PHYSICS 211

LAB #3: Frictional Forces

A Lab Consisting of 4 Activities

Name: ______________________________

Section: ______________________________

TA: ______________________________

Date: ______________________________

Lab Partners: ______________________________

____

____

Circle the name of the person to whose report
your group printouts will be attached. Individual printouts should be
attached to your own report.

Physics Lab 211-3

Equipment List
Motion detector
Force probe
Level
211 friction cart with reflector
Standard cart track setup
Meter stick
Set of 3 wood blocks including one with a reflector

Computer File List
MacMotion file Ò211-03 Block DragÓ
MacMotion file Ò211-03 Data Entry 1Ó
MacMotion file Ò211-03 Up and Down the InclineÓ

Investigation 1: Static and Kinetic Frictional Forces

Goal: • To study the characteristics and origins of frictional forces

Introduction: If you want to drag a crate between two points along the ground, you need to (a) find a better hobby, and (b) apply a non-zero force to get the crate moving and keep it moving. The latter requirement results from the fact that there is a force exerted by the ground on the crate which acts parallel to the surface of the ground and in the direction opposite that of your applied force.

This parallel force is called a *frictional force*, and it exists between two surfaces in contact with each other either

- when one surface is sliding along the other surface (*kinetic friction*), or
- when the surfaces are being pushed relative to one another, but are not moving (*static friction*).

In the following activity, you will study both static and kinetic frictional forces.

Activity 1: The Great Works of Friction

Introduction: In this activity, you will use the force probe to examine the frictional forces present between a block and the aluminum track when the block is at rest and when it is sliding.

Procedure: 1. Measure and record the mass of your block.

m = ________ kilograms

2. Open the *MacMotion* program, by double-clicking on the *MacMotion* icon.
   - **Open...** (under the **File** menu) the file ***BLOCK DRAG*** in the **Lab 3** folder. The graph in Figure 1 should appear on the screen.

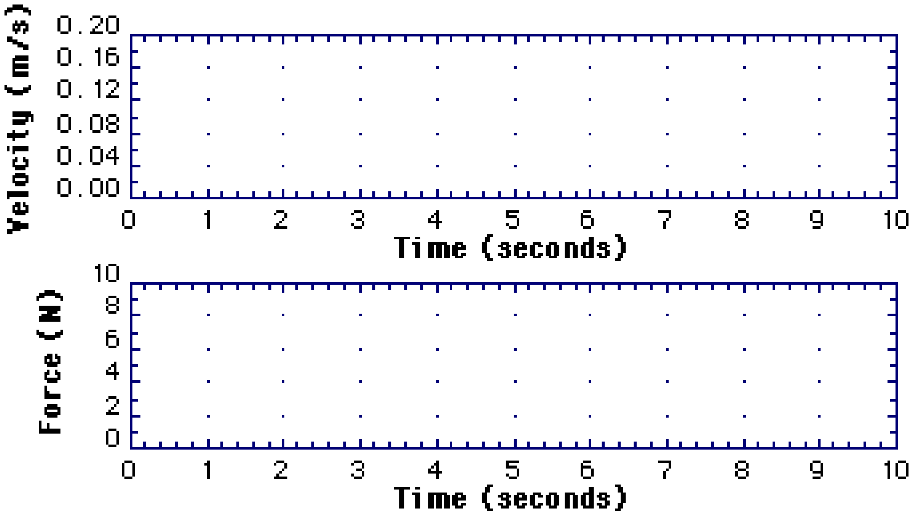


Figure 1. Block drag graph format for Activity 1

Procedure: (continued)

3. Set up the block, track, and force probe as shown in Figure 2. The motion detector should already be mounted on the track. Don't let the block get too close to the detector.

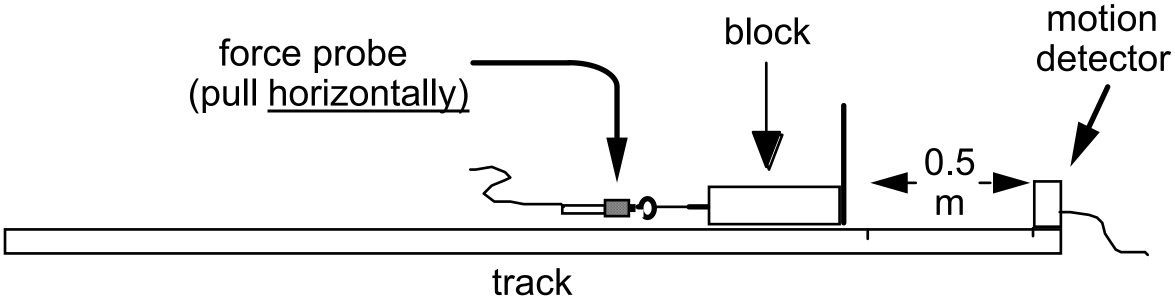


Figure 2. Experimental setup for Activity 1

Prediction: • Sketch in Figure 3 the velocity vs. time and (pulling) force vs. time graphs you expect if you slowly pull an initially stationary block with the force probe until the block is sliding with a constant velocity. Make sure to label important features as carefully as possible, including:

