is not a substitute for the preparation you will need to do before teaching. Be sure you read the student lab manual completely. They will have questions. Also, do not let students see this instructor guide – should students have access to it, their discovery experience would become irrelevant.

THE GOALS OF LAB

The goal of the introductory physics labs at the University of Minnesota is to provide students with practice and coaching in using a logical, organized problem solving process to solve problems. The goal of the labs is the *same* as the goal of the discussion section – to help students slowly abandon their novice problem-solving strategies (e.g., plug-and-chug or pattern matching) and adopt a more logical, organized problem-solving procedure that includes qualitative analysis of the problem.

Since one reason that students cannot solve physics problems is that they have misconceptions about physics, a second goal is to confront some of those misconceptions in the laboratory. The labs include problems that try to illuminate known misconceptions and help students connect their lab experience to reality – all problems begin with a context statement. Now more than ever, the labs give the students a chance to learn physics in the real world. Because your students are so unfamiliar with this material, they may find the labs more frustrating than usual. This lack of familiarity coupled with misconceptions will often lead the students to conclude that the equipment "does not work," since it does not behave the way they think it should. If you are prepared, this is the ideal teaching opportunity. Your students will need you more than ever, and it is crucial that you are familiar with the equipment.

The U of M problem-solving labs do not contain step-by-step instructions; students are generally told *what* to measure, but they must decide in groups *how* to make the measurements (guided qualitative exploration). The students must also decide in their groups the details of the analysis. At the conclusion of the lab session, students must determine if their own ideas (predictions) match their measurements.

LAB SESSION STRUCTURE

OPENING MOVES:

Typically, the first 15-20 minutes of lab are spent preparing students for group work and focusing the lab session on what students should learn. Your “opening moves” as a TA begin when you ask the members of each group to arrive at a consensus about one or two of the warm-up and prediction questions. You should decide which warm-up questions to have students discuss and put on the board from your examination of the answers your students turned in before lab. Make sure to give an explicit time limit for this group discussion; for most lab problems it should take no more than 5-10 minutes (however the discussion for more difficult problems may take longer.)

At the end of the group discussion time, have one representative from each group put their group’s answers to the selected warm-up questions on the board. Ask each group to give their reasons for their answers, and then conduct a class discussion comparing and contrasting their answers and reasons. ***The discussion need not arrive at the correct answers to the questions.*** In fact, more learning occurs in a lab session when there are unresolved disagreements. Wait to resolve the disagreement in the closing discussion, after students have completed checking their solution.

After the opening discussion, *briefly* discuss the measurements students will make to check their solutions. It is often a good idea to ask students, "What are we trying to measure in this lab?" to get their mind focused on the target quantity or quantities. This is also a good time to point out the pieces of equipment they will be using, or give particular instructions about the equipment. This Instructor's Guide also includes suggestions for what to discuss. For the students to get the most out of their lab experience:

DO NOT LECTURE AT THE BEGINNING OF LAB!

Reasons:

1. There is already a lecture component of the course; lab is a time for students to *apply* the theories from their text and lecture. Even though they are unsure of themselves and might *think* they would benefit from explanations of the material, more lecturing will not help - experience and coaching will. Do not reduce the time the students need for hands-on learning activities. If students have not yet attended a lecture on the material, you might need to give them helpful hints to get them started, but keep it short. The lab experiences will serve as a good introduction to the material when it comes up in lecture.

2. If you give the students the answers before they start, you are telling your students that you do not care about their ideas and that they should not care either. Answer their questions only after they have made their best attempt to answer it themselves and within their groups. Let them investigate their own ideas to find which are correct and which are misconceptions. When they are cognitively engaged, they learn.

3. Lecturing often places the listeners in a passive mode, but effective learning takes place in an active mode. Students are in an active mode when they are doing or thinking about a specific problem. Active modes are what the laboratory and discussion sections are designed to evoke.

It is **your responsibility to inform the professor** for the course if topics are not synchronized, as well as about any other issues involving the lab and lecture sequence. If you notice this is the case, bring it up at your team meetings and respectfully request a slower pace until the lectures catch up, or discuss alternative methods to approaching the lab topics. You should **resist** if the professor asks you to introduce a new topic in lab by giving students a lecture! Another option would be to hold a problem solving session during lab to allow the lecture to "catch up".

MIDDLE GAME:

During the lab session, your role is one of observer, listener, and coach. You should circulate around the room, observing what groups are doing, listening to what students are saying, and observing what the groups are writing in their lab journals. Intervene when a group needs to be coached on an aspect of physics or the Exploration, Measurement, or Analysis procedure.

It is your job as a TA to guide the lab groups and help them focus their questions. Here's where you really earn your money, because it's up to you to decide when and how to help the student groups. It is important that they attempt to work through the problem themselves. However, if they struggle too much they will gain nothing from the lab except frustration and despair.

With 10-20 minutes left of class, have a representative from each group put their group's *corrected* answers to the warm-up questions on the board (if possible, below their original answers.)

END GAME:

A good end game helps students consolidate their ideas and explicitly summarizes the learning focus for the lab session. Give students a few minutes to examine what other groups wrote on the board, and then lead a whole-class discussion of the results (how do their measurements and predictions compare?) and the objectives for the lab session. Depending on time constraints, you may decide to discuss some of the answers to the warm-up and prediction questions.

When you were an undergraduate, your laboratory instructor probably did not stop you to have a class discussion. Doing this is one of the hardest things you will have to do as a TA. You may be tempted to either let students keep working so that they can get as much done as possible, or let them go home early so they will like you better. However, students do not learn from their laboratory experiences unless they are actively engaged in figuring out what they have learned.

TEACHING TIPS

1. Carefully tell the students what you expect of them in the laboratory and why these rules are necessary. Be very strict in enforcing these rules during the first half of the semester. It is easier to establish good habits in your students early in the semester than to try to establish them later. If you are strict and fair, your students will respect you for it. If you do not consistently enforce your rules, some students will never believe anything you say. If you have any questions about this concept, please talk about it to your mentor TAs.

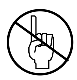
2. Always tell students explicitly that they should hand in answers to both the Predictions and Warm-up questions for the problem(s) that you assign before they come to lab. The deadline for handing them in will be decided in your teaching team – it is usually 1 or 2 days before the lab session. *Make sure the students understand that the Warm-up questions are there to help guide them through the analysis*, as well as to help them solve the problem. Even though the Prediction comes first in the lab manual, they should do the Warm-up questions before the Prediction.

3. It is well known that students do not like to read instructions. They will come to you and ask questions that are answered in the lab manual. If this happens, first ask the student a question to determine if they have read the manual. If not, refer them back to the manual. If they have, give them a straightforward answer.

4. Tell the students what resources are available to them and encourage going to the tutor room 137 if they have any questions. The student lab manual has plenty of information in the Appendices. For example, there are sample lab reports (do not assign these problems for reports!)

SAFETY

Your students' safety is your primary responsibility. A first aid kit is available in room 135 on the second floor, for minor cuts and scrapes. Make sure you are the only person to access the kit unless there is an emergency and an urgent need to do otherwise.



It is important to **verbally warn students about potential dangers.** The lab manual and this guide provide warnings, which are marked with a symbol of a hand with one finger raised in warning, as seen to the left.

EQUIPMENT

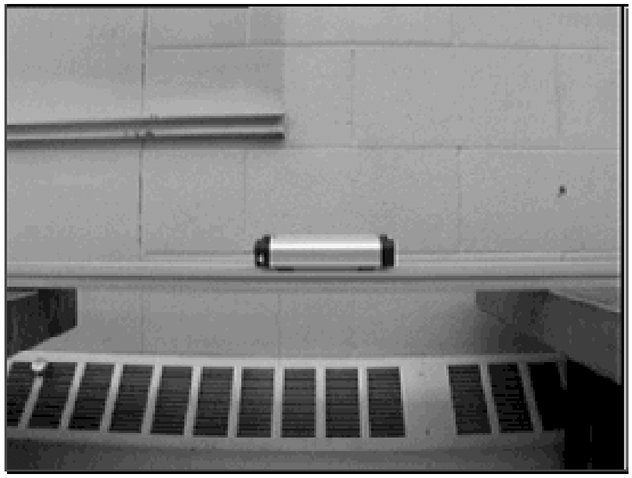
1. If there is any bad, broken, or erratic equipment, send an e-mail directly to the lab coordinator at labhelp@physics.umn.edu. Be sure to include a complete description of the problem, and the room number. **If the problem isn't resolved before you leave lab, make a note on** the blackboard to inform the next TA of the problem, and that a problem report form has already been submitted.
2. Be sure that students treat the equipment with respect. Keep the following in mind:
   - After the students have finished with the computers and cameras, have them shut down the computer.
   - Never turn off the power to a computer without shutting it down first.
3. If there is no video image in the *Video Camera* window, check the following:
   - The camera power light is on.
   - The cable is plugged into the back of the camera and computer.

5. Electrical equipment tips:
   - **Check all of the DMMs before your students enter the classroom** and make sure you have enough working before class begins.
6. Some suggestions about the camera and video analysis program:
   - Take a few moments to learn how to focus the camera.
   - The object the students use to calibrate their movies MUST be in the plane of motion of what they are measuring.
   - Keep the camera level with the motion being recorded.
   - Make sure to tell students to write in their lab journals their predictions and data fits as they go (including both the equation and the coefficients). The computer will not show these values once they move to a different stage in the analysis. This is done on purpose to force the students to keep an organized lab journal.

Some hints to make sure your students have useful movies

You will have to keep quite a close eye on your students' movie making within the first few weeks of class to help them get into good habits. If their movies are poor, their conclusions will be incorrect, perhaps perpetuating the misconceptions they brought to class.

A good movie:



Notice that in this movie frame:

- The camera is level with the cart's motion.
- The cart's motion is centered in the screen.
- The cart's motion will fill the entire screen.
- The camera is the "perfect" distance away from the cart. If we were closer, we wouldn't have as many data points.
- The adjustments on the camera are just about right. The picture is not too light, nor is it too dark and the cart is in focus.
- In this case we would use the cart to calibrate the movie. It is in focus, and more importantly, it is in the plane of motion.

A bad movie:

Notice that in this movie frame:

- The camera is not level with the cart's motion. The video is shot from above, which causes the cart's image to be distorted. Notice that the right side of the cart is visibly closer to the camera than the left side. Thus our 2-D picture has a 3-D component for which we cannot account – this will cause the analysis of the movie to be incorrect.
- The cart's motion takes place only in the top portion of the screen. You can even see that the track looks like it is curved.
- The camera is a bit too far away from the cart. It is thus more difficult to focus on the cart.

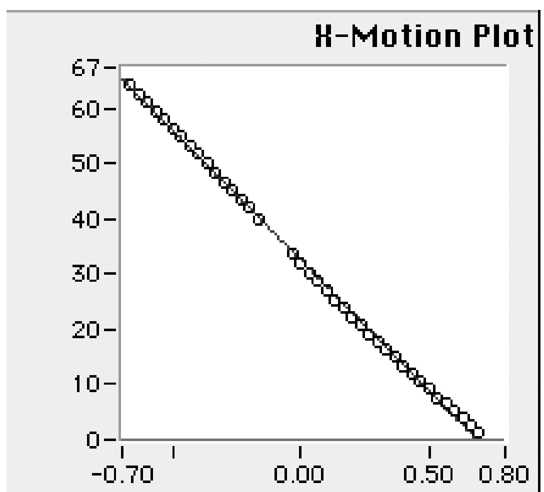
- The adjustments on the camera lens are not correct. The picture is lacking contrast since we can't even make out the top edge of the cart. The focus is as good as we could get it at this distance (which is not very good).
- The students WILL make movies like this and then wonder why their conclusions are coming out incorrectly. The first thing that you should check when the students come to you with bad conclusions is their movie. The next thing to do is ask them what they used to calibrate the movie. If they used an object that is not within the plane of the motion of interest, their results will most likely be wrong (in most cases, VERY wrong).

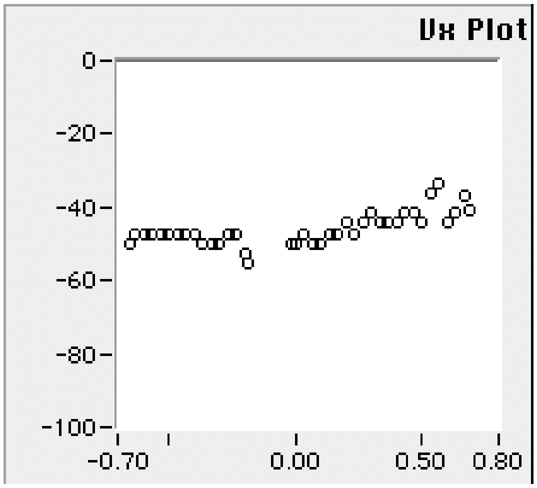
Analysis of our movies

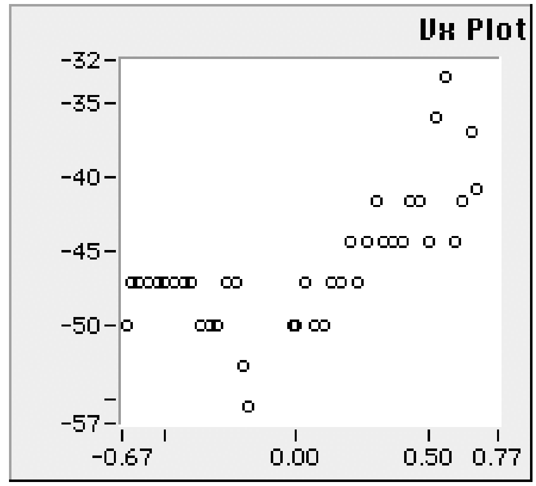
Here we analyze the movies (two frames of which are shown on the previous pages). The motion is that of a cart moving with constant velocity along the track. Although the velocities are different, we can still use the movies to compare what are considered good results with those that are bad.

The good movie:

Below are the position and velocity graphs for the good movie. Notice that even though we went to great lengths to make this movie well, the x versus t graph of constant velocity motion is not quite a straight line and the computer skipped some frames (the missing data points in the middle of the graph are indicative of frame-skipping). Retaking the movie would probably eliminate the skipped frames. The plot curves slightly at the edges of the video screen.





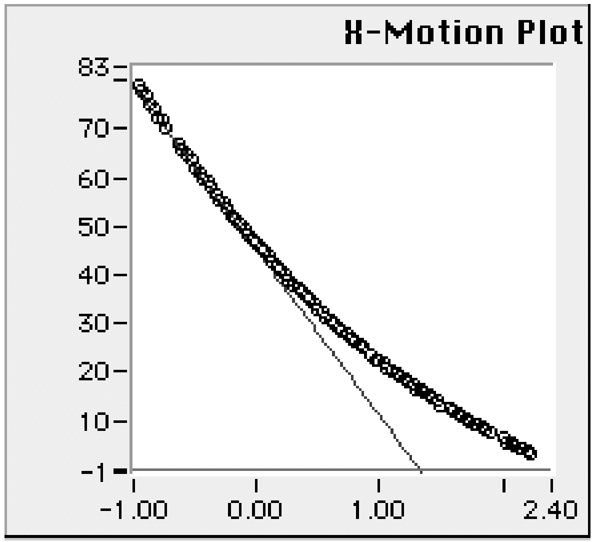


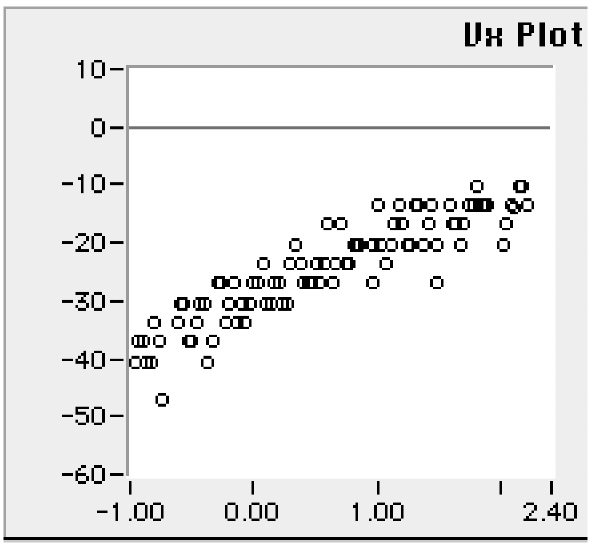
We include two velocity-versus-time graphs for the good movie. In the plot on the left we put in the axis limits ourselves. The plot on the right is "autoscaled." (Both plots are identical except for the y-axis scaling.) We include both graphs to show how "autoscale" may mislead the students into thinking their data is not very good. The students should really only use this feature to help them find their data before analysis. Even the plot on the left shows that our efforts to make a good movie were not perfect. With practice, students should be able to reduce the scatter. In this case we would have the students use the slope of their x versus t graph for their experimental velocity.

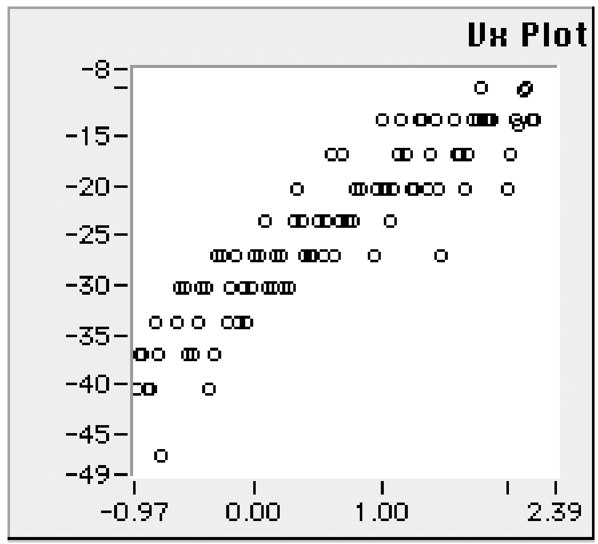
You may have noticed that some of the data points were taken at "negative" time (the horizontal axis is the time axis). This is due to the fact that we forwarded the movie to the frame in which the cart was at the center of the screen to do our calibration. We then reversed the movie so we could start taking data points when the car just appears on the screen. The calibration point is the point at which the computer attaches t = 0. Make sure your students understand why their time (or position in some cases, e.g., analysis of a falling ball) is negative.

The bad movie:

Below is the analysis of the bad movie. The x versus t graph is NOT the expected straight line. For most problems, this type of poor analysis would cause the students to have conclusions that are not within 10% of the correct result. The cart in this movie was going slower than in the good movie (and the camera was further away), so we have many more data points. In reality there are too many data points. It is tedious to go through every frame of the movie, so you may want to suggest that the students use the controls on the bottom of the movie player to "fast-forward" through some of the data (e.g., perhaps they could skip every other data point). The computer will take the time difference into account. Of course a "good" movie should be designed to avoid taking too many data points, but sometimes it is unavoidable.







Again we include an "autoscaled" graph (on the right) and one we scaled by hand. There is obviously a non-zero slope in these velocity-versus-time graphs, along with the scatter discussed previously. After seeing this plot, it is more apparent that the velocity-versus-time graph for the good movie is that of constant velocity.

USING THIS INSTRUCTOR'S GUIDE

This instructor's guide is designed to help you help your students, make sure you:

1. Don't rely on it too much. It is only a guide, not a substitute for preparation. Make sure you prepare to teach the lab as if you didn't have this manual.
2. **Don't let students have access to it**. It's basically like having a solution manual for textbook problems. It can short circuit the learning process.

We are continually working to improve the instructor's guide. **To add any suggestions,** e-mail the information to labhelp@physics.umn.edu

Information from previous laboratory instructors was used to construct this guide as well as modify this year's student lab manuals. Your input is greatly appreciated. Include anything that you feel will be useful. Your notes may include additional comments to be included in the Instructor's Guide, difficulties you or your students had with the problems or the apparatus, and suggestions for changes in the labs.

At the start of each chapter in this guide is a **flow chart** that shows the connections between the different problems in that lab. This chart is designed to help you plan your lessons. The elements of the flow charts have the following definitions:

- Bold ovals are the problems that contain knowledge and techniques that are prerequisites to other problems. It is strongly suggested students be required to do these problems.
- The arrows on the connecting lines are directional symbols.
- Dashed lines are optional paths.
- The X across a connecting line implies that if a group has completed one of the problems, that group should skip the other problem.
- Any one group can do any number of problems on the same level.

As the instructor who knows the students, you are the only one who can determine the right number of problems for a given group to solve to keep them intellectually engaged in the primary purpose of the laboratory. If you assign too many problems to a group, the students may simply rush through data taking without spending enough time exploring their own ideas or the real behavior of the apparatus. If you assign too few problems, they may not get the repetition they need to consolidate their developing sense of physics or come to grips with a topic that will help them identify a misconception. Because your groups will be different, it is not necessary or even desirable that all groups complete the same number of problems in a laboratory. From past experience, an average of two problems per week is the usual range that a group can complete. The minimum for a two-week laboratory is usually three problems and the maximum is five.

The range of available problems allows you to assign tasks to groups that reflect the needs of the students in that individual group. Some problems are basically repetitions of a previous problem for those groups who you judge do not quite understand the central idea of the lab. Others are challenging extensions to enable groups that solidly understand the basic concepts to increase their knowledge. The problems you assign should also reflect the emphasis of the class, which is decided upon in your team meetings.

Lab 1: Laboratory Skills

The three problems in this laboratory are all meant to be done during one lab session, and are designed to introduce students to certain skills that they will need throughout the rest of the laboratory course. The first problem is meant to introduce students to measurement and how to of presenting data using graphs. The second problem is meant to introduce students to the motion cameras and the behavior of simple functions. The last lab problem is meant to introduce students to the concepts of uncertainty and error in measurement. Class discussion about the skills in each of these problems will be essential in helping students to learn the relevant skills and overcome any confusion they may have regarding how to perform the lab problems and collect data.

Lab 1 Problem #1: Constant Velocity Motion I
Problem #2: Constant Velocity Motion II

Purpose:

- To introduce students briefly to the need for experimental technique, by analyzing motion in one dimension.
- To get familiar with the camera and video analysis software and to show its limitations, features, and reliability.
- To become familiar with how to correctly graph data.
- To become familiar with the names and behavior of simple functions.
- To solidify the relationship between position, velocity, and acceleration for constant velocity.
- To get the students thinking about experimental uncertainty.

Teaching Tips:

1. Every group must do these problems. Since it is the first lab, it will take longer than you think. Give them at least 40 minutes for each problem to work with the equipment. This is best to get out of the way during the first week of class after introductions and diagnostic testing

2. Be sure to go over the introduction to the labs with your students. DO NOT assume they will read it. It is included in the lab manual to allow the students to reference it throughout the semester. Problem #1 continues this general introduction to the lab format.

3. In Problem #2 students may become overwhelmed by the computer and forget the purpose of this lab. You will need to remind them that they are trying to describe the motion of a car moving with constant velocity.

4. You should suggest to your students that they should investigate the edges of the cameras image. This is their chance to understand if the camera has limitations. If they do not find limitations, they will not be able to claim difficulties or errors coming from the equipment later in the semester.

5. Since the video analysis software calculates the velocity data from the position data using simple point-by-point differences, the velocity data always appears somewhat scattered. This scatter will be reduced if the students are careful in collecting their data. Part of the purpose of this lab is to get the students acquainted with experimental uncertainty and how to limit it.

6. Most groups will only want to analyze one movie. You should therefore make it clear, early in the semester, that the measurements should be done more than once. Emphasize the importance of reproducibility.

7. Make sure everyone in each group gets the chance to analyze a movie. There tends to be at least one "computer-hog" per group and some students <u>will</u> be left out unless you intervene. If you have time, you can ask for each group member to make a movie enforcing everyone in the group to operate the computer.

8. Have a discussion with your class about the proper way to label a graph.

9. Have a discussion with your class about the names and behavior of simple functions.

Difficulties and Alternative Conceptions:

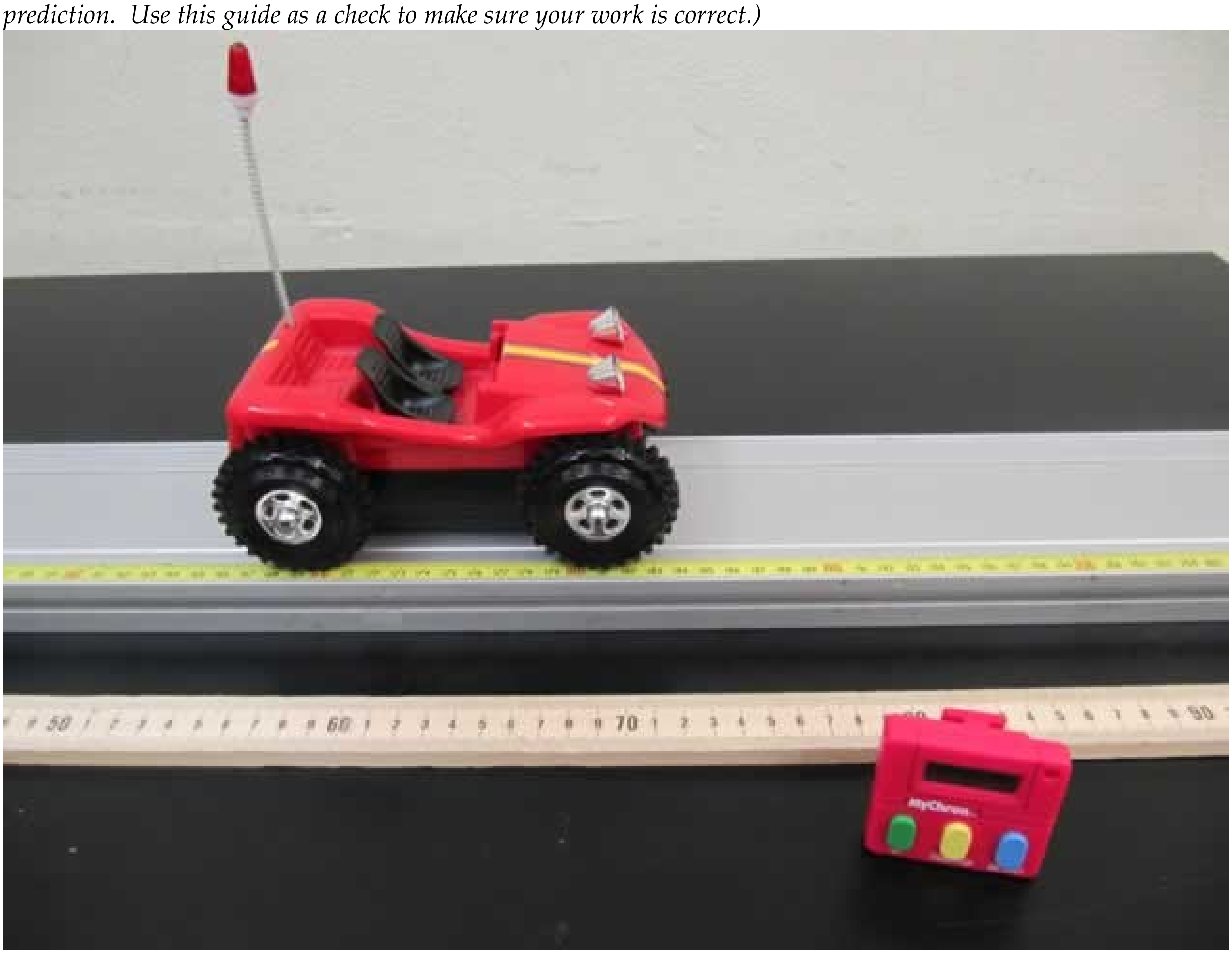
Students have difficulty connecting graphs with physics and connecting graphs with the real world. For example, just because the position vs. time graph slopes upwards does not mean that the cart is moving on an upward slope. Since the motion here is simple, it should be easy to identify these students and help them. Emphasize that the velocity they measure with the stopwatch is the velocity they should use in their prediction. They should understand why the average velocity of the cart equals its instantaneous velocity in this case. Make sure they understand the meaning of a positive or negative slope of the position vs. time graph. Also make sure they know where the origin of their graph is and what the origin means.

Students may have confusion about the proper way to label a graph or the names and behavior of simple functions. Attempt to deal with remaining confusion on these points during class discussion.

Prediction and Warm up questions:

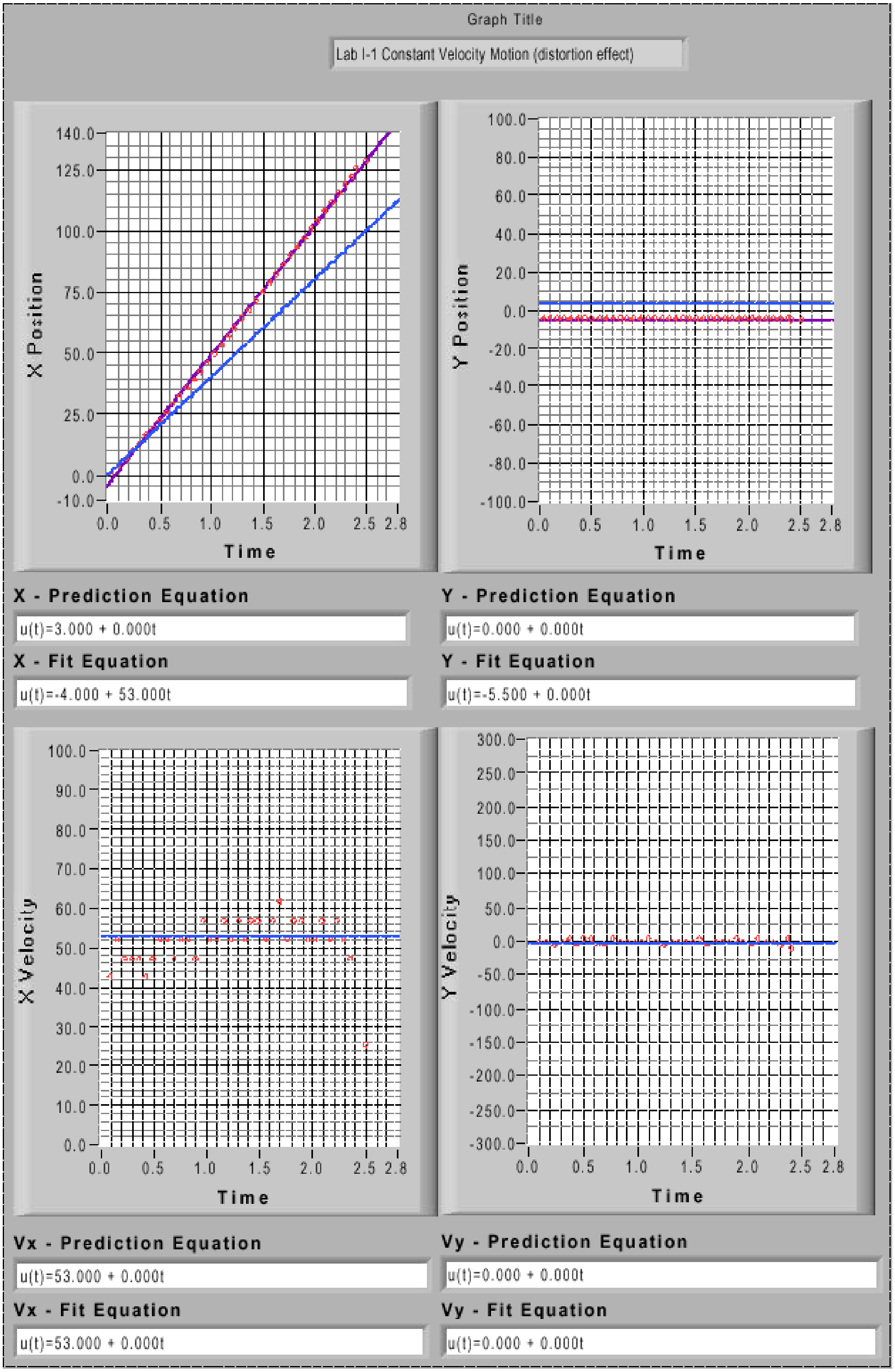
The prediction and warm up questions are straightforward.

(Note: In all cases the prediction and warm up questions are your responsibility. You must complete them on your own in preparation to teach. Only for the more complex labs will this guide provide you the answer to the prediction. Use this guide as a check to make sure your work is correct.)



Sample Data:

Velocity of Toy Car is about 53cm/s.


Graph Title
Lab I-1 Constant Velocity Motion (distortion effect)
X Position
Time
Y Position
Time
X - Prediction Equation
u(t)=3.000 + 0.000t
X - Fit Equation
u(t)=-4.000 + 53.000t
Y - Prediction Equation
u(t)=0.000 + 0.000t
Y - Fit Equation
u(t)=-5.500 + 0.000t
X Velocity
Time
Y Velocity
Time
Vx - Prediction Equation
u(t)=53.000 + 0.000t
Vx - Fit Equation
u(t)=53.000 + 0.000t
Vy - Prediction Equation
u(t)=0.000 + 0.000t
Vy - Fit Equation
u(t)=0.000 + 0.000t

Lab 1 Problem #3: Measurement and Uncertainty

Purpose:

- To introduce students to the concepts of uncertainty and error in measurement.

Teaching Tips:

- If students do not have time to complete this problem try to have a discussion about types of uncertainty with students.

Laboratory 2: Motion and Force

This section deals with the interplay between force, energy and motion. Students will get familiar with tools such as the video camera system and LabView™ software and they should also learn to analyze basic kinematics.

Things to Remember:

- Send an email to labhelp@physics.umn.edu to report any problems with the equipment.

By the end of this lab students should be able to:

- Make and test quantitative predictions about the relationship of the sum of forces on objects to the motion of those objects for real systems.
- Determine which object is exerting a given force on another object.
- Use forces as vector quantities.
- Determine the characteristics of an "unknown" force.
- Determine the motion of an object in freefall by considering what quantities affect the motion.

Things to check before entering a lab with students: (Takes about 15 minutes)

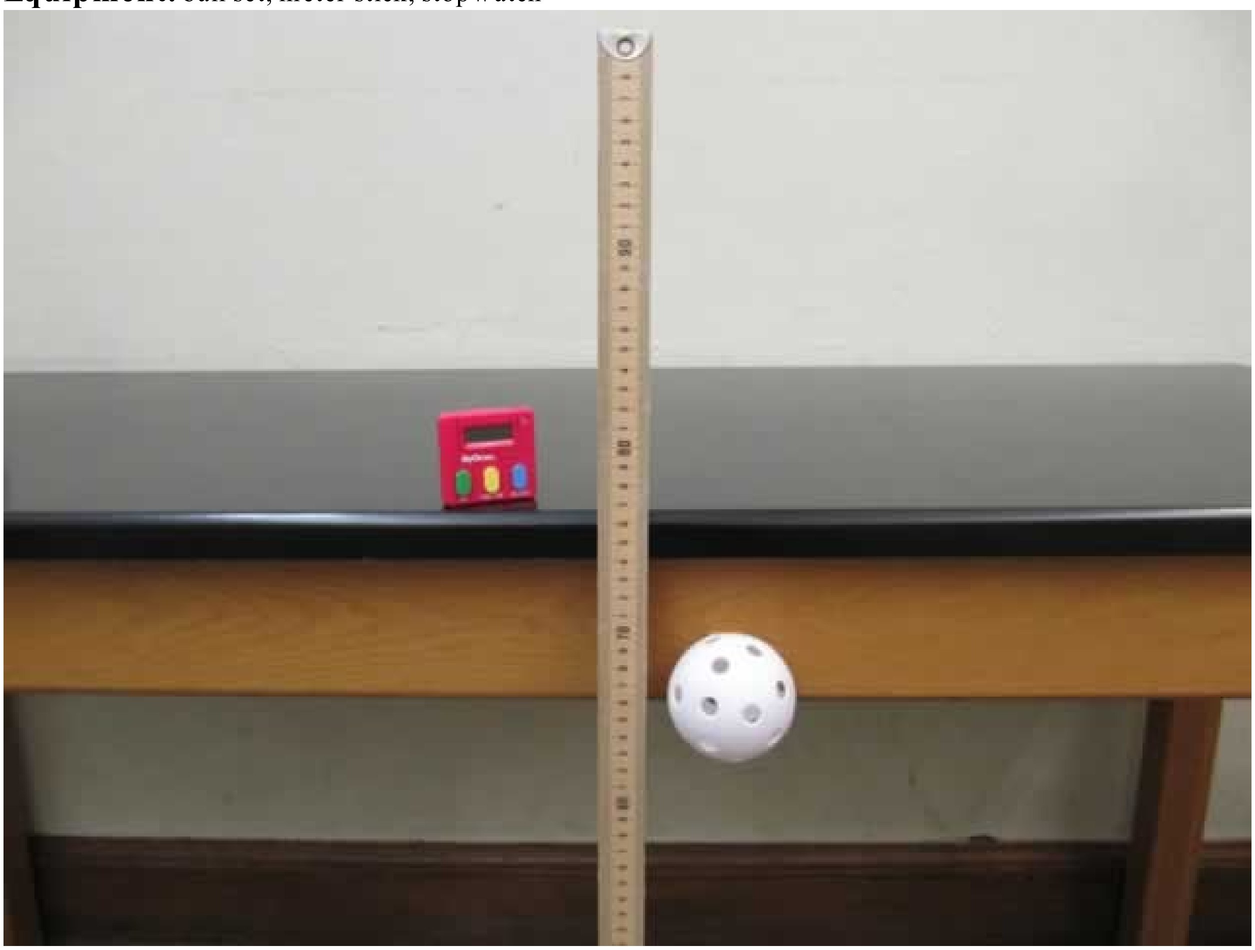
- Check the equipment to see if there is anything missing.
- Make sure the pulleys that the students will use turn freely.
- See what the best place is to position a camera for problems in which video-capture is required.
- Find out what range of angles gives the best results for motion down (up) an incline.

Lab 2 Problem #1: Falling

Problem:
Determine the acceleration and velocity of an object dropped from rest while it is falling. Determine if the velocity or acceleration of a falling object depend on the object's mass.

Purpose:
- The students' first lab problem involving 1-D motion under a constant force. This problem is meant to be studied using forces and Newton's Laws.
- To demonstrate the importance of good data-taking and analysis techniques.
- To emphasize the importance of graphical representations of motion.
- To show students the effect of the real world on physics experiments. Specifically, to show how much (or little) air resistance affects the acceleration of a freely falling object.

Equipment: ball set, meter stick, stopwatch



Teaching Tips:
1. The answer to this problem is different from that in the text; namely, students should observe that heavier objects fall faster. You should be sure that your students understand that this is a small effect for most common objects and is caused by the interaction of the object with the air. You should be sure that this result does not reinforce the idea that heavier things "naturally" fall faster.

2. To make this "mass effect" clearer to you, we include the following equations:

$$F_t = W_t - F_{Air} \qquad F_s = W_s - F_{Air}$$

$$a_t = g - \frac{F_{Air}}{m_t} \qquad a_s = g - \frac{F_{Air}}{m_s}$$

3. Where t and s stand for tennis ball and Styrofoam ball, respectively (we use these for an example). F is the total force on the ball (=ma), W is the weight of the ball (=mg), F_{Air} is the air-resistance force, which is decided by the size, the shape and the speed of the ball. However, the effect of F_{Air} on the acceleration is decided by the ratio of F_{Air} to mass (or gravity). You can have a discussion with your students about the effect of F_{Air} based on their measurement.
4. Some students may be helped by looking at the limiting values – what would be the acceleration of an infinitely heavy/ light object? You can use the common example of a rock as opposed to a feather. What would be the acceleration if there were no air?
5. Whatever approach you decide to use, its effectiveness will be enhanced if you listen to what the student believes. Let your students do the thinking as you ask questions to bring them to the correct conclusion.
6. Encourage your students to use significant mass differences. Ask them what a significant difference is.
7. Parallax must be taken into account; this is why the students are asked to use the object in motion to calibrate their computers. Shadows and image resolution may prevent an accurate calibration from the balls in flight. In this case, the students should put an object of known length *in the plane of motion*.
8. The video camera's interlaced scan (may not be true for newer cameras) essentially breaks a frame up into two different frames (scanning every other line of a frame) 1/ 60 sec apart. When the object in free fall reaches a high enough speed, you can actually see both images on the screen. It is therefore important to use a consistent edge of the image to track the motion at time intervals of 1/ 30 sec.

Difficulties and Alternative Conceptions:

Some common alternative conceptions in this problem are that heavier masses fall faster because they weigh more, or, although the acceleration is the same (g), the heavier mass will still fall faster, or since gravity pulls on a heavier object more than a lighter object (true) the heavier object has the greater acceleration (false). A common graphical misconception is that if the position-versus-time graph is a curve, then the trajectory of the object is that same curve. Here students can observe (especially if you point it out) that the object certainly follows a straight path even though the position-versus-time graph is a curve.

Prediction and Warm-up Questions:

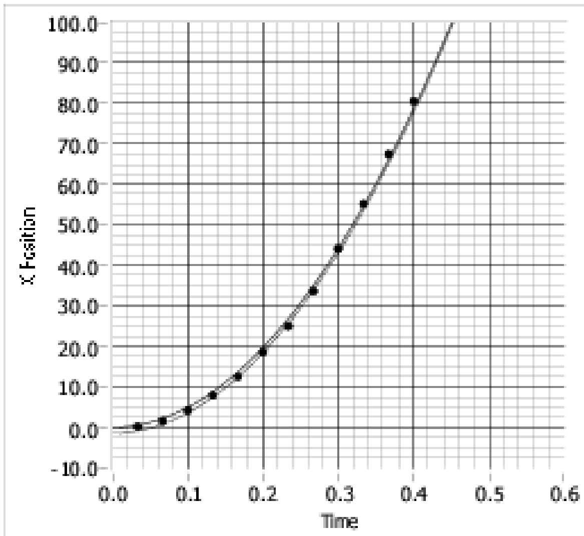
Neglecting air-resistance, all the balls should fall with the same acceleration: *g*.

