

## AS 101 - Lab Exercise Gravity and the Laws of Motion (Manual)

### Definitions:

**Velocity:** The speed of a moving object and its direction

**Acceleration:** A change in velocity (speed or direction)

**Force:** What you need to apply to a mass to accelerate it (change its velocity)

### Introduction:

Until the time of Galileo, everyone accepted the Aristotelian concepts of physics. Aristotle taught that everything tries to seek its “proper place.” In Aristotle’s time it was thought that matter was made of four elements: air, fire, earth and water. Accordingly, he thought lighter objects fall more slowly than heavier ones simply because lighter things contain more of the lighter elements, air and fire, and heavier things tend to fall faster because they contain more earth and water. Similarly, Aristotle said that the natural state of an object is to be at rest, so that an object will stop moving as soon as the force acting on it is removed. Aristotle had no concept of acceleration.

Galileo did a series of experiments to show that all bodies accelerate toward the earth and that they all accelerate in the same way. He also showed that in the absence of friction, bodies would keep moving forever. In effect, he achieved a partial understanding of gravity, and he discovered the concepts of acceleration and inertia.

Galileo (and Newton after him) showed that the acceleration of gravity is a constant for all objects at the surface of the Earth, which means that the velocity of a falling object increases continuously. In Newtonian terms, Galileo found that the following relations hold:

A ball is released and rolls down an inclined plane (ramp) a distance  $\Delta x$  in a time  $\Delta t$ . The symbol  $\Delta$  is used to represent “change in”, so  $\Delta t$  means “change in  $t$ ”, where  $t$  is time

$$\bar{V} = \frac{\Delta x}{\Delta t} \quad \text{The average velocity of the ball}$$

$$V_f = 2\bar{V} = a\Delta t \quad \text{The final velocity of the ball when it reaches the distance } \Delta x$$

$$a = \frac{V_f}{\Delta t} \quad \text{The acceleration of the ball as it rolls down the ramp}$$

So far we have not addressed gravity at all. It is the force of gravity that causes the ball to roll. On Earth, the downward acceleration caused by gravity is

$$g = 9.8 \text{ meters/s}^2$$

The acceleration of a free-falling body due to gravity is  $\mathbf{g} = 9.8 \text{ meters/s}^2$  and it is the same for all objects, independent of the objects’ mass.

This was quite profound in Galileo’s time. Newton proved with his mathematical formulation of gravity what Galileo had shown experimentally, that if you drop a heavy object and a lighter object off the top of a building at the same time, they will hit the sidewalk at the same time (neglecting the effects of air resistance). Gravitational force and energy are dependent on mass, while gravitational acceleration is not.

The last thing we have to consider in our experiment is that a ball rolling down an inclined plane is not in free-fall. The inclined plane exerts some force on the ball. The larger the inclination of the plane, the smaller the force exerted by the plane, and the closer the ball will be to free-fall. The acceleration of the ball in the direction it rolls down the ramp ( $\mathbf{a}$ ) is not the full acceleration of gravity. The acceleration is some fraction of  $\mathbf{g}$ , and that fraction must have

something to do with the inclination of the ramp. Let's define the angle  $\theta$  as the angle of inclination of the ramp. When  $\theta = 0^\circ$ , the acceleration of the ball is zero (the ramp is flat), when  $\theta = 90^\circ$  the acceleration of the ball is  $g$ , because it is in free-fall. What trigonometric function (sine, cosine) behaves like this?  $\sin(\theta)$  is zero when  $\theta = 0^\circ$ , and is equal to one when  $\theta = 90^\circ$ . So we might simply guess that the way to relate  $a$  to  $g$  would be:

$$a = g \sin(\theta)$$

This is exactly correct, and can be shown with a little bit of trigonometry and a discussion of vectors, which we will do in lab.

You know how to calculate  $a$ . If you can calculate  $\sin(\theta)$  of your ramp, you can get an experimental value for  $g$ .

### **Available equipment:**

Balls of different materials and sizes, scale for weighing the balls, ramps and air tracks ("Inclined planes"), stopwatch, ruler.

### **Outline of Experimental Procedure:**

As with any experiment, you should make predictions about the outcome of the experiment based on your previous knowledge. At the end of the experiment you will compare your predictions to the observed outcome. If your predictions do not match the observed outcome, you will need to supply reasons as to why they did not concur. These reasons may be because of errors, equipment failure, inaccuracies in the measurements, or they may mean that the theory itself needs to be rethought.