- the behavior of the applied force and block velocity before the block begins to slide
- the behavior of the applied force and block velocity after the block begins to slide
- the kinetic and static frictional forces

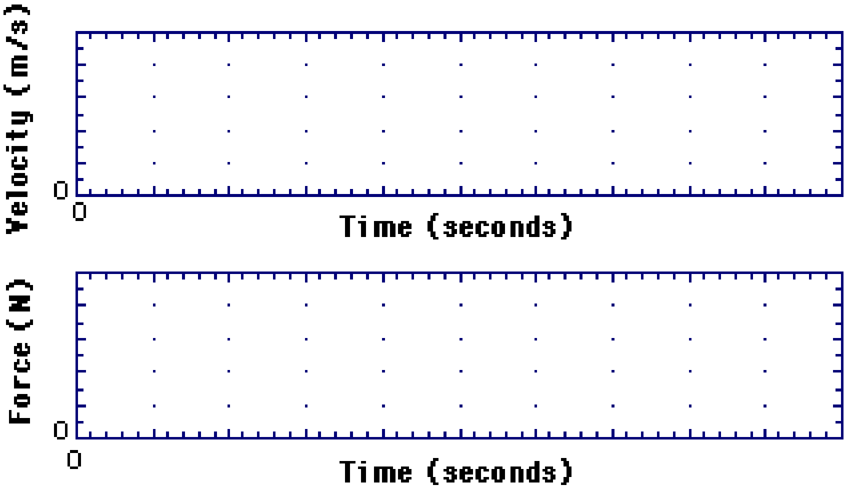


Figure 3. Predicted force and block velocity for Activity 1

Procedure: (continued)

4. Zero the force probe while it is in the horizontal position shown in Figure 2 (with no force applied), by clicking **Zero** on the bottom of the screen.

5. Make a graph while pulling a single block.
    - Place the block with a force probe attached beyond the 0.5 meter line.
    - **Start** graphing, then pull very gently on the block with the force probe (away from the motion detector), increasing the force very slowly.
    - When the block begins to move, pull only hard enough to keep it moving with a small velocity which is as constant as possible.

6. Estimate as accurately as possible from your graphs the values of the maximum static and mean kinetic frictional forces, F_s and F_k, and record in Table 1, as well as in the first row of Table 2 for later comparison.

Mass of Block (kg)	Maximum Static Frictional Force, F_s (N)	Mean Kinetic Frictional Force, F_k (N)

Table 1. Static and kinetic friction results from Activity 1

☐ TA Discussion Checkbox

Procedure: (continued)

7. Move your graphs to **Data B** so they will be available to compare with graphs created later.

Questions:

- Locate the time on your force graph when the block *began to move*. What features identify this time?

  ____

  ____

- As you pull harder and harder, but *before the block starts moving*, what happens to the frictional force exerted on the block by the track?

  ____

- What happens to the frictional force *just as* the block begins to slide? Look at your graph carefully. What is the explanation for this behavior?

  ____

  ____

Activity 2: It's Rough In Here: The Coefficients of Friction

Introduction: A measure of the static and kinetic friction present between two surfaces in contact is provided by the coefficients of friction. In this activity you will examine how static and kinetic frictional forces vary as the normal force between an object and a surface is changed, and with your results you will estimate the coefficients of static and kinetic friction for the surfaces involved.

Procedure: Be sure that your graphs from Activity 1 are still in **Data B** (green).

1. If you haven't already done so, record your results from the previous activity in the appropriate (1 block) row of Table 2.

Prediction:

- How do you expect both the static and kinetic forces on the block to change with increasing block mass? If possible, write your answer mathematically, including as much information as you can.

____

____

2. Repeat the experiment in Activity 1, this time with increasingly larger mass.
    - Place a second block *securely* on top of the first block in order to roughly double its mass.
    - Determine the mass of, and normal force on, the two blocks; record these values in Table 2.
    - Zero the force probe (with no force applied), by placing the probe horizontally on the track as in Activity 1.
    - Pull the block exactly as in the last activity: start with the string loose, then gradually pull very gently. After the block starts moving, move it as closely as possible to the same constant velocity as before.
3. Measure the forces.
    - Select **Analyze Data A** from the **Analyze** menu.
    - Estimate from your graph (**Data A**) the maximum *static* frictional force *just before* the block starts sliding. Record this result in Table 2.
    - Estimate from your graph the *average kinetic* frictional force *while the block is sliding* with a constant velocity using the averaging capability of the computer. Record your result in Table 2 below.
4. Make a labeled record of your comparative experiment.
    - **Set Graph Title...** to include your names and the phrase ***"ONE AND TWO BLOCKS"***.
    - **Print** one copy for your group. Label your graphs (e.g., "One Block," "Two Blocks").

Procedure: (continued)

5. Make a third and final measurement, this time with three blocks. Securely add a third block and zero the probe (horizontally).
   - Determine the mass of, and normal force on, the three blocks and record these values in Table 2.
   - Gently pull the blocks until they move with the same constant velocity as in step 2.
   - Determine the maximum *static* and mean *kinetic* frictional forces, and record these values in Table 2 below.