Sample Data:

	Mass (g)	Diameter (cm)	Acceleration (cm/ s^2)
Baseball	145.30	7.37	980.0
Tennis Ball	57.00	6.56	980.0
Street Hockey Ball	47.90	6.31	980.0
Foam Ball	12.70	6.85	980.0

Graph Title

1201 Lab V Prob #2 Baseball

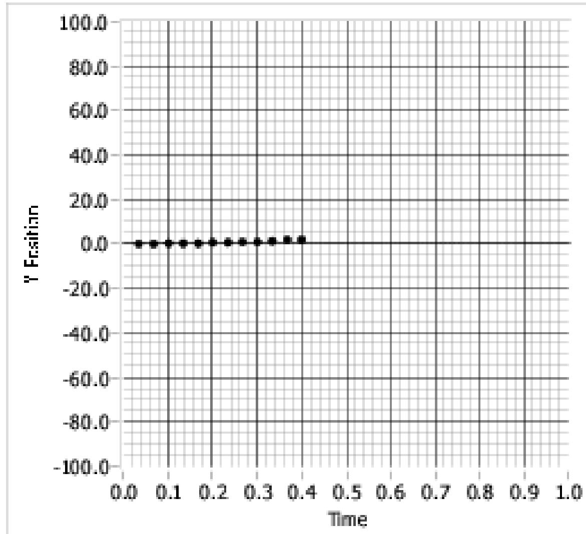


X - Prediction Equation

u(t) = 0.000 + 0.000 t + 490.000 t^2

X - Fit Equation

u(t) = -1.510 + 1.270 t + 490.000 t^2

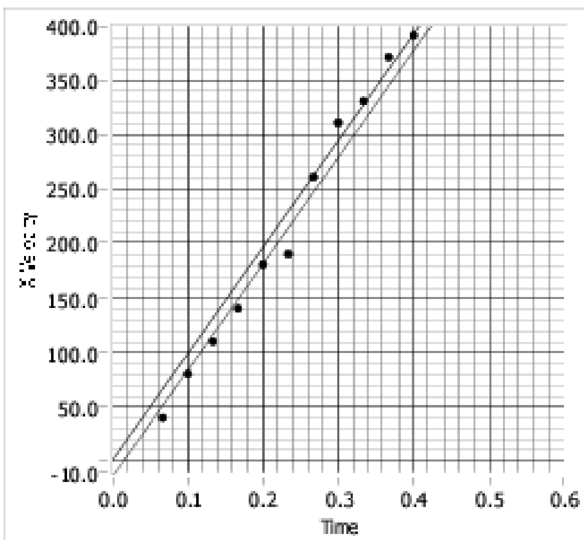


Y - Prediction Equation

u(t) = 0.000 + 0.000t

Y - Fit Equation

u(t) = 0.000 + 0.000t

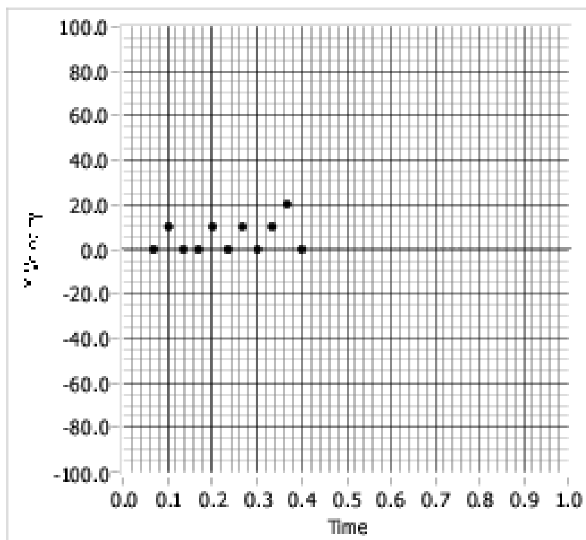


Vx - Prediction Equation

u(t) = 0.000 + 980.000t

Vx - Fit Equation

u(t) = -15.330 + 980.000t



Vy - Prediction Equation

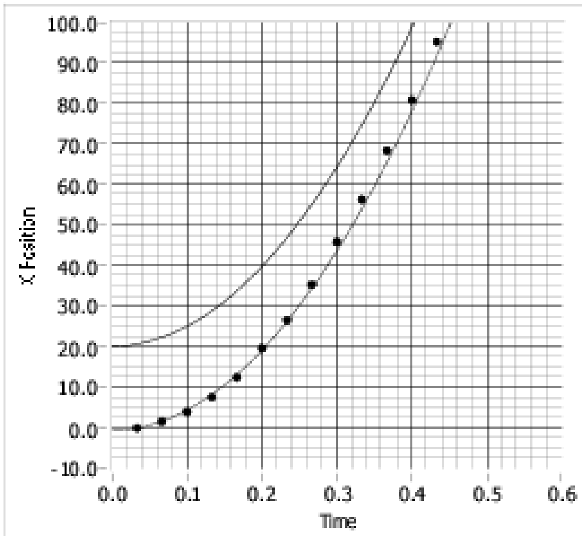
u(t) = 0.000 + 0.000t

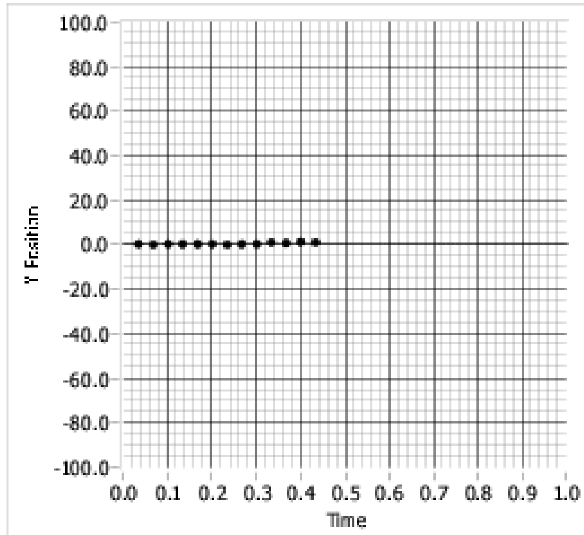
Vy - Fit Equation

u(t) = 0.000 + 0.000t

Graph Title

1201 Lab V Prob #2 Tennis Ball





X - Prediction Equation

u(t) = 20.000 + 0.000 t + 490.000 t^2

X - Fit Equation

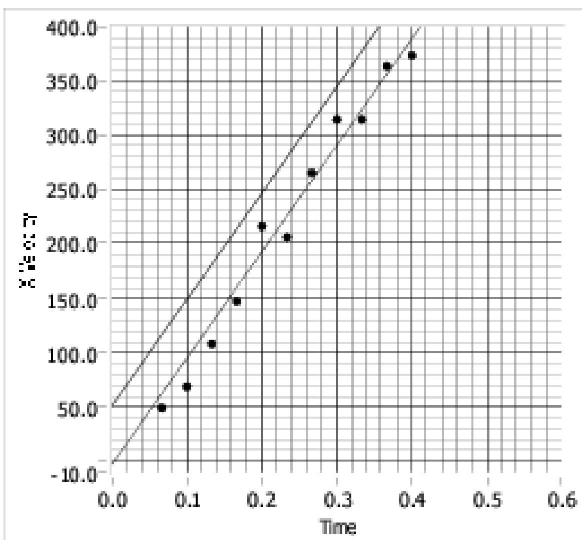
u(t) = -0.700 + 0.000 t + 490.000 t^2

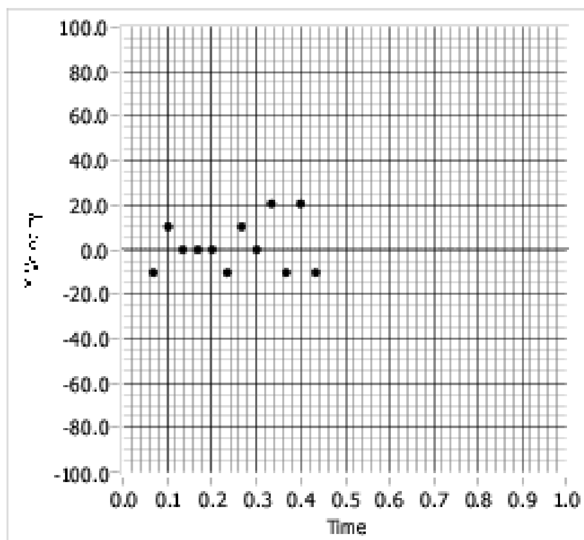
Y - Prediction Equation

u(t) = 0.000 + 0.000t

Y - Fit Equation

u(t) = 0.000 + 0.000t





Vx - Prediction Equation

u(t) = 50.000 + 980.000t

Vx - Fit Equation

u(t) = -4.000 + 980.000t

Vy - Prediction Equation

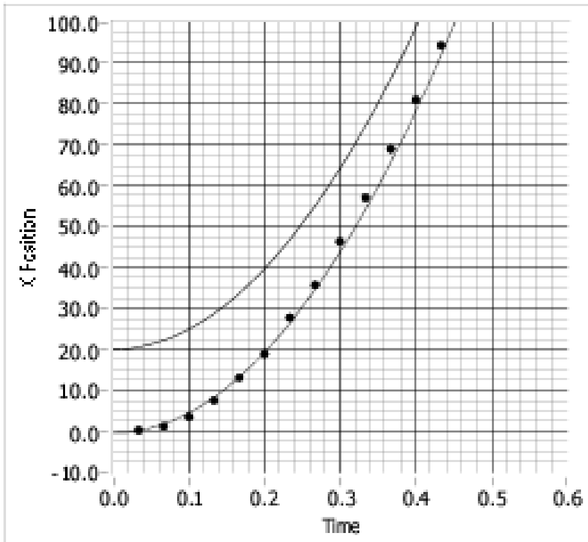
u(t) = 0.000 + 0.000t

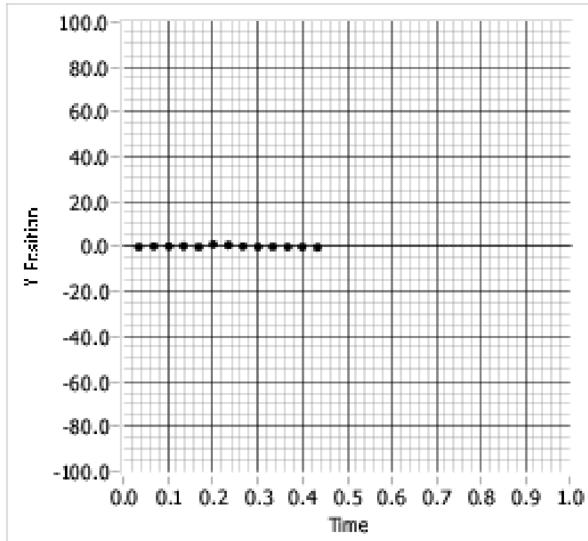
Vy - Fit Equation

u(t) = 0.000 + 0.000t

Graph Title

1201 Lab V Prob #2 Street Hockey Ball





X - Prediction Equation

u(t) = 20.000 + 0.000 t + 490.000 t^2

X - Fit Equation

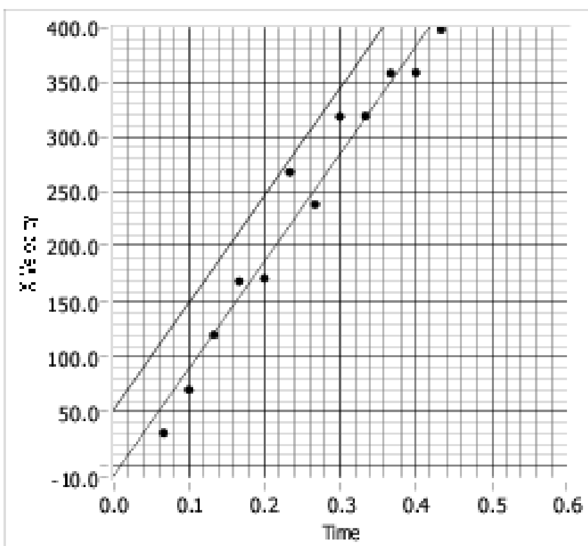
u(t) = -0.460 + 0.000 t + 490.000 t^2

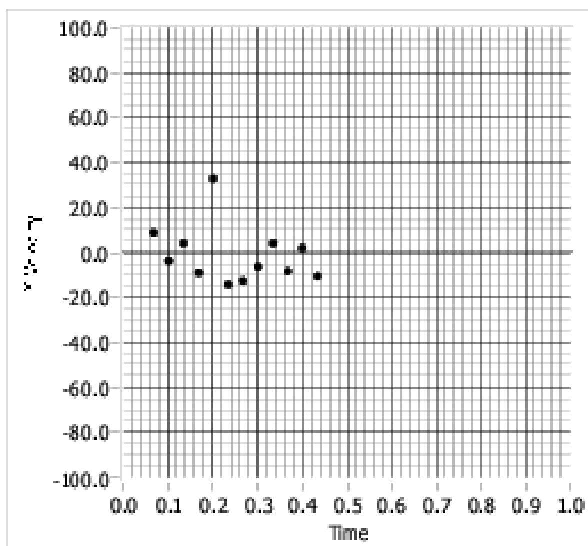
Y - Prediction Equation

u(t) = 0.000 + 0.000t

Y - Fit Equation

u(t) = 0.000 + 0.000t





Vx - Prediction Equation

u(t) = 50.000 + 980.000t

Vx - Fit Equation

u(t) = -10.000 + 980.000t

Vy - Prediction Equation

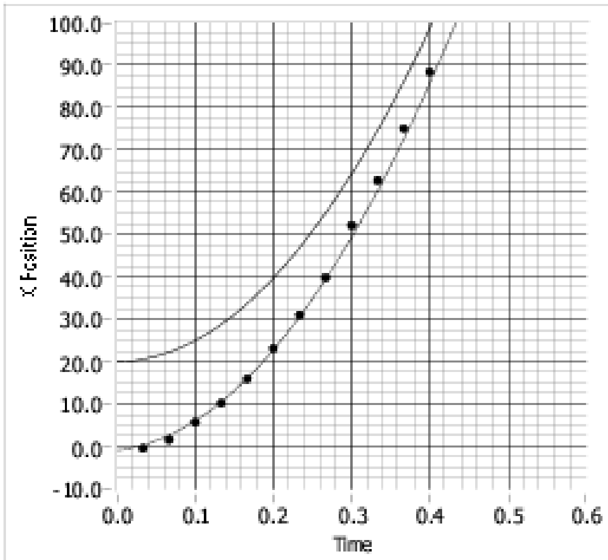
u(t) = 0.000 + 0.000t

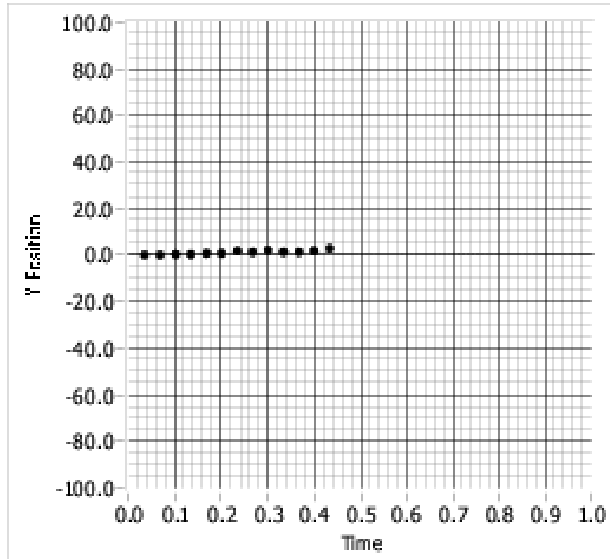
Vy - Fit Equation

u(t) = 0.000 + 0.000t

Graph Title

1201 Lab V Prob #2 Foam Ball





X - Prediction Equation

u(t) = 20.000 + 0.000 t + 490.000 t^2

X - Fit Equation

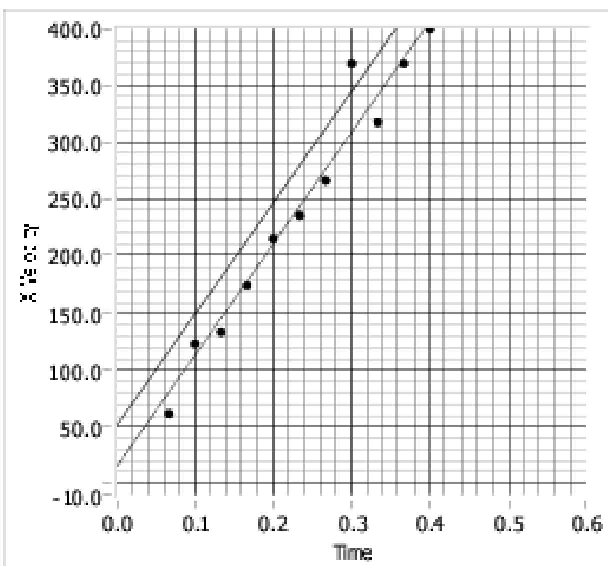
u(t) = -1.000 + 20.110 t + 490.000 t^2

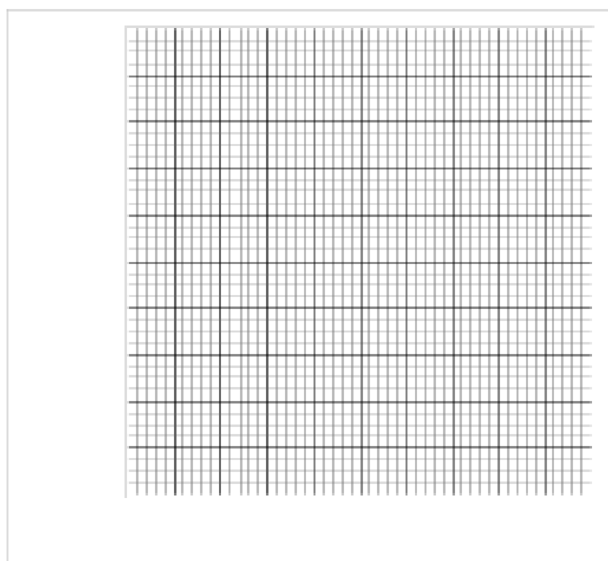
Y - Prediction Equation

u(t) = 0.000 + 0.000t

Y - Fit Equation

u(t) = 0.000 + 0.000t





Vx - Prediction Equation

u(t) = 50.000 + 980.000t

Vx - Fit Equation

u(t) = 14.010 + 980.000t

Vy - Prediction Equation

u(t) = 0.000 + 0.000t

Vy - Fit Equation

u(t) = 0.000 + 0.000t

Lab 2 Problem #2: Motion Down an Incline

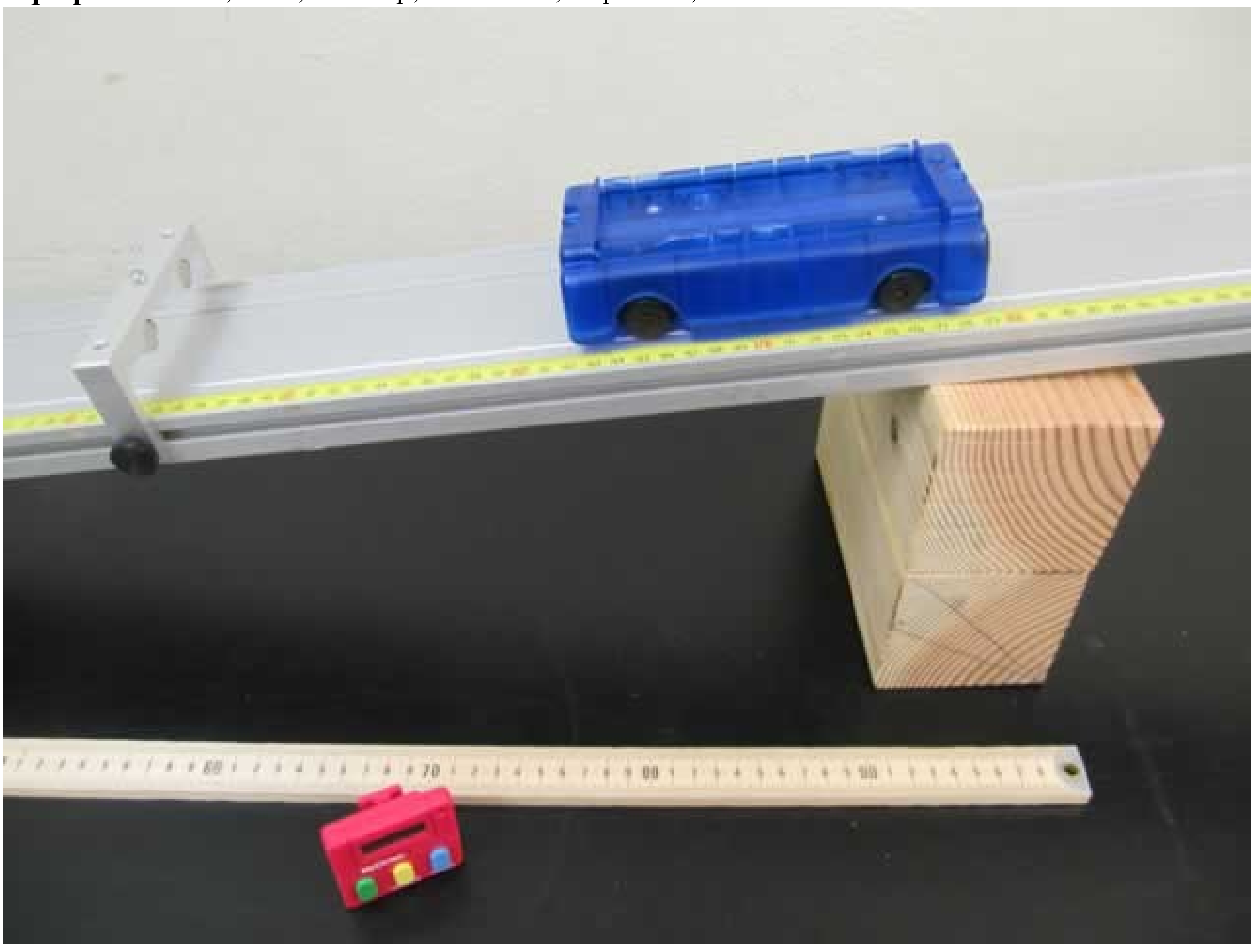
Problem:

Calculate the acceleration and velocity of a cart while it is traveling down an inclined plane. Determine if/ how the acceleration depends on the angle of the track and the mass of the cart.

Purpose:

- To show that there is a constant, non-zero acceleration of the cart down an inclined track.
- To recognize that in this situation $\boxed{v_{avg} \neq v_{inst}}$ but $\boxed{a_{avg} = a_{inst.}}$ because the acceleration is constant.

Equipment: cart, track, end stop, meter stick, stopwatch, wood block



Make sure your students catch the cart before it hits the end stop!

Teaching Tips:

1. Some students may be confused about the friction on the cart. You can instruct your students to ignore it because the rotational friction is small. It's also why a cart instead of a block is used in this problem.
2. It will be a good idea for the students to clearly identify the forces acting on the cart and to be able to resolve and quantify these forces.

Prediction and Warm-up Questions:

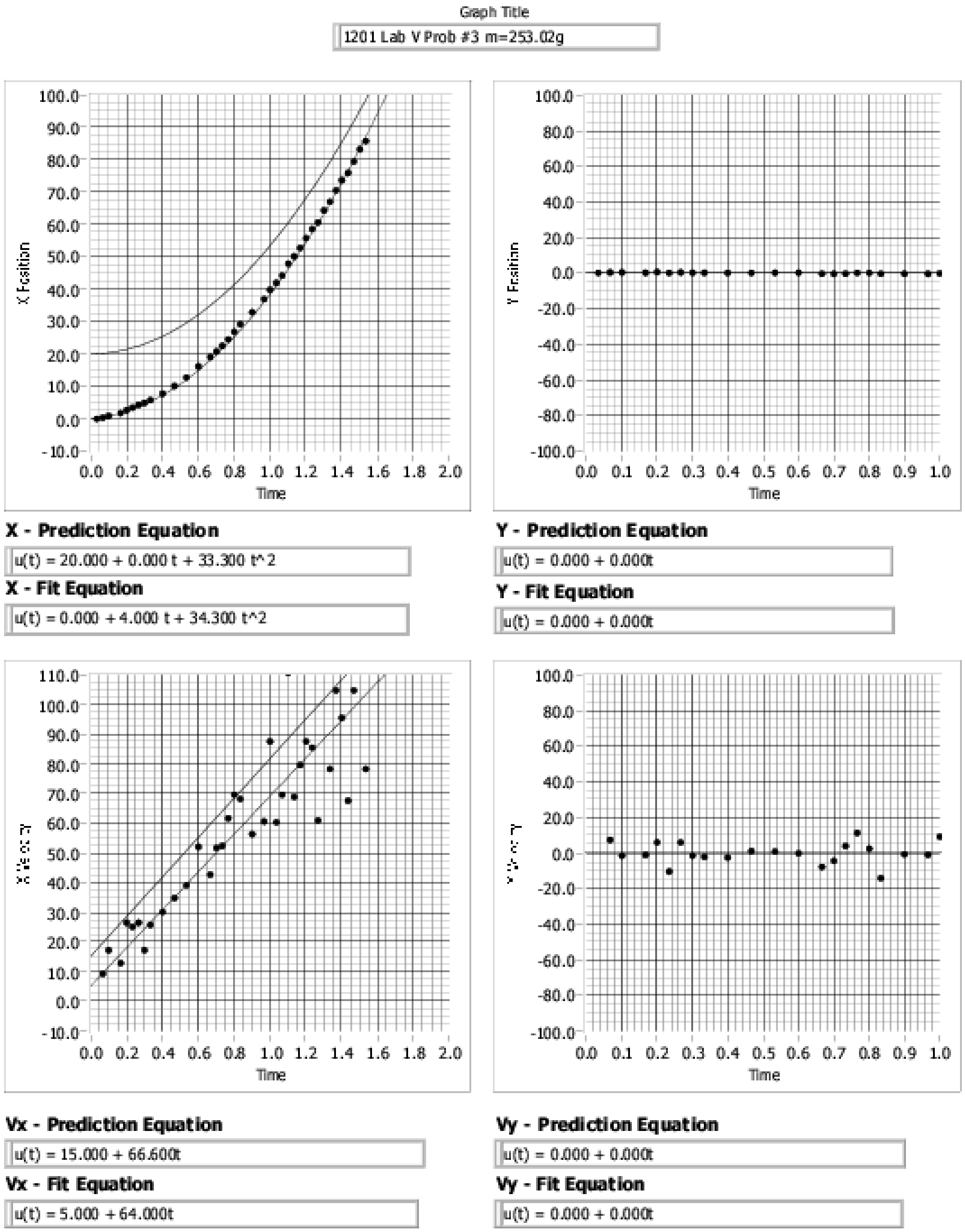
Acceleration is a constant of g sinθ, regardless of time and mass. Velocity is independent of the mass.

Sample Data:

Inclined angle: $\sin^{-1}(8.7/128)=3.90$ degree;

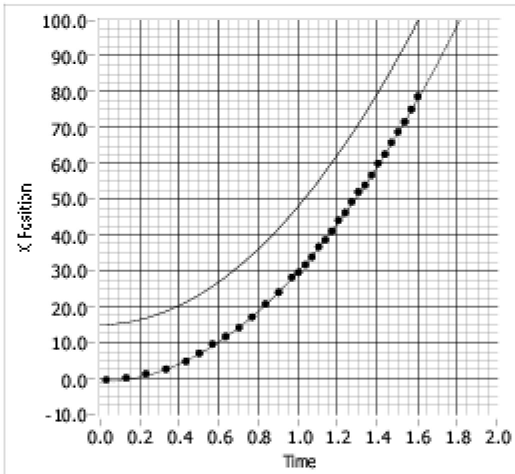
Acceleration: $a=68.6 cm/s^2$ where m=253.02g

$a=61.4 cm/s^2$ where m=552.50g



Graph Title

1201 Lab V Prob #3 m=552.50g

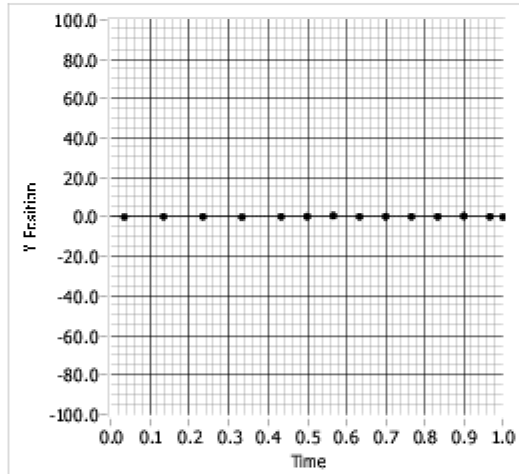


X - Prediction Equation

u(t) = 15.000 + 0.000 t + 33.000 t^2

X - Fit Equation

u(t) = -1.000 + 0.100 t + 30.700 t^2

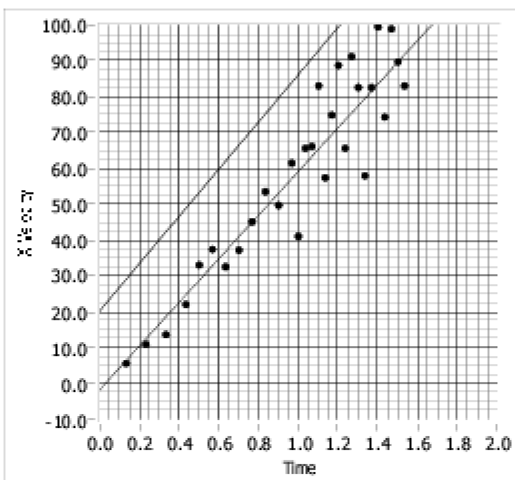


Y - Prediction Equation

u(t) = 0.000 + 0.000t

Y - Fit Equation

u(t) = 0.000 + 0.000t

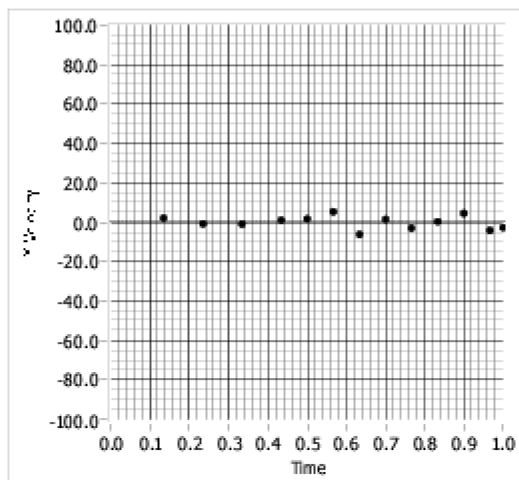


Vx - Prediction Equation

u(t) = 20.000 + 66.000t

Vx - Fit Equation

u(t) = -2.000 + 61.000t



Vy - Prediction Equation

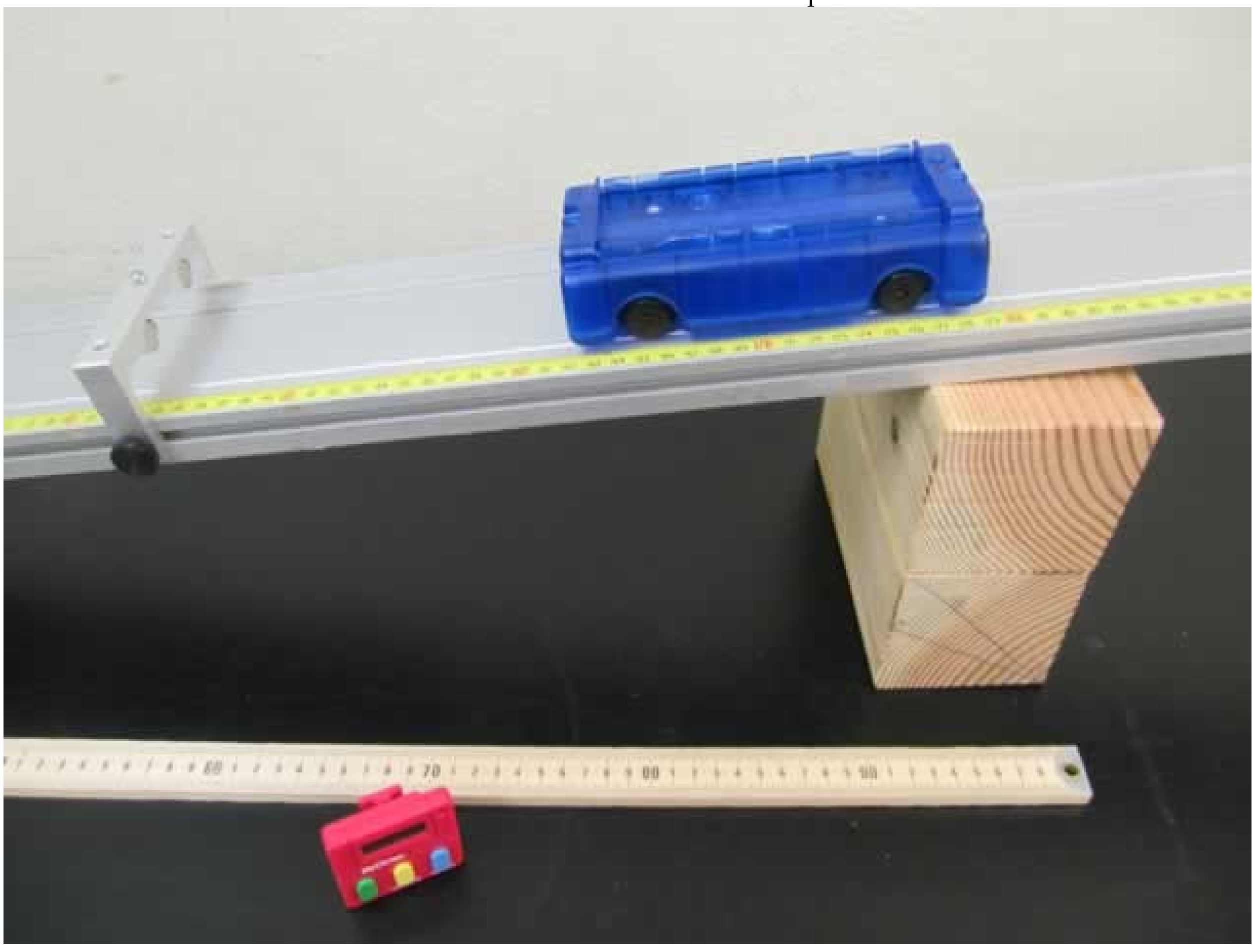
u(t) = 0.000 + 0.000t

Vy - Fit Equation

u(t) = 0.000 + 0.000t

Lab 2 Problem #3: Motion Up and Down an Incline

Purpose:
To show students that the acceleration is the same for motion both up and down an incline.

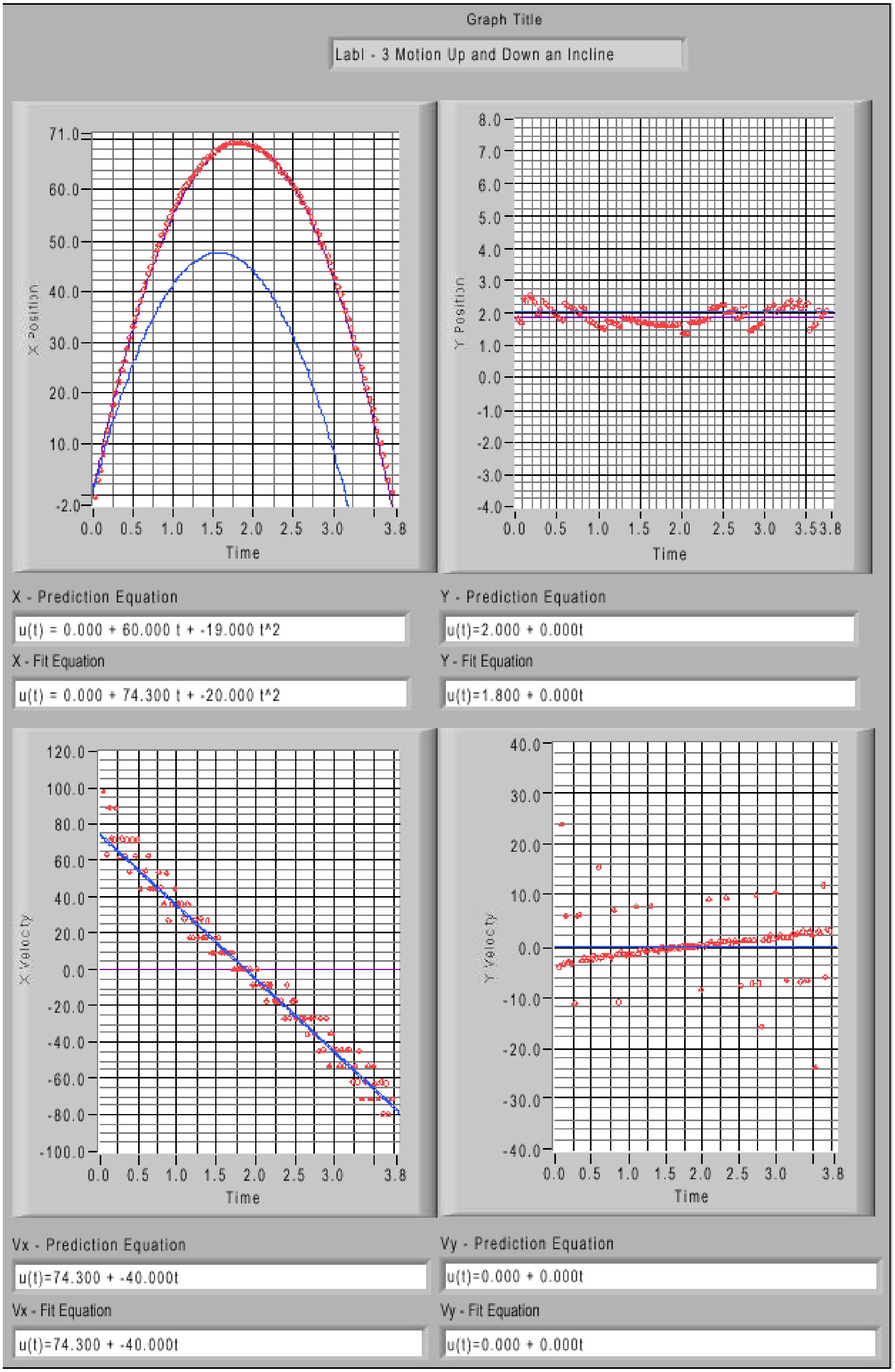


Teaching Tips:
Have the students compare the results of the motion of the cart up and down the incline. Watch for students who think the acceleration changes direction for the two cases. The graphical analysis is very useful here if the students understand the meaning of the slope of the velocity vs. time graph. If a group is having trouble, it is useful to ask the direction of the change of velocity as the cart goes up the ramp, comes down the ramp, and is at its highest point on the ramp. Point out the connection between the direction of an object's change of velocity and the direction of its acceleration.

Difficulties and Major Alternative Conceptions:
Many students believe that the acceleration decreases as the cart moves up the incline and assume that it goes to zero at the top. These students will probably incorrectly say that the cart "stops" at its highest point. Some students believe the acceleration goes from negative to positive as it moves up the incline. Others may believe that the acceleration is necessarily in the direction of motion.

Prediction and Warm up questions:
Constant and identical acceleration for ALL parts of the motion.

Sample Data:
Inclined angle: $\sin^{-1}(8.7/220.5)$;
Acceleration: $a=40 cm/s^2$.


Graph Title
Labl - 3 Motion Up and Down an Incline
X Position
Time
Y Position
Time
X - Prediction Equation
u(t) = 0.000 + 60.000 t + -19.000 t^2
X - Fit Equation
u(t) = 0.000 + 74.300 t + -20.000 t^2
Y - Prediction Equation
u(t)=2.000 + 0.000t
Y - Fit Equation
u(t)=1.800 + 0.000t
X Velocty
Time
Y Velocty
Time
Vx - Prediction Equation
u(t)=74.300 + -40.000t
Vx - Fit Equation
u(t)=74.300 + -40.000t
Vy - Prediction Equation
u(t)=0.000 + 0.000t
Vy - Fit Equation
u(t)=0.000 + 0.000t

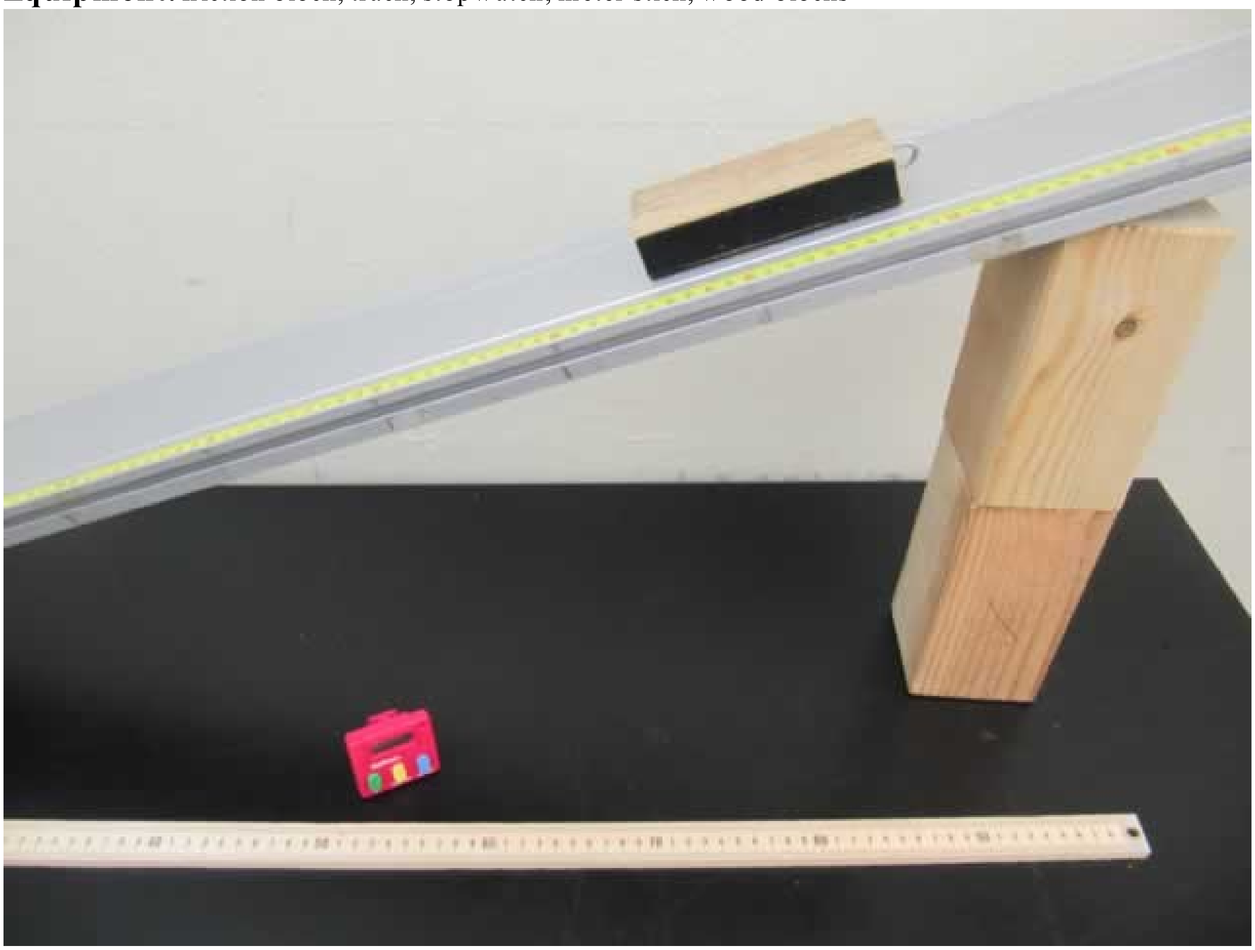
Lab 2 Problem #4: Normal Force and Frictional Force

Problem: Calculate the frictional force on an object sliding down a ramp, given the distance the acceleration of the object, the angle of the ramp, and the weight of the object. Based on that information, calculate the coefficient of kinetic friction for wood on aluminum. Sketch a graph of the kinetic frictional force on the block as a function of the normal force on the block.