#### 1. Acceleration of Gravity – Galileo's Experiment

Galileo found that he could not measure motions of falling bodies directly, because they accelerated too quickly. Instead, he did experiments by rolling balls down inclined planes, so that the acceleration was much slower. You will repeat Galileo's experiment. There are however, two problems with this technique. The first is friction. A rolling ball is not subject to much friction, but the friction is not zero. Additionally, it takes energy to make things spin. As the balls roll down the incline plane and some of the gravitational potential energy goes into making the ball spin and that energy isn't helping the ball accelerate down the ramp. We will not take this effect into account. First, make a prediction on how the size of the ball will affect its acceleration. Roll some balls down the inclined plane, and measure their average velocity and acceleration by finding how much time it takes the ball to reach the bottom of the inclined plane. Compare your observations to your predictions.

#### 2. Acceleration of Gravity – Cart Track Experiment

Here you will use a cart on an incline plane or track to repeat the above experiment. The main difference between the balls and the cart is that the carts have very little in the way of rotating mass, less mass that needs to spin (they have wheels but they are quite small and made of light plastic). With less mass that needs to spin up less energy will be sapped from the acceleration down the track.

Use the computer to measure the position of the cart versus time. To do this make sure the motion sensor is plugged into the Lab Pro device and the Lab Pro's USB cable is plugged into the computer. Open *Logger Pro* using the icon on the desktop.

Logger Pro should automatically recognize the sensors, if it doesn't:

Under the *Experiment* tab mouse over to *Set Up Sensors* and under the pop up tab select *LabPro: 1*

A window will open with a picture of the LabPro. Select the *Dig/Sonic 1* box in the upper right hand corner and choose the *Motion Detector*

You can close the LabPro window now.

You can take measurements of the carts position versus time by clicking the *Collect* button ( a little green button with and arrow). It is located above the graph.



When you hear the motion detector start to tick it is taking measurements.

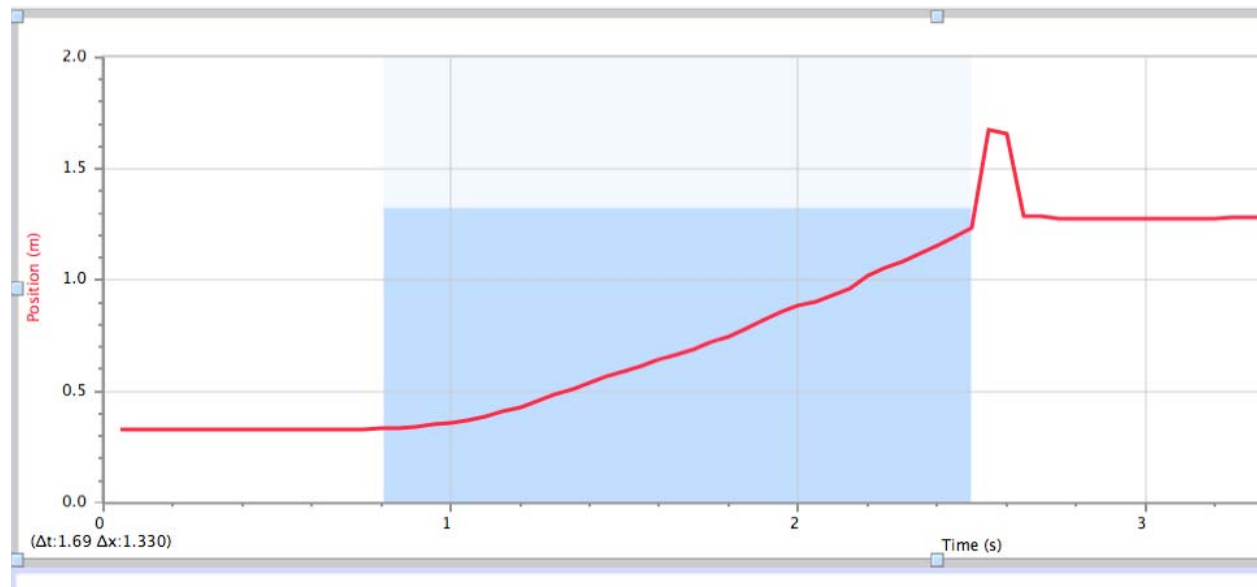
You should zero the motion detector by going to the *Experiment* tab, and within the drop down menu you will see *Zero*. Make sure the cart to be measured by the detector is at its zero (closest to the detector it can be) position and Click *Zero*. If you move the detector or the start position of the cart you will have to re-zero it.