No. of Blocks	Mass of Block(s) (kg) m	Normal Force (N) $\lvert F_{\perp}\rvert = \lvert F_g\rvert = mg$	Maximum Static Frictional Force, F_s (N)	Mean Kinetic Frictional Force, F_k (N)
0	0	0	0	0
1				
2				
3				

Table 2. Frictional force results for Activity 2

Questions:

- How does the maximum static frictional force vary as the normal force is increased? Try to state a precise mathematical relationship.

____

____

- How does the kinetic frictional force appear to vary as the normal force is increased? Again, try to state a precise mathematical relationship.

____

____

An Aside: Coefficients of Friction

Static friction between two surfaces is characterized by the *coefficient of static friction*, μ_s, which relates the maximum frictional force to the normal force. You should have found experimentally in the previous experiment that both the static and kinetic frictional forces, F_s and F_k, are proportional to the normal force, F_n.

The coefficient of static friction, μ_s, relates the static frictional and normal forces,

$$F_s = \mu_s F_n, \qquad \text{(Eq. 1)}$$

and thus the maximum static frictional force is related to the normal force by the relationship,

$$F_{s,max} = \mu_s F_n \qquad \text{(Eq. 2)}$$

Similarly, the *coefficient of kinetic friction*, μ_k, relates the kinetic frictional force to the normal force, according to the relationship,

$$F_k = \mu_k F_n \qquad \text{(Eq. 3)}$$

Procedure: (continued)

6. Estimate the coefficients of friction in your experiment.

   By plotting your measured values (see Table 2) for maximum static friction, $F_{s,max}$, and mean kinetic friction, F_k, as a function of the measured normal force, F_n, you should be able to estimate the coefficients of static and kinetic friction, μ_s and μ_k, in your experiment.

   - **Open...** the file ***DATA ENTRY 1*** in the **Lab 3** folder.
   - Select **Data A Table** under the **Windows** menu. You should see a new window labeled "**Data A**" similar to that shown in Figure 4. You can enter numerical data directly into the table in the spaces shown.
   - Record your maximum static frictional force, mean kinetic frictional force, and normal force values in the three columns in the on-screen table illustrated in Figure 4.
   - When all your data has been entered, click once on the graph window to bring it to the front and view your points.
   - If static friction, $\mathbf{F_{s,max}}$ (**F_s,max**), is not already displayed on the y-axis, select this data set by clicking the mouse cursor on the y-axis label and dragging down to select **F_s,max**.
   - Double-click on the graph window and adjust the scale so that your points are visible.

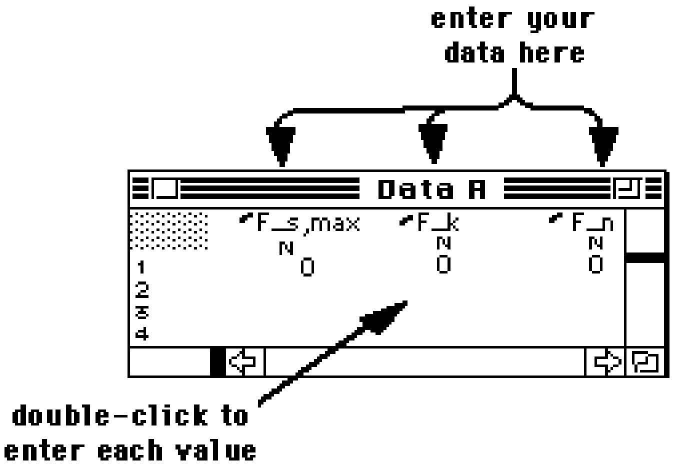


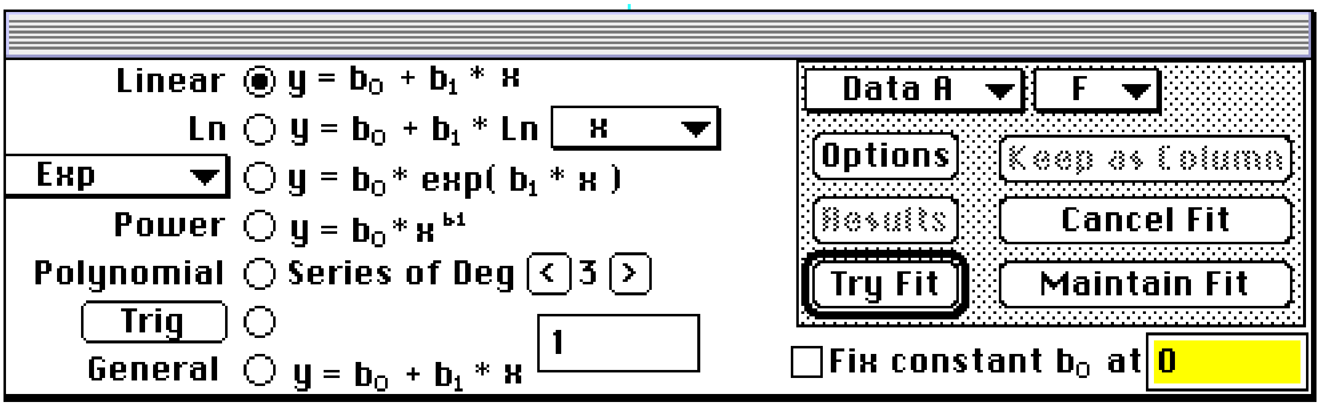
Figure 4. Data entry table for maximum static friction, $F_{s,max}$ (F_s,max), kinetic friction, F_k (F_k) and normal force, F_n (F_n)