Purpose:

- Another lab problem involving motion under a constant force in which components have to be resolved non-trivially. A new ingredient is the retarding force due to friction. This problem was meant to be solved using force arguments and Newton's Laws.
- To learn a way to measure a frictional coefficient.

Equipment: friction block, track, stopwatch, meter stick, wood blocks



Teaching Tip:

1. Be sure the block doesn't slide along the yellow ruler tape.
2. Don't let the block crash into the end stop. Be sure to remove the end stops before sliding the blocks down the track.
3. It is important that the wooden block accelerate smoothly down the ramp, otherwise the friction force will not be constant. Increasing the angle of incline will help solve this problem.

Difficulties and Alternative Conceptions:

The normal force is difficult for the students. Students generally believe that the normal force is always either a constant or equal to the weight of an object. They do not associate the normal force with a physical interaction with another object. These students believe that there is always a normal force, even if there is nothing touching the object. The students often have difficulty relating the angle of the incline to the direction of the normal force.

Prediction and Warm-up Questions:

$N = mg\cos\theta$,

$f_k = mg\sin\theta - ma$,

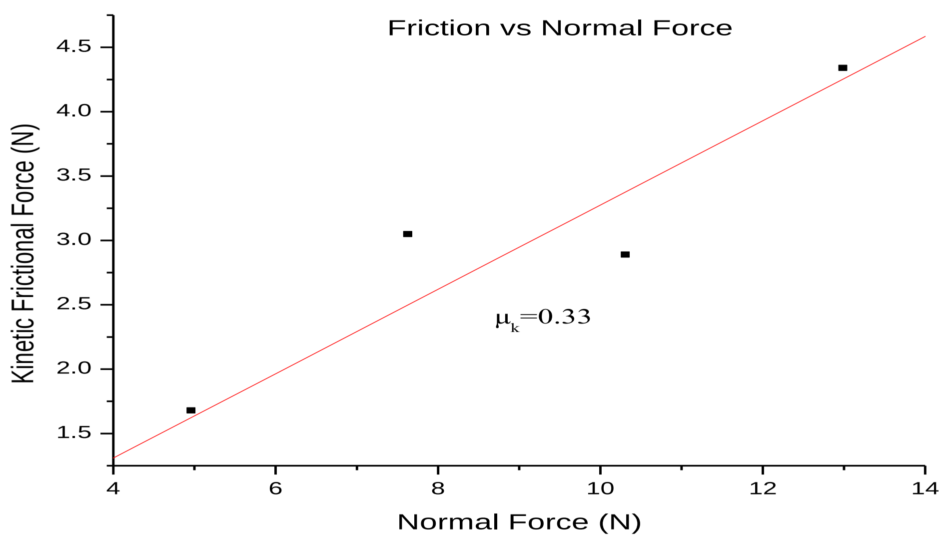
where θ is the angle of incline of the track to the horizontal, m is the mass of the wooden block, a is the acceleration of the wooden block moving down along the inclined track, d is the distance traveled by the block.

The graph of f_k-N is a slope line, which indicates f_k is proportional to N.

Sample Data:

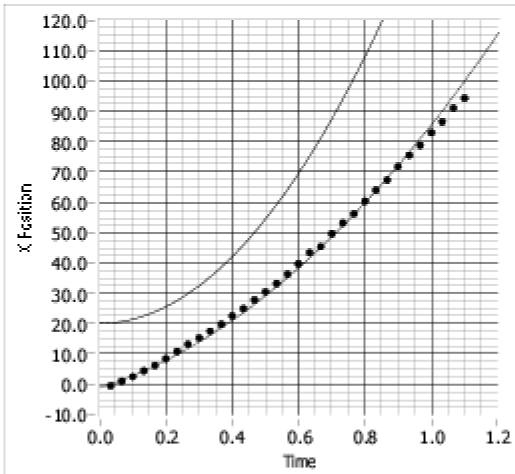
Inclined angle: $\sin^{-1}(76.5/185.2)=24.40$ degree

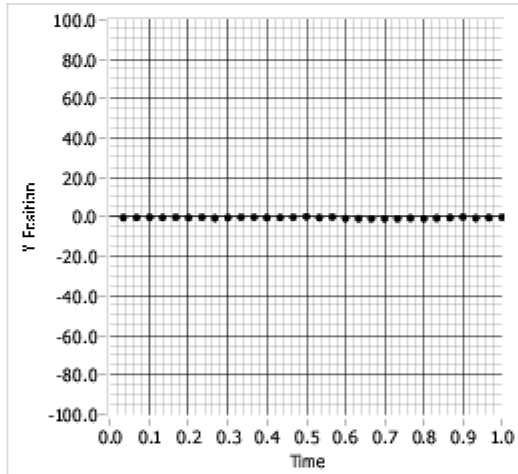
m (g)	557.58	856.88	1157.70	1457.80
a (cm/s^2)	103.6	50.0	156.0	108.0
Normal force N (N)	4.98	7.65	10.33	13.01
Frictional force. f_k (N)	1.67	3.04	2.88	4.33



Graph Title

1201 Lab V Prob #5 m=557.58g





X - Prediction Equation

u(t) = 20.000 + 0.000 t + 137.000 t^2

X - Fit Equation

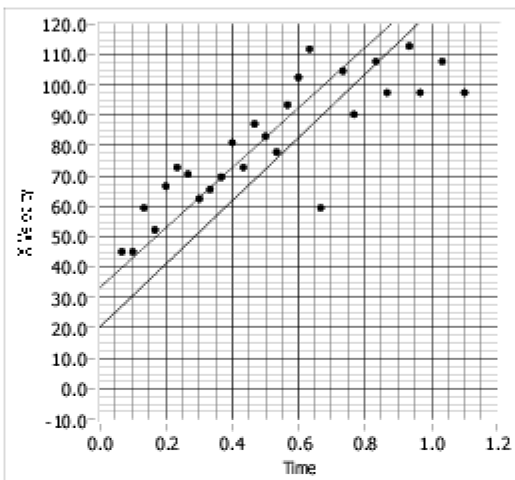
u(t) = -1.300 + 34.800 t + 51.800 t^2

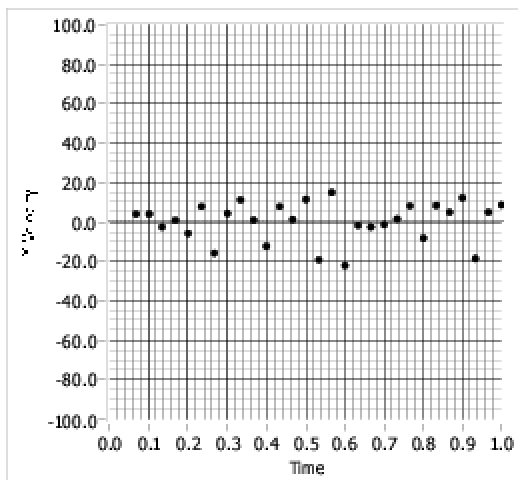
Y - Prediction Equation

u(t) = 0.000 + 0.000t

Y - Fit Equation

u(t) = 0.000 + 0.000t





Vx - Prediction Equation

u(t) = 20.000 + 104.000t

Vx - Fit Equation

u(t) = 33.000 + 98.700t

Vy - Prediction Equation

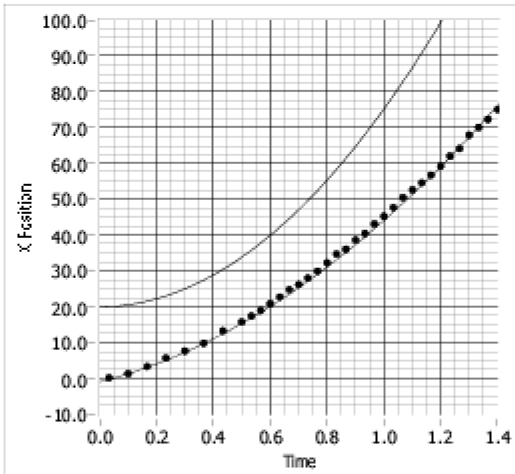
u(t) = 0.000 + 0.000t

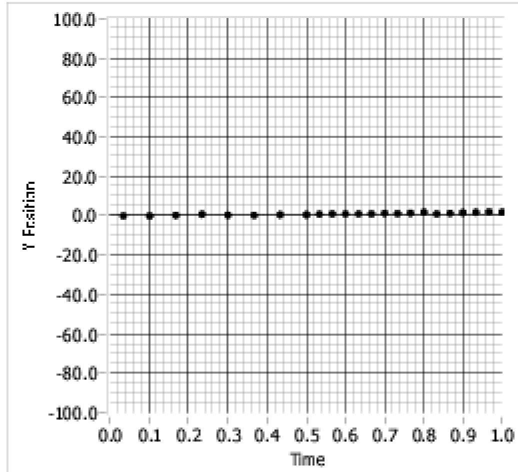
Vy - Fit Equation

u(t) = 0.000 + 0.000t

Graph Title

1201 Lab V Prob #5 m=856.88g





X - Prediction Equation

u(t) = 20.000 + 0.000 t + 55.000 t^2

X - Fit Equation

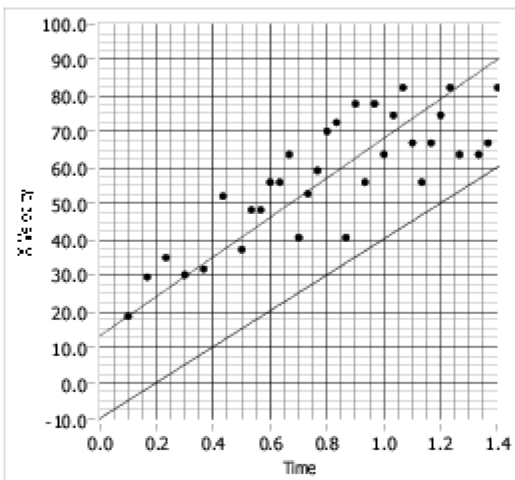
u(t) = -1.000 + 20.000 t + 25.000 t^2

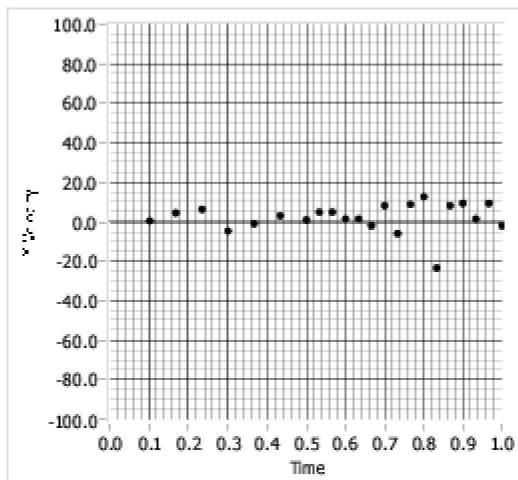
Y - Prediction Equation

u(t) = 0.000 + 0.000t

Y - Fit Equation

u(t) = 0.000 + 0.000t





Vx - Prediction Equation

u(t) = -10.000 + 50.000t

Vx - Fit Equation

u(t) = 13.000 + 55.000t

Vy - Prediction Equation

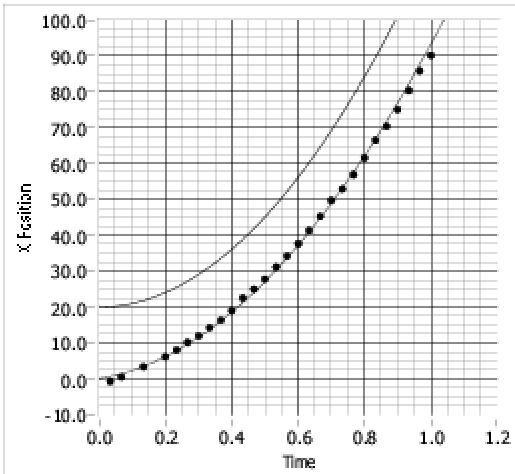
u(t) = 0.000 + 0.000t

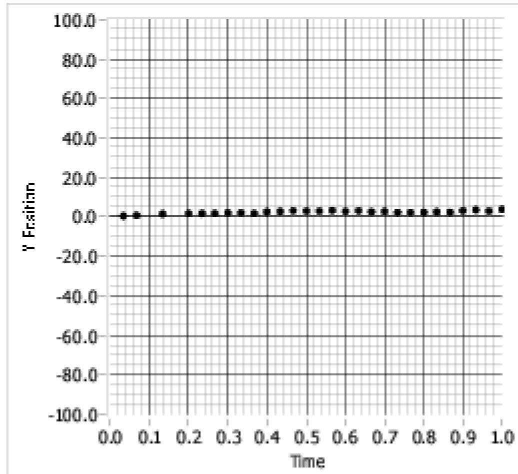
Vy - Fit Equation

u(t) = 0.000 + 0.000t

Graph Title

1201 Lab V Prob #5 m=1157.70g





X - Prediction Equation

u(t) = 20.000 + 0.000 t + 100.000 t^2

X - Fit Equation

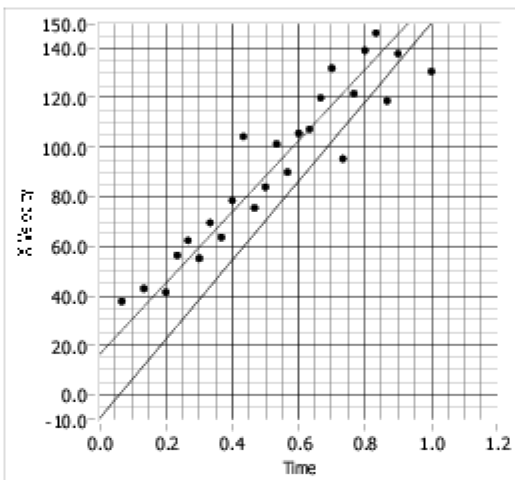
u(t) = 0.000 + 15.000 t + 78.000 t^2

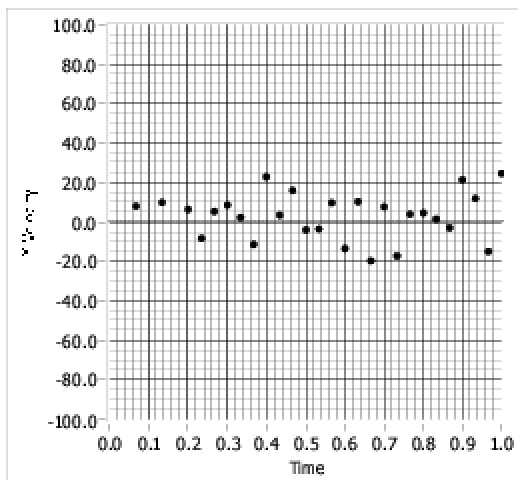
Y - Prediction Equation

u(t) = 0.000 + 0.000t

Y - Fit Equation

u(t) = 0.000 + 0.000t





Vx - Prediction Equation

u(t) = -10.000 + 160.000t

Vx - Fit Equation

u(t) = 16.000 + 144.000t

Vy - Prediction Equation

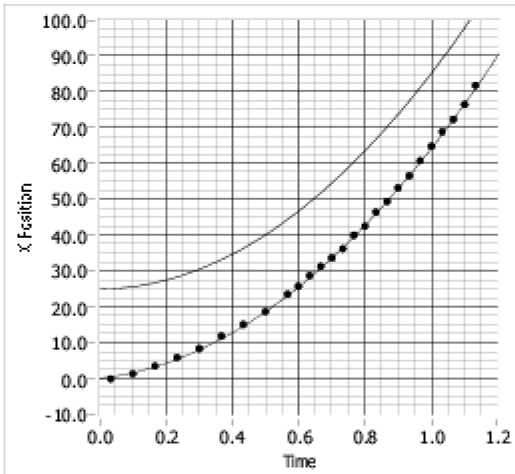
u(t) = 0.000 + 0.000t

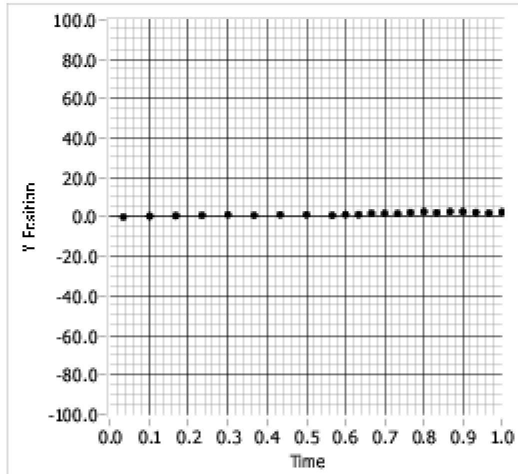
Vy - Fit Equation

u(t) = 0.000 + 0.000t

Graph Title

1201 Lab V Prob #5 m=1457.80





X - Prediction Equation

u(t) = 25.000 + 0.000 t + 60.000 t^2

X - Fit Equation

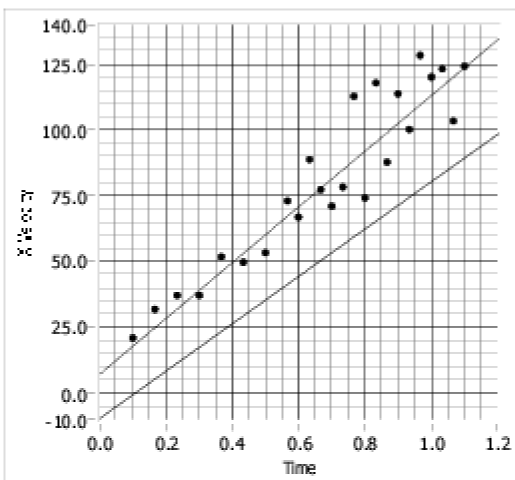
u(t) = 0.000 + 10.000 t + 54.000 t^2

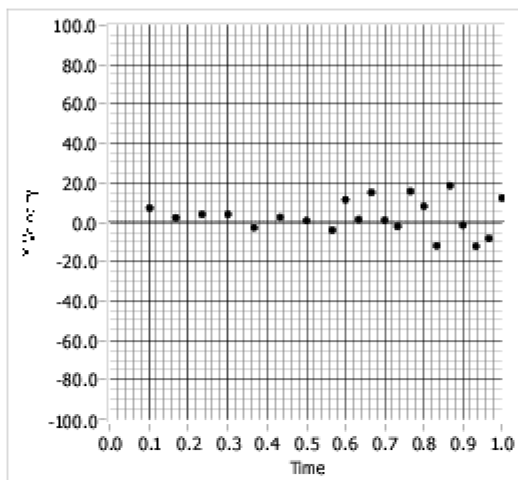
Y - Prediction Equation

u(t) = 0.000 + 0.000t

Y - Fit Equation

u(t) = 0.000 + 0.000t





Vx - Prediction Equation

u(t) = -10.000 + 90.000t

Vx - Fit Equation

u(t) = 6.800 + 106.000t

Vy - Prediction Equation

u(t) = 0.000 + 0.000t

Vy - Fit Equation

u(t) = 0.000 + 0.000t

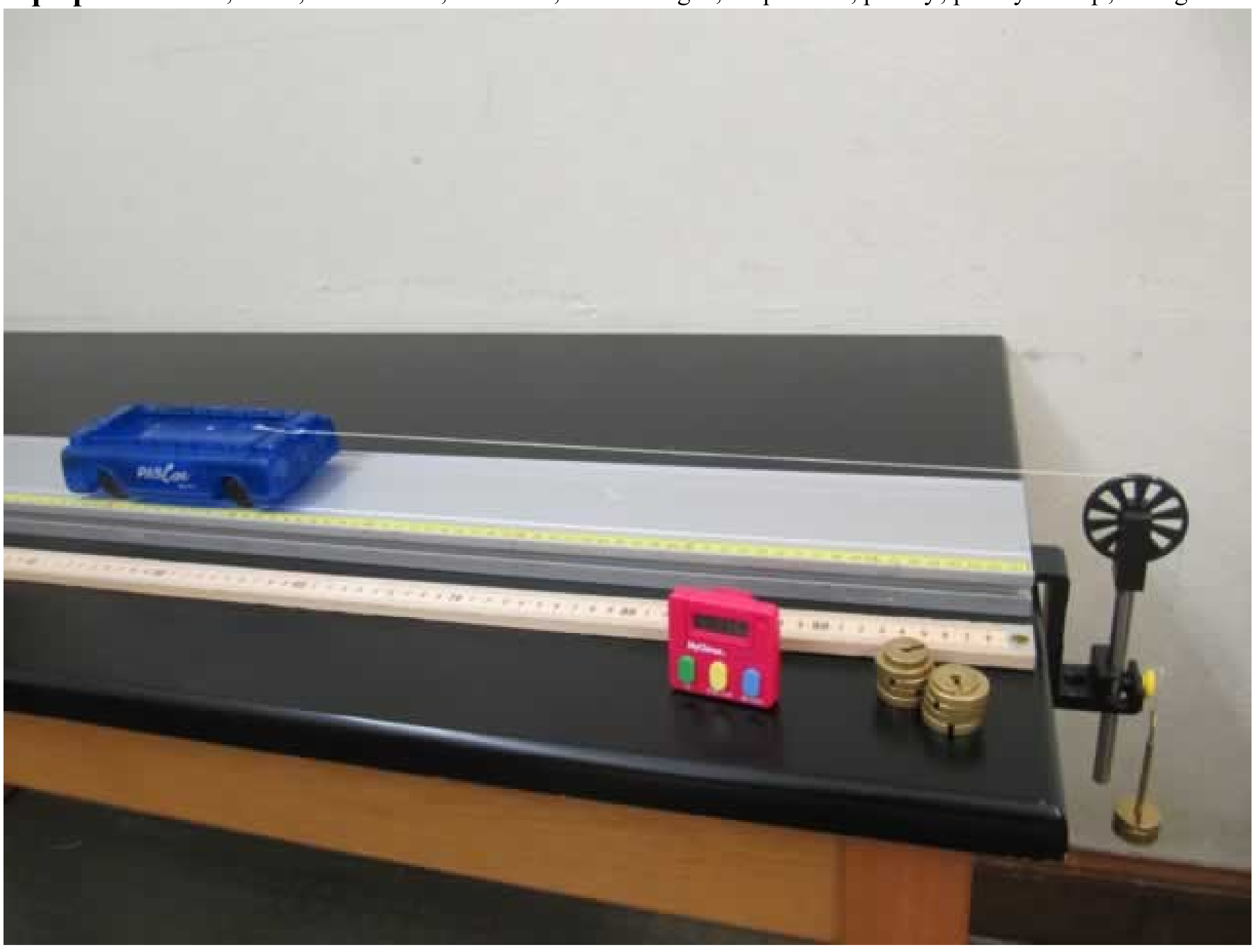
Lab 2 Problem #5: Velocity and Force

Problem: Calculate the velocity and acceleration of a cart being accelerated by a hanging weight; find the velocity and acceleration both before and after the hanging weight has reached the floor. Determine whether the force exerted by the string on the cart is equal to the weight of the hanging object.

Purpose:

- Another lab problem involving motion under a constant force, where more than one object have to be analyzed. This problem is meant to be studied using forces and Newton's Laws.
- To understand why the force on the rope is not equal to the weight of the hanging mass. (Weight has to be larger than the tension for the hanging object to accelerate downward.)

Equipment: cart, track, meter stick, mass set, mass hanger, stopwatch, pulley, pulley clamp, string.



Teaching Tips:

1. The students need enough string to hang over the pulley, but it should be long enough so that the mass hits the ground **before** the cart runs out of track.
2. It is amazing how quickly students forget kinematics. This problem will reinforce the idea that physics builds upon itself.
3. Many students may have difficulty with the necessity of drawing the two force diagrams required to solve this problem. Most will want to equate the force on the cart with the weight hanging on the string. Avoid using the "clever" system of the weight + string + cart in your explanations. This system tends to confuse students and obscure the connection of forces with physical interactions.

Difficulties and Alternative Conceptions:

Many students believe that the weight of the hanging mass is a force on the cart. Others know that the string is exerting a force on the cart but believe that the string tension is equal to the weight of the hanging mass.

Prediction and Warm-up Questions:

Before object A hits ground

Constant acceleration a=mg/ (m+M)

$$T = \frac{mMg}{m+M}$$

After object A hits ground

$$v = \sqrt{\frac{2mgh}{m+M}} \quad ,$$

where v is the velocity of the cart after the hanger hits ground, T is the force on the string before the hanger hits ground, m is the mass of object A, M is the mass of the cart and h is the height through which object A falls.

Sample Data:

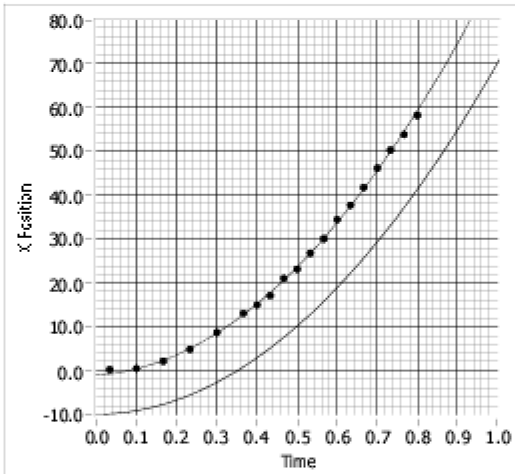
The printout for the measurement of final velocity of the cart is included at the end of following sample data.

h=38.2cm M=251.78g m=50.07g
Predicted final velocity of the cart: 111.43 cm/ s
Measured final velocity of the cart: 99.3 cm/ s

Predicted force on the string before hitting the floor: 4.09 N
Measured force on the string before hitting the floor (M*a): 4.38 N

Graph Title

1201 Lab V Prob #6 Before hitting floor

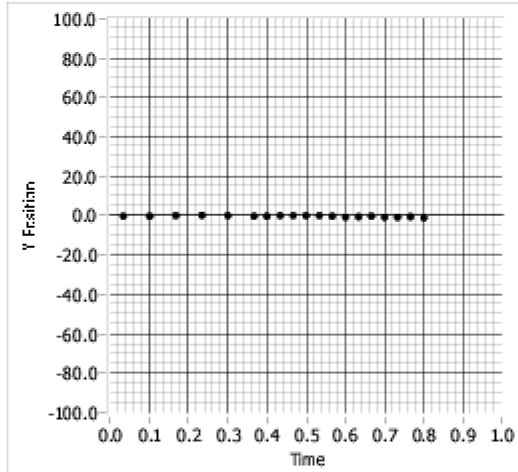


X - Prediction Equation

u(t) = -10.000 + 0.000 t + 80.000 t^2

X - Fit Equation

u(t) = -1.100 + 5.700 t + 87.000 t^2

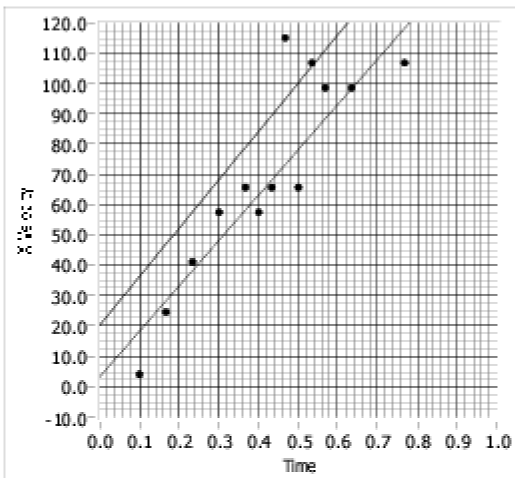


Y - Prediction Equation

u(t) = 0.000 + 0.000t

Y - Fit Equation

u(t) = 0.000 + 0.000t

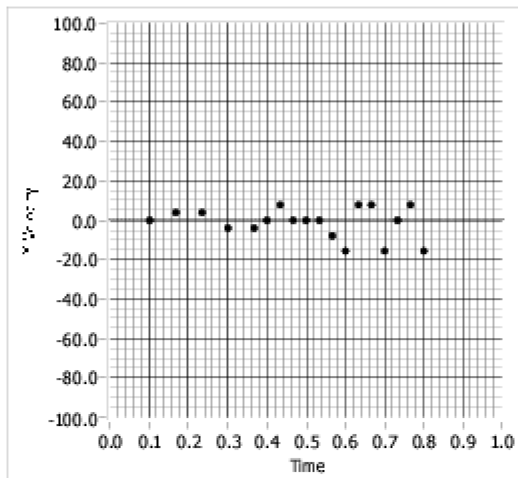


Vx - Prediction Equation

u(t) = 20.000 + 160.000t

Vx - Fit Equation

u(t) = 3.000 + 150.000t



Vy - Prediction Equation

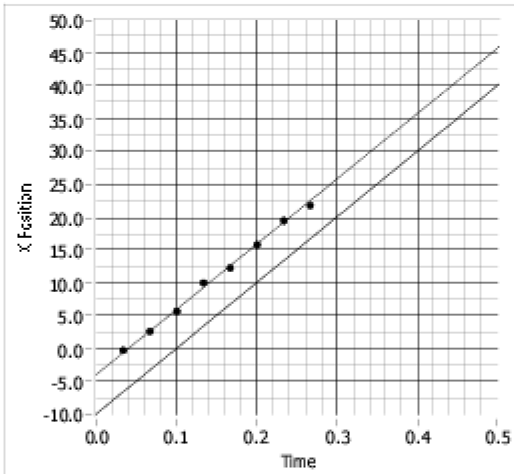
u(t) = 0.000 + 0.000t

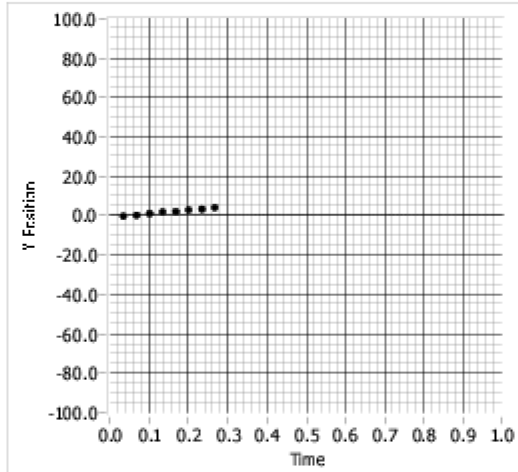
Vy - Fit Equation

u(t) = 0.000 + 0.000t

Graph Title

1201 Lab V Prob #6 after hitting floor





X - Prediction Equation

u(t) = -10.000 + 100.000t

X - Fit Equation

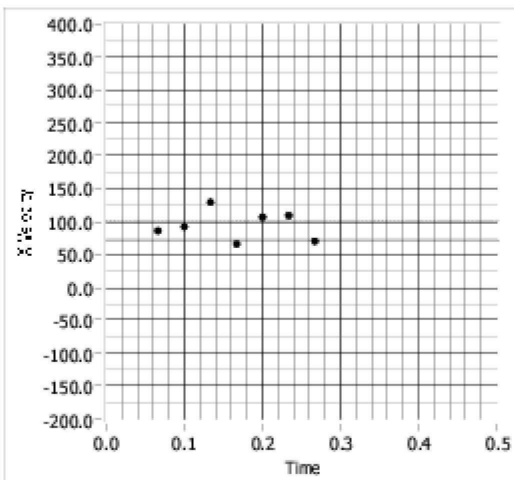
u(t) = -4.000 + 99.300t

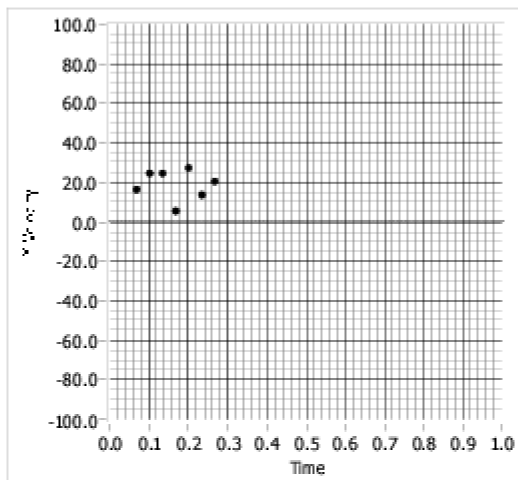
Y - Prediction Equation

u(t) = 0.000 + 0.000t

Y - Fit Equation

u(t) = 0.000 + 0.000t





Vx - Prediction Equation

u(t) = 70.000 + 0.000t

Vx - Fit Equation

u(t) = 100.000 + 0.000t

Vy - Prediction Equation

u(t) = 0.000 + 0.000t

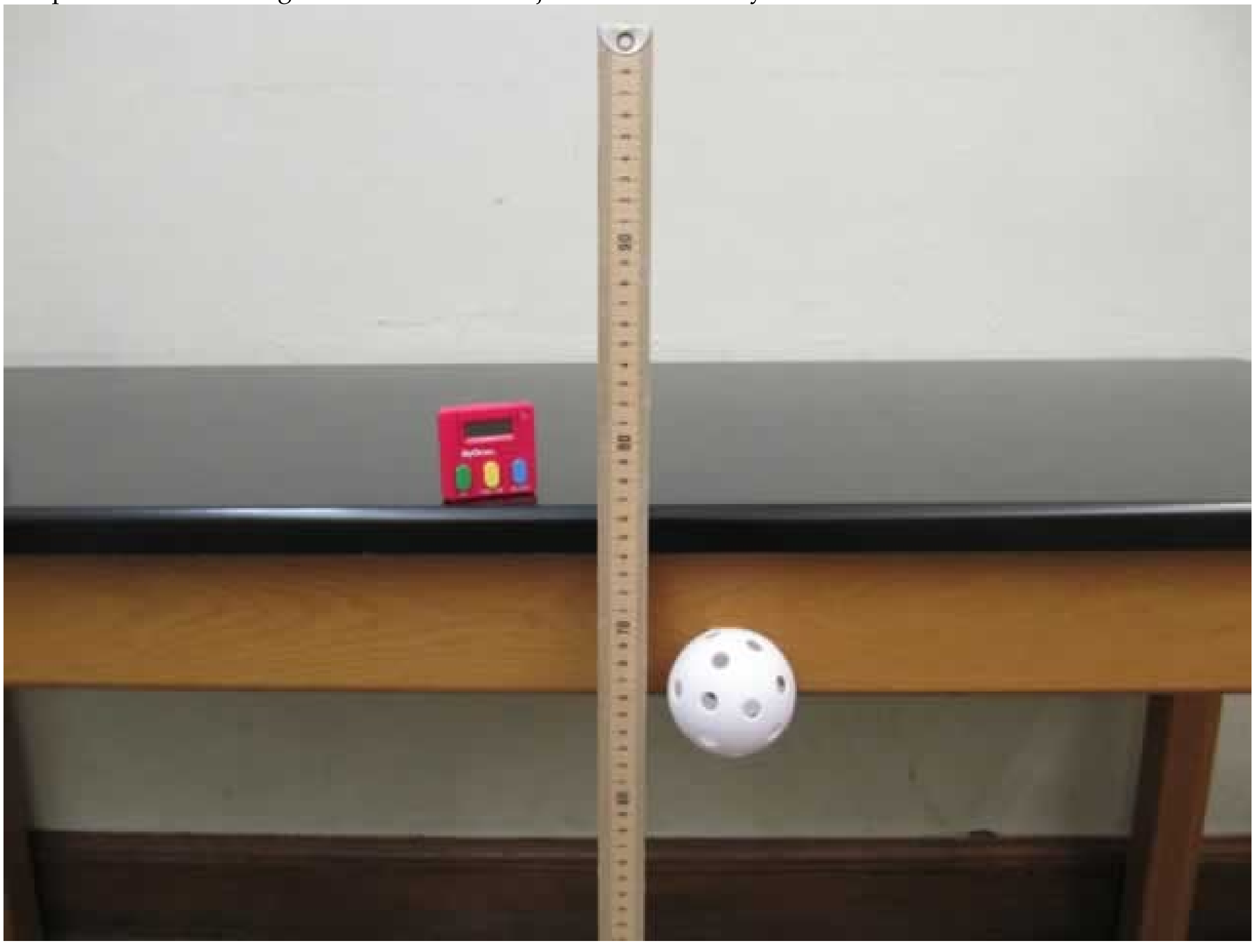
Vy - Fit Equation

u(t) = 0.000 + 0.000t

Lab 2 Problem #6: Two Dimensional Projectile Motion and Velocity

Purpose:

- To show the students that two-dimensional motion can be treated as two separate one-dimensional problems describing the motion of the object simultaneously.



Teaching Tips:

1. This is a great lab for the students to practice decomposing vectors. This is difficult for most of them to accept intellectually and they need the practice.

2. Parallax does influence the outcome of the movie analysis. It can skew the results by 10%, or even more if the students are not thoughtful about their movie making. The parallax issue is why the students are asked to use the object in motion to calibrate their computers. Shadows and image resolution may prevent an accurate calibration from the balls in flight. In this case, the students should put an object of known length *in the plane of motion*.

Difficulties and Alternative Conceptions:

Students have difficulty with two-dimensional motion. Part of this difficulty is mathematical in nature (i.e., solving systems of equations), but most of it is physics. The concept that horizontal and vertical motions are independent is difficult. Be on the lookout for students who draw V-shaped velocity-time graphs.

Prediction and Warm up questions:

The horizontal and vertical positions and velocities are given by:

$$x(t) = v_{ix}t\,, \qquad v_x(t) = v_{ix}\,,$$

$$y(t) = v_{iy} - \tfrac{1}{2}gt^2\,, \qquad v_y(t) = v_{iy} - gt\,,$$

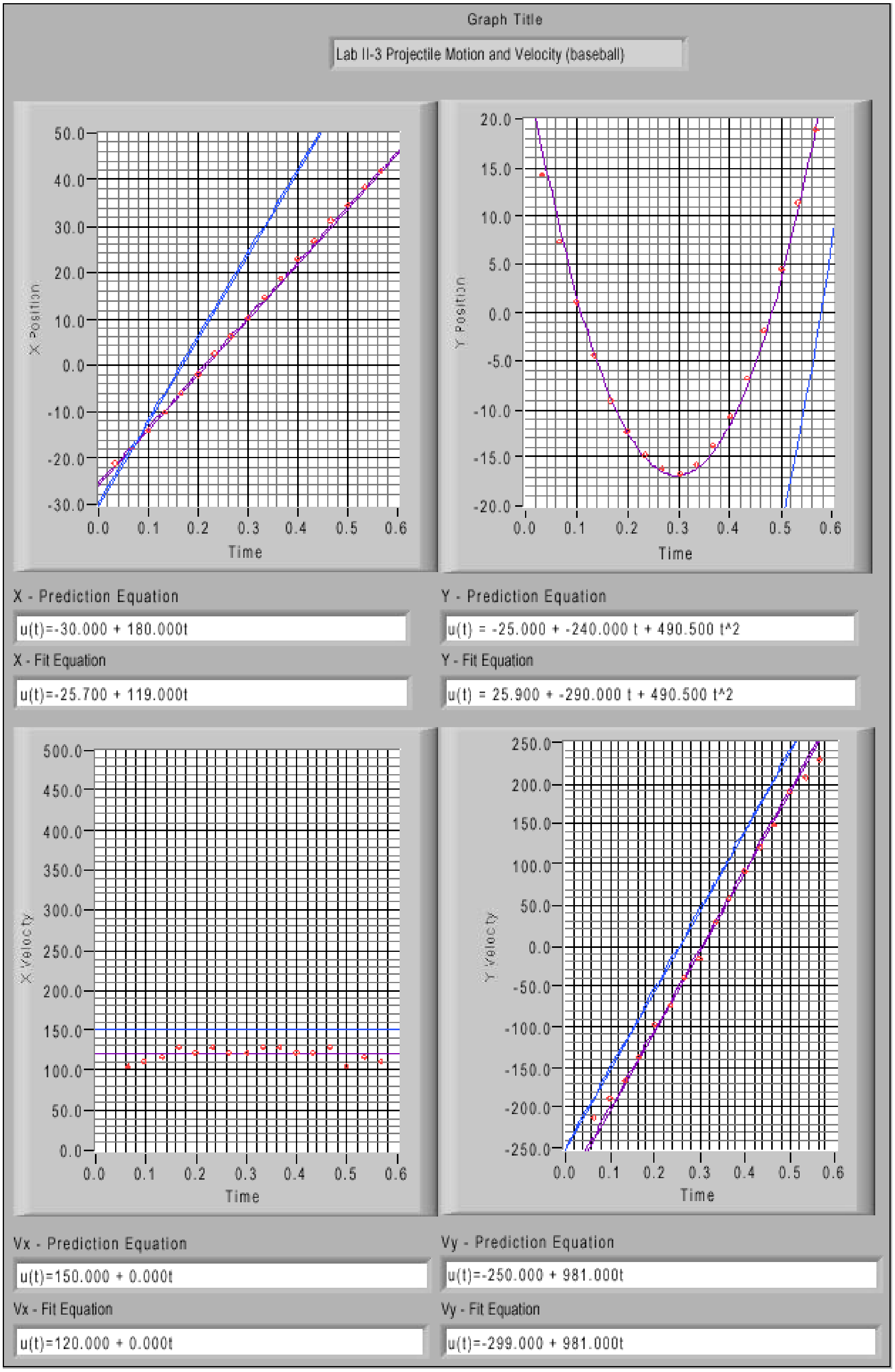
where v_{ix} is the horizontal component of the initial velocity, v_{iy} is the vertical component of the initial velocity, and the initial position of the ball is taken to be the origin of the coordinate system.

