Experiment 5:
Newton's Laws of Motion, Part I

I. All you need to know about this laboratory unit.

OBJECTIVE

To experiment using Newton's laws of motion.

ABOUT NEWTON'S LAWS OF MOTION

First Law: An object moves with a constant velocity if and only if the net force acting on the object is zero.

Second Law: Force = mass × acceleration

Third Law: For two interacting objects, the force acting on object 1 due to object 2 is equal in magnitude and is opposite in direction to the force acting on object 2 due to object 1.

FORCES

When you look at Newton's Laws, stated in the previous section, you see that there are two new terms, force and mass. If we want to discuss Newton's laws in their most common form as above, we need to define force and mass clearly. There are many elegant ways to do this. Here we use the most simple way, which is to borrow the idea of force from our daily life experience. For example, we always use force to push or pull an object. We use force to throw an object. If you are hit by a baseball, the baseball will exert a tremendous amount of force on your body during a very short time of contact. You may ask if it is necessary to have direct contact in order to exert force. Not so. For example, Earth is exerting its gravitational pull on you even when you are sky diving. The Sun is pulling on the Earth even though they are not touching each other. It is not too difficult to get an idea of force, but how are you to measure it? Suppose we are pulling an object with a string, how do we measure the force we use? What we need to do is to cut the string and tie a spring in between. As you can imagine, the spring will become longer as we pull the object. The larger the force, the longer the spring. More advanced analysis will show us that the extension of the spring is actually proportional to the magnitude of the force. This is called Hooke's Law, which we shall investigate in a later experiment. This is exactly how a spring balance works. If we follow international standards, force is measured in newtons, abbreviated N. So, what we need to know now is how much force is needed to extend the spring by exactly 1 meter. This is called the spring constant, with units of N/m. To measure the force, we just need to multiply the spring constant in N/m by the extension of the spring measured in meters.

MASS AND WEIGHT

We do not distinguish the difference between mass and weight very carefully in our daily life. In physics, these two quantities are different and have different units. We have already learned the meaning of weight in class. Weight is the gravitational force acting on us because of the Earth. Since weight is a force, it is a vector, acting downward towards the ground. Its unit is the newton. As you get farther and farther away from the Earth, you will lose some weight because the gravitational pull from the Earth will become weaker and weaker. On the surface of the Moon, your weight is only 1/6 of your weight on the surface of the Earth.

Mass is quite a different concept. It is a number we assign to every object as a measure of how difficult it is to accelerate the object. With the same push of force, a more massive object will accelerate slower than a less massive one. If you were an astronaut in outer space, you could compare the mass of two bowling balls even though none of your spring balances will work in that "weightless" condition. What you would do is to give both balls the same push, measured with the compression of a spring: the one which moves slower has a larger mass. Mass is just a number: it has no directional meaning. We measure mass in pounds (lb) in our daily life. The scientific unit of mass is the kilogram (kg). To measure the mass of an object we need to apply a force on the object and measure its acceleration. Then, the mass of the object is defined by Newton's Second Law. For example, if the force is 1 N and the acceleration is 0.4 m/s^2, then the mass of the object is m = (1 N)/(0.4 m/s^2) = 2.5 kg. Unlike weight, mass is not dependent on the gravitational pull of the planet you are living on. You have the same mass no matter where you are.

Mass and weight can be converted one to the other. In other words, if we know the weight of an object on the Earth's surface, we can calculate its mass, and vice versa. Use Newton's Second Law again, with the acceleration due to gravity g: the weight W is equal to its mass m times g. We just need to divide the weight of the object on Earth's surface by g = 9.8 m/s^2, to get its mass. For example, the mass of an object is 0.5 kg and its weight is 4.9 N on Earth. The weight of the same object, however, will be 0.82 N (1/6 of 4.9 N) on the Moon's surface while its mass will be the same, 0.5 kg. This provides another method for us to measure mass. We can use a spring balance to measure the weight of an object first and then convert the reading to mass by dividing it by 9.8 m/s^2.

NEWTON'S FIRST LAW OF MOTION

Newton's First Law says that an object will move with a constant velocity if all of the forces acting on it add to zero. In reverse, for an object moving with constant velocity, the total force acting on it must be zero. Note that "zero total force" does not mean that there is no force: it can be two or more forces *adding* to zero.