Procedure: (continued)

7. Create a "fit" to your static friction (**$F_{s,max}$**) data.

- Select **Fit...** under the **Analyze** menu. A dialog like that in Figure 5 will appear in which you can specify the kind of mathematical formula to try.
- Make sure that **Linear** is selected, as above, and then click on **Maintain Fit**. You should see a straight line on top of your graph. The computer has tried to draw a "best fit" through all the data points.
- Re-adjust your display scale if necessary to better view the points.
- Record the slope of the "best fit" through your static friction vs. normal force data below.

b_1^{stat} = ________


Linear ● $y = b_0 + b_1 * x$

Ln ○ $y = b_0 + b_1 * \mathrm{Ln}$ x

Exp ○ $y = b_0 * \exp(b_1 * x)$

Power ○ $y = b_0 * x^{b1}$

Polynomial ○ Series of Deg 3

Trig ○

General ○ $y = b_0 + b_1 * x$ 1

☐ Fix constant b_0 at 0

Figure 5. Window for selecting a fitting function for your plot in Activity 2

Procedure: (continued)

8. Create a "fit" to your kinetic friction, $\mathbf{F_k}$ (**F_k**), data.

   - Select the kinetic friction ($\mathbf{F_k}$) data set by clicking the mouse cursor on the y-axis label and dragging down to select **F_k**.
   - Rescale if necessary so that there is not a lot of blank space.
   - Fit your data with a linear function by repeating step 7 for the kinetic friction ($\mathbf{F_k}$) data set.
   - Record the slope of the "best fit" through your kinetic friction vs. normal force data below.

$\mathbf{b_1^{kin}}$ = ________

9. What is the relationship between the "best fit" slopes through your data, b_1, and the coefficients of static and kinetic friction, μ_s and μ_k?

____

Use this relationship and the slopes through your data to obtain measured values for μ_s and μ_k. Record these values in Table 3.

Quantity	Measured
μ_k	
μ_s	

Table 3. Results for coefficients of friction in Activity 2

Questions:

- Are your results for the coefficients of static and kinetic friction, μ_s and μ_k in Activity 1 reasonable? Why or why not?

____

____

- Several objects lie in the bed of a truck that is initially at rest. The coefficient of static friction between the truck bed and the objects is μ. If the truck slowly increases its acceleration from zero, will the objects slide initially? Why or why not? If the truck continues to increase its acceleration, what will eventually happen to the objects? Can you write an equation describing the condition under which this will happen?

____

____

____

____

Investigation 2: Motion in the Presence of a Frictional Force

Activity 3: Look What the Cart Dragged On

Introduction: You have already studied in Laboratory 1 the kinematics of a cart traveling up and down an inclined ramp, and you should have found that this motion is in many respects analogous to throwing a ball straight up in the air. In order to examine how friction and other damping forces influence the kinematics of objects, you will study in this activity the influence of a constant drag force on a cart moving up and down an inclined ramp (Figure 6 (b)). With regard to our "tossed ball" analogy, this is tantamount to including the viscous drag effects of the air on the ball (Figure 6 (a)). (Actually, the latter case is somewhat more complicated, as the drag force is not constant in the case of air resistance, but is instead a function of the object's velocity. Nevertheless, the qualitative behavior explored in this activity is similar to that of a ball tossed into the air).