Sample Data:

The printouts for all measurements are included at the end of following sample data.

Using baseball: mass = 144.50g, diameter = 7.40cm.

The motion along X (horizontal) axis is a constant velocity motion with velocity 119 cm/s, and the motion along Y (vertical) axis is a constant acceleration motion with acceleration 981 cm/s^2, with the defined positive directions for both axes.


Graph Title
Lab II-3 Projectile Motion and Velocity (baseball)
X Position
Time
Y Position
Time
X - Prediction Equation
u(t)=-30.000 + 180.000t
X - Fit Equation
u(t)=-25.700 + 119.000t
Y - Prediction Equation
u(t) = -25.000 + -240.000 t + 490.500 t^2
Y - Fit Equation
u(t) = 25.900 + -290.000 t + 490.500 t^2
X Velocity
Time
Y Velocity
Time
Vx - Prediction Equation
u(t)=150.000 + 0.000t
Vx - Fit Equation
u(t)=120.000 + 0.000t
Vy - Prediction Equation
u(t)=-250.000 + 981.000t
Vy - Fit Equation
u(t)=-299.000 + 981.000t

Laboratory 3: Statics

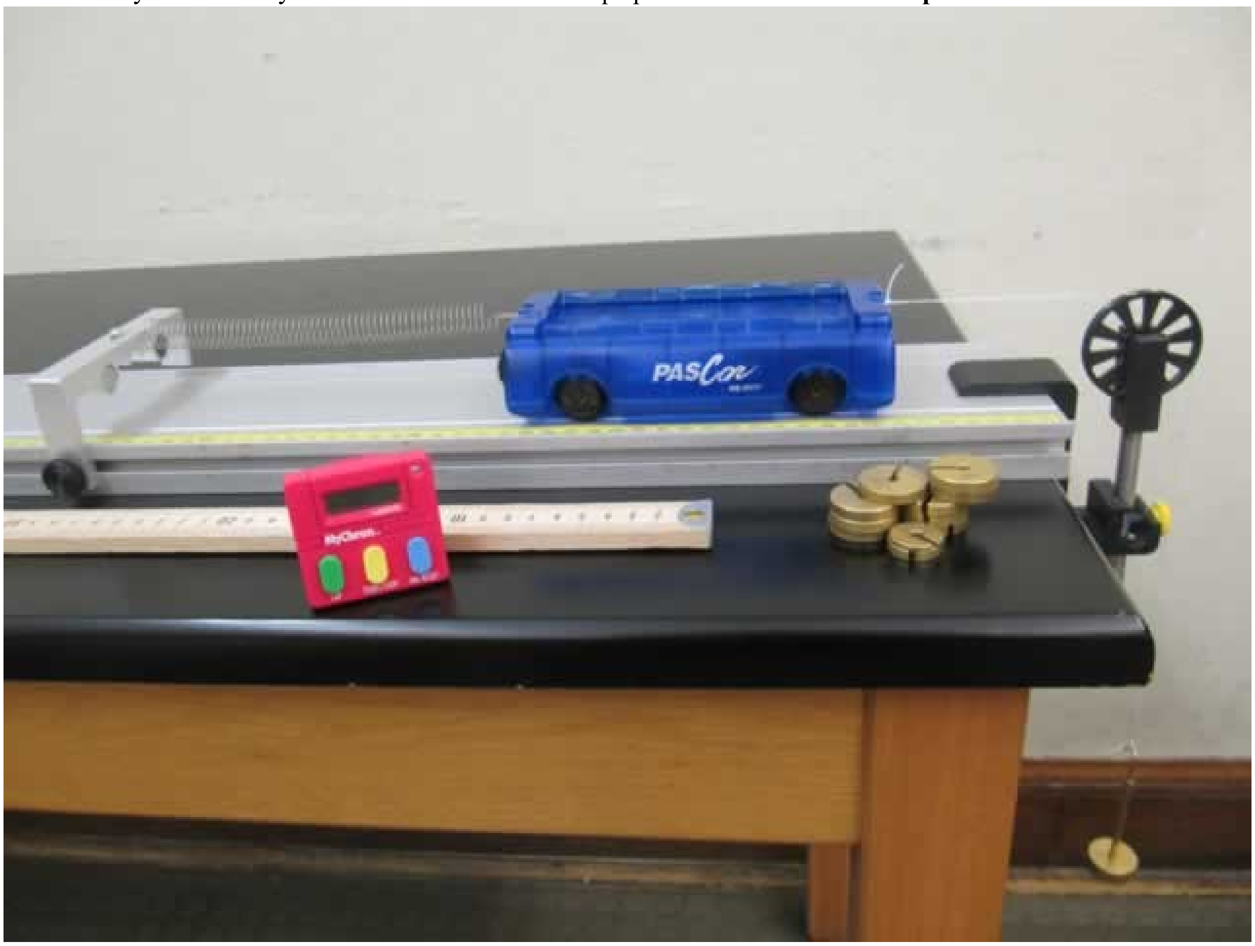
This Lab offers students a chance to study the conditions of static equilibrium and use the equilibrium conditions to solve problems. Problems #1-#2 concern one-dimensional statics involving springs. Problems #3 and #4 present slightly harder problems in statics that require thinking about components of vectors (forces). The last problem (#5) involves torques.

Based on your experience and your knowledge of your students, you may wish to design your own variations of experiments, e.g. balancing using a meterstick as a 'see-saw', or using disks with strings wrapped around them to demonstrate the concept of torque. If you find them useful, please describe them on the Lab Evaluation sheet at the end of the Instructor's Guide and submit to labhelp@physics.umn.edu.

Lab 3 Problem #1: Springs and Equilibrium I
Problem #2: Springs and Equilibrium II

Purpose:
- One-dimensional statics.

Equipment:
Spring, string, mass set, mass hanger, cart, pulley, meter stick, aluminum track, end stop.
Make sure you remind your students to treat the equipment with **care and respect**.



Problem #1:
Calculate the extension of a spring when (a) a mass is hanging from it and (b) the spring is attached to a cart on a horizontal track, the cart is attached to a string, the string runs over a pulley, and a mass hangs from the other end of the string.

Problem #2:
Calculate the extension of a spring (a) when it is attached to an end-stop, and to a mass by a string over a pulley; (b) when it is attached to two masses by strings over pulleys.

Prediction:
Force should be proportional to extension within the elastic limit. The spring constant characterizes the stiffness of the spring. The S.I. units are N/ m or dynes/ cm = 0.001N/ m.
The cart should not affect the spring constant. The spring should stretch the same amount if all the weights are the same in problem#2.

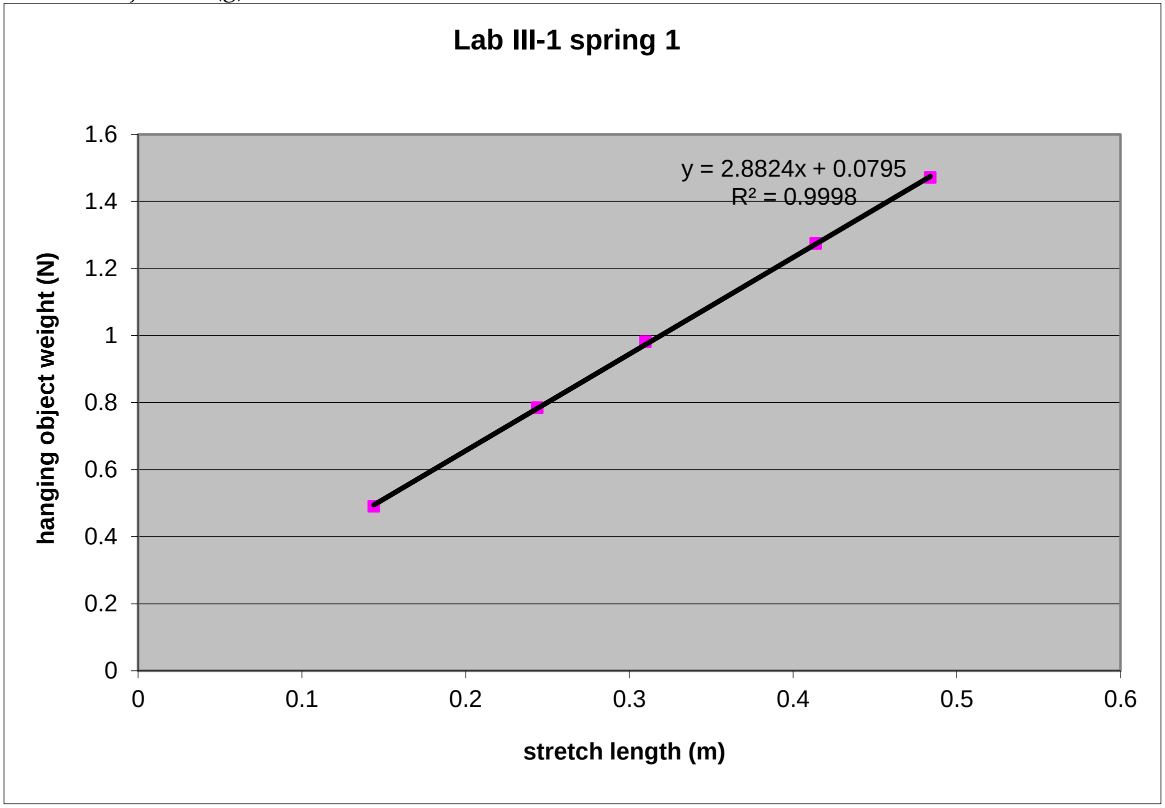
Sample Data:

Please refer to the first problem in the Oscillation lab for sample measurements of the spring constant. A typical value for the spring constant of the larger springs is 2.7 N/ m.

note: The ABSOLUTE extension of the spring may be misleading as a measure of the force it exerts; it may not extend at all for small forces. It is probably reasonable to assume that once two forces are large enough to stretch the spring, the difference in spring extensions (delta-x) is proportional to the difference in forces exerted (= delta-F/k).

1) Spring1

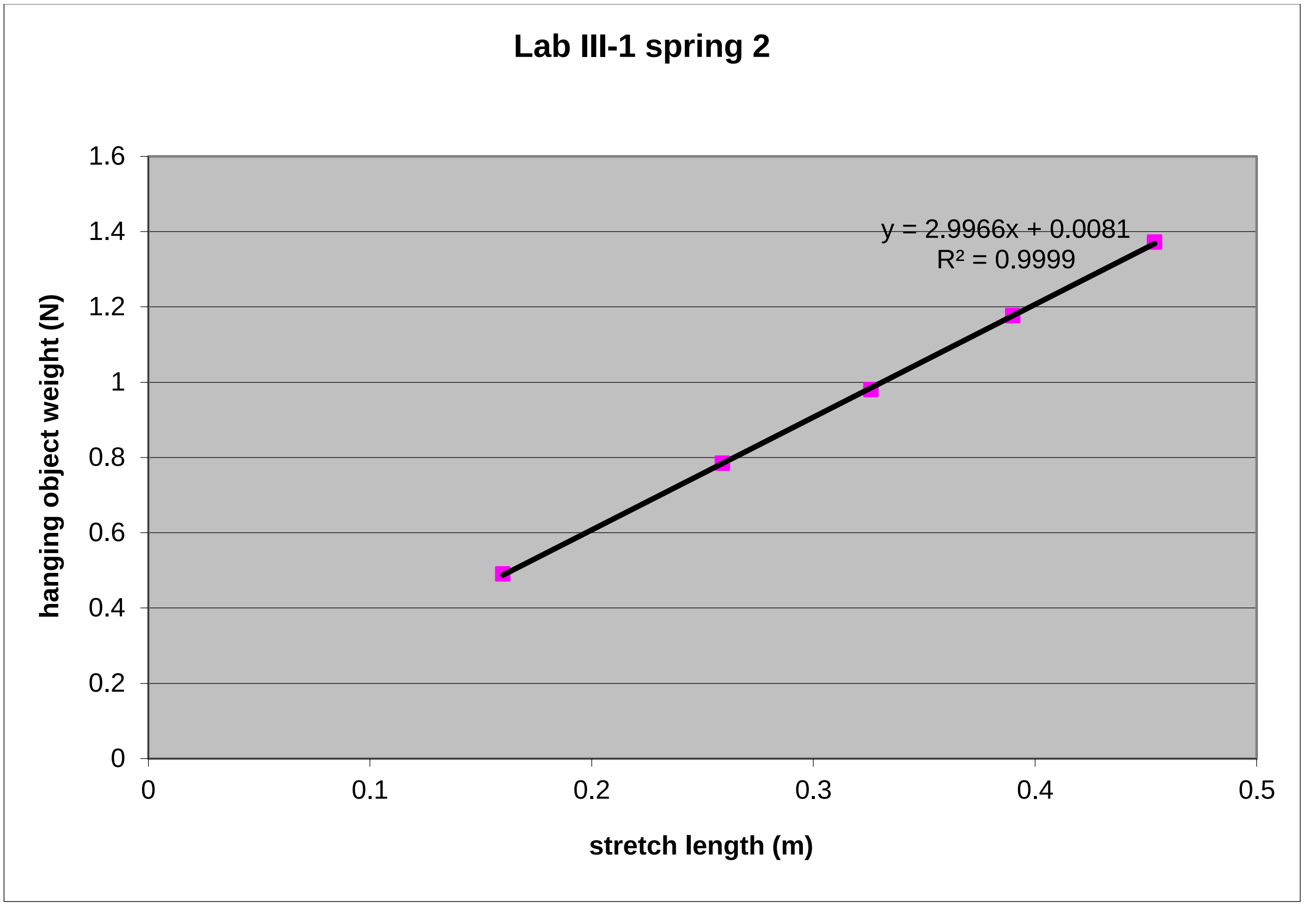
Stretch length d (cm)	14.4	24.4	31	41.4	48.4
Mass of object m (g)	50	80	100	130	150



Spring constant $k_1 = 2.882$ (N/m).

2) Spring 2

Stretch length d (cm)	16	25.9	32.6	39	45.4
Mass of object m (g)	50	80	100	120	140



Spring constant $k_2 = 2.997$ (N/m).

Lab 3 Problem #3: Leg Elevator

Purpose:

- The students' first lab problem in 2D statics. Non-trivial components of vectors need to be resolved.

Equipment: aluminum track, end-stop, end-of-track pulley, spring, mass set, mass hangers, cart, cart masses, string, meter stick, wood blocks.

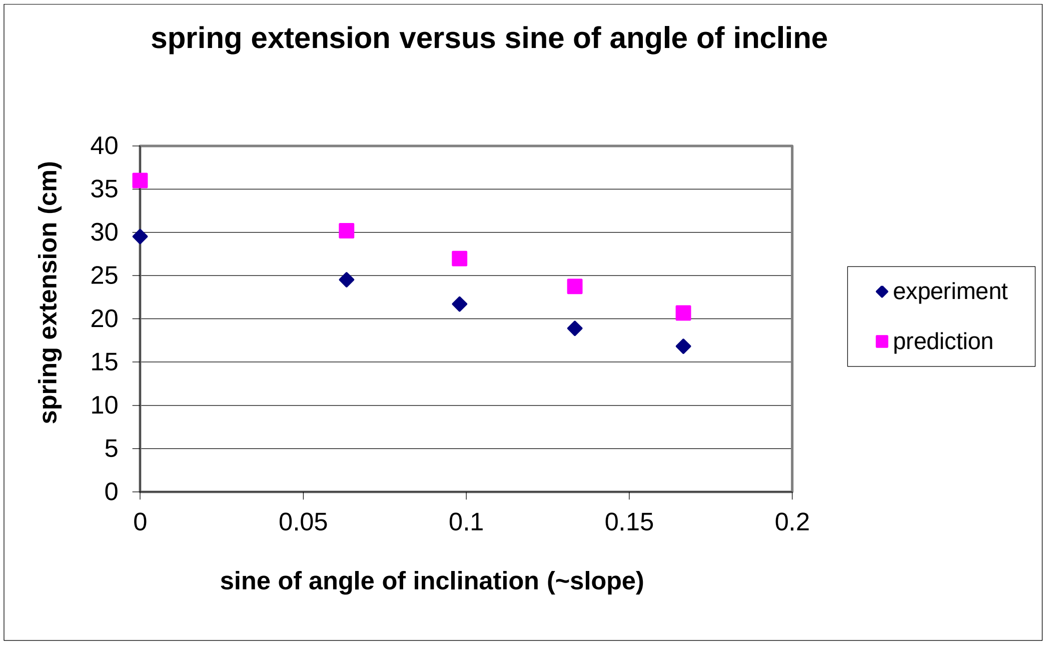
Problem:

Calculate the spring extension as a function of the track angle.

Prediction:

$$kx = m_w g - M_{cart} g \sin\theta$$

Sample Data:



The trend in the prediction and the measurements look the same. The consistent slight difference or shift in the data points might be due to friction.

*note: The ABSOLUTE extension of the spring may be misleading as a measure of the force it exerts on the cart, because it may not extend at all for small forces. In the graph above, it looks as if the graph's **slope** is within 10% of the predicted slope ... in other words, assume that once the force is large enough to stretch the spring, the difference in extensions (delta-x) is proportional to the difference in forces exerted (= delta-F/k).*

Lab 3 Problem #4: Equilibrium of a Walkway

Purpose:

- To have students use Newton's second law in a situation that requires the use of force components and the knowledge of the relationship of the direction of the forces to the geometry of the situation.

Teaching Tips:

1. It is a good idea to tell your students, **before they come to lab**, that the algebra is messy. Students often think that they are doing something wrong if the algebra isn't simple. It is interesting to point out to your students that the equation is **not** simple even though the system is not particularly complicated. This is a good example of how quickly the mathematics can become complicated in the real world yet the problem remains soluble.

2. Students will have trouble with the predictions. You should insist they do them before they arrive, but be prepared to dedicate class time to letting the students work on their predictions again after you compare group predictions in class. Lead a class discussion to highlight the difficulties that students are having and suggest solutions to those difficulties.

3. Resist the urge to do the problem for the class. The students can do this problem if you have confidence in them. Let them try.

4. Often students leave such quantities as θ in their equation. If another group does not point out that θ can be determined by measuring lengths, make sure you do so.

5. This is a good opportunity to encourage your students to use extreme cases to check their results. Ask them to determine what happens when $M \rightarrow 0, \infty$. A discussion of taking limits is probably best done in the closing discussion after all measurements have been made.

6. The students need a large enough mass range to show them that the curve is **not linear**. If the students aren't using a large enough range of masses, remind them to look at how the deflection depends on other quantities. They can bring the pulleys together or add masses to the outside weights to increase the range of the central mass before it hits the floor.

7. For the sake of the analysis, assume no error on the masses. They can check this assumption with a balance.

8. Encourage the students to explore both mass ranges $0<M<m$ and $M>m$.

9. An interesting test of the frictionless pulley assumption is to put unequal masses on each side (A and C) and find the maximum difference between A and C that causes the masses to move.

Difficulties and Alternative Conceptions:

Many students do not connect the concept of a force with a physical interaction. They cannot determine the direction of a force from the physical connections of real objects. Some students still confuse the components of a force with the entire force.

Prediction and Warm up questions:

$$h = \frac{LM}{2\sqrt{(2m)^2 - M^2}},$$

where M is the mass of object B, m is the mass of each of the objects A and C, L is the separation of the pulleys, and h is the vertical displacement of object B.

$$[\sin\theta = \frac{M}{2m} \Rightarrow \tan\theta = \frac{M}{\sqrt{(2m)^2 - M^2}}.]$$

Sample Data:

$m_A = 119.12$g; $m_C = 119.21$g
Distance between two pulleys: $L = 40.0$cm

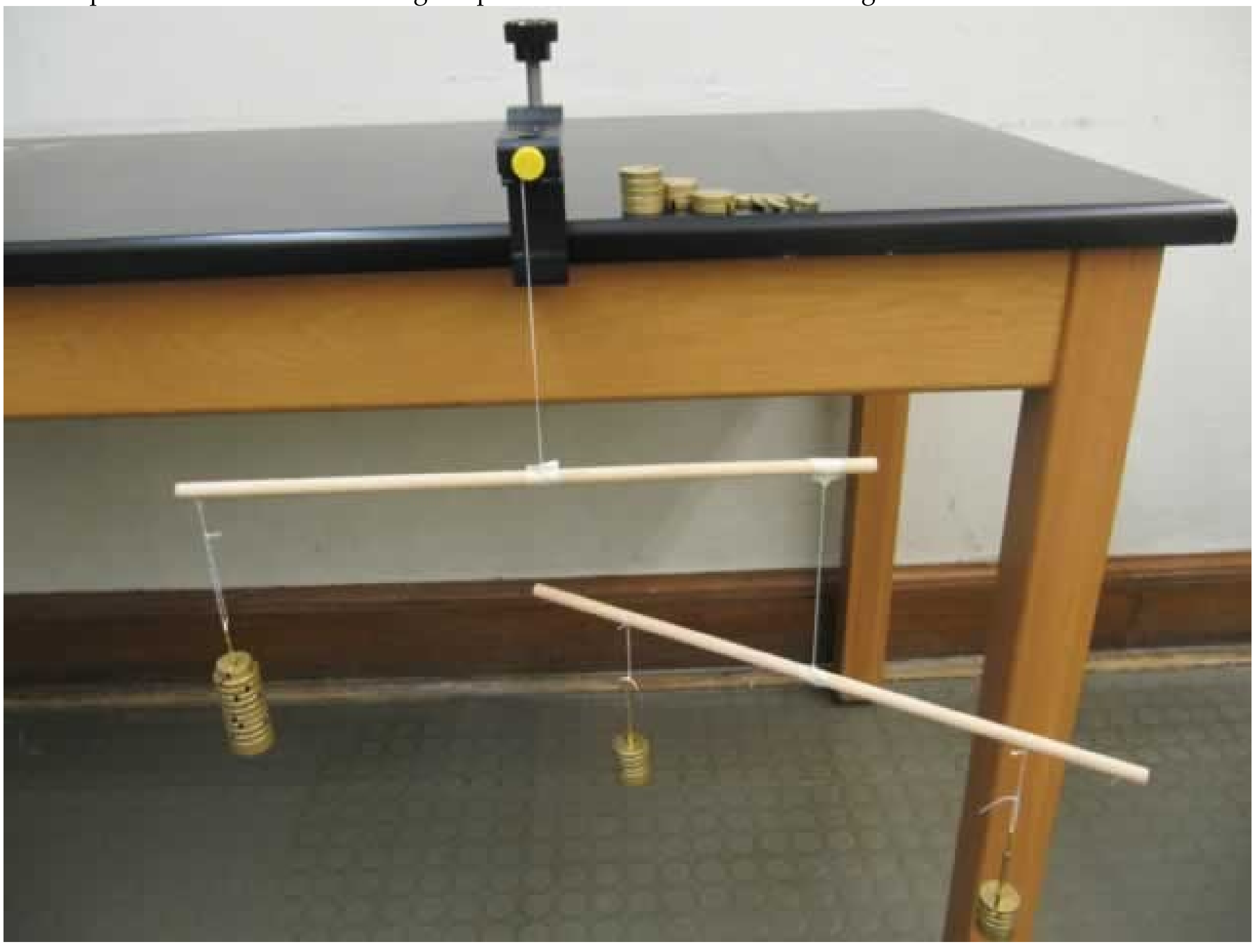
Mass of the suspended object M (g)	Predicted vertical displacement h (cm)	Measured vertical displacement h (cm)
49.48	4.2	4.2
68.85	6.0	6.0
77.92	6.9	6.9

In the calculation of the predicted vertical displacement the average value of m_A and m_C was used for m.

Lab 3 Problem #5: Designing a Mobile

Purpose:

- To present the idea of balancing torque and forces in a familiar setting.



Teaching Tips:

1. The wooden dowel rods do not have a uniform mass density, so the students are asked to find the center of mass of each rod. When you assign the problem, you should point this out to your students!

2. Building a mobile might be common sense for some people. To discourage them from building the mobile first and then predicting the results, you should keep the masses until you are satisfied that they have completed the prediction.

3. You will need to decide which masses to give to each group. Mix it up. Do not use masses larger than 50g, but feel free to bundle some masses together (i.e. a 20g mass and a 10g mass together). Have your students use unequal masses for the lower dowel. They already know that equal masses will balance with the string at the center of mass of the rod.

4. If the students mark the dowel rods for the string placements, ask them to erase the marks when they are done. Don't encourage the students to make marks, but don't discourage it either. We are using wood dowel rods because they are cheap, reusable in the next lab, and erasable. You should have extra dowel rods on the prep table, so replace the rods when they are no longer usable.

5. The prediction equations are messy, but every term is identifiable and the mobile won't balance if they leave out a term (or use the center of the rod for the center of mass!), so expect good results. Note that the torque equations for the two rods are similar, but the final equations should be expressed in terms that the students can measure in the lab (e.g., mass and length).

Difficulties and Alternative Conceptions:

Torque is mystical to most students. Beware of students simply summing up all the torque without taking the direction of rotation into consideration.

Prediction and Warm up questions:

$$r_1 = \frac{l_1(m_b + m_c + m_2) + d_1 m_1}{m_a + m_b + m_c + m_1 + m_2},$$

$$r_2 = \frac{l_2 m_c + d_2 m_2}{m_b + m_c + m_2},$$

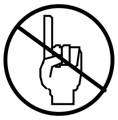
where r_1 and r_2 are the distance of the string positions from mass A and mass B, respectively; l_1 and l_2 are the lengths of rod 1 (rod with mass A) and rod 2 (rod with mass B and mass C), respectively; m_1 and m_2 are the masses of rods 1 and rod 2, respectively; and d_1 and d_2 are the distances from mass A and mass B to the centers of mass of rod 1 and rod 2, respectively.

Sample Data:

Mass of rod 1: m_1 = 25.90(g)
Length of rod 1: l_1 = 52.10(cm)
Center of mass of rod 1: d_1 = 25.70(cm)
Mass of rod 2: m_2 = 20.60(g)
Length of rod 2: l_2 = 50.80(cm)
Center of mass of rod 2: d_2 = 25.00(cm)
Mass of mass A: m_A = 59.70(g)
Mass of mass B: m_B = 55.00(g)
Mass of mass C: m_C = 70.00(g)

Predicted hanging position on rod 1: 35.69(cm)
Measured hanging position on rod 1: 35.67(cm)
Predicted hanging position on rod 2: 27.96(cm)
Measured hanging position on rod 2: 27.90(cm)

Lab 3 Problem #6: Mechanical Arm



MAKE SURE YOUR STUDENTS DO NOT RELEASE THE ARM ABRUBTLY. HAVE THEM CHECK TO ENSURE THE SYSTEM IS CLOSE TO EQUILIBRIUM BEFORE FULLY RELEASING THE SYSTEM. IF THE ARM IS LOADED INCORRECTLY, THE ARM CAN SWING QUICKLY AND FLING PROJECTILES.

Purpose:

- Predict the angle of the system equilibrium. Practice solving rotational statics problems.

Equipment:

Large mass set and hanger, regular mass set, crane bar with hinge, string, pulley, pulley clamp

Problem:

Calculate the how the angle of the boom to the horizontal depends on the weight to be lifted.

Teaching Tips:

1. The rod has a uniform mass density, so it should be easy for the students to find the center of mass of the rod.

2. To discourage students from building the system first and then predicting the results, you should keep the masses until you are satisfied that they have completed the prediction.

3. You will need to decide which masses to give to each group. Mix it up. Use masses in excess of 1 kg for the support line, and feel free to bundle some masses together. Also, give each group different values for the angle between the support line and the rod.

4. If the students mark the rod for the string placements, ask them to erase the marks when they are done. Don't encourage the students to make marks, but don't discourage it either. We are using steel rods because they are reusable in the next lab, and are easy to erase if marked with a pencil. However, the rods are slippery, so you will need to inform your students to wrap the parts of interest with tape. Make sure they take the tape off after they are done.

5. The prediction equations are messy, but every term is identifiable and the crane won't balance if they leave out a term, so expect good results. Note that the torque equation is the only one that's really needed, but you should have the students write down the force equations if they exhibit insufficient understanding of static equilibrium. The final form should be expressed in terms that the students can measure in the lab (e.g., mass and length).

Difficulties and Alternative Conceptions:

Torque is mystical to most students. Beware of students simply summing up all the torque without taking the direction of rotation or angle into consideration.

Prediction and Warm-up Questions:

$$\theta = \arctan\left(\frac{W_A d_A + \frac{1}{2} mgd}{m_B g d_B}\right),$$

where W_A is the weight of object A, m_B is the mass of object B; m is the mass of the bar; $d_A(d_B)$ is the distance between pivot and the point where the string from object A(B) is connected to the bar; and d is the length of the bar.

Sample Data:

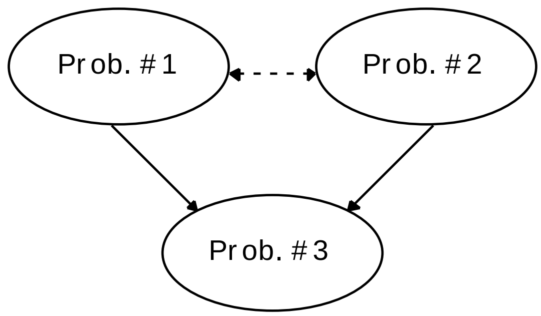
$d_A = 33.2$ (cm), $d_B = 23.6$ (cm),
$d = 36.8$ (cm), $m = 160.6$ (g), $m_B = 196$ (g)

m_A (g)	Predicted angle θ (degrees)	Measured angle θ (degrees)
50.	44.9	45.1
100.	53.6	55.0
150.	59.8	60.6

Laboratory 4: Circular Motion and Rotation

The purpose of this lab is to familiarize the students with the link between linear and rotational motions. As you probably know, rotational kinematics is a very elusive concept the first time around. It is good to discuss it with analogies to 1D kinematics. This lab also should help the students see some of the connections between linear velocity, angular velocity, linear acceleration, tangential acceleration, and centripetal acceleration. They should also be able to identify the relationships between linear motion and rotational motion.

By looking at the flow chart you can see that only two problems are required in this lab. Problems #1 and #2 are very similar – your students probably do not have to do both of these, unless they are having difficulties understanding the concepts of Problem #1.



Things your students should know by the end of this lab:

- Relate the concepts of linear velocity, linear acceleration, angular speed, and angular acceleration for rigid bodies.

Things to check out given fifteen minutes with the equipment:

- Check wheels on the carts to see if they spin freely.
- It is very important to get a flat camera angle. The masses should fall in a plane perpendicular to the camera angle. Placing the setup on a stable chair on the table worked well.
- Make sure you know how the spool setup works.
- For Problem #2, there are two ways of performing the experiment, as described in the exploration: (i) By pushing the cart so that it unwinds the string from the ring at a constant rate; (ii) By spinning the disk so that the string winds up on the ring, pulling the cart at a constant speed. You may need to tilt the track in each of these cases, since it is important that the string remains taut at all times. You should test this out in both cases before you teach the lab, so that you can most effectively help the students if needed.
- For Problem #3, it's good to try attaching some string and masses to the different setups to see what masses work. Too much mass will cause the string to break at the spool. When they are performing the exploration, encourage your students to increase the mass in reasonable amounts (about 100 g).

Lab 4 Problem #1: Circular Motion

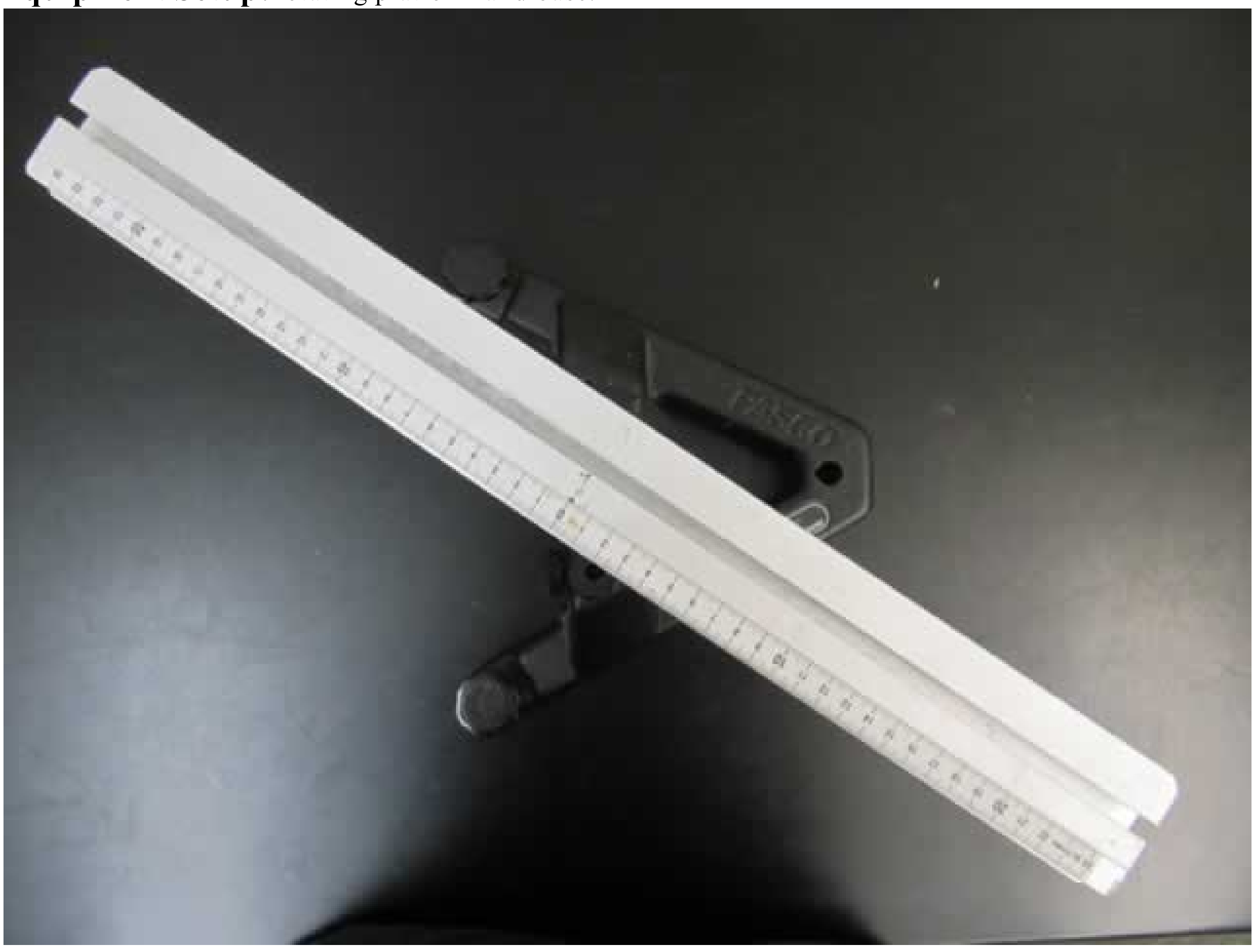
Purpose:

- To show students that objects with constant speed can be accelerating. To give an example of 2-D motion with non-constant acceleration.

Problem: For circular motion at a constant speed, calculate:

- acceleration as function of linear speed and position
- perpendicular components of velocity
- graph position components vs. time and velocity components vs. time
- based on calculated velocity equations, calculate acceleration's magnitude as function of time

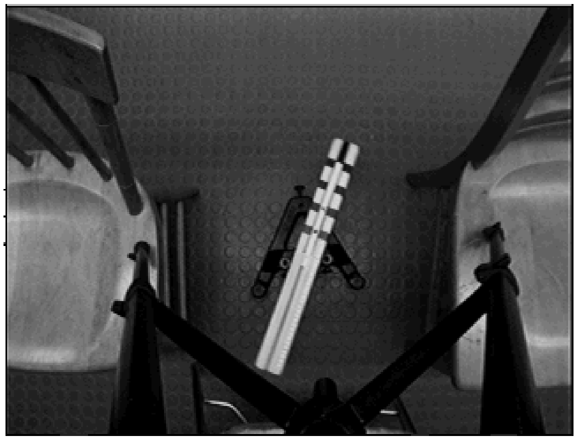
Equipment Setup: rotating platform and base.



Teaching Tips:

1. Your students will find these problems challenging since most students do not understand vectors or kinematics well. Try to let them work on it on their own before stepping in to help. They generally just assume that the velocity is tangent to the circle, because the book says so. They do not assume that they can understand this sort of motion using just the definitions of velocity and acceleration.

2. On the next page is a frame of a "good" video. Notice that the camera is mounted directly above the center of the spinning apparatus. There is very little clutter, the picture is clear, and the contrast is about right. If you could see the entire movie, you would find that the arm is visible at all points of the movie, thus we will not lose any data points due to blocking of the picture by the tripod or other objects.



3. To get these problems to work properly the students MUST use the arm of the spinning apparatus to calibrate their movie. When we analyzed the movie we found that when we used the base of the apparatus for calibration our best fit was $y(t) = 78.1 + 12.8\sin(2.7t + 1.89)$. When we used the rotating platform for calibration the best fit was $y(t) = 62.9 + 10.2\sin(2.7t + 1.89)$. The radius at which we did the analysis was supposed to be 10 cm. Obviously using the arm gave us a much better results for the radius.

4. Watch for students who insist on talking about the "centrifugal" force … you may want to think about how you'll deal with that ahead of time.

Difficulties and Alternative Conceptions:

- Again, you will come up against the misconception that the acceleration must be in the direction that the object is moving. If they have read the book (or remember high school physics) they might believe that the acceleration points inward as a matter of faith. They don't understand that the same definitions they used for linear motion will get them to this result when the magnitude of the velocity isn't changing but the direction is.
- Students also may believe there is an outward acceleration, based on their personal experience with circular motion.

Predictions and Warm-Up Questions:

$$x = x_c + r\sin(\omega t + \theta_0), \qquad y = y_c + r\cos(\omega t + \theta_0),$$
$$v_x(t) = \omega r\cos(\omega t + \theta_0), \qquad v_y(t) = -\omega r\sin(\omega t + \theta_0),$$
$$a_x(t) = -\omega^2 r\sin(\omega t + \theta_0), \qquad a_y(t) = -\omega^2 r\cos(\omega t + \theta_0),$$
$$a = \omega^2 r,$$

(Here x_c and y_c are position components for the center of the circular orbit, θ_0 is the initial angle that the object makes with the x-axis, r is the radius of the circle, and ω is the constant angular speed, T is the period of the orbit.)

Sample Data:

The printouts for all measurements are included at the end of following sample data.

Measured angular speed: 2.93 (rad/ s),
Measured radius of rotation: 12.2 (cm),
Acceleration : $a = 104.6$ (cm/ s^2)

Lab 4 Problem #2: Rotation and Linear Motion at Constant Speed

Purpose:

To reproduce the relationship between the constant angular speed of an object and the linear speed that causes it.

Teaching Tips:

1. Have the students try spinning the system at many different speeds. Make sure they take a movie of each trial to determine the range of speeds that will yield the best data.
2. As you well know, the position and the angle of the camera will affect the accuracy of the data. Make sure that the camera is positioned directly over the center of the system. Have your students try this at several different heights.
3. Have your students find the best distance and angle such that the motion has the least amount of distortion for both the linear part and the rotational part. See Lab II Problem 5 of this guide for an example of a "good movie."
4. Make sure that the string does not slip at the ring.
5. Make sure that the string is relatively taut throughout the entire motion capture, or at least during the time when the students will be taking data.

Difficulties and Alternative Conceptions:

Even though this scenario should not be new to your students, most of them will still have difficulties dealing with it. The idea of tying linear motion into rotational motion is still new to them, so be careful of the analogies between the two. The students believe that a relationship exists, but may not know why it does.