It takes the computer about 2 seconds to begin taking data after you click *Collect*. Use this time to start the cart's motion.

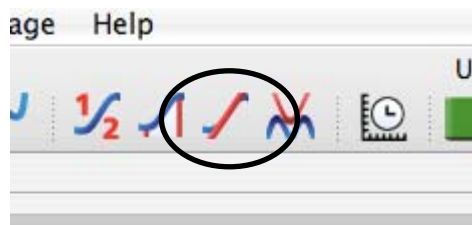
You should see the data represented by a line on the graph. You can open another graph window by clicking *Graph* under the *Insert* tab. By double clicking on the graph you will bring up the Graph Options window. Under *Axes Options* you can choose to display the Acceleration, Velocity, or Position.

To find the average slope of a line on the graph:

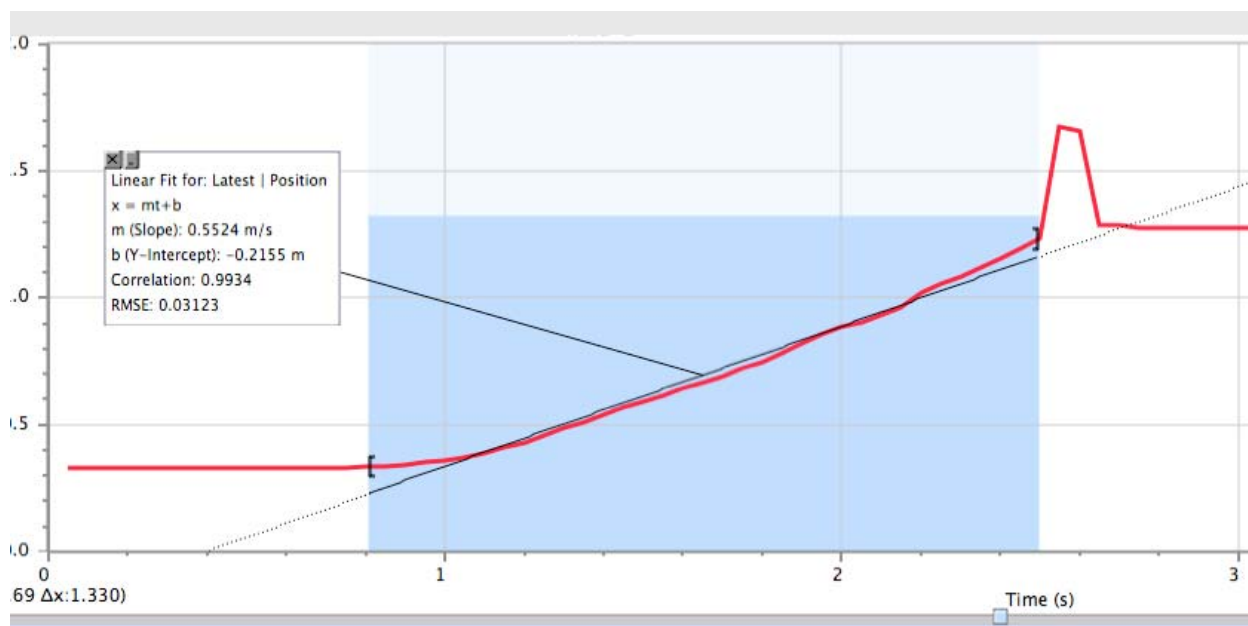
First you need to decide from what part of the graph you want the slope. In our example it is a graph of Position vs. Time. We want the average velocity while the cart was moving. We need to click and drag the mouse over the portion of the line that represents the moving cart thus highlighting it. Be careful to only highlight the part of the line in which you need. The bump at the end of the graph is where the cart was kept from hitting the sensor by someone's hand and shouldn't be included in our slope calculations.



Now click the linear fit button.



The computer will fit the line and give you the formula of the line in the  $f(x) = mx + b$  format, where  $x$  is the independent variable ( $t$  in our example),  $m$  is the slope and  $b$  is the  $y$  intercept.