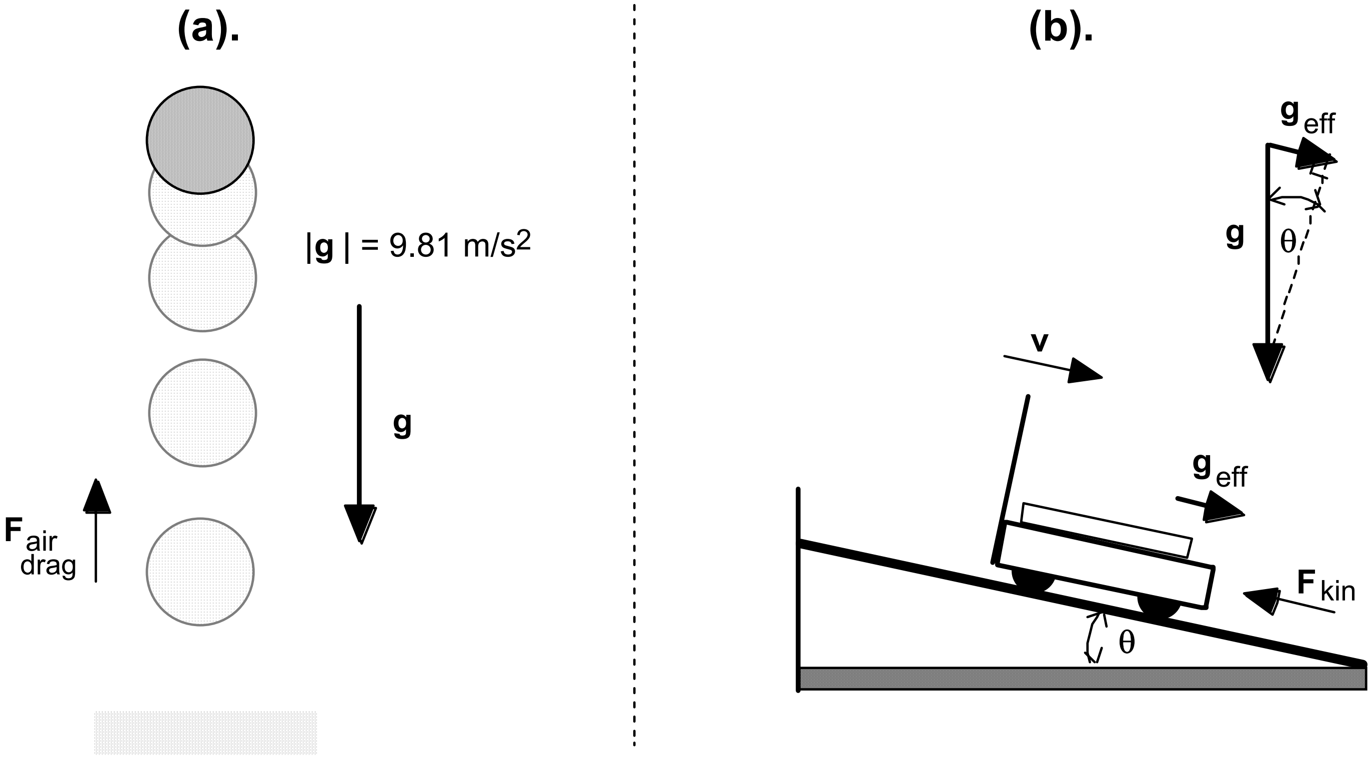


Figure 6. Comparison between (a) "free-fall" motion and (b) a cart rolling down an incline in the presence of a drag force

Procedure:

1. Set up the motion detector, ramp and cart as shown in Figure 7.
   - Raise the detector end of the ramp about 15 cm above the *level track height* (x = 15 cm), and make sure that the motion detector has a good view of the cart all the way down the ramp. *Initially, there should be no friction set on the cart*.

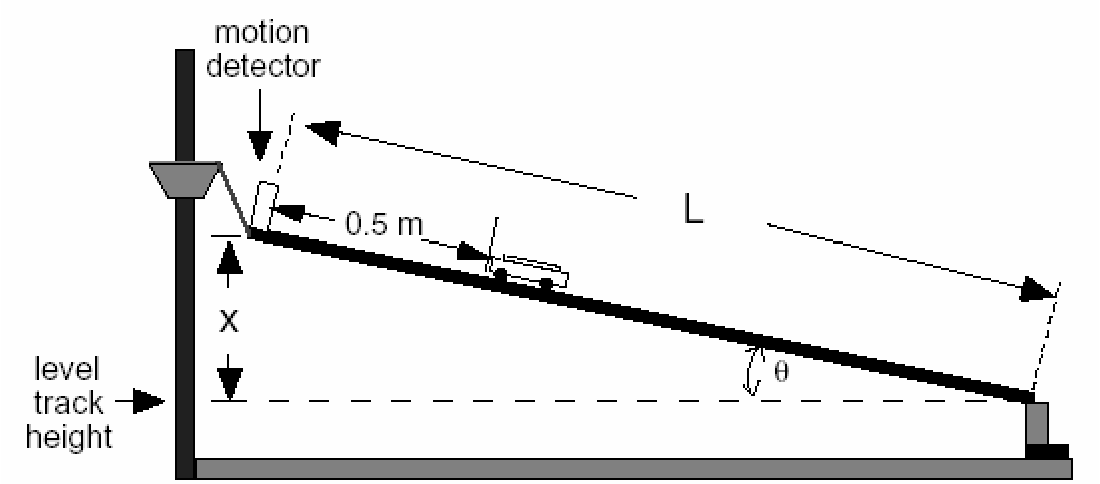


Figure 7. Experimental setup for Activity 3

   - Measure and record x and L (see Figure 7), as well as the mass of the cart in your experimental setup, for later analysis.

x = ______________ **L** = _____________ $\mathbf{m_{cart}}$ = ____________

2. Set up to graph distance, velocity, and acceleration.
   - **Open** ***UP AND DOWN THE INCLINE*** in the **Lab 3** folder. The graph shown in Figure 8 should appear.