Prediction and Warm up questions:

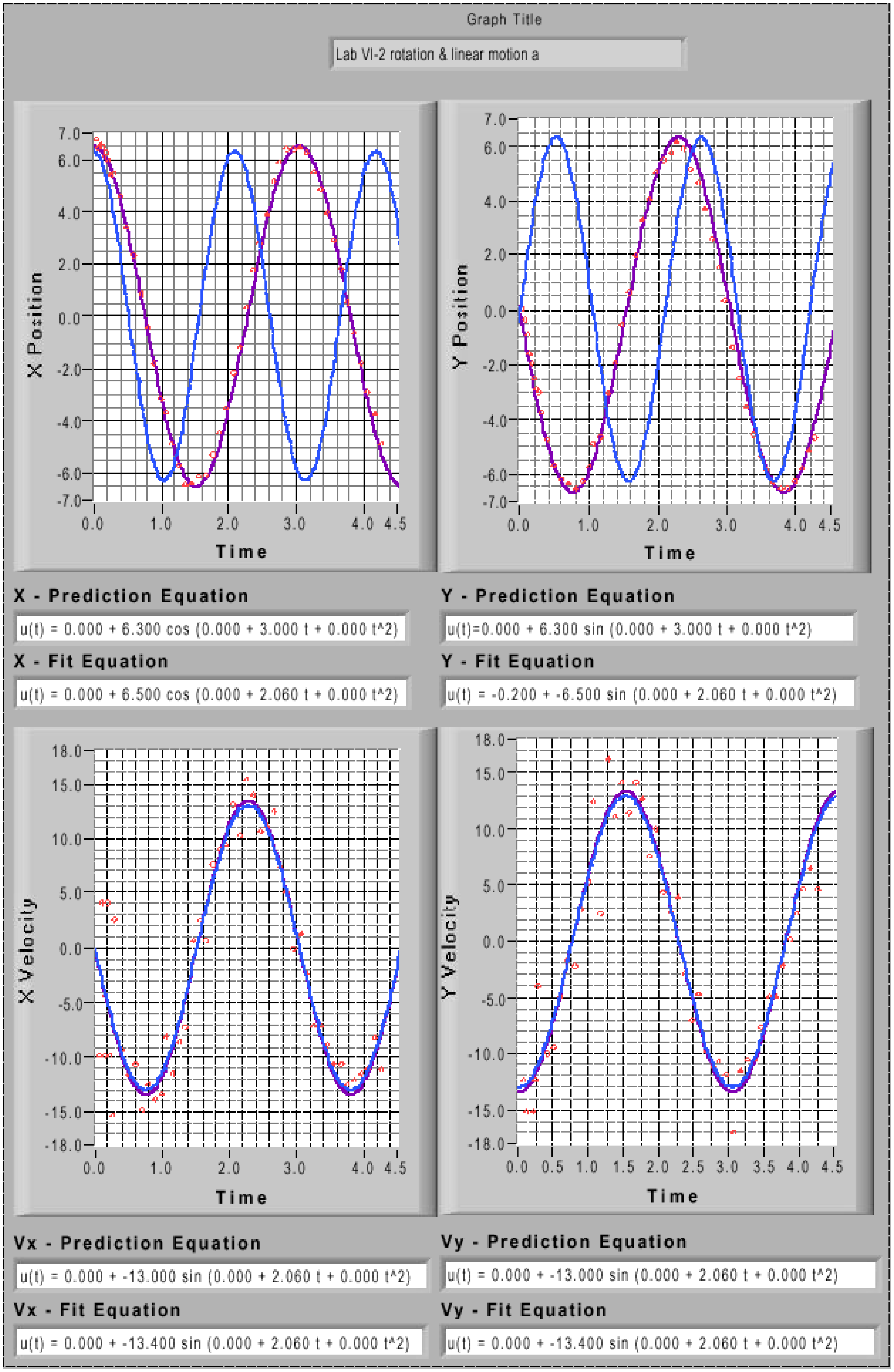
$$\omega = \frac{v}{r}$$

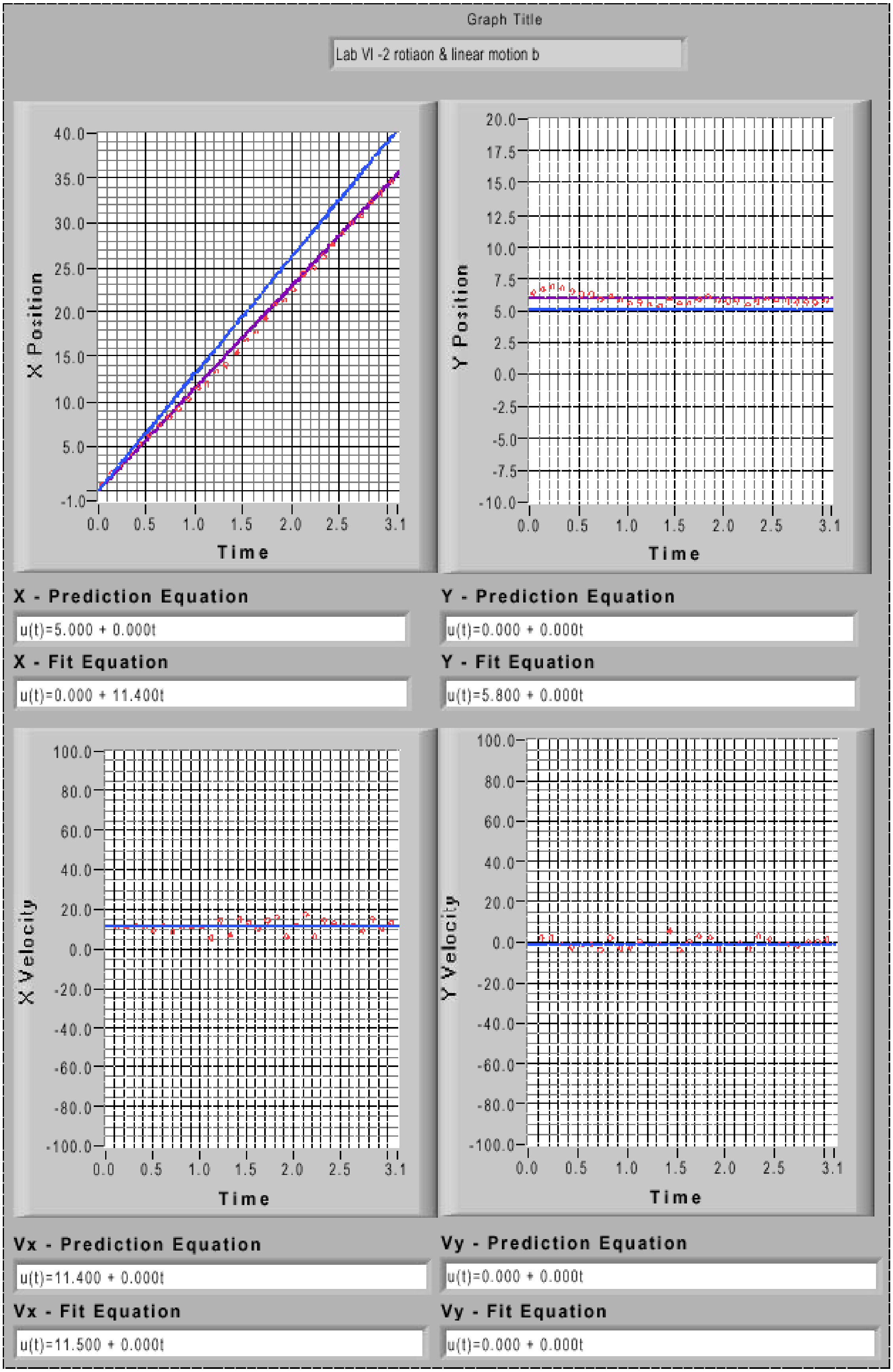
where ω is the angular speed of the disk, r is the radius of the ring, and v is the speed of the cart.

Sample Data:

The printouts for the measurements of speed and angular speed are included at the end of the following sample data.

$r = 6.3$ (cm), $v = 11.5$ (cm/s),
predicted angular speed ω =1.825(s^{-1}),
measured angular speed $\omega = 2.06$ (s^{-1}).


Graph Title
Lab VI-2 rotation & linear motion a
X Position
Time
Y Position
Time
X - Prediction Equation
u(t) = 0.000 + 6.300 cos (0.000 + 3.000 t + 0.000 t^2)
X - Fit Equation
u(t) = 0.000 + 6.500 cos (0.000 + 2.060 t + 0.000 t^2)
Y - Prediction Equation
u(t)=0.000 + 6.300 sin (0.000 + 3.000 t + 0.000 t^2)
Y - Fit Equation
u(t) = -0.200 + -6.500 sin (0.000 + 2.060 t + 0.000 t^2)
X Velocity
Time
Y Velocity
Time
Vx - Prediction Equation
u(t) = 0.000 + -13.000 sin (0.000 + 2.060 t + 0.000 t^2)
Vx - Fit Equation
u(t) = 0.000 + -13.400 sin (0.000 + 2.060 t + 0.000 t^2)
Vy - Prediction Equation
u(t) = 0.000 + -13.000 sin (0.000 + 2.060 t + 0.000 t^2)
Vy - Fit Equation
u(t) = 0.000 + -13.400 sin (0.000 + 2.060 t + 0.000 t^2)


Graph Title
Lab VI -2 rotiaon & linear motion b
X Position
Time
Y Position
Time
X - Prediction Equation
u(t)=5.000 + 0.000t
X - Fit Equation
u(t)=0.000 + 11.400t
Y - Prediction Equation
u(t)=0.000 + 0.000t
Y - Fit Equation
u(t)=5.800 + 0.000t
X Velocity
Time
Y Velocity
Time
Vx - Prediction Equation
u(t)=11.400 + 0.000t
Vx - Fit Equation
u(t)=11.500 + 0.000t
Vy - Prediction Equation
u(t)=0.000 + 0.000t
Vy - Fit Equation
u(t)=0.000 + 0.000t

Lab 4 Problem #3: Angular and Linear Acceleration

Purpose:

To reproduce the relationship between the angular acceleration of an object and the linear acceleration that causes it.

Teaching Tip:

1. Have the students try many different masses to produce different speeds. Make sure they take a movie of each trial to determine the range of masses that will yield the best data.

2. As you well know, the position and the angle of the camera will affect the accuracy of the data. Make sure that the camera is positioned directly over the center of the beam. Have your students try this at several different heights.

3. Have your students find the best distance and angle such that the motion has the least amount of distortion for both the linear part and the rotational part. See Lab II Problem 5 of this guide for an example of a "good movie."

4. Make sure that the string does not slip at the spool.

5. Make sure that the string is relatively taut throughout the entire motion capture, or at least during the time when the students will be taking data.

6. Make sure that the students have the predictions as close to the correct answer as possible; they won't know what to look for or how to match the data otherwise.

Difficulties and Alternative Conceptions:

Even though this scenario should not be new to your students, most of them will still have difficulties dealing with it. The idea of tying linear motion into rotational motion is still new to them, so be careful of the analogies between the two. The students believe that a relationship exists, but may not know why it does.

Prediction:

$$\alpha = \frac{a}{r}$$

where α is the angular acceleration of the disk, a is the acceleration of the weight, and r is the radius of the spool.

Warm up questions:

$$x(t) = A + r\cos\theta(t),\ y(t) = B + r\sin\theta(t),$$

where the coordinates of the axis of rotation are (A,B), and the time dependence of θ for constant angular acceleration is given by $\theta(t) = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$.

Differentiating with respect to time:

$$v_x(t) = -r\theta'(t)\sin\theta(t),\ v_y(t) = r\theta'(t)\cos\theta(t)$$

Differentiating again with respect to time:

$$a_x(t) = -r\theta''(t)\sin\theta(t) - r(\theta'(t))^2\cos\theta(t),$$
$$a_y(t) = r\theta''(t)\cos\theta(t) - r(\theta'(t))^2\sin\theta(t)$$

Now, $a^2 = a_x^2 + a_y^2 \Rightarrow a(t)^2 = r^2(\theta''(t))^2 + r^2(\theta'(t))^4$

Using $\theta'(t) = \omega_0 + \alpha t$ and $\theta''(t) = \alpha$, we get:

$$a(t) = \sqrt{[r\alpha]^2 + \left[r(\omega_0 + \alpha t)^2\right]^2} \qquad \text{(A)}$$

Now, the centripetal acceleration is given by $a_C(t) = \omega(t)^2 r$, whereas the time dependence of the angular speed is given by $\omega(t) = \omega_0 + \alpha t$, so:

$$a_C(t) = r(\omega_0 + \alpha t)^2$$

The centripetal and tangential accelerations are perpendicular, and so:

$$a(t) = \sqrt{a_C(t)^2 + a_T(t)^2} = \sqrt{\left[r(\omega_0 + \alpha t)^2\right]^2 + a_T(t)^2} \qquad \text{(B)}$$

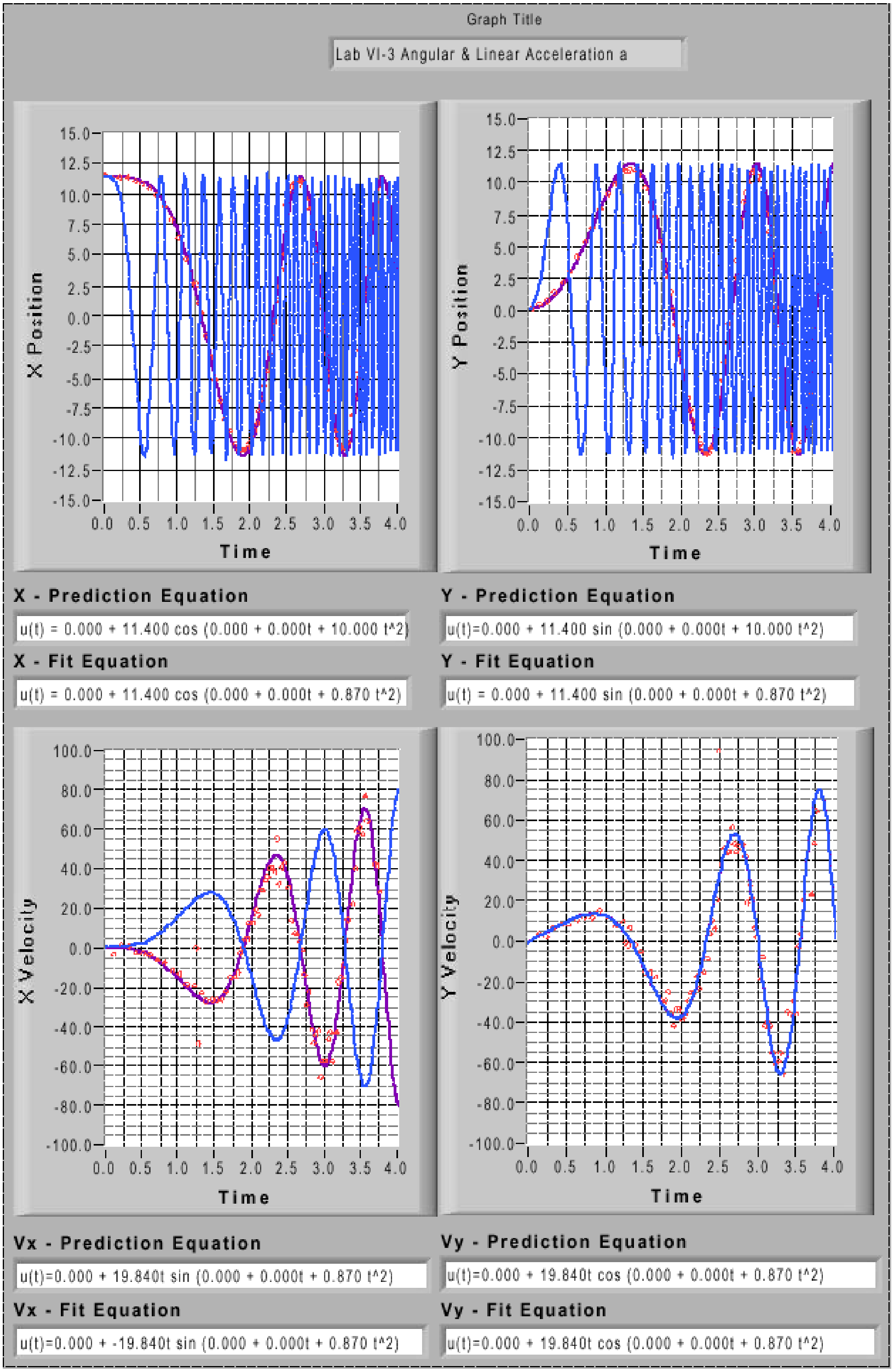
Comparing equations (A) and (B), the tangential acceleration is given by:

$$\boxed{a_T(t) = r\alpha}$$

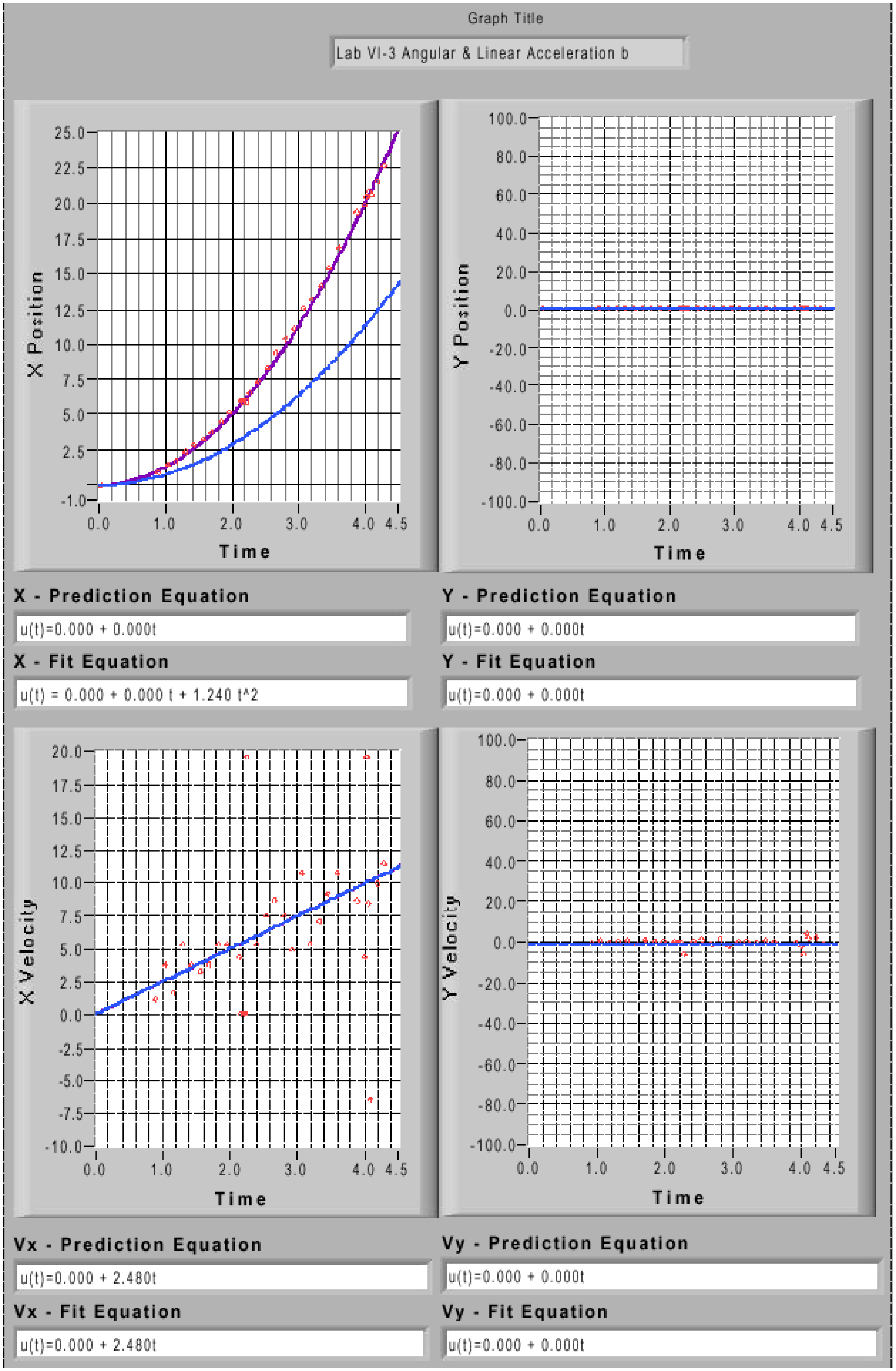
Sample Data:

The printouts for the measurements of speed and angular speed are included at the end of the following sample data.

$r = 1.5$ (cm), $a = 2.48$ (cm/s²),
predicted angular acceleration $\alpha = 1.65$ (s^{-2}),
measured angular acceleration $\alpha = 1.74$ (s^{-2}).



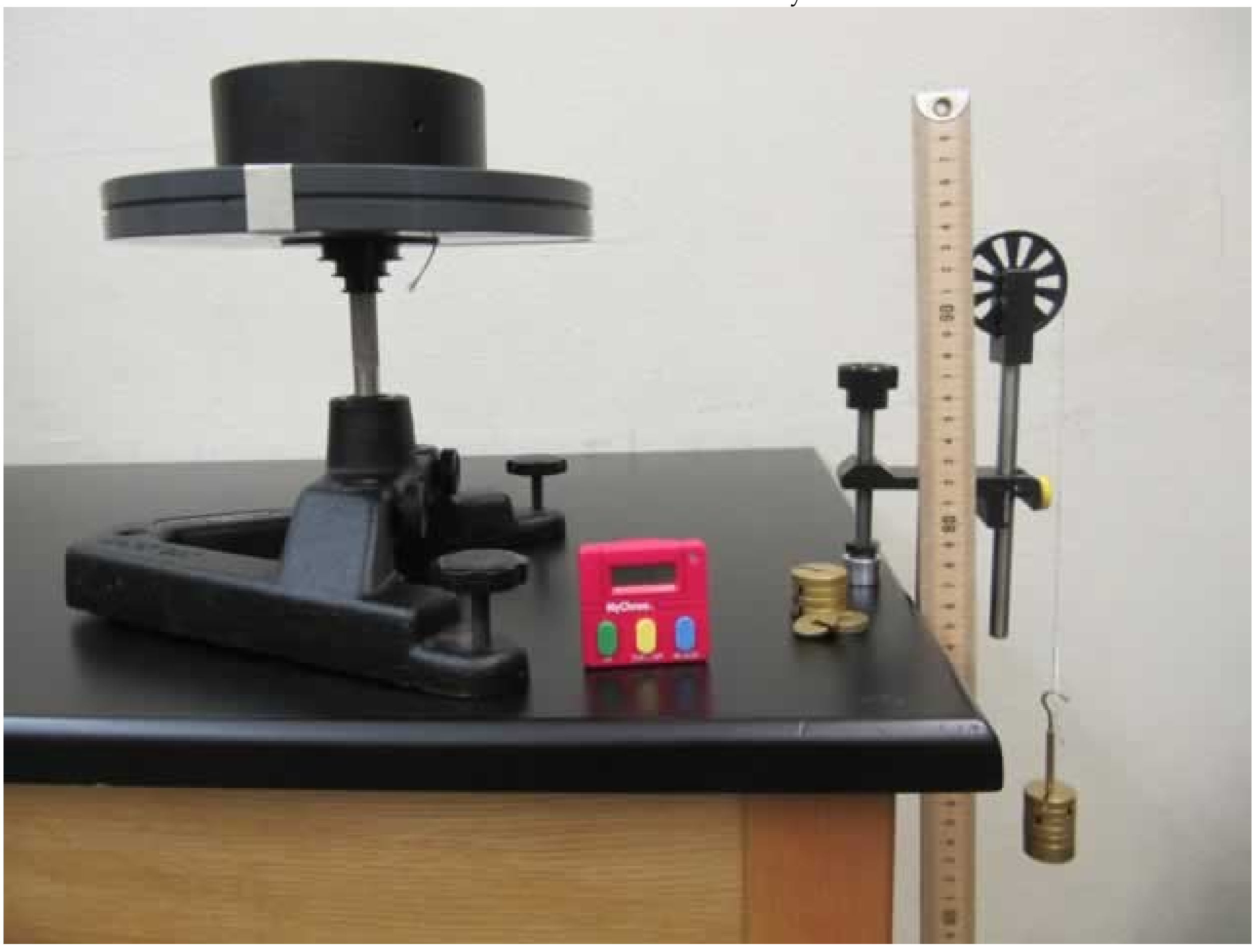
Graph Title
Lab VI-3 Angular & Linear Acceleration a
X Position
Time
Y Position
Time
X - Prediction Equation
u(t) = 0.000 + 11.400 cos (0.000 + 0.000t + 10.000 t^2)
X - Fit Equation
u(t) = 0.000 + 11.400 cos (0.000 + 0.000t + 0.870 t^2)
Y - Prediction Equation
u(t)=0.000 + 11.400 sin (0.000 + 0.000t + 10.000 t^2)
Y - Fit Equation
u(t) = 0.000 + 11.400 sin (0.000 + 0.000t + 0.870 t^2)
X Velocity
Time
Y Velocity
Time
Vx - Prediction Equation
u(t)=0.000 + 19.840t sin (0.000 + 0.000t + 0.870 t^2)
Vx - Fit Equation
u(t)=0.000 + -19.840t sin (0.000 + 0.000t + 0.870 t^2)
Vy - Prediction Equation
u(t)=0.000 + 19.840t cos (0.000 + 0.000t + 0.870 t^2)
Vy - Fit Equation
u(t)=0.000 + 19.840t cos (0.000 + 0.000t + 0.870 t^2)


Graph Title
Lab VI-3 Angular & Linear Acceleration b
X Position
Time
Y Position
Time
X - Prediction Equation
u(t)=0.000 + 0.000t
X - Fit Equation
u(t) = 0.000 + 0.000 t + 1.240 t^2
Y - Prediction Equation
u(t)=0.000 + 0.000t
Y - Fit Equation
u(t)=0.000 + 0.000t
X Velocity
Time
Y Velocity
Time
Vx - Prediction Equation
u(t)=0.000 + 2.480t
Vx - Fit Equation
u(t)=0.000 + 2.480t
Vy - Prediction Equation
u(t)=0.000 + 0.000t
Vy - Fit Equation
u(t)=0.000 + 0.000t

Lab 4 Problem #4: Moment of Inertia Of A Complex System
Problem #5: Moment of Inertia About Different Axes

Purpose:

- **Problem #4:** To show the students that the rotational inertia of a system can be found by knowing the rotational inertia of the parts that make up the system.
- **Problem #5:** To determine how different axes of rotation of a system affect the moment of inertia.



Teaching Tips:

1. These problems are very similar. They have similar predictions and warm up questions. Needless to say, the exploration, measurement, and analysis are also similar. You might consider dividing the class up and have groups who did the same problem report their average to the class. It will be useful to compare and contrast mass and rotational inertia.
2. When the string needs to be attached to the spool, the hanging mass needs to be large to overcome the friction of the rod, to provide enough torque to spin the entire system, and to create an acceleration that the camera and analysis software can pick up. 1 kg worked well.
3. The spool adds a small bit to the moment of inertia of the system, but it is negligible. If a group forgets about it, but argues convincingly about being able to forget it, you might let it pass. You may want to have them figure out what percent of the total it is, though.
4. Be sure the students use the correct radius for the spool. Some students may be tempted to use the larger radius of the edges of the spool, but what is correct is to use the inner radius – where the string is actually wrapped.

Difficulties and Alternative Conceptions:

Rotational inertia is a new concept to most students and they do not have an intuitive feel for magnitudes. They may not understand the importance of the axis of rotation and the distance from that axis.

Prediction and Warm up questions:

Problem #1:

$$I_{TOT} = I_{ring} + I_{disk} + I_{shaft}$$

$$I_{TOT} = \tfrac{1}{2} M_R \left(R_0^2 + R_1^2\right) + \tfrac{1}{2} M_D R_D^2 + \tfrac{1}{2} M_S R_S^2$$

Problem #2:

$$I_{TOT} = I_{disk} + I_{shaft}$$

Axis through center: $I_{TOT} = \tfrac{1}{2} M_D R_D^2 + \tfrac{1}{2} M_S R_S^2$.

Axis through diameter: $I_{TOT} = \tfrac{1}{4} M_D R_D^2 + \tfrac{1}{12} M_D L^2 + \tfrac{1}{2} M_S R_S^2$.

Problem #3:

$$I_{TOT} = I_{ring} + I_{disk} + I_{shaft}$$

$$I_{TOT} = \tfrac{1}{2} M_R \left(R_0^2 + R_1^2\right) + M_R d^2 + \tfrac{1}{2} M_D R_D^2 + \tfrac{1}{2} M_S R_S^2,$$

where M_R is the mass of the ring; M_D is the mass of the disk; M_S is the mass of the shaft$_0$ and R_1 are the inner and outer radii of the ring, respectively; R_D is the radius of the disk; L is the thickness of the disk; and R_S is the radius of the shaft.

Problem #1, #2, and #3:

The moment of inertia of the system can be calculated from the acceleration of the hanging weight, using the following expression:

$$I_{TOT} = \frac{R_S^2}{a} m(g - a),$$

where R_S is the radius of the spool, a is the linear acceleration, and *m* is the mass of the hanging weight.

Sample Data:

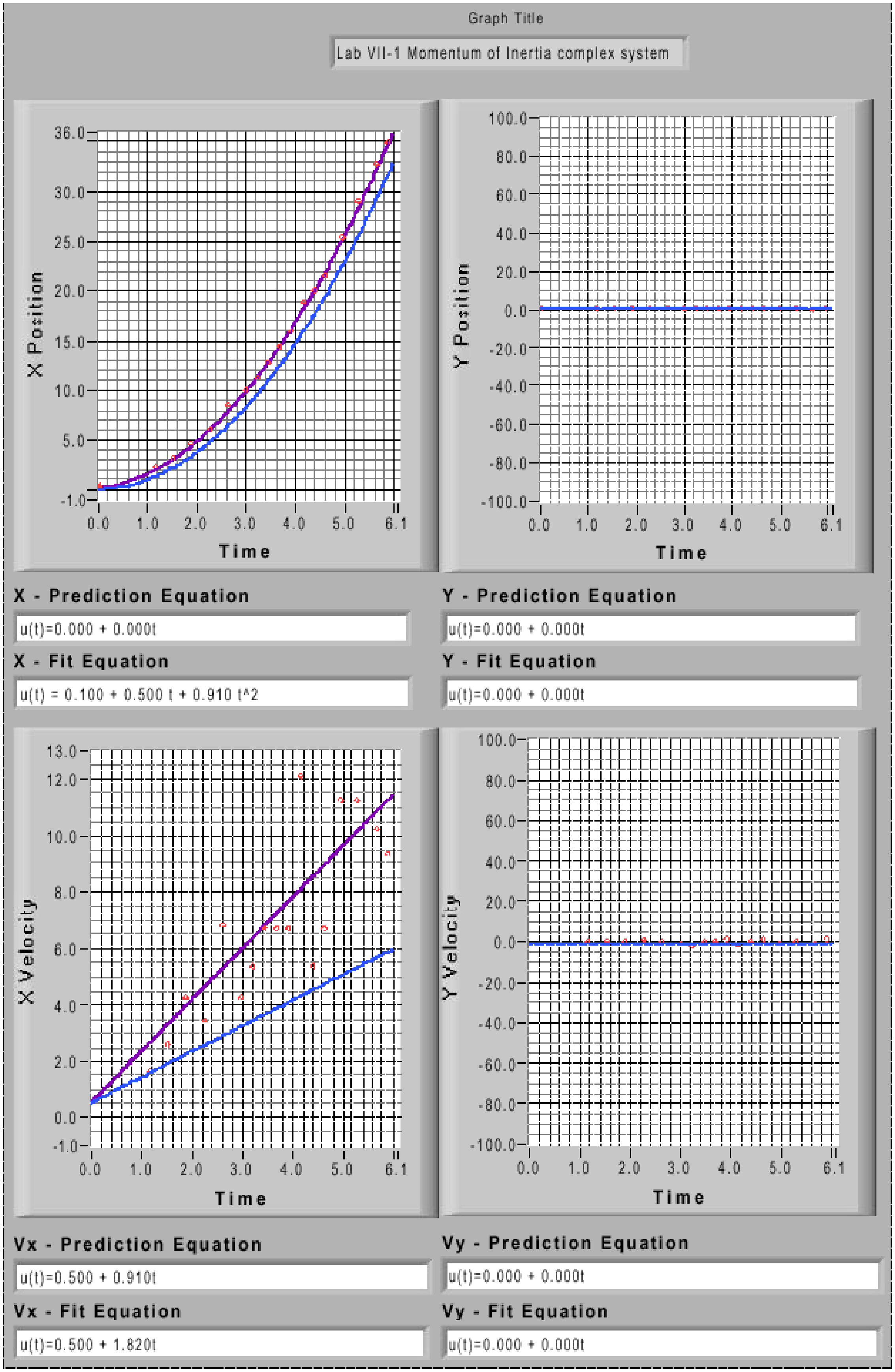
The printouts for the measurements of all accelerations are included at the end of following sample data.

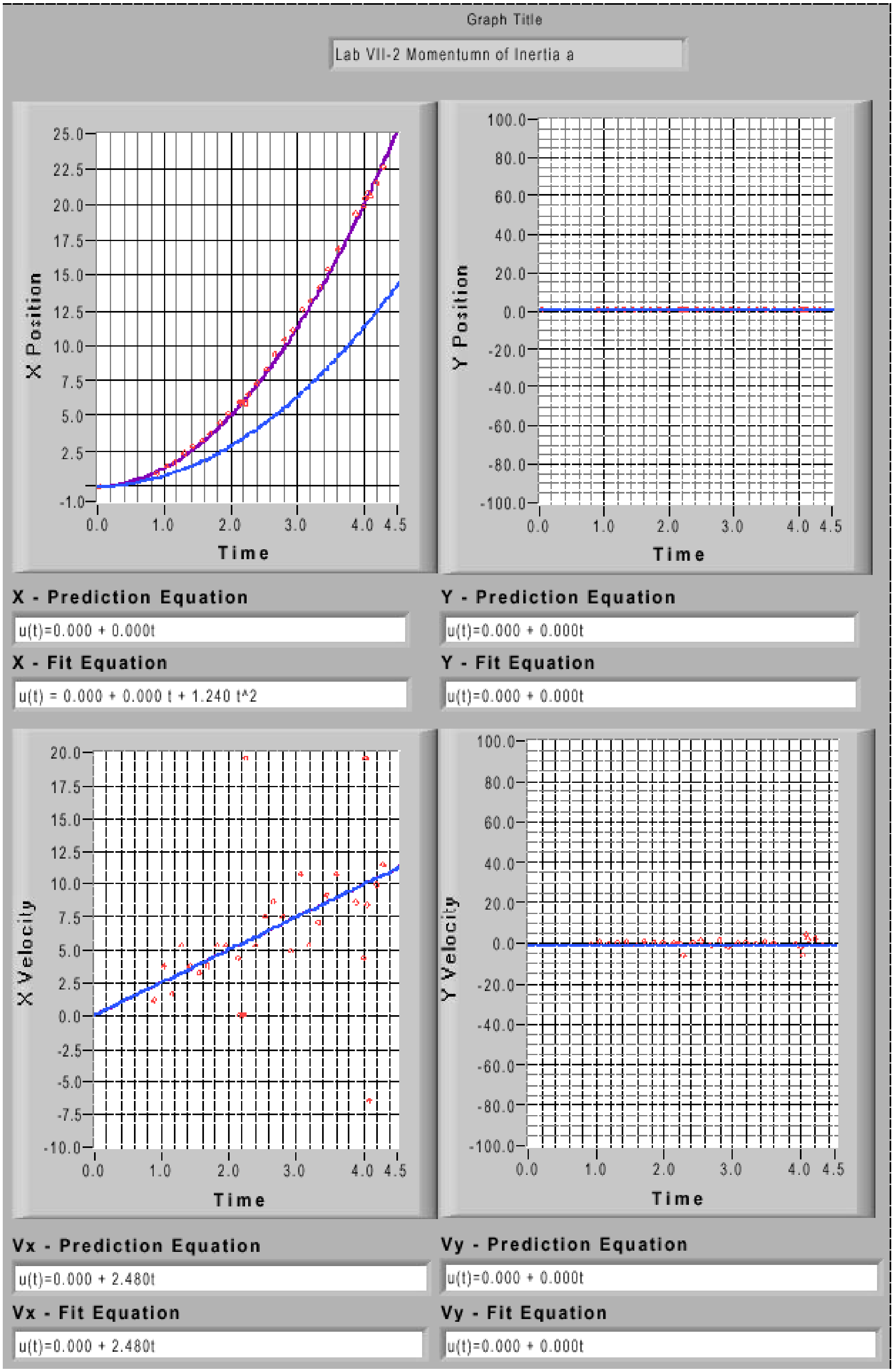
	Shaft	Disk	Ring	Spool
Mass (g)	222.5	1364.6	1431.1	-----
Radius (cm)	0.67	11.4	5.3/6.3	1.6

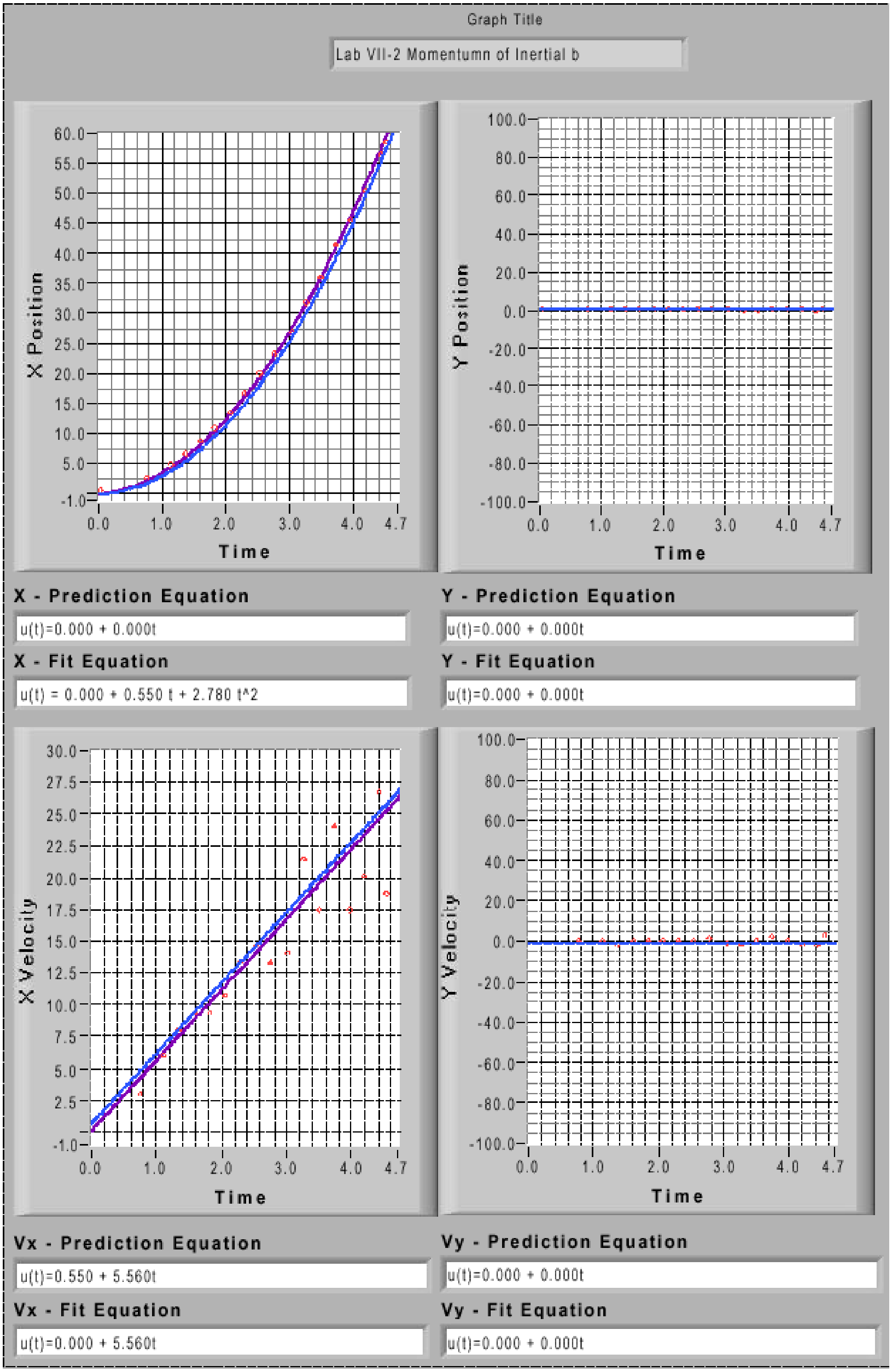
Problem #4
Measured acceleration: $a = 1.82$ (cm/s²),
Mass of hanging object: $m = 100$ (g),
Momentum of Inertia from sum: I_{TOT}=1.372e-2(kg*m²),
Momentum of Inertia from acceleration: I_{TOT}=1.376e-2(kg*m²).

Problem #5
1) axis through center
Measured acceleration: $a = 2.48$ (cm/s²),
Mass of hanging object: $m = 100$ (g),
Momentum of Inertia from sum: I_{TOT}=8.87e-3(kg*m²),
Momentum of Inertia from acceleration: I_{TOT}=1.01e-2(kg*m²).

2) axis through diameter
Measured acceleration: $a = 5.56$ (cm/s²),
Mass of hanging object: $m = 100$ (g),
Momentum of Inertia from sum: I_{TOT}=4.51e-3(kg*m²),
Momentum of Inertia from acceleration: I_{TOT}=4.49e-3(kg*m²).


Graph Title
Lab VII-1 Momentum of Inertia complex system
X Position
Time
Y Position
Time
X - Prediction Equation
u(t)=0.000 + 0.000t
X - Fit Equation
u(t) = 0.100 + 0.500 t + 0.910 t^2
Y - Prediction Equation
u(t)=0.000 + 0.000t
Y - Fit Equation
u(t)=0.000 + 0.000t
X Velocity
Time
Y Velocity
Time
Vx - Prediction Equation
u(t)=0.500 + 0.910t
Vx - Fit Equation
u(t)=0.500 + 1.820t
Vy - Prediction Equation
u(t)=0.000 + 0.000t
Vy - Fit Equation
u(t)=0.000 + 0.000t


Graph Title
Lab VII-2 Momentumn of Inertia a
X Position
Time
Y Position
Time
X - Prediction Equation
u(t)=0.000 + 0.000t
X - Fit Equation
u(t) = 0.000 + 0.000 t + 1.240 t^2
Y - Prediction Equation
u(t)=0.000 + 0.000t
Y - Fit Equation
u(t)=0.000 + 0.000t
X Velocity
Time
Y Velocity
Time
Vx - Prediction Equation
u(t)=0.000 + 2.480t
Vx - Fit Equation
u(t)=0.000 + 2.480t
Vy - Prediction Equation
u(t)=0.000 + 0.000t
Vy - Fit Equation
u(t)=0.000 + 0.000t


Graph Title
Lab VII-2 Momentumn of Inertial b
X Position
Time
Y Position
Time
X - Prediction Equation
u(t)=0.000 + 0.000t
X - Fit Equation
u(t) = 0.000 + 0.550 t + 2.780 t^2
Y - Prediction Equation
u(t)=0.000 + 0.000t
Y - Fit Equation
u(t)=0.000 + 0.000t
X Velocity
Time
Y Velocity
Time
Vx - Prediction Equation
u(t)=0.550 + 5.560t
Vx - Fit Equation
u(t)=0.000 + 5.560t
Vy - Prediction Equation
u(t)=0.000 + 0.000t
Vy - Fit Equation
u(t)=0.000 + 0.000t

Lab 4 Problem #6: Rolling and Torque

Purpose:
To improve student's skill in using torque to solve problems, especially in situations involving rolling without slipping.

Teaching Tips:
Students may be surprised that at for some string angles the spool rolls *toward* the string. Discuss why this happens and how it can be predicted using the concept of torque. A surprising result can afford a good opportunity to help students deepen their knowledge.

Difficulties and Alternative Conceptions:
Many students may feel that pulling on the string should always "unwind" the spool. Also, students may have difficulty understanding the rolling without slipping condition and how to use it. Students will have difficulty obtaining a prediction from their torque equations; talk through this at some point so that students understand how to do it before the lab ends.