Use the computer and sensors to measure gravity by inclining the track by a small amount (the feet of the track can be unscrewed to raise the track) and measuring the cart's average velocity and acceleration. Again, compare your observations to your predictions.

For each experiment you perform print a graph of one of your runs. First you will have to connect to the wireless network. Click the *Cisco VPN Client* on the desktop and doubleclick *bu-uncampus*. Enter in your username and Kerberos password to connect.

To print, under *File* go to *Page Setup* and select the icon which represents landscape printing, then under *File* go to *Print Graph*.

### 3. Force and Acceleration – Cart Track Experiment

Level the track. Place the pulley at the end of the track opposite the motion detector. It is possible to attach a string to the cart. The string can then be looped over the pulley at the end of the track and weighted down. This causes a constant force to be applied to the cart. If you maintain the same weight on the end of the string, then the force exerted on the cart should be constant. Measure the cart's acceleration for three or four different cart weights (vary the cart weight by adding weights to the cart). For each acceleration measurement, weigh the cart's total mass on a scale, and compare your observed and predicted acceleration using Newton's formula,  $\mathbf{F} = \mathbf{ma}$ . Print a graph of one of your runs.

#### 4. Momentum – Track Experiment

Newton's laws are all a natural consequence of the conservation of momentum. His first law states that an object's velocity will not change unless a force acts upon it. This can be approximately verified by simply pushing a cart on the track. If the tracks were infinitely long and carts were truly frictionless, and the bumpers did not dissipate any energy, then the cart would never stop after you pushed it. In reality, of course, the track has some friction, and the bumpers dissipate some energy, so the cart will eventually come to a stop. Nonetheless, the track is remarkably close to being friction-free. So it's worth spending some time verifying Newton's first law. Now we will try to demonstrate the conservation of momentum.

After you have gotten bored with one cart, it's time to see how momentum is conserved when two carts collide. Remove the pulley from the track and put the bumper on the same end. The carts have Velcro on one end. If oriented correctly, the carts will stick when they run into each other (inelastic collision). With the opposite orientation, the carts will not stick (elastic collision). With the equally massive carts oriented for an elastic collision, propel them into each other at equal speed. Then place one at rest and propel the other cart. Now perform the same experiments for inelastic collisions. In each case, compare your observations with your qualitative predictions (pre-lab).

Now it's time to get quantitative. First measure the mass of each cart with the scale. Depress the plunger (all the way) at the end of cart 1 (with mass  $M_1$ ). When you tap the post above the plunger the plunger will pop out. Use your ruler to tap the post. Place cart 1 (with the plunger depressed) against the barrier. Place cart 2 (with mass  $M_2$ ) **30cm** away from cart 1. Note the position of the edge of cart 2 that will be hit by cart 1: we will call this position  $d$ . Begin collecting data. Tap the plunger of cart 1 with the ruler. It should be propelled down the track, collide and stick with cart 2 at position  $d$ . Don't let the carts hit the motion detector. Looking at the data table to the left of the graph, find and record the highest velocity,  $v_{12}$ , of carts after the collision, before friction has much time to act. Perform this part of the experiment multiple times and record your data so you can take an average, being careful to place cart 2 in the same place each time. Print a graph.

Set up cart 1 again, but by itself this time. We now are going to measure the velocity of cart 1 right before it would have hit cart 2. Start taking data (Click the *Collect* button) and then quickly tap the post so the plunger extends and the cart is propelled down the track. Don't let the cart hit the motion detector. We need to know the velocity that cart 1 has when it would have hit cart 2 at position  $d$ . Look at the data table to the left of the graphs. Scroll down to the position  $d$  in the previous attempt. Record the velocity,  $v_1$ , of cart 1 at position  $d$ . Perform this part of the experiment multiple times and record your data so you can take an average. Print a graph.

The combined carts should have the same momentum as the single cart. So,

$$M_1 v_1 = (M_1 + M_2) v_{12} \quad (1)$$

where  $v_1$  is the speed of cart 1 in the first measurement, and  $v_{12}$  is the combined speed of cart 1 and 2 in the second measurement.

$$v_{12} = \frac{M_1 v_1}{(M_1 + M_2)} \quad (2)$$

Now that you have calculated and measured  $v_{12}$ , compare the two measurements and describe why there might be differences. With your measurements of the cart masses, the travel times, and estimated uncertainties in your measurements, you will determine if Newton's first law is really correct (if not, we have some textbooks to rewrite).