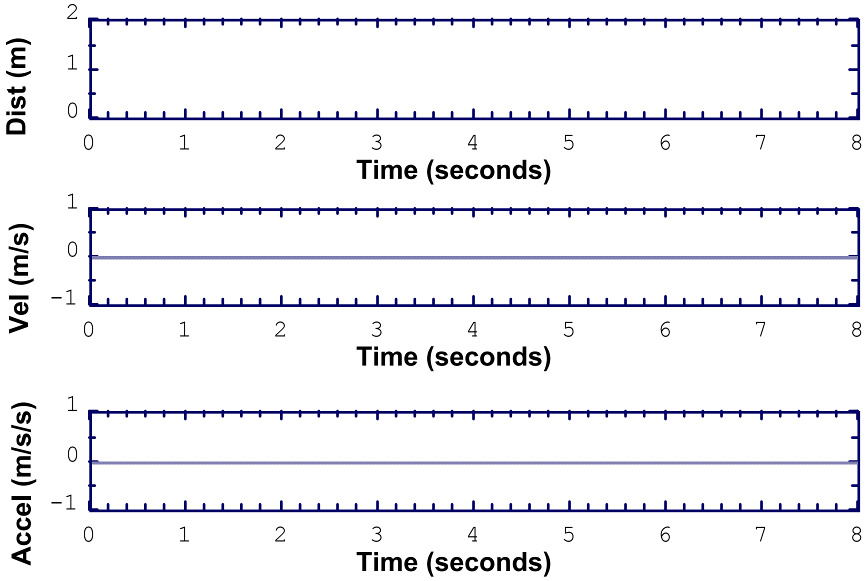


Figure 8. Up and down the incline graph format for Activity 3

Procedure:
(continued)

3. Perform the experiment without friction.

   - Click on **Start**. Wait until you hear the clicking of the motion detector, then push the cart so that it travels up the incline and back. Repeat if necessary to obtain a “nice” set of curves.

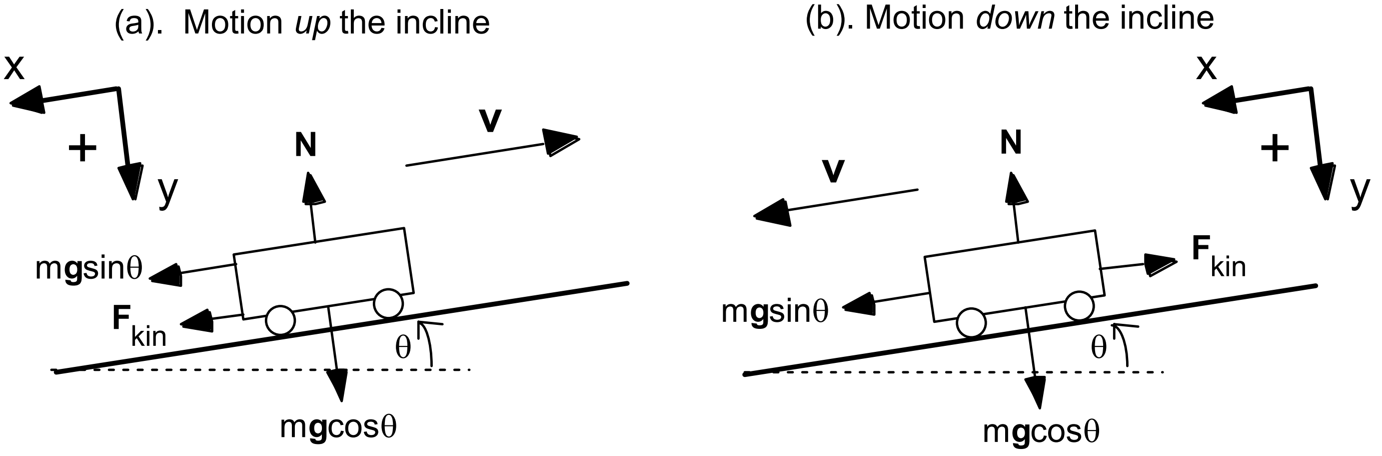
4. Record your measured value for the cart’s acceleration. You should use the averaging capability of the computer, and obtain the mean acceleration exhibited by the cart in the absence of friction (be sure to average only a range of values over which the cart experiences a roughly constant acceleration).

   $\mathbf{a}_{\mathbf{cart}}$ = ____________

5. Move your plots to **Data B** so they will be available to compare with graphs created later. To do this, use **Data A-->Data B** in the **Data** menu.

6. Add friction to your experiment. Leaving the track and graph configurations *untouched*, adjust the friction pad, enough so that there is substantial contact between the pad and the track, but not so much that the cart no longer accelerates down the incline. You are now ready to repeat the previous measurement with friction present.

Predictions: Below you will make several predictions about the effects of friction on a cart which rolls up and down and incline. To help you with these predictions, consider Figure 9, which shows the free-body (force) diagrams for the cart in the case of (a) motion up the incline and (b) motion down the incline, in the presence of a constant frictional force. If you don’t understand the free-body diagrams, ask your TA for help.


(a). Motion *up* the incline

(b). Motion *down* the incline

Figure 9. Free body diagrams for motion of a cart (a) up an incline and (b) down an incline in the presence of friction

- For both cases (a) and (b) in Figure 9, write below Newton’s second law for the net force acting on the cart in the x-direction. Take the positive x- and y-directions to be those defined by the axes shown in Figure 9.