Prediction and Warm up questions:
Torque from the string: $\tau_s = -F_s R_1$

Torque from frictional force with the table: $\tau_t = F_t R_2$

Total torque: $\tau = \tau_s + \tau_t$, $\tau = F_t R_2 - F_s R_1 = I\alpha$

Sum of forces in horizontal x-direction: $F_x = F_s \cos\theta - F_t = ma_x$

No slip condition: $a_x = R_2\alpha$

$$F_t = \frac{I}{R_2}\alpha + F_s\frac{R_1}{R_2}\ , \quad ma_x = F_s\cos\theta - \frac{I}{R_2}\alpha - F_s\frac{R_1}{R_2}$$

$$ma_x + \frac{I}{R_2}\alpha = F_s\left(\cos\theta - \frac{R_1}{R_2}\right)$$

$$\left(m + \frac{I}{R_2^2}\right)a_x = F_s\left(\cos\theta - \frac{R_1}{R_2}\right)$$

The spool will be drawn toward the string if a_x is positive, and away from it if negative. Whether it will be positive or negative depends on the sign of $\left(\cos\theta - \frac{R_1}{R_2}\right)$. This changes from positive to negative depending on the angle theta. The critical angle where the behavior changes from causing the spool to roll toward to causing the spool to roll away is given by:

$\theta_{crit} = \cos^{-1}\left(\frac{R_1}{R_2}\right)$. If the angle is below θ_{crit} the spool will roll toward the string, if the angle is above θ_{crit} it will roll away.

Laboratory 5: Conservation of Energy

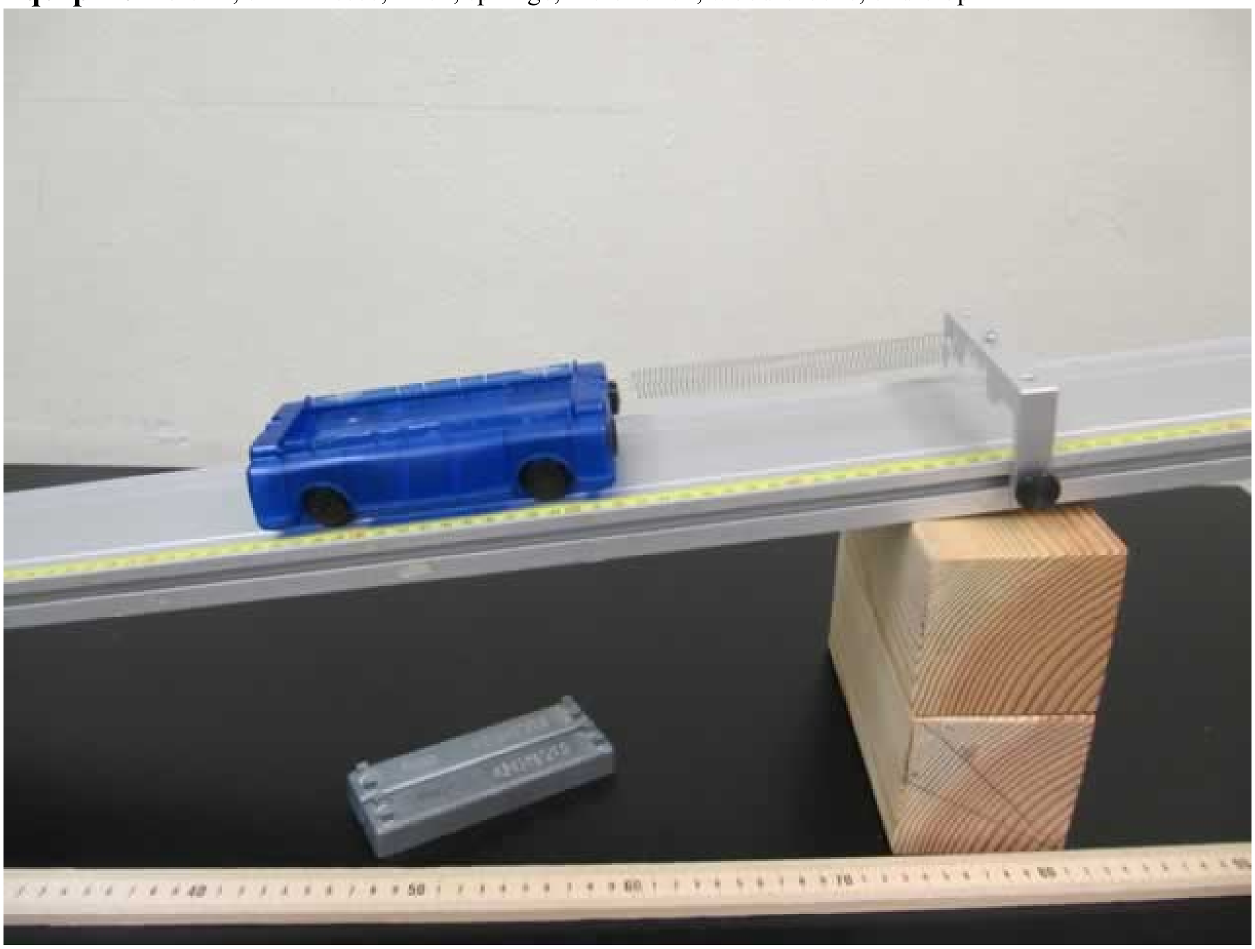
These laboratory problems serve as an exercise in the explicit use of the concept of conservation of energy to solve problems. The problems here can of course be solved by other means in which forces have to be invoked explicitly. The students are invited to work out these problems in more than one way. You may start with any lab problem in this section.

Lab 5 Problem #1: Elastic and Gravitational Potential Energy

Purpose:

- To give students an example of a problem conveniently described by conservation of energy involving kinetic, elastic, and gravitational potential energy.
- To give students more exposure to filming motion and constructing, analyzing and interpreting graphs.

Equipment: cart, cart masses, track, springs, meter stick, wood blocks, end stop



Question:

Determine the maximum elongation of the spring after the cart is released from rest along an inclined track. Compare the maximum elongation to the amount the spring stretches to support a stationary cart. Determine the maximum velocity of the cart and the position of the cart at the instant the maximum velocity is reached.

Prediction:

$$\tfrac{1}{2}mv^2 + (mg\sin\theta)(x_{\max} - x) + \tfrac{1}{2}kx^2 = E = const$$

$$(mg\sin\theta)x_{\max} = kx_{\max}^2 / 2$$

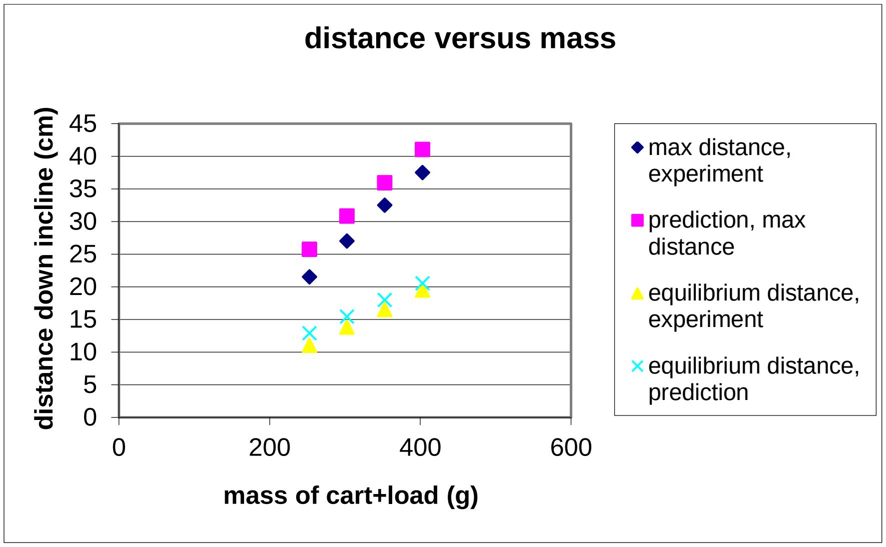
$$-mg\sin\theta + kx_{equil} = 0 \rightarrow v_{\max}^2 = (g\sin\theta)x_{equil}$$

Here x is the displacement of the cart from its initial position with the spring unstretched. The maximum displacement is linearly related to the mass of the cart. The equilibrium displacement is half the maximum displacement and is also the displacement at which the maximum velocity occurs, as can be verified using the simple calculus of extremas.

Sample Data:

Angle of incline: $\arcsin\left[\frac{27cm}{(227cm-77cm)}\right]=10.4°$

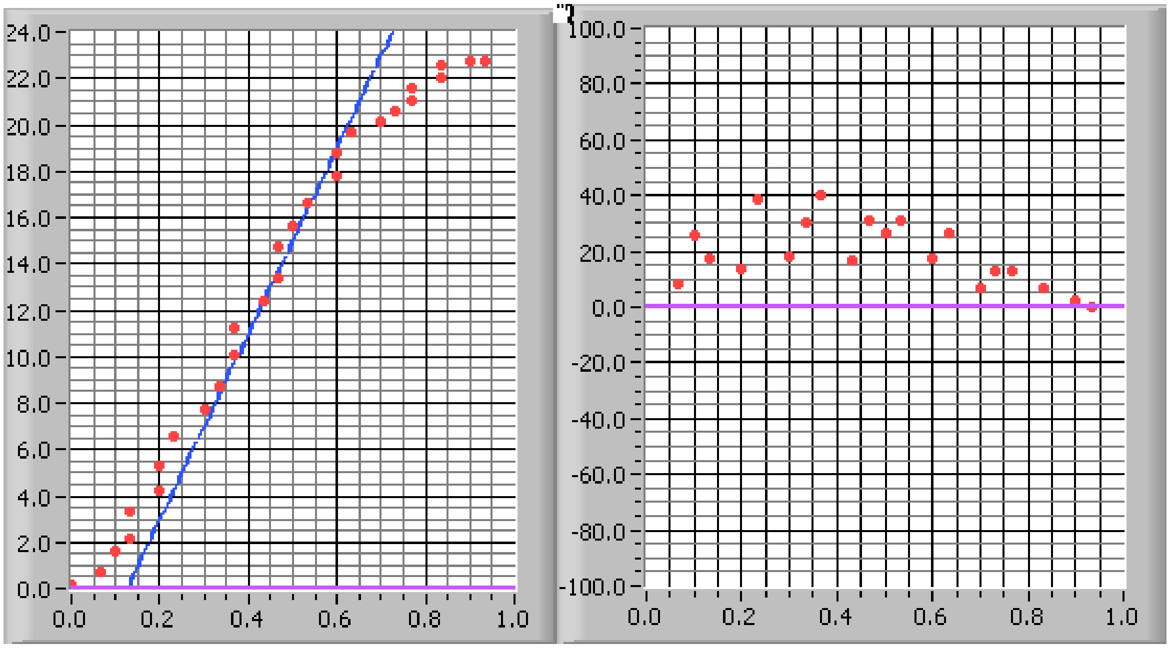
For the 'fat' spring k=2.7N/ m.



	Experimental		*Predicted*	
Mass(g)	maximum x(cm)	equlbrium x	x in $kx=2mg\sin\theta$	x in $kx=mg\sin\theta$
253	21.5	11	25.73853	12.86927
303	27	13.8	30.8252	15.4126
353	32.5	16.5	35.91187	17.95593
403	37.5	19.5	40.99853	20.49927

Agreement is good. Maximum displacement is about twice the equilibrium displacement. The measured displacements are consistently smaller than the predictions, perhaps indicating the effect of friction. ***(or that the spring doesn't extend at all until it exerts some small but non-zero force … perhaps better to compare a measured slope for differences in displacements with different masses vs. a predicted slope of the same thing?)*** A measurement was done with a smaller angle of incline (about 8 degrees) and the agreement between experiment and theory was worse, although the slope of the lines agree.

The first image below gives the position (cm) versus time (sec) while the second image gives the velocity (cm/ s) along the incline versus time. The position at which the maximum velocity occurs is located at the point of inflection of the graph. The slope of the line (40cm/ s) gives the velocity. The predicted value is $\sqrt{981cm/s^2\cdot\sin 10.4\cdot 11cm}=44cm/s$.


24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.0 0.2 0.4 0.6 0.8 1.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
0.0 0.2 0.4 0.6 0.8 1.0

Lab 5 Problem #2: Pendulum Velocity

Purpose:

- To give students an example of conservation of energy involving curvilinear motion.
- To give students an exercise in constructing, handling and interpreting graphs.

Equipment: stopwatch, protractor, string, mass set, meter stick, rods and clamp to secure pendulum to table, video camera and computer with video analysis software.

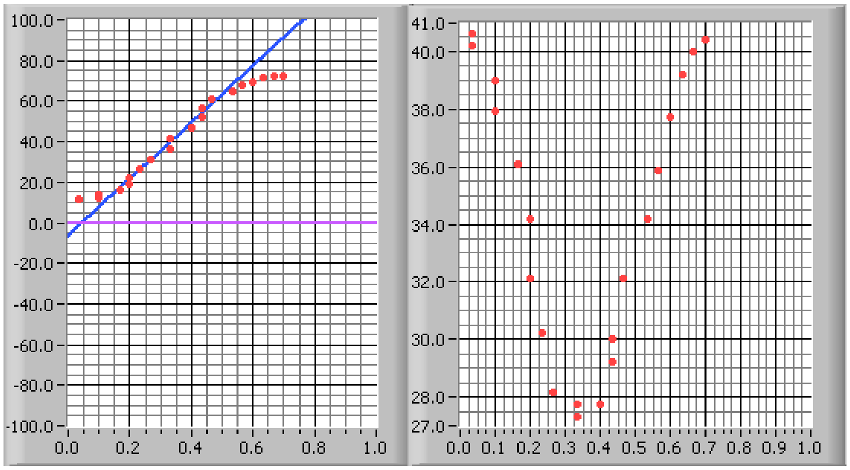
Prediction:

$$\tfrac{1}{2} v_{max}^2 = gh = gl(1 - \cos\theta)$$

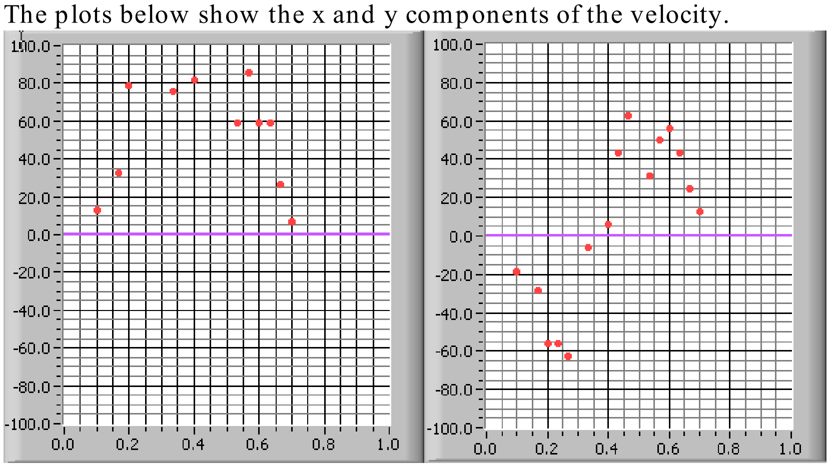
Sample Data:

String length: 44cm
Hanging mass: 200g

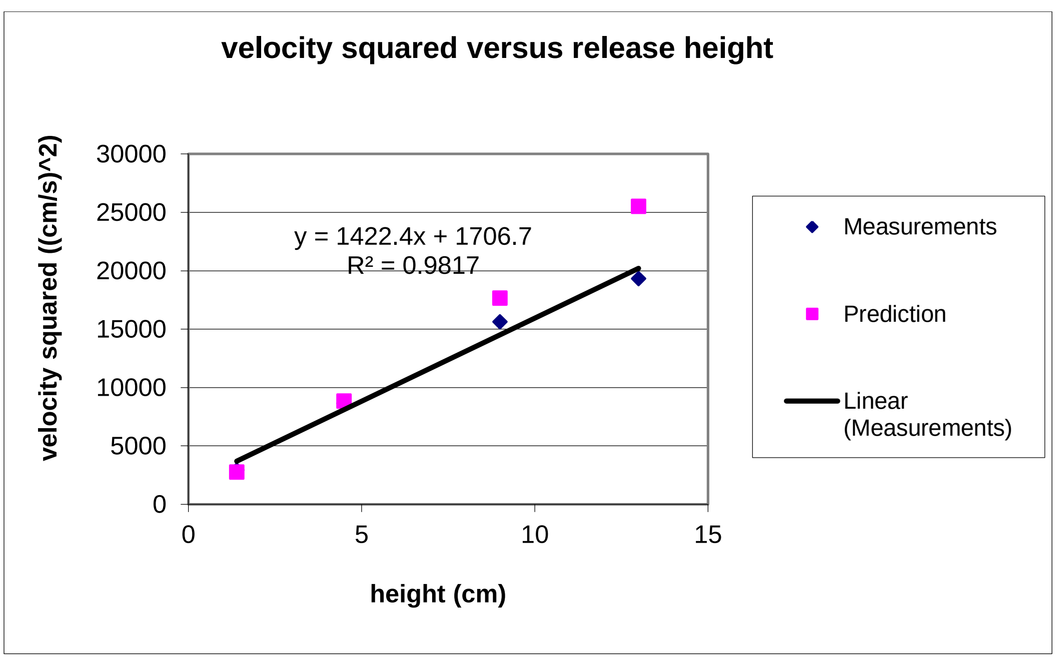
The graphs below show the x and y components of the position. The velocity at the lowest point can be inferred from the point of inflection of the x-coordinate and the minimum of the y-coordinate. The slope of the tangent line is taken as the speed of the pendulum at the lowest point. The height of release is measured as the difference between the highest and lowest values of the y-coordinate.



The plots below show the x and y components of the velocity.



The data from the video measurements were assembled into the following graph. The pendulum becomes less ideal for greater release heights.



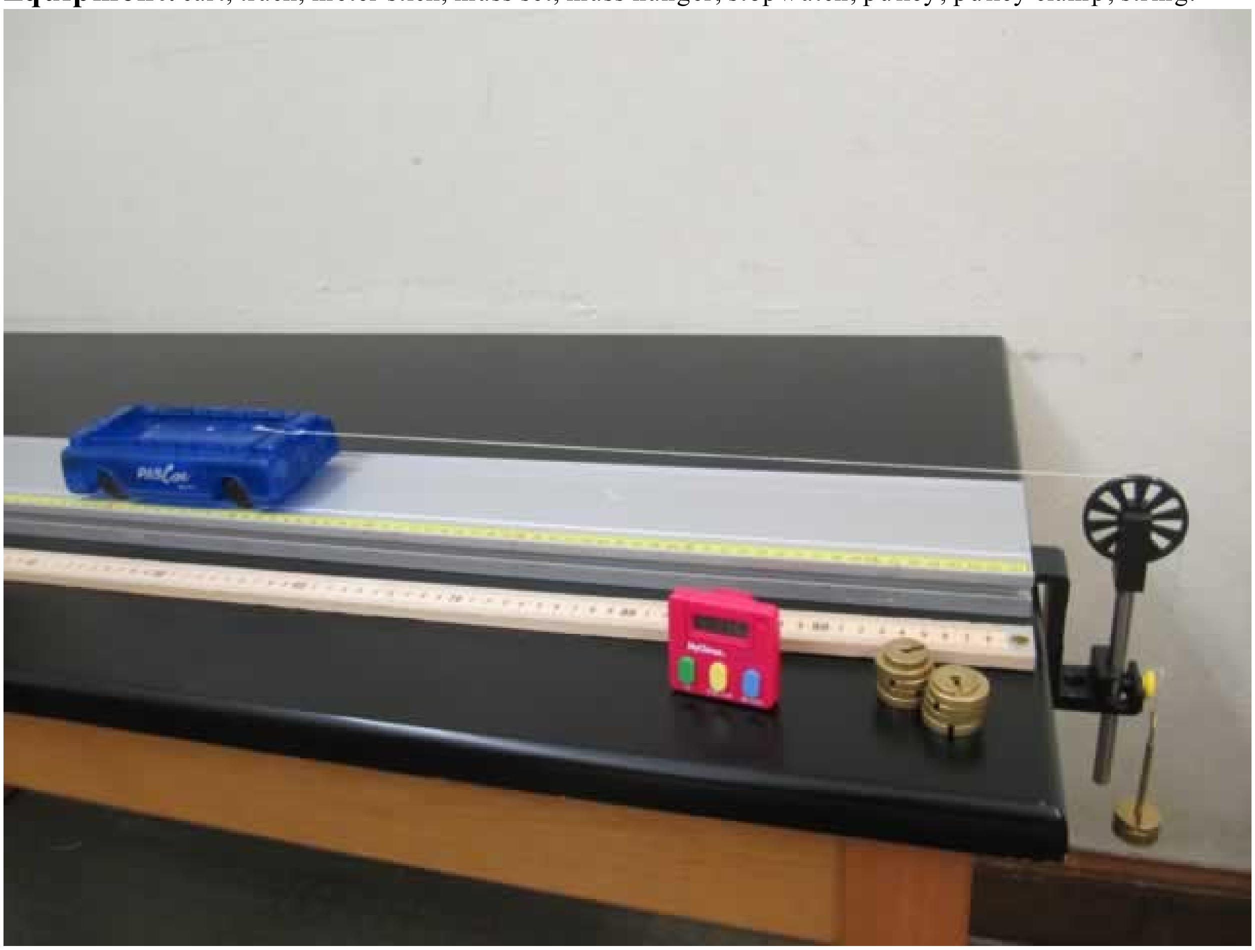
Lab 5 Problem #3: Velocity and Energy

Problem: Calculate the velocity and kinetic energy of a hanging weight and a cart such that the weight is attached over a pulley to the cart on a horizontal track just before the weight hits the floor, given the height of release and the masses of the cart and weight. Determine whether the force exerted by the string on the cart is equal to the weight of the hanging object.

Purpose:

- Another lab problem involving motion under a constant force, where more than one object have to be analyzed. This problem is meant to be studied using the work-kinetic energy relation to relate the velocity to the height the object is dropped from, as Newton's second law and acceleration may not have been introduced at this point.
- To understand why the force on the rope is not equal to the weight of the hanging mass. (Weight has to be larger than the tension for the hanging object to accelerate downward.)
- The setup of this problem is similar to that of Lab III, problem #2, with a slightly different emphasis.

Equipment: cart, track, meter stick, mass set, mass hanger, stopwatch, pulley, pulley clamp, string.



Teaching Tips:

1. The students need enough string to hang over the pulley, but it should be long enough so that the mass hits the ground **before** the cart runs out of track.
2. It is amazing how quickly students forget kinematics. This problem will reinforce the idea that physics builds upon itself.
3. Many students may have difficulty with the necessity of drawing the two force diagrams required to solve this problem. Most will want to equate the force on the cart with the weight hanging on the

string. Avoid using the "clever" system of the weight + string + cart in your explanations. This system tends to confuse students and obscure the connection of forces with physical interactions.

4. (Work-energy analysis) Using energy arguments as is suggested in the student manual, the work done by earth's gravitational pull and the tension(T) on the weight(m) falling a distance d is $(mg-T)d$. This equals the change in kinetic energy $(mg-T)d=½mv^2$, if the system starts from rest. The work done by the weight 'pulling' on the cart is the tension(T) times distance, Td, which is just the kinetic energy of the cart alone, $Td=½ Mv^2$. By eliminating the speed v^2, the relationship between the hanging weight and the tension becomes $mg=T(M+m)/M$ i.e. the tension should be smaller than the hanging weight, as the analysis using Newton's laws (tip 3) can verify.

Difficulties and Alternative Conceptions:

Many students believe that the weight of the hanging mass is a force on the cart. Others know that the string is exerting a force on the cart but believe that the string tension is equal to the weight of the hanging mass.

Prediction and Warm-up Questions:

Before object A hits ground

Constant acceleration a=mg/ (m+M)

$$T = \frac{mMg}{m+M}$$

After object A hits ground

$$v = \sqrt{\frac{2mgh}{m+M}} ,$$

where v is the velocity of the cart after the hanger hits ground, T is the force on the string before the hanger hits ground, m is the mass of object A, M is the mass of the cart and h is the height through which object A falls.

Sample Data:

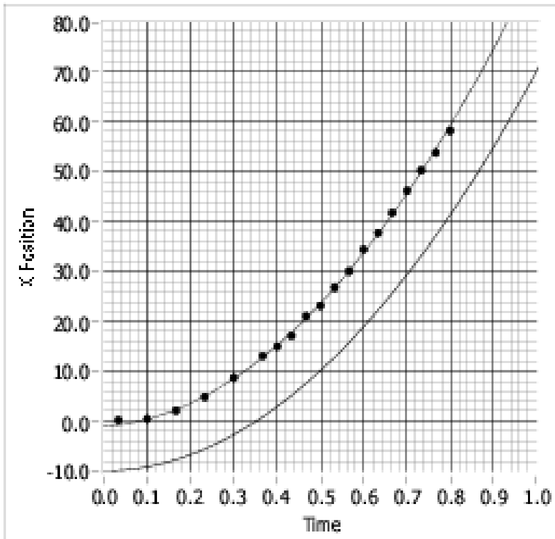
The printout for the measurement of final velocity of the cart is included at the end of following sample data.

h=38.2cm M=251.78g m=50.07g
Predicted final velocity of the cart: 111.43 cm/ s
Measured final velocity of the cart: 99.3 cm/ s

Predicted force on the string before hitting the floor: 4.09 N
Measured force on the string before hitting the floor (M*a): 4.38 N

Graph Title

1201 Lab V Prob #6 Before hitting floor

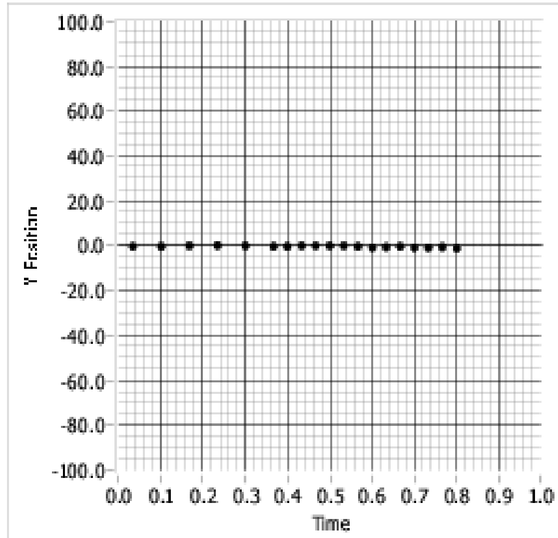


X - Prediction Equation

u(t) = -10.000 + 0.000 t + 80.000 t^2

X - Fit Equation

u(t) = -1.100 + 5.700 t + 87.000 t^2

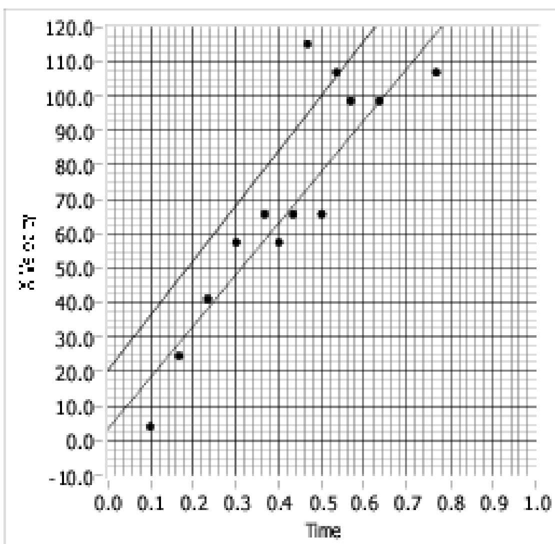


Y - Prediction Equation

u(t) = 0.000 + 0.000t

Y - Fit Equation

u(t) = 0.000 + 0.000t

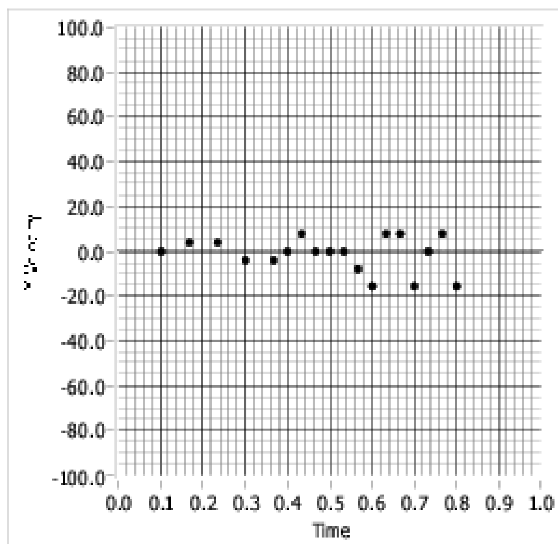


Vx - Prediction Equation

u(t) = 20.000 + 160.000t

Vx - Fit Equation

u(t) = 3.000 + 150.000t



Vy - Prediction Equation

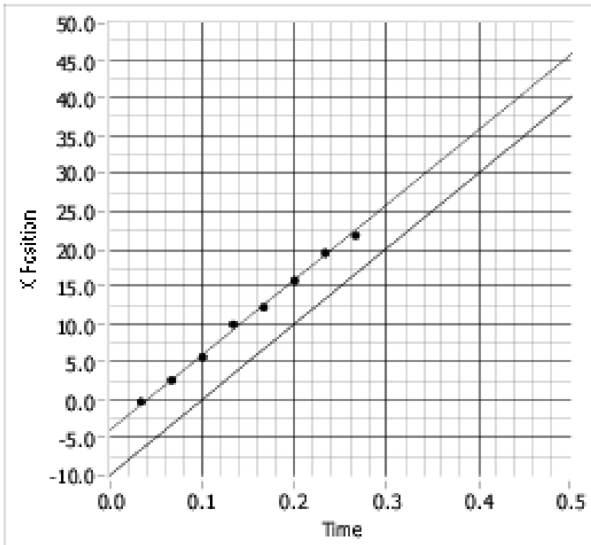
u(t) = 0.000 + 0.000t

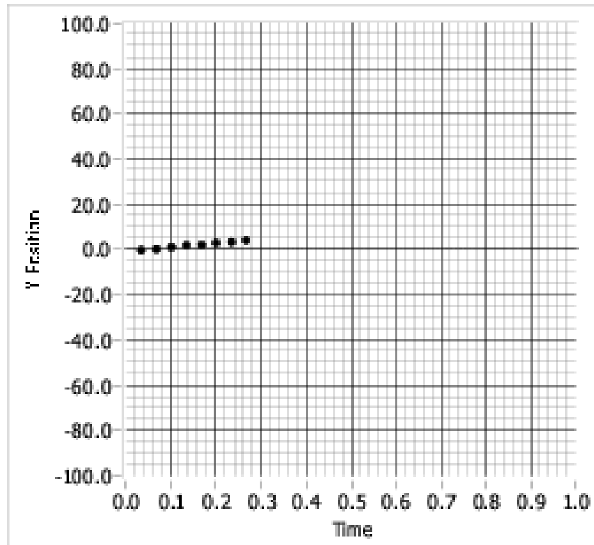
Vy - Fit Equation

u(t) = 0.000 + 0.000t

Graph Title

1201 Lab V Prob #6 after hitting floor





X - Prediction Equation

u(t) = -10.000 + 100.000t

X - Fit Equation

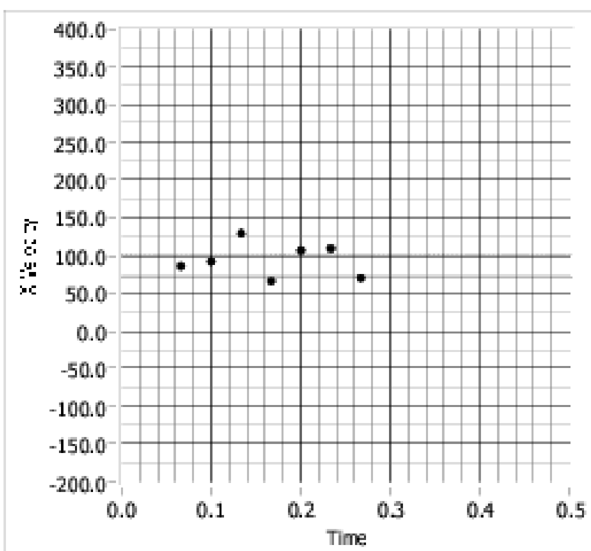
u(t) = -4.000 + 99.300t

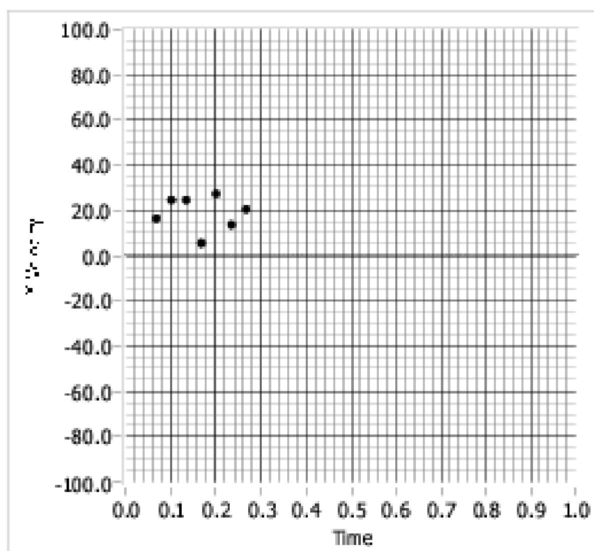
Y - Prediction Equation

u(t) = 0.000 + 0.000t

Y - Fit Equation

u(t) = 0.000 + 0.000t





Vx - Prediction Equation

u(t) = 70.000 + 0.000t

Vx - Fit Equation

u(t) = 100.000 + 0.000t

Vy - Prediction Equation

u(t) = 0.000 + 0.000t

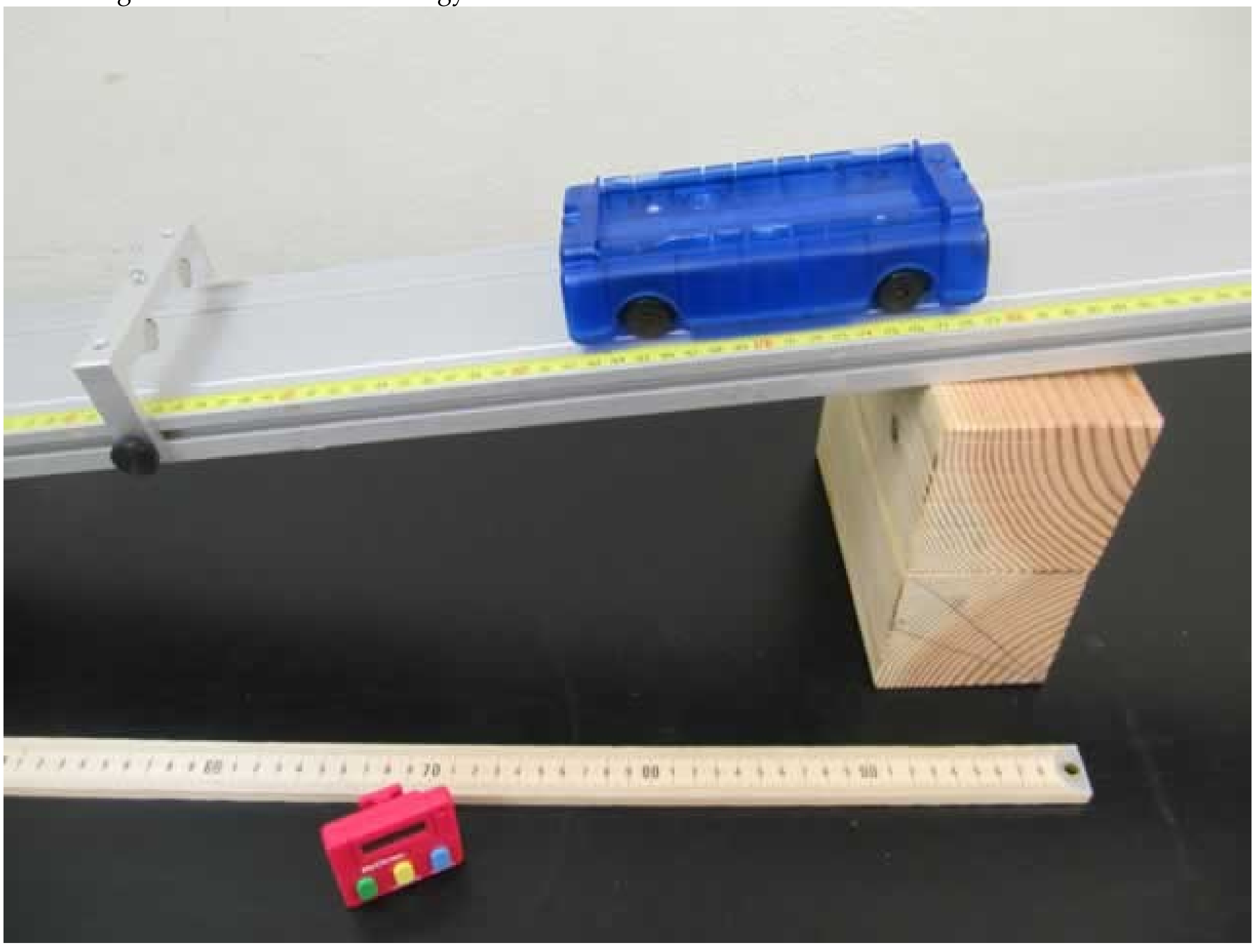
Vy - Fit Equation

u(t) = 0.000 + 0.000t

Lab 5 Problem #4: Kinetic Energy and Work I
Problem #5: Kinetic Energy and Work II

Purpose:

- To introduce the students to the concepts of kinetic energy and work and how they are related through the conservation of energy.



Teaching Tips:

1. This problem is a simple application of energy conservation that only requires the students to understand the concepts of kinetic energy and work.
2. Do not lecture on potential energy; the lecture will probably not talk about potential energy until after the first week of this lab. You do not need the concept of potential energy for this lab. Having the students figure out the problem in terms of work gives them good practice using this difficult concept.
3. Remember to warn your students to avoid having their carts jump off the track.
4. Warn your students to avoid the cart contacting the end stop during collisions. Have them try small velocities for problem #1 or small inclined angles for problem #2.
5. Be sure to have the students share their results on the board. These results shouldn't vary too drastically from cart to cart. If the results do vary, it is most likely because of an analysis mistake. The students need an average value from everyone's results to apply to the equipment they use the following week.
6. Suggest your students to correct the efficiency obtained in problem #2 by considering the dissipated energy from friction.

Difficulties and Alternative Conceptions:

The common usage of the word "work" and the students' previous experience with energy may leave them confused about the usefulness of the principles of kinetic energy and work. Students tend not to differentiate well between energy, force, power, and speed. Many students believe that energy is only conserved if a system has no interactions with its environment. Some also believe that conservation of energy means that the final kinetic energy of an object or group of objects equals its initial kinetic energy. It is a common misconception that dissipated energy has been destroyed. Students are especially confused about work and potential energy. The whole idea that you need to define the system with which you are dealing before you can identify energy terms is foreign to most students. Students will tend to resist using energy when they first see it, since forces have been useful thus far.

Prediction and Warm up questions:

1) Problem #1

$$\text{Efficiency (level track)} = \left(\frac{v_f}{v_i}\right)^2,$$

where v_i is the velocity before the collision and v_f is the velocity after the collision.

2) Problem #2.

$$\text{Efficiency (inclined track)} = \frac{h_f}{h_i} = \frac{d_f}{d_i},$$

where h_i is the release height, h_f is the maximum height reached after the collision, d_i is the distance along the incline from the point of release to the bumper and d_f is the maximum distance along the incline from the bumper reached after the collision. The efficiency given in terms of the distance along the incline reinforces the concept of work while its relationship to height is a good introduction to the concept of potential energy.