(a). F^{x}_{net} = ______________________ = ma_{up} (b). F^{x}_{net} = ____________________ = ma_{down}

Predictions: (continued)

- Now, on the graph in Figure 10 below, sketch using a dashed line your results from the first part of this activity for the motion of the cart without friction. Next, after studying your free body diagrams above, sketch with solid lines your predictions for the acceleration vs. time and velocity vs. time plots of a cart moving up and down an incline in the presence of friction. Clearly label significant features that you expect in the plot.

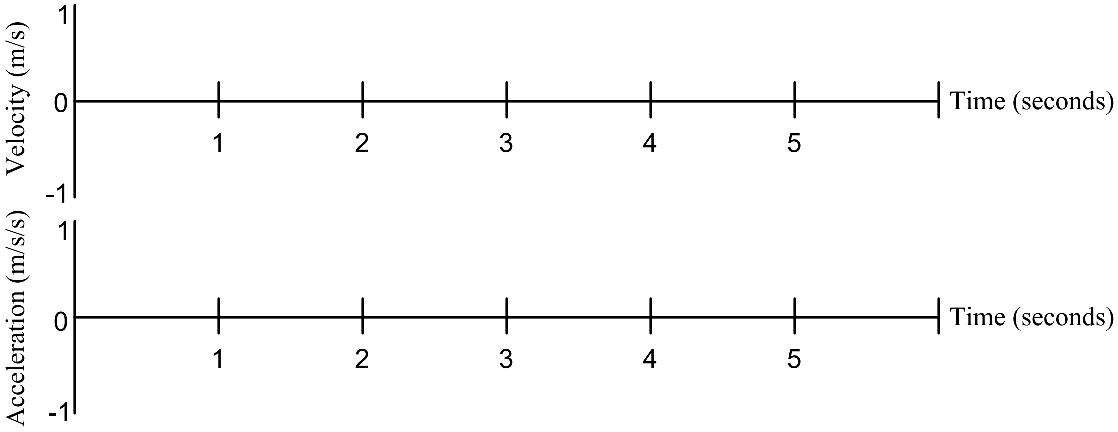


Figure 10. Predictions for velocity and acceleration for Activity 3

Procedure: (continued)

7. Test your predictions: repeat the previous experiment with friction present.
   - Click on **Start**. Wait until you hear the clicking of the motion detector, then again push the cart so that it travels up the incline and back. Repeat if necessary to obtain a “nice” set of curves.
8. **Print** your results, using **Set Graph Title...** to label it with your names and the title ***UP AND DOWN WITH FRICTION***. Make a copy for each person.
9. Take your printout and label your *velocity graph only* with—

   "**A**" where the cart started being pushed

   "**B**" where the push ended (where your hand left the cart)

   "**C**" where the cart reached the top (and is about to start down)

   "**D**" where the cart reached the bottom again

Question:

- How did you identify each of the points in step 9?

Procedure:
(continued)

10. Analyze your data. You are now in a position to determine the values of the force of kinetic friction, F_{kin}, and of the coefficient of kinetic friction, μ_k, present in your experiment.

    - Record your measured value(s) for the cart's acceleration in the presence of friction for motion both up and down the incline. Use the averaging capability of the computer, and obtain the mean acceleration in each range (be sure to average only a range of values over which the cart experiences a roughly constant acceleration).

$a_{\mathbf{up}}$ = ______________ $a_{\mathbf{down}}$ = ______________

11. Find a relationship between F_{kin}, a_{up}, and a_{down} that does not depend on the angle θ. To do this, combine the force equations ((a) and (b)) you derived in your predictions so that the angle θ is eliminated. Write this relationship below.

F_{kin} = ________________________

12. Using the measured values above, calculate the value of the kinetic frictional force in this experiment, and write this estimate below (with units).

F_{kin} = ________________

13. Below, write the relationship between the kinetic frictional force, the normal force, and μ_k.

μ_k = ________________

14. Using known and measured values, obtain a value for the coefficient of kinetic friction in your experiment. Record this value below.

☐
TA Discussion
Checkbox

μ_k = ________________

Question:

- Is your value for the coefficient of kinetic friction in this activity reasonable? Why or why not?

____

____

____

Activity 4: "I've Fallen, and I Can't Speed Up!"

Introduction: Drag forces are funny things. If you fall out of a car at high speeds, drag forces are bad. But if you fall out of an airplane at high altitudes, the drag force becomes your best friend (and possibly your last). Why? An object falling in response to the gravitational force, but also subject to a viscous drag force, will eventually reach a "terminal" speed at which the acceleration of the object is zero. Parachutes, for example, are designed to dramatically reduce a skydiver's terminal speed (note again that this situation is more complicated than that explored in this Activity, as the drag force is not constant in the case of air resistance). In the following activity, you will use the cart and incline to study the conditions under which an object in the presence of friction can "fall" with a constant velocity.

Procedure: In this activity, you will keep the cart friction the same as in the last activity, and you will vary the inclination angle θ until the cart attains a constant velocity.

1. Leave your experimental setup the same as in the previous activity (see Figure 9). Important: *Do not alter the friction pad adjustment* from that used in the last activity!
2. Keep the distance, velocity, and acceleration plots the same as in the previous activity.

Predictions: Consider the free body diagram for a cart rolling down an incline in Figure 11.