<u>Correction for efficiency of problem #2:</u>

Given active length of magnets d_m, mass of the cart m, frictional force between cart and inclined track f and the inclined angle θ, we have

Kinetic energy just after collision (adding the dissipated energy from friction)

$$K_f = mg * d_f \sin\theta + f * d_f ,$$

Kinetic energy just before collision

$$K_i = mg * d_i * \sin\theta - f * d_i .$$

Corrected $\mathit{Efficiency}\ \text{(inclined track)} = \frac{d_f}{d_i} * \frac{g\sin\theta + \frac{f}{m}}{g\sin\theta - \frac{f}{m}}.$

From acceleration before collision a_{before} and acceleration after collision a_{after} we can figure out frictional force f and inclined angle θ.

$$f = m*(a_{after} - a_{before})/2$$
$$g\sin\theta = (a_{after} + a_{before})/2$$

Sample Data:

1) Problem #1

V_i=46 cm/s ; V_f=45 cm/s ;

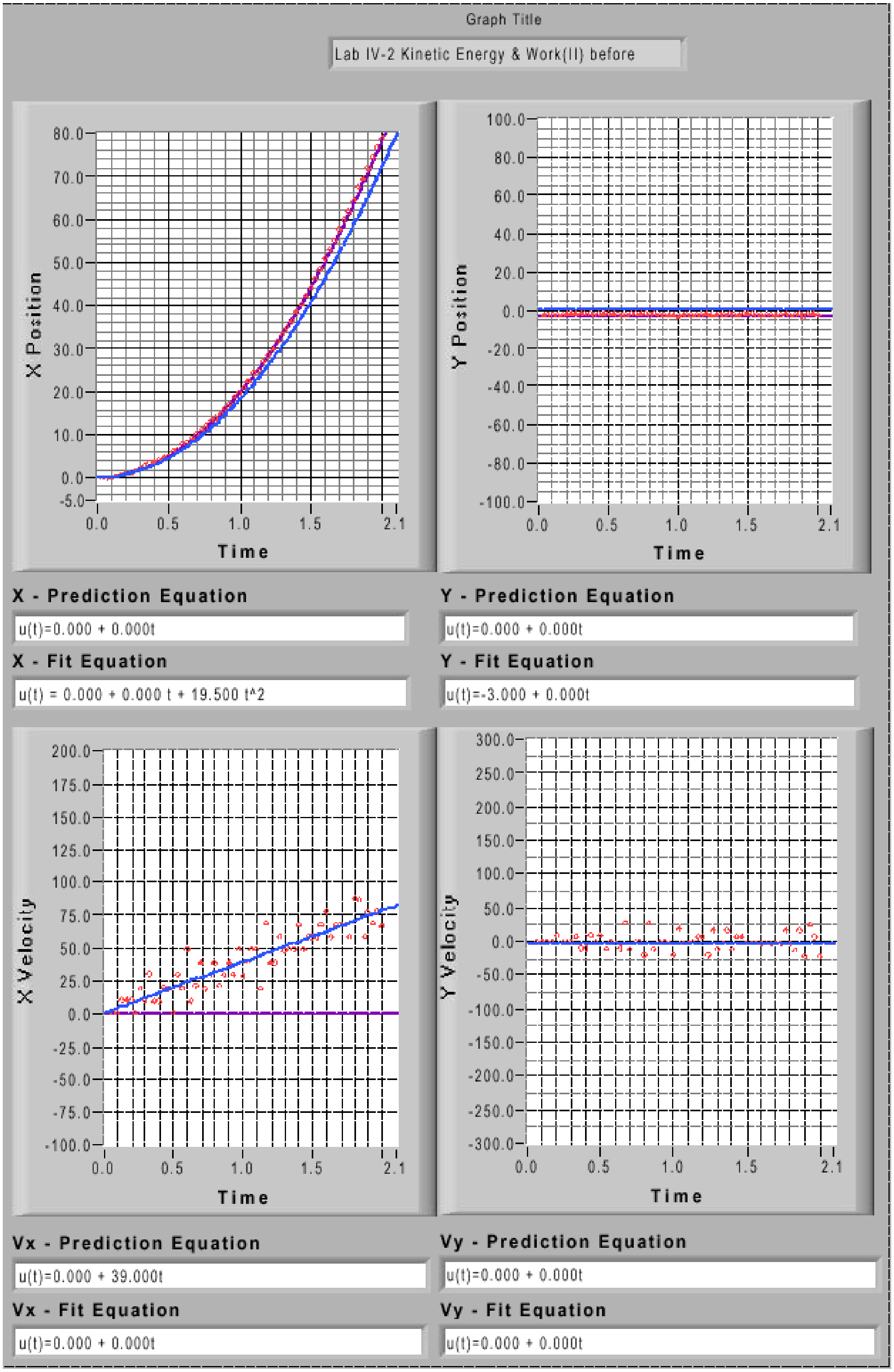
Efficiency=0.96.

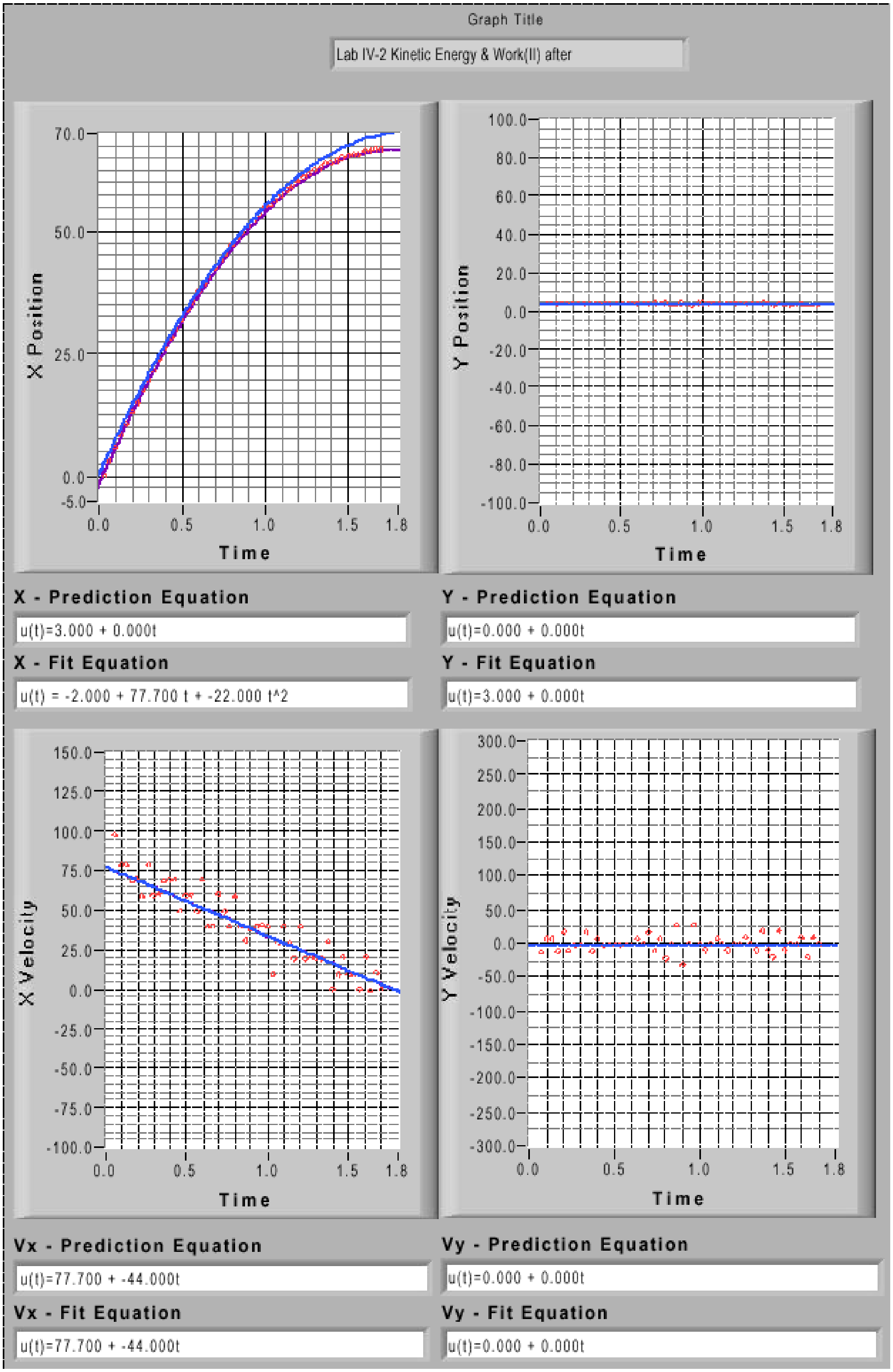
2) Problem #2

d_f=64 cm ; d_i=80 cm ; d_m=5cm ;

a_{before}=39 cm/s^2 ; a_{after}=44 cm/s^2.

Efficiency(before correction)=0.80,
Efficiency(after correction)=0.91.
So we can consider that the efficiency of bumper is close to 1.


Graph Title
Lab IV-2 Kinetic Energy & Work(II) before
X Position
Time
Y Position
Time
X - Prediction Equation
u(t)=0.000 + 0.000t
X - Fit Equation
u(t) = 0.000 + 0.000 t + 19.500 t^2
Y - Prediction Equation
u(t)=0.000 + 0.000t
Y - Fit Equation
u(t)=-3.000 + 0.000t
X Velocity
Time
Y Velocity
Time
Vx - Prediction Equation
u(t)=0.000 + 39.000t
Vx - Fit Equation
u(t)=0.000 + 0.000t
Vy - Prediction Equation
u(t)=0.000 + 0.000t
Vy - Fit Equation
u(t)=0.000 + 0.000t


Graph Title
Lab IV-2 Kinetic Energy & Work(II) after
X Position
Time
Y Position
Time
X - Prediction Equation
u(t)=3.000 + 0.000t
X - Fit Equation
u(t) = -2.000 + 77.700 t + -22.000 t^2
Y - Prediction Equation
u(t)=0.000 + 0.000t
Y - Fit Equation
u(t)=3.000 + 0.000t
X Velocity
Time
Y Velocity
Time
Vx - Prediction Equation
u(t)=77.700 + -44.000t
Vx - Fit Equation
u(t)=77.700 + -44.000t
Vy - Prediction Equation
u(t)=0.000 + 0.000t
Vy - Fit Equation
u(t)=0.000 + 0.000t

Laboratory 6: Conservation of Momentum

General Teaching Tips

1. These problems may precede the lecture by a few days. Resist the urge to lecture on the topics. These labs can serve as a good introduction to the lectures. If your students have the habit of preparing for lab, then they should be able to complete these problems.

Things to Remember:

- Send an email to labhelp@physics.umn.edu to report any problems with the equipment.

By the end of this lab students should be able to:

- Use the principle of conservation of momentum as a means of describing the behavior of a system.

Things to check out before teaching the lab:

- Check every wheel for every plastic cart to see if it can continue rotating at least two seconds after a gentle push.

Lab 6 Problems #1 and #2: Inelastic and Elastic Collisions

Purpose:

- To use the concept of conservation of momentum to predict physical behavior.

Teaching Tips:

1. The solution to the prediction equation for Problem #2 difficult for students. Be aware that mathematically this prediction is very messy. The students have a very hard time with this prediction.
2. Do not let a single student monopolize either the computer or the equipment.

Difficulties and Alternative Conceptions:

Many students do not have different concepts of energy and momentum. They are used interchangeably. The students cannot or do not want to decide in which situations they can most easily apply conservation of energy or conservation of momentum or both. Students still have difficulty with the necessity of defining an appropriate system.

Prediction and Warm up questions:

Problem 1: $$v' = \frac{m_1 v_1}{m_1 + m_2}$$

where m_1 is the mass of the cart1 initially in motion and m_2 is the mass of the cart2 initially at rest, v_1 is the initial velocity of cart1, and v' is the final velocity of both carts.

Problem 2:

$$v_1' = \frac{\frac{m_1}{m_2} \pm \sqrt{Eff\,(1 + m_1/m_2) - m_1/m_2}}{(1 + m_1/m_2)} \cdot v_1$$

$$v_2' = \frac{1 \mp \sqrt{1 - (m_1/m_2 + 1)(1 - Eff)}}{(1 + m_2/m_1)} \cdot v_1$$

where m_1 is the mass of the cart1 initially in motion, m_2 is the mass of the cart2 initially at rest, v_1 is the initial velocity of cart1, v_1' is the final velocity of cart1, v_2' is the final velocity of cart2, and *Eff* is the efficiency of the magnets bumper at the end side of carts. Of course things are simplified if you use the approximation that the efficiency is approximately one

Sample Data:

Problem 1: (stick together)

1) $m_1 = m_2$
Mass of cart 1: m_1 = 503.60g; Mass of cart 2: m_2 = 503.12g
Initial velocity of cart 1: v = 52.70 cm/s
Predicted final velocity of both carts: v' = 26.36 cm/s
Measured final velocity of both carts: v' = 26.50 cm/s

2) $m_1 > m_2$
Mass of cart 1: m_1 = 753.80g; Mass of cart 2: m_2 = 252.92g
Initial velocity of cart 1: v = 43.10 cm/s
Predicted final velocity of both carts: v' = 32.27 cm/s
Measured final velocity of both carts: v' = 32.50 cm/s

3) $m_1 < m_2$
Mass of cart 1: m_1 = 252.80g; Mass of cart 2: m_2 = 753.92g
Initial velocity of cart 1: v = 91.00 cm/s
Predicted final velocity of both carts: v' = 22.85 cm/s
Measured final velocity of both carts: v' = 23.80 cm/s

Problem 2: (bounce apart)

1) $m_1 = m_2$
Mass of cart 1: m_1 = 503.60g; Mass of cart 2: m_2 = 503.12g
Initial velocity of cart 1: v = 61.20 cm/s
Energy efficiency: Eff = 0.97 (from Lab IV-4)
Predicted final velocity of cart 1: v_1' = 0.97 cm/s
Measured final velocity of cart 1: v_1' = 0.00 cm/s
Predicted final velocity of cart 2: v_2' = 60.29 cm/s
Measured final velocity of cart 2: v_2' = 60.30 cm/s

2) $m_1 > m_2$
Mass of cart 1: m_1 = 753.80g; Mass of cart 2: m_2 = 252.92g
Initial velocity of cart 1: v = 62.80 cm/s
Energy efficiency: Eff = 1.00 (from Lab IV-4)

Predicted final velocity of cart 1: $v_1' = 31.27$ cm/s
Measured final velocity of cart 1: $v_1' = 32.80$ cm/s
Predicted final velocity of cart 2: $v_2' = 93.97$ cm/s
Measured final velocity of cart 2: $v_2' = 92.40$ cm/s

3) $m_1 < m_2$
Mass of cart 1: $m_1 = 252.80$g; Mass of cart 2: $m_2 = 753.92$g
Initial velocity of cart 1: $v = 51.70$ cm/s
Energy efficiency: Eff = 0.98 (from Lab IV-4)
Predicted final velocity of cart 1: $v_1' = -25.22$ cm/s
Measured final velocity of cart 1: $v_1' = -25.50$ cm/s
Predicted final velocity of cart 2: $v_2' = 25.79$ cm/s
Measured final velocity of cart 2: $v_2' = 25.70$ cm/s

Lab 6 Problem #3: Conservation of Angular Momentum

Purpose:

- To demonstrate the concept of conservation of angular momentum by measuring the angular velocity before and after an inelastic collision.

Teaching Tips:

1. The consistency of the timekeeper is the largest source of error in this problem. Tell your students to have everyone try for consistent times by turning the timer on and off as quickly as possible. The most consistent person should time. Estimate their error by this test.
2. The timing error comes in twice; once to start the watch and again to stop it.
3. The disk should be rotating quickly enough so that the students can barely time it.
4. I found it useful to put a small piece of tape on the disk as a reference point. Be sure your students remove it when they leave the room.
5. The students should drop the ring **GENTLY**.
6. Have the students perform multiple runs.

Discussion Questions:

What other ways can one change the angular velocity based on the conservation of angular momentum?

A good starting point is the traditional figure skating problem: when his arms are brought closer to the body, the skater rotates faster.

Difficulties and Alternative Conceptions:

This is an on-axis rotational inelastic collision. Students may still have difficulty with collisions and rotational coordinates, especially concerning the direction of the angular momentum.

Prediction and Warm up questions:

$$\omega' = \frac{(I_{Disk} + I_{Shaft})}{(I_{Disk} + I_{Shaft} + I_{Ring})}\omega,$$

where ω is the initial angular velocity of the system, and ω' is the final angular velocity of the system.

Sample Data:

The printouts for the measurements of all final angular speeds are included at the end of following sample data.

	Shaft	Disk	Ring	Spool
Mass (g)	222.5	1364.6	1431.1	-----
Radius (cm)	0.67	11.4	5.3/6.3	1.6

$I_{Disk} = 8.867$ e-3(kg*m^2),

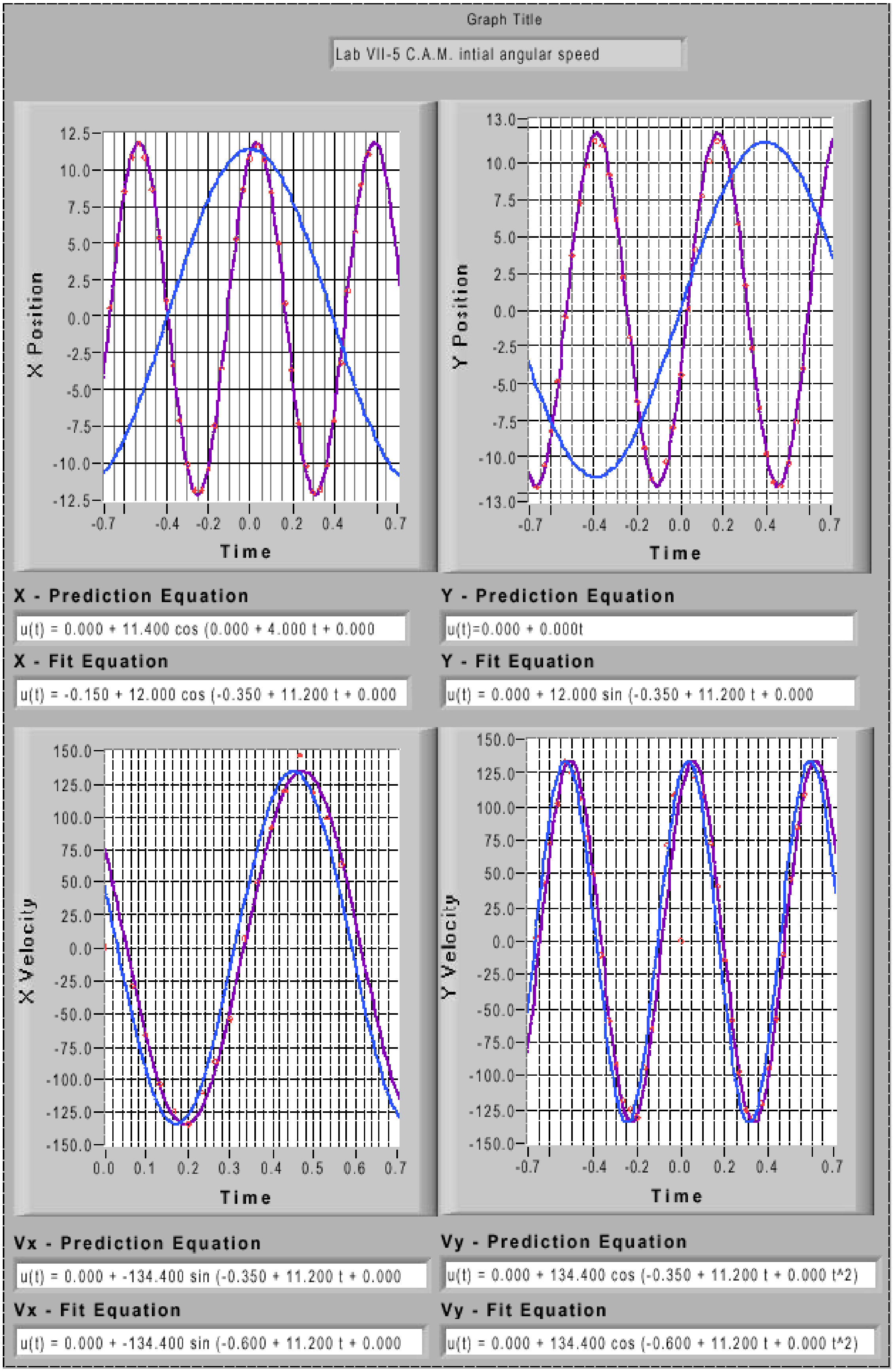
$I_{Ring} = 4.85$ e-3(kg*m^2),

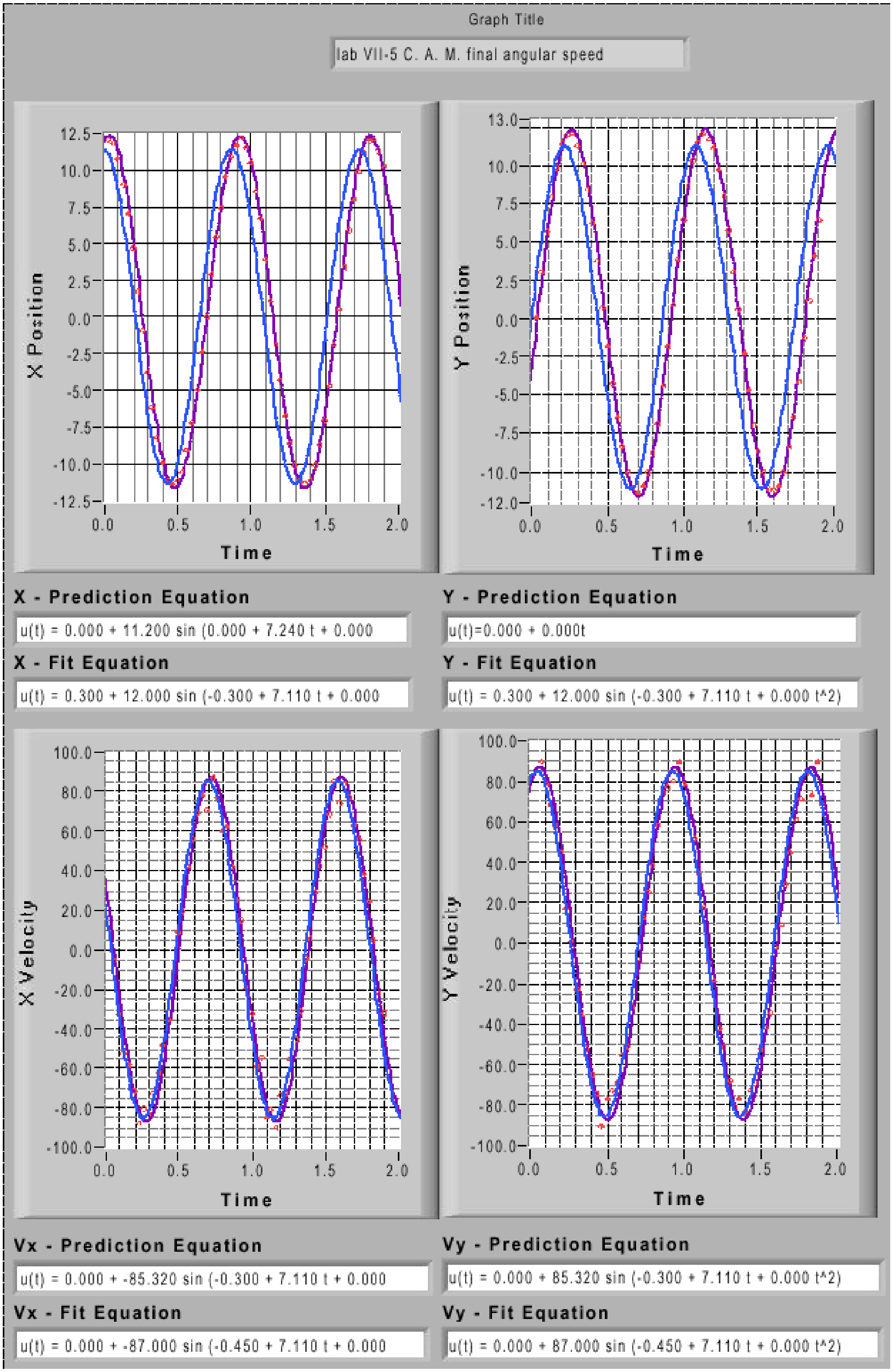
$I_{Shaft} = 4.994$ e-6(kg*m^2),

Initial angular speed $\omega_i = 11.2$ (s^{-1}),

Predicted final angular speed ω_f =7.24(s^{-1}),

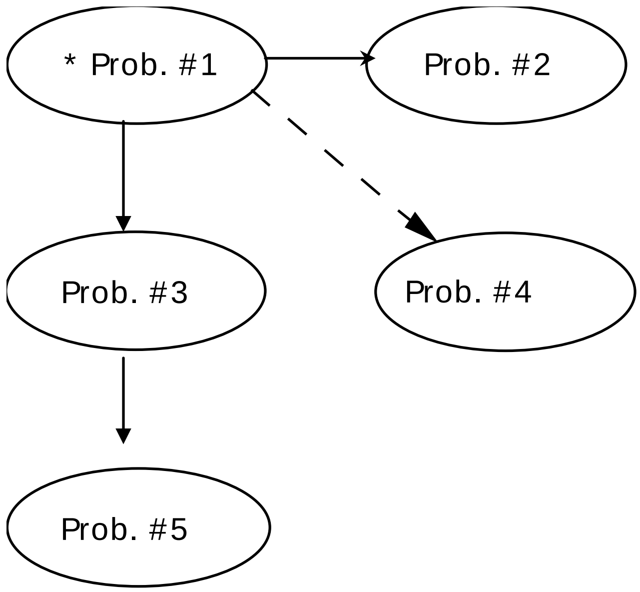
Measured final angular speed ω_f =7.11(s^{-1}).


Graph Title
Lab VII-5 C.A.M. intial angular speed
X Position
Time
Y Position
Time
X - Prediction Equation
u(t) = 0.000 + 11.400 cos (0.000 + 4.000 t + 0.000
Y - Prediction Equation
u(t)=0.000 + 0.000t
X - Fit Equation
u(t) = -0.150 + 12.000 cos (-0.350 + 11.200 t + 0.000
Y - Fit Equation
u(t) = 0.000 + 12.000 sin (-0.350 + 11.200 t + 0.000
X Velocity
Time
Y Velocity
Time
Vx - Prediction Equation
u(t) = 0.000 + -134.400 sin (-0.350 + 11.200 t + 0.000
Vy - Prediction Equation
u(t) = 0.000 + 134.400 cos (-0.350 + 11.200 t + 0.000 t^2)
Vx - Fit Equation
u(t) = 0.000 + -134.400 sin (-0.600 + 11.200 t + 0.000
Vy - Fit Equation
u(t) = 0.000 + 134.400 cos (-0.600 + 11.200 t + 0.000 t^2)


Graph Title
lab VII-5 C. A. M. final angular speed
X Position
Time
Y Position
Time
X - Prediction Equation
u(t) = 0.000 + 11.200 sin (0.000 + 7.240 t + 0.000
Y - Prediction Equation
u(t)=0.000 + 0.000t
X - Fit Equation
u(t) = 0.300 + 12.000 sin (-0.300 + 7.110 t + 0.000
Y - Fit Equation
u(t) = 0.300 + 12.000 sin (-0.300 + 7.110 t + 0.000 t^2)
X Velocity
Time
Y Velocity
Time
Vx - Prediction Equation
u(t) = 0.000 + -85.320 sin (-0.300 + 7.110 t + 0.000
Vy - Prediction Equation
u(t) = 0.000 + 85.320 sin (-0.300 + 7.110 t + 0.000 t^2)
Vx - Fit Equation
u(t) = 0.000 + -87.000 sin (-0.450 + 7.110 t + 0.000
Vy - Fit Equation
u(t) = 0.000 + 87.000 sin (-0.450 + 7.110 t + 0.000 t^2)

Laboratory 7: Oscillations

The purpose of this lab is to give the students hands-on experience in analyzing basic oscillatory phenomena. Along the way, basic concepts associated with oscillatory motion are discussed. In this lab, students will use different methods to determine the spring constant and investigate the quantities that determine the oscillation frequency of a system. This lab should also serve as a review of basic kinematics, dynamics and energy transfer.



All problems involve springs, except problem #5, which deals with a simple pendulum (a late addition). You may work on problem #5 before proceeding to the other problems. It also seems natural for Problem #4 to follow Problem #2 since Problem #4 needs some parameter (natural frequency) from Problem #2.

Discussion Questions:

What determines the oscillation frequency of a system? (e.g. masses of cart and object, spring constant of springs.) How does the additional force affect the amplitude of oscillation? What effect does friction have on the frequency of oscillation? How do the kinetic and potential energies vary during the oscillatory motion?

Things to Remember:

- Use the problem report form on the computers to report any problems with the equipment.

Things your students should know by the end of this lab:

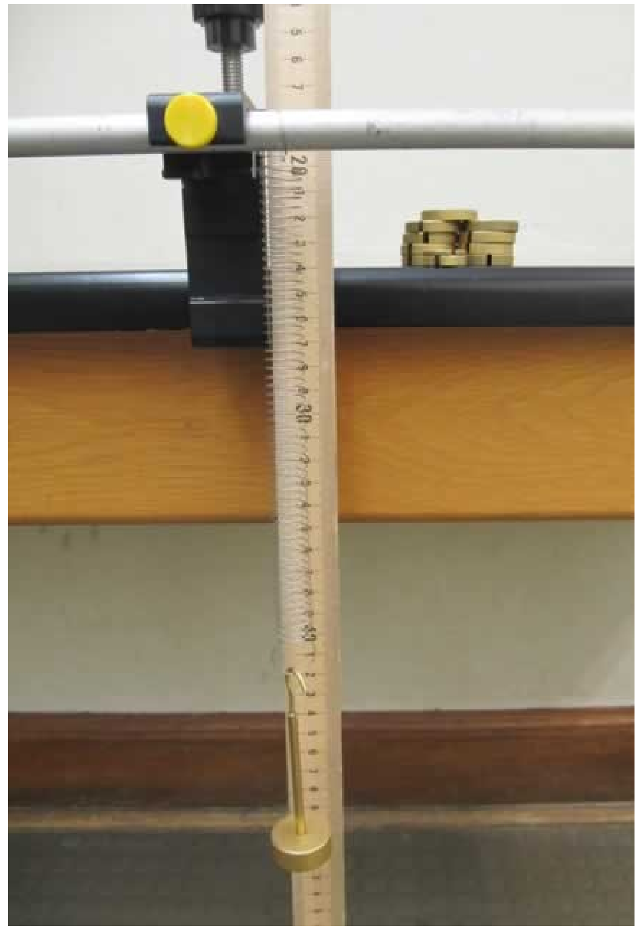
- Explain qualitatively the behavior of an oscillating system.
- Describe quantitatively the influence of physical quantities that determine the period of the oscillatory motion.
- Be familiar with simple mathematical methods employed in describing oscillatory motion.
- Describe qualitatively the effect of additional forces on an oscillator's motion.

Things to check out before this lab:

- Check every wheel of every plastic cart to see if the wheel can rotate at least two seconds after a gentle push.
- For Problem #3, try different hanging masses but avoid passing the elastic limit of the springs. Check the pulley to make sure it can rotate freely without binding. Replace any that don't work.

NOTE: The elastic limit of the springs (at least the big ones) is about 60 cm. Don't pass this limit during the experiment.

Lab 7 Problem #1: Measuring Spring Constants



Purpose:

- To familiarize students with the properties of a spring and the simple oscillatory motion driven by a spring.

Equipment: metal rod, table clamp, meter stick, mass set, mass hanger, spring

Teaching Tips:

1. Be sure not pass the elastic limit of springs (about 60 cm).

2. During measuring, fix the top of the spring. Don't let it slide along ring stand. Try to keep spring-object system moving vertically without wobbling.

3. Choose the reference point at the mass holder and not at the spring since the spring will stretch during oscillation.

4. For method #2, when digitizing data, it is better to start at the maximum displacement from the equilibrium position. Students need to collect the data for at least two complete periods.

5. For method #2, students will use a lot of time to find the fit equations. They may need your help to get parameters in fit equations from graphs. (Previous version of manual: When we developed this experiment we took about 20 minutes to analyze data for one hanging mass.) If tim e is not enough, just choose one hanging mass.

Difficulties and Alternative Conceptions:

- Students do not realize that the spring constant is a property of a spring. They may think the spring constant will change with different hanging mass.
- The relationship between oscillation period and spring constant may also confound them.

Prediction and Warm-up Questions:

Both methods should give about the same spring constant.

Period of oscillations: $T = 2\pi\sqrt{\frac{m}{k}}$,

where m is the mass of the hanging object at the free end of a spring, and k is the spring constant of springs.

Sample Data:

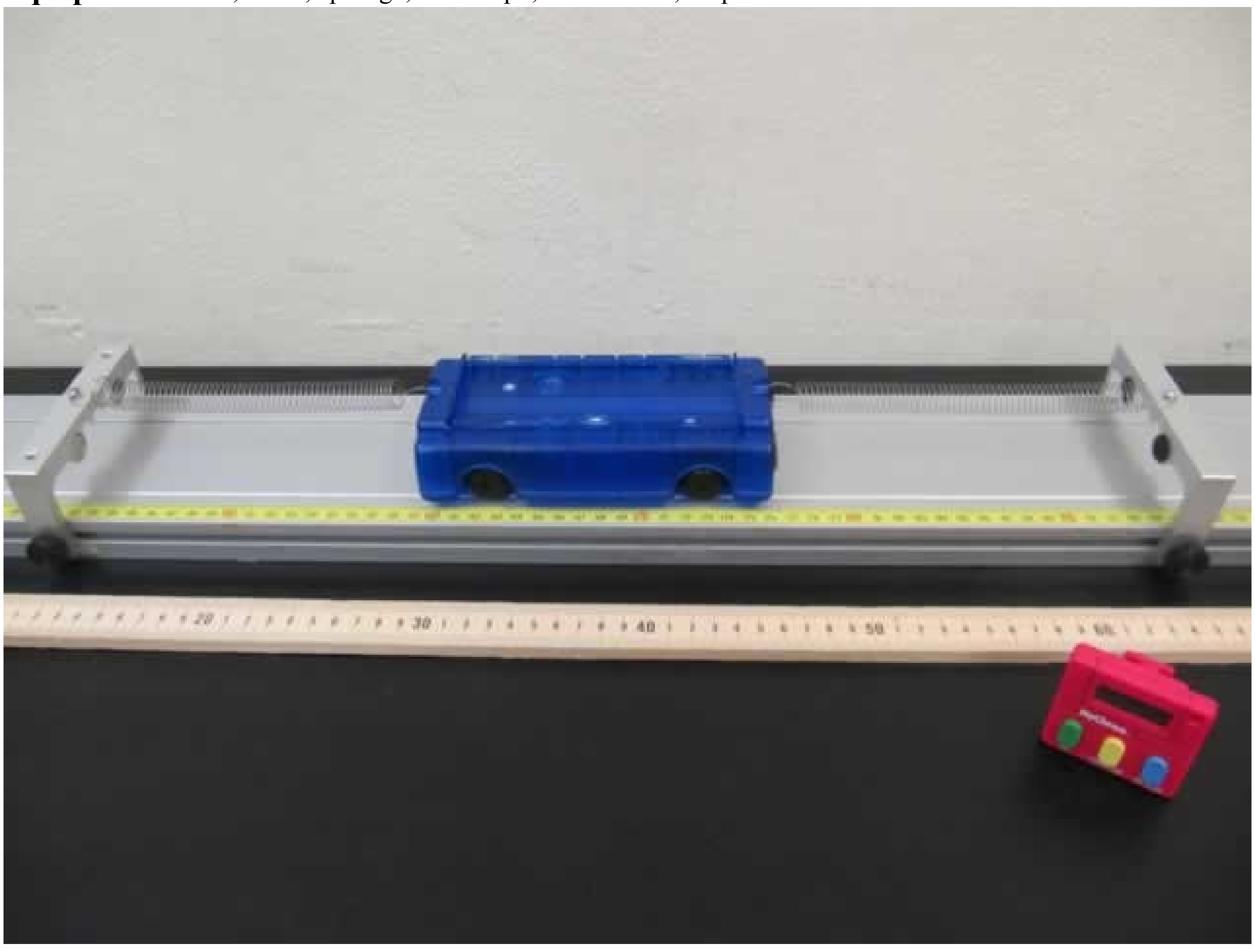
Look at the sample data for the next problem for the measurement of the spring constants by (1) constructing a force versus extension curve (FEC) and (2) measuring the period of oscillations. The period of oscillation is measured using (1) a stopwatch and (2) video software applications in LabVIEW™.

Lab 7 Problem #2: Oscillation Frequency with Two Springs

Purpose:

- To describe quantitatively the influence of physical quantities that determines the oscillation frequency for a complex spring-cart system.

Equipment: cart, track, springs, end stops, meter stick, stopwatch.



Teaching Tips:

1. In equilibrium, the springs in the system must be stretched out (the springs are not compressible like bed springs). The initial amplitude of oscillation should also not have the springs exceed the elastic limit.

2 Require students to record at least 3 periods of oscillatory motion of the cart in their video and analyze the data for two complete periods. In analyzing the video, start at the moment when the cart reaches the maximum distance from the equilibrium position.

3 Ask the students to check that the amplitude of oscillation decreases because of friction but the period does not vary noticeably from one cycle to the next. The period should also not be sensitive to the initial amplitude.

Prediction and Warm-up Questions:

Oscillation frequency: $f = \frac{1}{2\pi}\sqrt{\frac{k_1 + k_2}{m}}$,

where m is the mass of the cart. k_1 and k_2 are the spring constants of the two springs.

Sample Data:

Before calculating the period of oscillation of the system, the spring constants of the component springs must be measured. Using a stopwatch, a 50g weight/ hanger and two soft, 'fat' springs, the first spring took 25.54 seconds to cycle 30 times, while the second spring took 25.69 seconds to cycle 30 times. These give for the spring constants:

k1=2.72E+3 dyne/ cm=2.72N/ m

k2=2.69E+3 dyne/ cm=2.69N/ m

The two springs are nearly identical.

For the system, the mass of the cart is 254 grams. The predicted period using the prediction expression is:

T=1/ f=1.36 seconds

Using a stopwatch, the following elapsed times were obtained after watching 10 oscillation cycles go by:

Starting amplitude	10 oscillation periods
10cm	13.23seconds
15cm	13.26seconds
20cm	13.24seconds

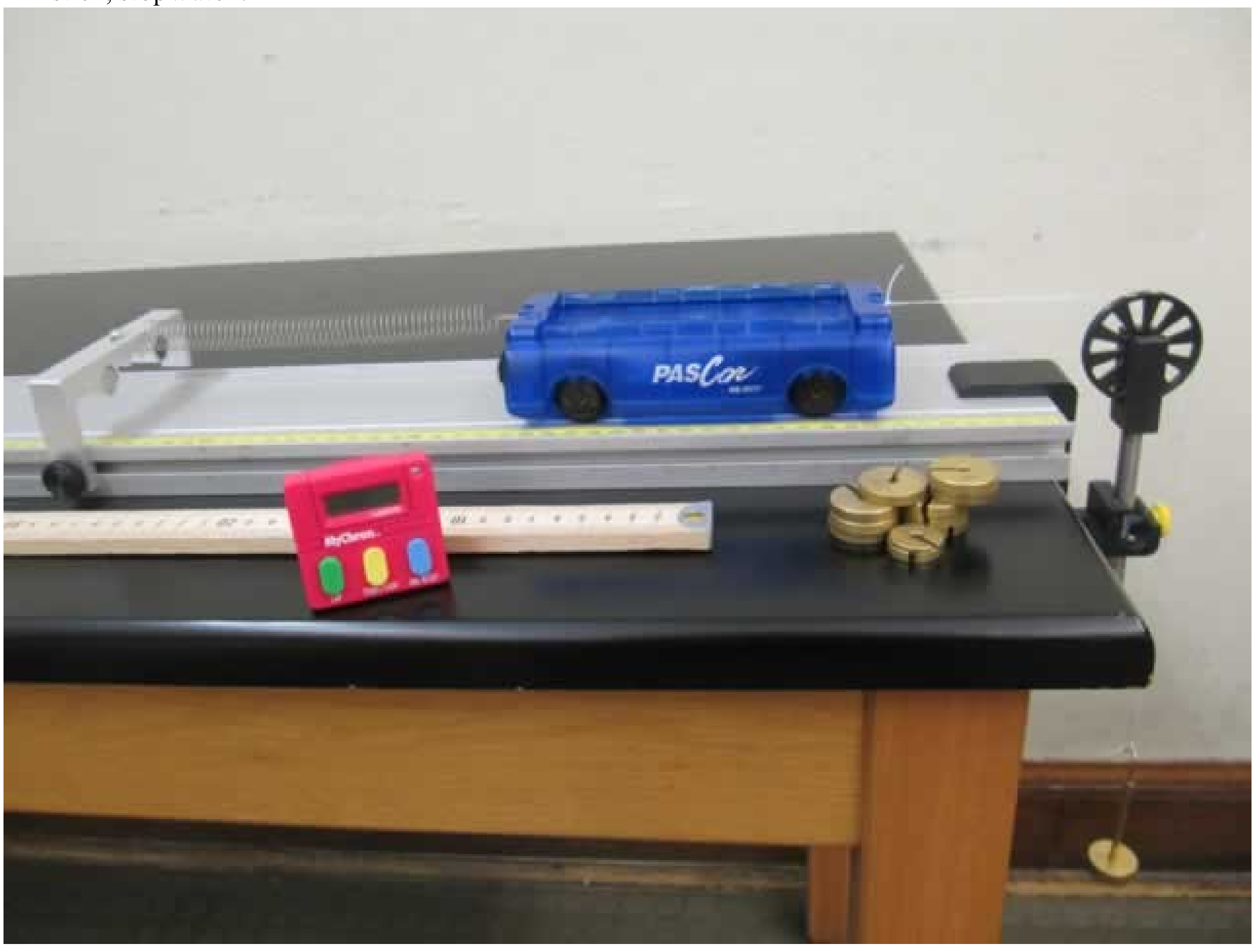
There was no noticeable dependence on the distance between the clamps. These measurements agree with the prediction quite well. You may also measure the period using the video tools.

Lab 7 Problem #3: Oscillation Frequency of an Extended System

Purpose:

- To describe quantitatively the influence of physical quantities that determines the oscillation frequency for an extended oscillation system.

Equipment: cart, spring, track, end stop, pulley, pulley clamp, string, mass set, mass hanger, meter stick, stopwatch.



Teaching Tips:

1. Require students to record at least 3 periods of oscillatory motion of the cart in their video and analyze the data of two complete periods. In analyzing the video, start at the moment when the cart reaches the maximum displacement from the equilibrium position.
2. The damping effect of friction is quite prominent in this experiment. The amplitude of oscillation will decrease because of friction but the frictional force does not change the oscillation frequency.

Prediction and Warm-up Questions:

Oscillation frequency: $f = \frac{1}{2\pi}\sqrt{\frac{k}{m+M}}$,

where m is the mass of the cart, k is the spring constant and M is the mass of the hanging object.

Sample Data:

In this experiment, the mass of the cart is 254g. The spring constant of the spring, calculated from the period of oscillation when the spring suspends a 50g weight/ hanger, is k=2.84N/ m.

Using a stopwatch, the following data were obtained:

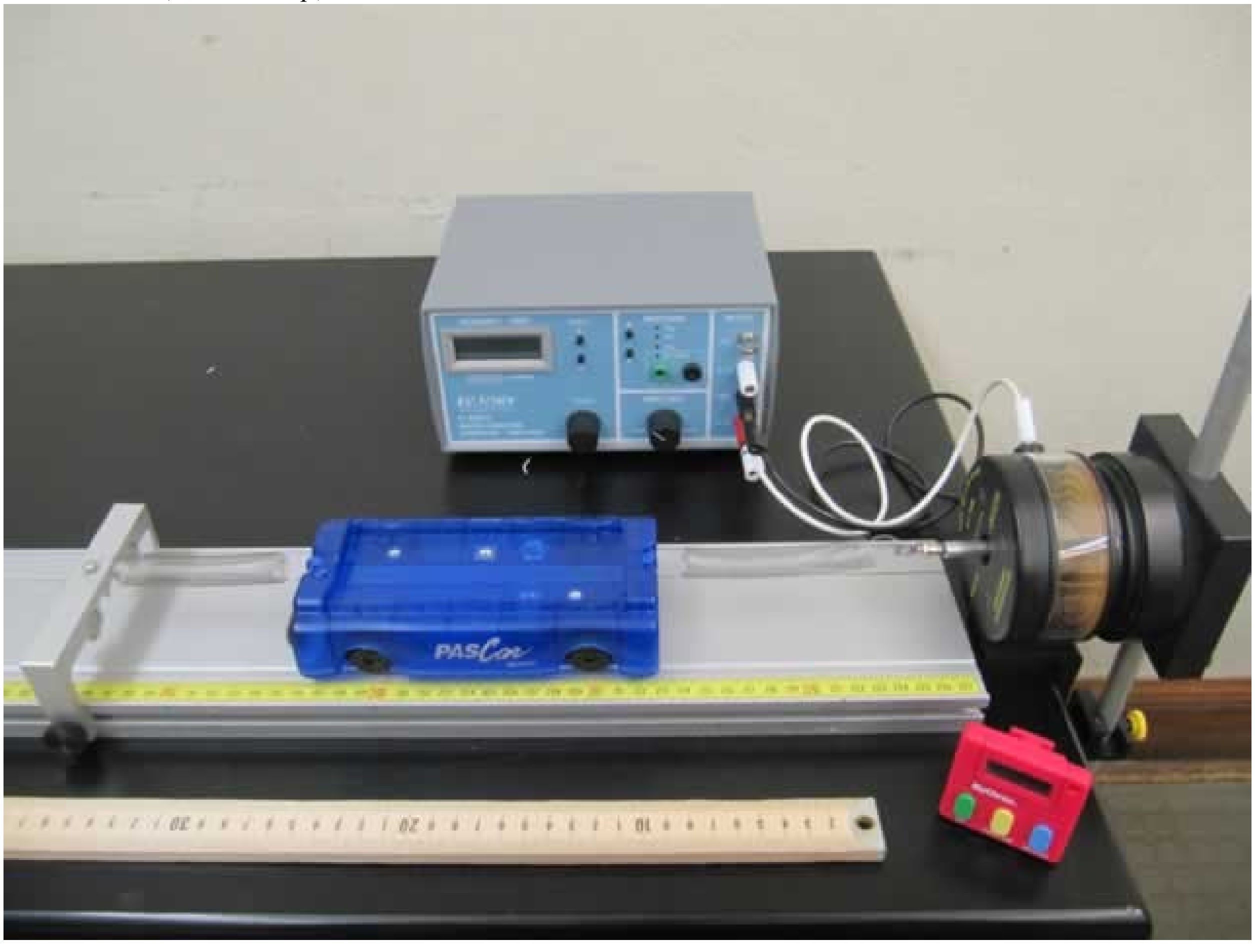
Hanging mass (M)	5 oscillation periods	1 period	Predicted
50g	10.06 seconds	2.012 seconds	2.06 seconds
100g	10.86 seconds	2.172 seconds	2.22 seconds
150g	11.21 seconds	2.242 seconds	2.37 seconds

Lab 7 Problem #4: Driven Oscillations

Purpose:

- To let students observe resonance in a driven oscillation.

Equipment: cart, track, end stop, springs, function generator, mechanical oscillator, meter stick, banana cables, table clamp, metal rod.



Teaching Tips:

1. The students may use the same components from Problem #3, as well as the results for the natural frequency.
2. For low driving frequency, the cart may not budge. You may need to give the cart a little nudge to get it going.
3. Near the natural frequency, choose 5 ~ 6 data points with an interval of 0.005 Hz.
4. For each driving frequency, start the cart from rest.

Difficulties and Alternative Conceptions:

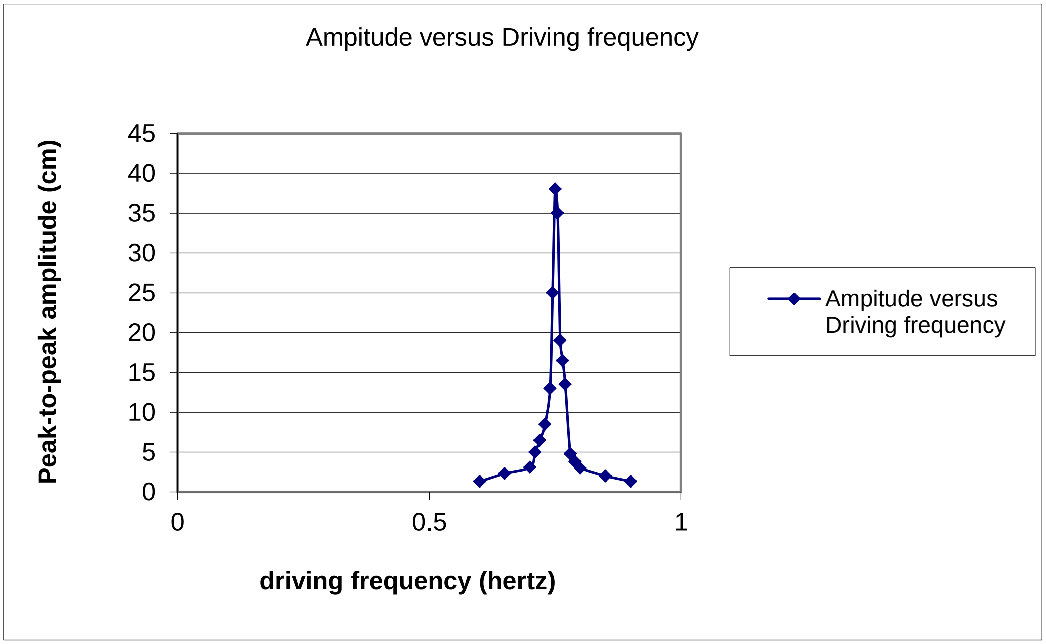
- Students may think the amplitude of oscillation is dependent on the amplitude of the driver and has nothing to do with the frequency of the mechanical driver.
- Another misconception is that the amplitude of oscillation will increase with the frequency of mechanical driver.

Prediction and Warm-up Questions:

The amplitude-frequency sketch is like that in the textbook. When the frequency of the mechanical driver is equal to the natural frequency, we get the maximum amplitude, i.e. resonance occurs.

Sample Data:

The predicted natural frequency is 0.744 Hz, using springs with spring constants k_1=2.71N/ m and k_2=2.84N/ m.



The peak here is at 0.75 Hz, with measured amplitude of 38cm.

Aside: Another nice resonance experiment involving a vibrating beam may be constructed with the available equipment. A meterstick may be secured onto a table edge with a clamp. The section of the meterstick protruding from the edge of the table may be made to oscillate by tying a part of the stick to the speaker/ mechanical driver. At least two resonance frequencies were observed. The length of the vibrating beam/ stick may be varied.

Lab 7 Problem #5: Simple Pendulum

Purpose:
- To let students explore another classic oscillatory mechanical system.

Equipment Setup: mass set, string, metal rod, wood dowel, rod/ rod clamp, table clamp

Teaching Tips:
1. This problem was once administered as a graded lab activity on the last lab session of fall 2003. The students were asked to calculate the value of *g* from the measured period (of the swinging mass tied to a wooden support by a string) and graded on the spot according to how close the value was to what the teaching assistants measured.
2. It is a good idea when measuring the period using a stopwatch to measure the time elapsed for several cycles instead of just one swing of the pendulum. The students have the option of filming the pendulum and extracting the period from the video analysis.
3. Remind the students to calculate the value of *g* from the slope of the graph of the square of the period of the oscillation (T^2) versus the length of the pendulum (L, which is to be varied by changing the length of the string). A linear fit using Excel seems convenient. The value obtained this way can be within 10% of the `accepted' value.

Question:
Measure the period for small oscillations of a simple pendulum for different string lengths and extract a value of the acceleration due to gravity from the relationship between period and length.

Prediction and Warm-up Questions:

$$T = 2\pi\sqrt{\frac{L}{g}}$$

Laboratory 8: Heat Energy and Fluid Motion

If the experiments are done carefully, students may not be able to complete more than one problem in a single session.

By the end of this lab students should:

- Understand the concept of thermal energy and be able to include it in energy conservation equations.
- Understand (hence be able to use) concepts of heat capacity and specific heat and distinguish between the two.
- Be able to describe the energy conversions between thermal, mechanical and electrical energy.
- Understand the concepts involved in fluid drag situations.

Things to check out before the lab:

- Check the DMM and thermometers. Check power supply for problem #1.
- Make sure that hot plates are working properly.
- Check if there's paper towel in the room (water may be spilled all around).
- Ice is available in room 135. Email labhelp@physics.umn.edu if the cooler of ice is getting low.

Lab 8 Problem #1: Power and Temperature Change

Problem: For a light bulb immersed in a water bath, find the rate that the temperature of the water increases as a function of the amount of water and the voltage across and current through the bulb.

Purpose:

- To introduce students to the idea that energy may be transferred between two objects at different temperatures without any macroscopic moving parts. This process is called heat. The change in the internal energy ('thermal' energy or energy associated with the macroscopic components) may be gleaned from the temperature change.
- To give an example of energy conversion from one form (e.g. electrochemical: battery) to another via heat and light.
- To show students application of the concept of a system in the context of thermal processes.

Equipment: Electrical Equivalent of Heat apparatus, water, 6V battery or 18V/ 5A power supply, DMM banana cables, stopwatch

Remind your students that they have TO CONNECT THE DMM CORRECTLY FOR EACH MEASUREMENT!

Warning: Use caution that the electrical devices are not short circuited by the thermometer or the container.

Teaching Tips:

1. This is the first problem of this lab. Students will need to familiarize themselves with use of thermometers, etc.
2. Energy loss (i.e. the energy not going into internal energy of the liquid) will be large during the experiment. Help students to realize and understand it and come up with possible ways to lower this loss. This will serve as actual check of their understanding of the connection between the power (input) and rate of change of thermal energy (and temperature).
3. Make sure the circuits are connected correctly, and that students do record the values of both current through the bulb and voltage across it (in practice the voltage and current are quite steady) Misunderstandings about how to measure the current may span from the first lab of the course.

Prediction:

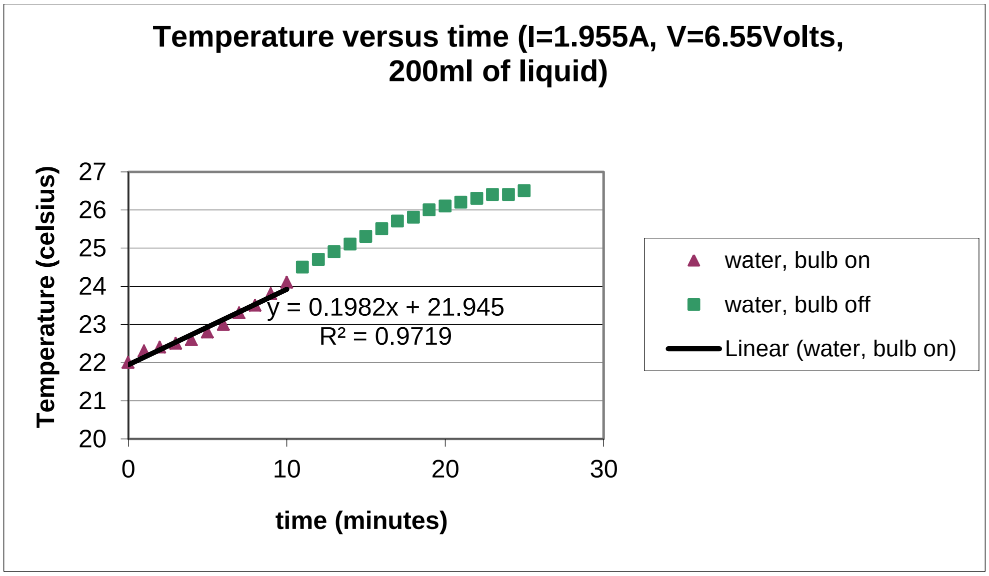
$(P_{in} - P_{out}) = C\ dT /\ dt$, with $P_{in\ /\ out}$ - power input and loss, t – time, C – heat capacity of bulk (liquid), T – temperature. If one were to use 'current times voltage' as the power input, understand that some (perhaps half) of this energy goes into radiation (light).

Data:

A PASCO container was filled to the 200ml level, submerging the metal base of the bulb (you might want to try only partially submerging the metal base). The thermometer probe was immersed with tip touching the base of the container. The Sorensen power supply gave steady values for voltage and current of 6.55 volts and 1.955 amperes, respectively.

Power was cut off at the 11^{th} minute. When the thermometer tip was placed in contact with the bulb, the temperature registered a few degrees higher, perhaps indicating that conduction is still occurring, which may explain why the temperature does not drop significantly after the bulb was turned off.

The bulb power would be (6.55V)(1.955A)=12.805Watts, which is way above the slope dT/ dt times the heat capacity: CdT/ dt=(0.7855g/ ml)(200ml)(2.48J/ g-degC)(0.9055J/ min)(1min/ 60seconds)=5.88Watts. From these two numbers, one may perhaps estimate the efficiency of the light bulb. Also note that instead of using the density of the liquid, you can weigh it directly with a balance.



Lab 8 Problem #2: Specific Heat of Simple Objects
Problem #3: Specific Heat of Complex Objects

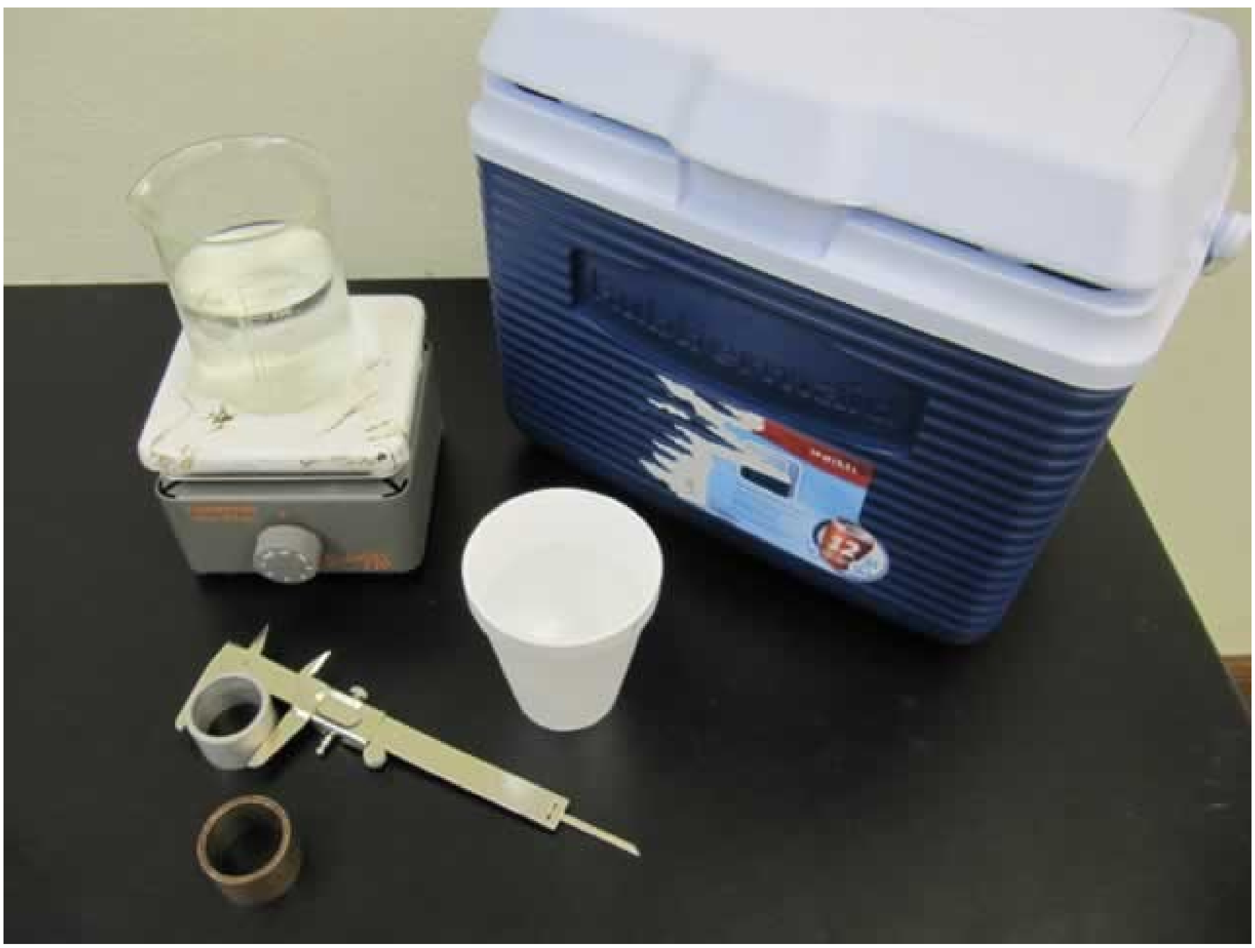
Problem:

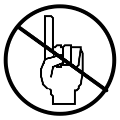
1. Given the initial temperature of a piece of metal, the initial temperature of a liquid bath, the final temperature of the metal and liquid after reaching equilibrium, and the heat capacity of the bath, calculate the heat capacity of the metal.
2. Determine the heat capacity of a complex object made of two different substances from their specific heats and the amount of each substance.

Purpose:

- To reinforce the concept of heat as a process by which energy is transferred as a consequence of a temperature difference.
- To show students that in some cases the change in internal energy is reflected by a change in temperature, which can be connected quantitatively using the mass and specific heat of an object.

Equipment: set of metal cylinders (aluminum, copper and complex cylinder made of aluminum and copper), styrofoam cup, hot plate, glass beaker, ice (optional), scale, thermometer, calipers.





Warning: Use caution with heating devices and glassware. Be careful not to get scalded while handling heated water, as well as the hot plates.

Teaching Tips:

1. A cylinder must be first set to some temperature. This is best done by placing the cylinder in a bath – either of ice or of hot/ cold water. Do not try to heat a cylinder on the hot plate itself, as this will not allow you to measure the cylinder's temperature correctly. Measure temperature of the bath instead, and let the cylinders to stay in it for a minute or more; you can also heat the liquid while the cylinder is immersed in it.
2. Cylinders are handled via a string tied to it. Do not let students move the cylinders by hand.
3. Make sure students measure and record masses of the cylinders.
4. Fill cups with cold tap water. Have students observe if its temperature begins to change (e.g. to increase to room temperature). Make sure students measure and record mass of the water immediately. They may want to replace the water each time they do a new measurement.
5. Make sure thermometers are on the Celsius scale.
6. Heat contact between the hot plates and beaker is not that good – allow about ten minutes for water to warm up.
7. As water gets hot, set the hot plate at scale range #7 – this will keep the water at about 70 degrees.
8. The change in temperature of water in Styrofoam cup after you transfer the cylinder into the cup is usually small (a few degrees). Using the least amount of water will help to reduce the error (let the cylinder be completely immersed in the water).
9. Aluminum has lower heat conductivity than copper – thus it will need more time to equilibrate (up to two minutes for aluminum, less than a minute for copper). It might be a good idea to have the students record the temperature for the first few minutes at about 30 sec intervals.
10. Have students do few measurements for each specimen and average the results for heat capacity at each set (this will decrease the error). Make sure that these are heat capacities or values for specific heat of metals that get averaged, not the changes in temperature, etc.
11. Using extra cups (e.g. cups inserted into each other) or covering the cup with another one does not seem to change much, but may be a lot of fun.
12. The ice you will hopefully get in the lab (alternatively you should ask Sean Albiston where you can get some before the lab) will **NOT** necessarily be made of water suitable for drinking.

Prediction:

Let the initial temperature of the cylinder be T_m, its heat capacity C_m. Similarly, for water in the cup, we use T_w and C_w. (The heat capacity of the system together is $C_m + C_w$, this is something students may miss.) If the final temperature is some T_f, then

$$(T_f - T_w) * C_w + (T_f - T_m) * C_m = 0$$

$$T_f = (T_w * C_w + T_m * C_m) / (C_m + C_w)$$ **(to predict the final temperature)**

$$C_m = - C_w * (T_f - T_w) / (T_f - T_m)$$ **(to calculate the heat capacity)**

Let c_{Al}, c_{Cu} stand for specific heat (heat capacity per unit mass) of pure aluminum and copper cylinders, m_{Cu}, m_{Al} be the masses of copper and aluminum portions of the complex cylinder. Then prediction for specific heat of complex cylinder is

$$\mathbf{c_{complex} = (c_{Al} * m_{Al} + c_{Cu} * m_{Cu}) / (m_{Al} + m_{Cu})}$$

Data:

1. Obtaining the heat capacity of a copper cylindrical shell:

After 'cooking' copper with mass 69g together with 150ml water in a beaker to a temperature of T_m=67.8degrees-celsius, the copper was transferred to a container with water initially at T_w=23.7degrees. This 'container' consisted of two long UDS styrofoam cups and a PASCO calorimeter cup (one inside the other inside the other) with two UDS cup covers. The temperature quickly settled to T_f=25.5degrees. This temperature dropped to 25.2degrees after 12minutes, so insulation seems pretty good. The change in temperature of copper is then 42.3degrees while that of the water is 1.8degrees. The formula above gives the following specific heat: **c_{Cu}=0.0925Cal/g-degC=0.387J/g-degC. The value from tables is 0.39J/g-degC**, which is quite good.

2. Obtaining the heat capacity of an aluminum cylindrical shell:

After 'cooking' aluminum with mass 16g together with 150ml water in a beaker to a temperature of T_m=64.8degrees-celsius, the aluminum was transferred to a container with water initially at T_w=25.2degrees. The temperature quickly settled to T_f=26.1degrees. This temperature dropped to 25.9degrees after 9minutes. The change in temperature of aluminum is then 38.7degrees while that of the water is 0.9degrees. The formula above gives the following specific heat: **c_{Al}=0.218Cal/g-degC=0.913J/g-degC. The value from tables is 0.900J/g-degC**, which is quite good.

3. Obtaining the heat capacity of complex cylinder:

Using a vernier caliper, the cylinder has inner diameter (copper core) of 1.250cm and an outer diameter of 2.285cm. Total mass is 72.5g.

From tables, copper density is 8.92g/ cm^3, while for aluminum 2.70g/ cm^3. From density and volume of cylinders, the copper core mass is m_{Cu}=41.76g while the aluminum cladding is m_{Al}=29.6g, which does not quite add up to 72.5g.

After 'cooking' the cylinder together with 150ml water in a beaker to a temperature of T_m=70.0degrees-celsius, the cylinder was transferred to a container with water initially at T_w=23.2degrees. The temperature settled to T_f=25.7degrees after a few minutes. This temperature dropped to 25.6degrees after 10minutes. The change in temperature of the cylinder is then 44.4degrees while that of the water is 2.4degrees. The formula above gives the following specific heat: **$c_{complex}$=0.112Cal/g-degC=0.468J/g-degC. The predicted value is 0.592J/g-degC**, not as good as in the homogenous cases.

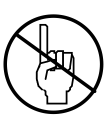
The slow equilibration (and perhaps the inaccuracy) may be due to the smaller surface area to bulk ratio of the complex cylinder.

Lab 8 Problem #4: Mechanical Energy and Temperature Change

Purpose:

- To show that the internal energy, as well as the temperature, of an object may increase if work is performed on it (Compare this problem with problem #1).
- To show the connection between the change in internal energy and work done on a system (hence the connection between 'thermal' and mechanical energy).

Equipment: Mechanical Equivalent of Heat apparatus, nylon rope, massive metal cylinder, DMM, meter stick



Warning: A crank not firmly attached to the table can fall. The hanging mass is heavy, please warn the students and warn them to keep their feet out from beneath it.

Teaching tips:

1. Make sure the lever setup is properly secured to the table. They tend to fall off, especially if crank is pushed in radial direction when rotated.
2. Make sure students do not put their feet below the block.
3. If the cylinder is taken out in order to measure its dimension, make sure that it is reinserted and screwed properly afterwards for use. The notches should fit the grooves in the cylinder and the copper plates on the cylinder should touch the (DMM) contact leads.
4. All DMM readings fit on 200kΩscale. Watch for students to scale their DMM properly.

5. *Counter* is triggered by the handle and should increase by one each time you turn the crank. Make sure this actually happens. To set the counter to zero, turn the little knob located on the side of the counter.
6. Wrapping the rope around the cylinder twice may be enough. Make sure the rope does not overlap with itself (friction will be much larger and the rope will stop slipping over the cylinder).
7. Once the rope is wrapped around the cylinder, hold the loose end of the rope and begin turning the cylinder. See if you can lift and adjust the height of the block by varying the (weak) pull on the loose end.
8. Best results (e.g. reduced heat loss) came out for small temperature changes (about 10 deg-C when starting at about room temperature). Students should let the cylinder cool down somewhat after each attempt.
9. Note that at the time of revising this manual, a description of an experiment using similar equipment can be found on the web.

Question:

Calculate the change of temperature of an object as a function of the force exerted on it, the distance over which that force is exerted, and the heat capacity of the object.

Prediction:

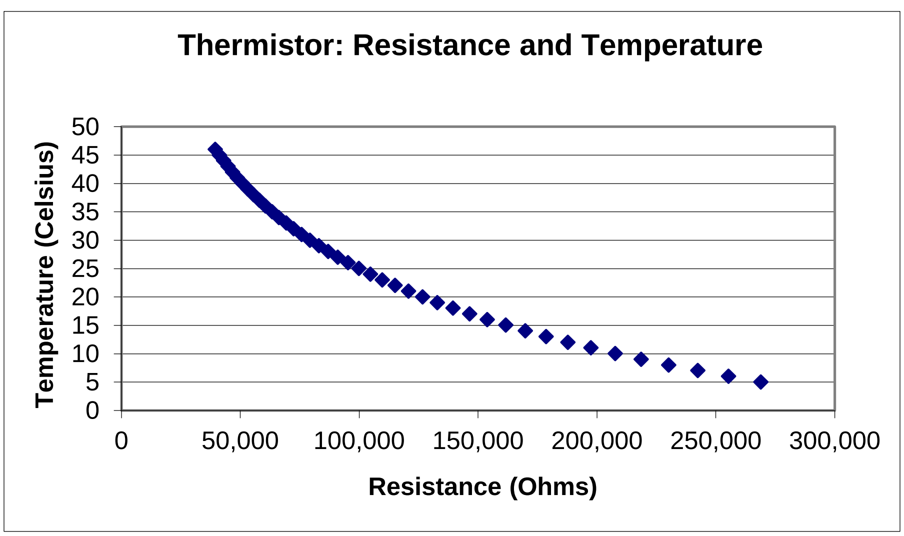
$M_{block} g * (\#\ Revolutions) * (Circumference) = m_{cylinder} * c * \Delta T$

Data:

The aluminum cylinder has diameter 4.480 cm and mass 203 g. The block has mass 8.40 kg (as indicated on the block itself). The specific heat of aluminum is 900J/ kg-degC. Using these numbers, the prediction relating temperature change and number of revolutions reduces to

$\Delta T = 0.06348 * (\#\ Revolutions)\ ^{o}C$

As to the actual experiment, the device was cranked to generate resistance (and hence temperature) changes corresponding to 20,40,60,80,100 and 200 revolutions of the cylinder. Three trials were made for a fixed number of revolutions (except for 200 revolutions). Each trial took about a minute. To check for 'leakage' to air, while idle, it was observed that the resistance changes by about 1kΩ in a minute (this depends on the temperature of course), which is significantly smaller than the resistance changes generated below. Resistances were translated to temperatures using a linear interpolation of the table provided in the PASCO thermistor/ lever setup. This table is reproduced below as a plot:

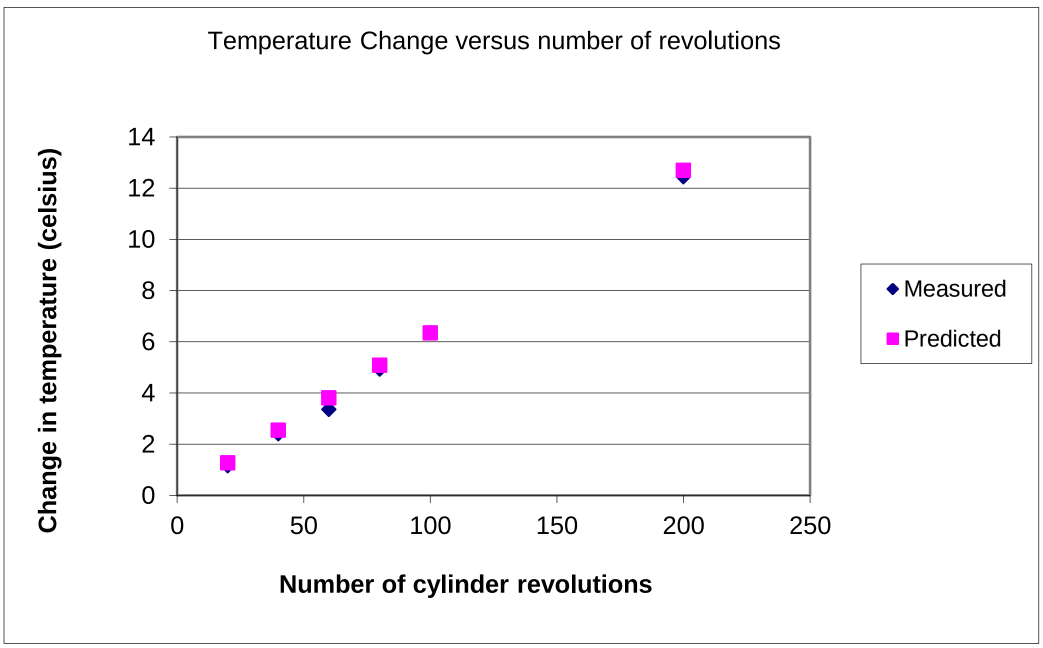


The table below is a snippet of the experimental results:

# Revs	$R_{initial}$, kΩ	R_{final}, kΩ	$T_{initial}$, °C	T_{final}, °C	ΔT, °C	$M_{cylinder*}c_*\Delta T$ (J)	Mech Work (J)
100	102.4	76.0	24.5	30.97	6.472	1183	1160
100	90.4	67.9	27.18	33.49	6.313	1153	1160
100	90.2	67.9	27.23	33.49	6.264	1144	1160
200	93.6	53.6	26.43	38.87	12.44	2274	2320

(The first row in the table above is somewhat anomalous. The higher value for the internal energy change compared to the mechanical work may result from the rope getting caught in the device as it is being cranked)

The change in temperature from trials with a fixed number of revolutions are averaged and plotted together with the prediction results below, as a function of number of cylinder revolutions. The difference between data and prediction is within 12%. The predicted temperature changes are larger compared to the observed changes (a measure of the 'loss' to the surroundings), except for the data point corresponding to 100 revolutions, but the difference in this case is very small (less than a tenth of a percent).

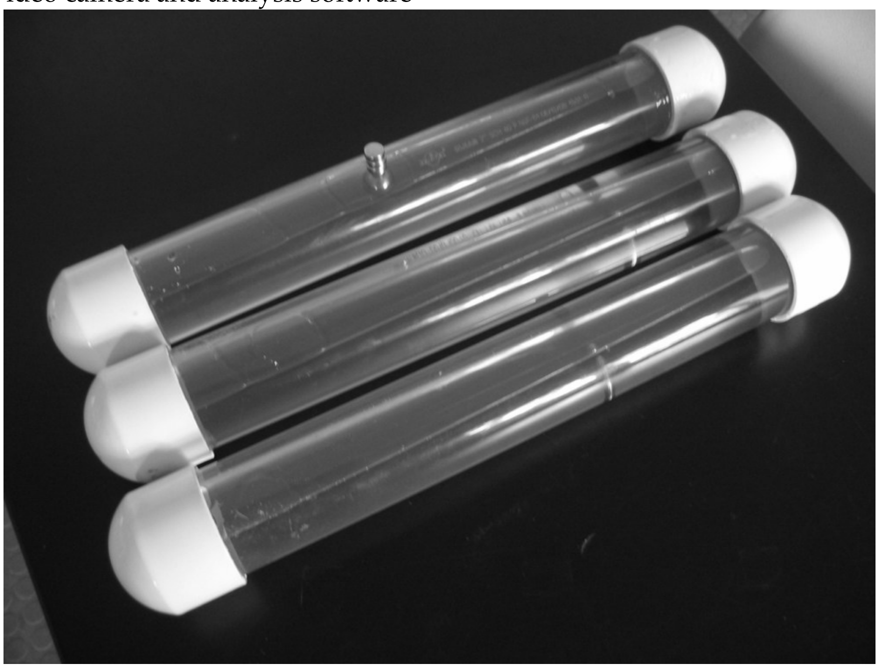


Lab 8 Problem #5: Motion in a Fluid

Purpose:

- To give students experience in describing the motion of an object in a type of environment relevant to microbiology.
- To give an example of situation with a non-stationary object in equilibrium.
- To give an instance of a non-conservative resistive force proportional to the velocity.
- To give students qualitative and quantitative understanding of a drag force and terminal velocity
- To give them practice solving an ordinary differential equation (guess and check) and qualitative understanding of the behavior.

Equipment: 3 steel balls enclosed in capped PVC sections filled with glycerin. Magnets for catching the steel balls. Video camera and analysis software



Teaching Tips:

1. There is a small chance students will have been exposed to Stokes' Law: $F_D=6\pi\eta Rv$. Instead students might have just have been exposed to the concept of a drag force proportional to velocity. $F_D=b\ v$. You might want to point out this is also an approximation. In some cases, drag forces are better represented as being proportional to the square of the velocity: $F_D=b\ v^2$

2. Flexibility is appropriate here in that not all classes would be capable of solving the differential equation. Be prepared to either adjust the lab or help with the calculus.

3. Due to the possibility that the glycerin may not be pure, the viscosity could vary from 0.05 - 1.41 kg/(m s). So have students calculate the velocity settling time, $\boldsymbol{\tau}$. This will help them choose the appropriate fit for their data. NOTE: the frame interval is about 33 ms.

4. The lab could be simplified in just a calculation/fit of the terminal velocity, $\mathbf{v}_t$. This doesn't mean that students shouldn't be taught how the ball reaches this terminal velocity.

5. You will likely find that in these labs the drag force is proportional to v^2 instead of v. The warm up questions have been designed to have students consider this possibility. Discuss how this affects the terminal velocity.

Difficulties and Alternative Conceptions of Students:

- Expect a lot of difficulty solving the differential equation.
- Fitting the data to the x(t) curve might be difficult and take multiple steps.
- Hard to tell if there is much of a settling time. Sample data doesn't show much of a settling time.

Prediction and Warm-Up Questions:

m - sphere mass
V - sphere volume
$\Delta\rho \equiv (\rho_{object} - \rho_{fluid})$ is the difference in density between the steel sphere and the liquid
R – sphere radius

Newton's 2[nd] Law:

$$m\frac{dv}{dt} = \Delta\rho V g - 6\pi\eta R v$$

Terminal Velocity:

$$\frac{dv}{dt} = 0 \Rightarrow v_t = \frac{2}{9}\frac{\Delta\rho R^2 g}{\eta}$$

Velocity as a function of time:

$$v(t) = v_t\left(1 - e^{-\frac{t}{\tau}}\right) \Rightarrow \tau \equiv \frac{m}{6\pi\eta R}$$

Position as a function of time:

$$x(t) = v_t\left(t + \tau\left(e^{-\frac{t}{\tau}} - 1\right)\right)$$

Sample Data:

Glycerin:

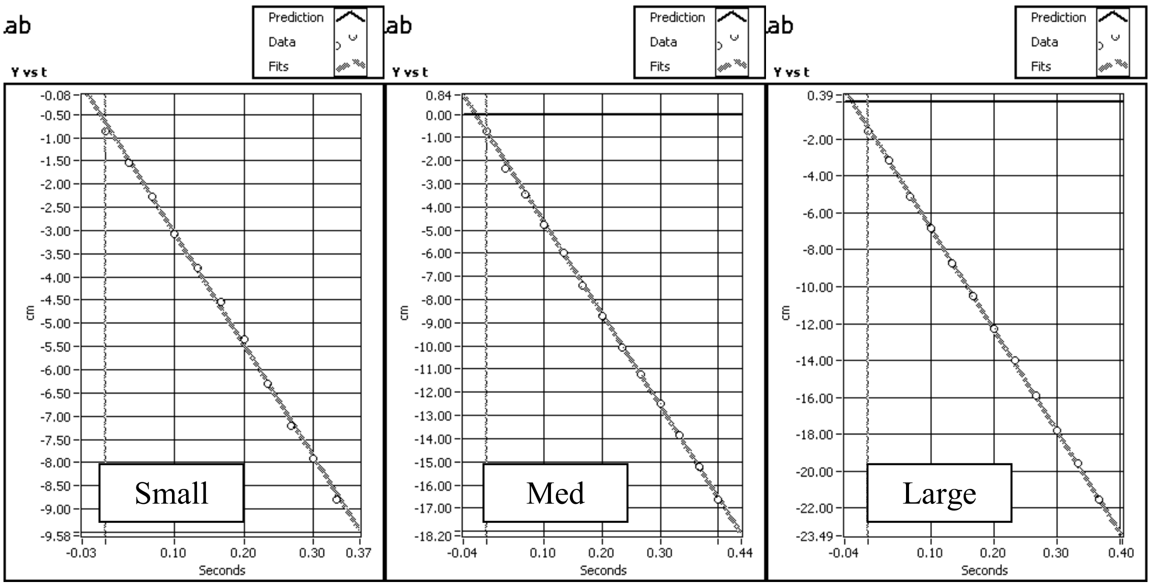
ρ – density 1261 kg/m^3

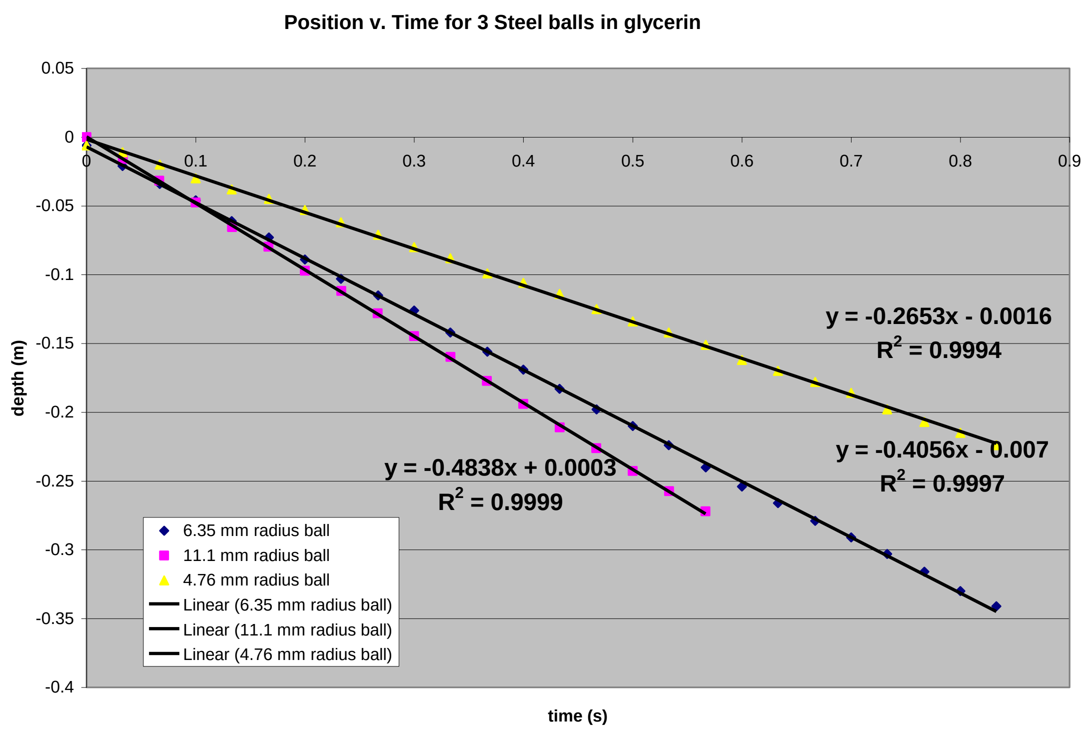
η – viscosity .05-1.41 kg/(m s) (the high value is for pure glycerin, the low value for ~70% purity at room temperature)

Steel Balls: (with predicted settling time, τ, and terminal velocity, v_t for pure glycerin at room temperature)

	Radius (m)	mass (kg)	density (kg/m^3)	settling time (s)	terminal velocity (m/s)
small	4.76E-03	3.50E-03	7.74E+03	2.77E-02	0.227
med	6.35E-03	8.40E-03	7.83E+03	4.98E-02	0.409
large	1.11E-02	4.47E-02	7.78E+03	1.51E-01	1.243

fluid density (kg/m^3)	accel. grav. (m/s^2)	Viscosity (kg/(m s))
1261	9.8	1.41


Prediction
Data
Fits
Y vs t
cm
Seconds
Small
Med
Large


Position v. Time for 3 Steel balls in glycerin
depth (m)
time (s)
y = -0.2653x - 0.0016
R2 = 0.9994
y = -0.4056x - 0.007
R2 = 0.9997
y = -0.4838x + 0.0003
R2 = 0.9999
6.35 mm radius ball
11.1 mm radius ball
4.76 mm radius ball
Linear (6.35 mm radius ball)
Linear (11.1 mm radius ball)
Linear (4.76 mm radius ball)

TA Lab Evaluations
Physics 1201 Lab _________

We strongly encourage you to report issues or problems with any aspect of the lab immediately after completing the lab; please email available information to labhelp@physics.umn.edu. Please try and include topics included below when emailing an evaluation. You may also print out and complete this form, then turn into the lab coordinator's mailbox located in rm. 139 if desired.

Instructors Pages:

Did you find the instructors pages useful? (circle one) yes / no
What additional information would you include in these pages?

____

____

Students:

Did the students find these exercises: (circle one) enlightening / boring / fun / other?
Do you have additional comments regarding student learning and these labs?

____

____

____

TA:

Given the choice, would you teach these exercises again? (circle one) yes / no
Why or why not?

____

____

____

Results:

Did the students obtain sensible results from these exercises? (circle one) yes / no
What were the best / worst sets of results? Why?

____

____

____

Lab Room:

Was the room kept neat and clean by your class and other classes? yes / no
Was the equipment functioning properly? Could you fix it? yes / no
Any other comments regarding the room and equipment?

____

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