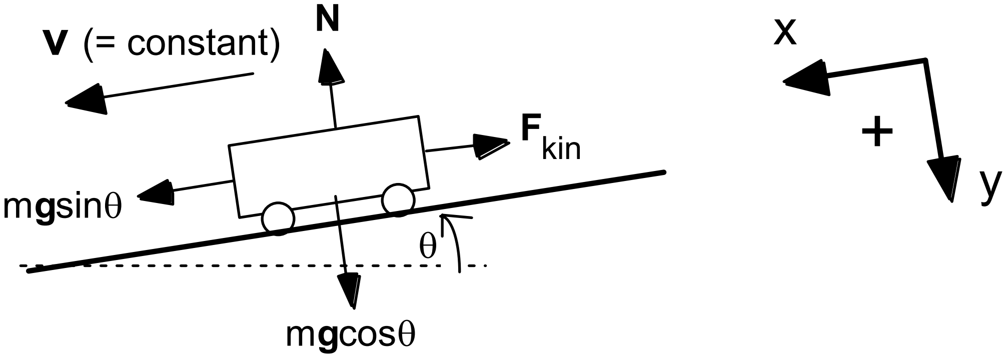


Figure 11. Free body diagram for Activity 4

- Assume that a cart is sliding down an incline in the presence of friction. Use the diagram in Figure 11 to determine a relationship for kinetic friction, F_{kin} (in terms of given parameters, m, g, and θ), when the cart slides down the incline with a constant velocity, $a_{cart} = 0$. Take the positive x- and y-directions to be in the directions shown by the axes in Figure 11.

F_{kin} = ______________________________

- Now, use the definition of kinetic friction, $F_{kin} = \mu_k N$, and the diagram in Figure 11 to derive an expression for the "critical" angle at which the cart will travel down the incline with a constant velocity.

θ_{crit} = __________________

Predictions: (continued)

- Using your measured values from the previous activity, predict the inclination angle, θ_{crit}, at which the cart will slide down the incline with a constant velocity, and record this value in Table 4.

- Sketch with dashed lines in Figure 12 the velocity and acceleration you expect for a cart rolling down an incline with angle $\theta = \theta_{crit}$.

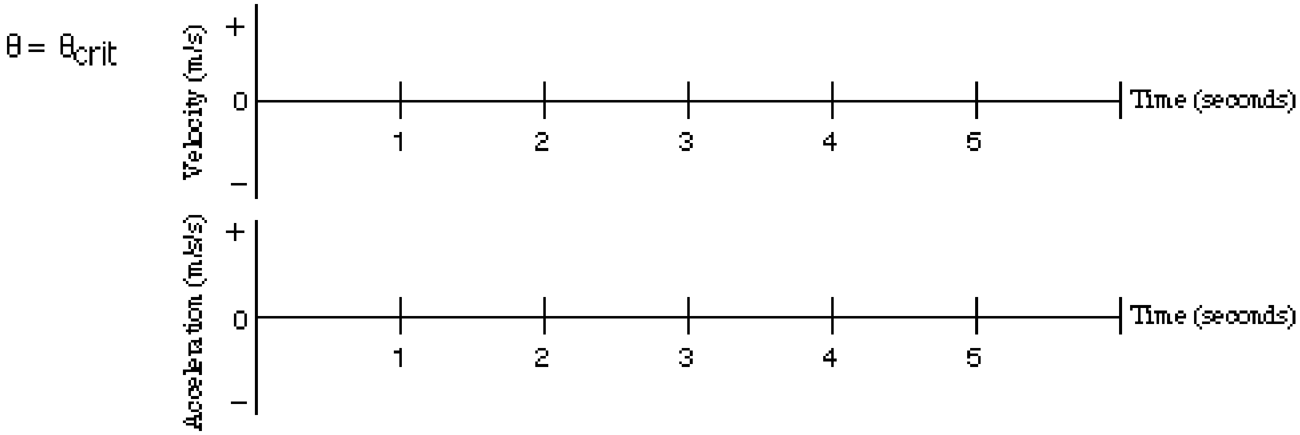


Figure 12. Predictions for Activity 4

Procedure: (continued)

3. Test your predictions.

   - Without adjusting the friction pad on the cart, decrease slightly the inclination angle, θ, of the track.
   - After adjusting the angle, click **Start**, then *give the cart a small push*, and let it slide down the incline. Check your results. Keep varying the inclination angle and repeating the measurement until the cart travels down the incline with a velocity that is as constant as possible. Sketch your results with a solid line in Figure 12.

4. Measure the "critical" angle, θ_{crit}, of the incline, by carefully measuring x (see Figure 7) and using your previous value of L. Record your predicted and measured values for θ_{crit} in Table 4.

Quantity	Predicted	Measured
θ_{crit}		

Table 4. Predictions for the critical inclination angle in Activity 4

☐ TA Discussion Checkbox

Questions:

- How closely did your measurement of the "critical angle" match your prediction? What are the possible sources of error?
- If you adjust the inclination angle so that it is significantly *larger* than the "critical" angle, θ_{crit}, i.e., $\theta > \theta_{crit}$, then give the cart a small push at the top of the incline, how will the cart behave? Give as detailed a description of this behavior as possible, and explain your reasoning.