When Newton proposed his First Law, a lot of people were suspicious about it because it simply did not make sense to them. People would argue that if you push a book across the table, the book would eventually stop. It was more reasonable to believe that everything will come to a halt if it is not being continuously pushed. Very likely you will agree with them because you think about the experience that if you take your foot off the gas pedal, the car will eventually stop. Let us set the record straight: all these arguments are *not* correct. If you stop pressing the gas pedal to remove the engine's push, the car will slow down. This is still in accordance with Newton's First Law. Obviously the car is not moving with constant velocity anymore. There must be some force (or forces) still acting on the car, and in this case they are the friction between the wheels and the road and also the air resistance. Similarly, as you push a book across the table, it will eventually stop after you are no longer pushing and will not move with a constant velocity, because there is a frictional force still acting on it. Note that once the book has stopped, nature will tune down the friction to zero. Otherwise the frictional force would start to move the book backward! and of course, this does not happen.

NEWTON'S SECOND LAW OF MOTION

Newton's Second Law says that $F = ma$. An object will accelerate as long as there is a net force acting on it. If we know the force, we can calculate the acceleration. In reverse, if we see an object being accelerated, then we know there must be a net force acting on it and we can estimate the force by using Newton's Second Law. Newton's First Law is actually a special case of the Second Law. If there is no net force acting on the object, $F = 0$, then a, the acceleration, must be zero according to the Second Law. This simply implies a constant velocity.

Now consider a freely falling object of mass m. Since the object is falling with acceleration g, there must be a net force acting on it. In this case, there is only one force, the gravitational pull, or weight. The magnitude of the gravitational pull is $F = ma = mg$ according to the Second Law. This is the reason why we have the conversion between mass and weight.

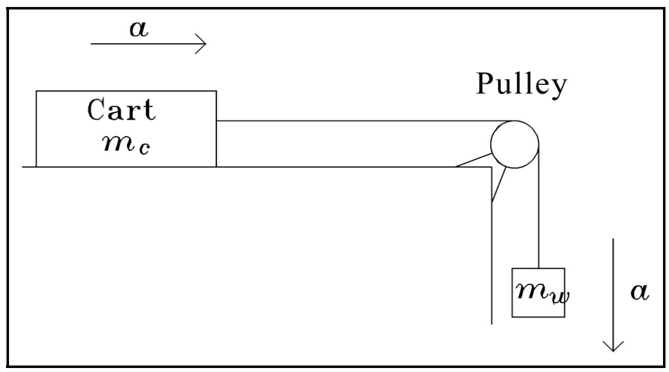
II. Prelaboratory Name ______________________________

1. An object of mass 2 kg moves with a constant acceleration. Its velocity at two different times is recorded in the following table.

t (s)	v (m/s)
1.1	2.3
1.6	7.3

Calculate the acceleration. How large is the total force acting on the object?

2. A cart of mass m_c is being pulled by an object of mass m_w as shown in the diagram.



(i) How many forces are acting on the cart? What are these forces?

(ii) Two of the forces above cancel each other. Which are these forces? How do you know that these two forces will add to zero?

(iii) What are the forces acting on the mass m_w?

(iv) If the tension in the string is T, what is the total force F_c acting on the cart, and what is the total force F_w acting on the hanging object?

F_c =____

F_w =____

(v) Derive how the acceleration a of the cart depends on the mass of the cart (m_c), on the mass of the object (m_w), and on the acceleration due to gravity g. (You will need to copy this equation so you can use it in your lab.)

III. The Experiment

Put the cart on the rail and push it slightly to get some feeling of the motion of the cart. Let us assume (i) there is no friction between the cart and the rail, and (ii) the rail is horizontal.

Newton's First Law

Question: Will an object stop without a force pushing it?

Put the CBR at one end of the rail and connect it to your calculator. Put the cart at the detector end, about half meter from it. Refer to the online appendix if you have trouble operating the CBR.

It is a good exercise to imagine how the *x-t* curve should look like before you begin the experiment. Start the motion detector and simultaneously push the cart towards the other end of the rail with a reasonable speed. Do not hold the cart for too long during the pushing process. Beware of your hand interfering with the motion detector. Make sure the cart bounces back from the other end of the rail. Stop the cart just before it hits the detector. The *x-t* graph for the motion of the cart will be shown on the calculator screen.

You may want to try several times for the best push before you take the final data and record it in Table I. The program will take data points according to your specifications. You may have to try several times to find a reasonable time frame to take data.

The whole trip of the cart may not consume all data points. Pay attention only to the data points that are meaningful. You do not need to enter all data in Table I; choose the representative data. We are not telling you what to choose; you have to decide yourself. Record enough data so that you can plot the *x-t* graph. If you have time and patience, you can record all data points.

Get out of the program after you finish this part of the experiment.

Acceleration Proportional to Force

Question: Is Newton's Second Law correct?

Measure the mass of the cart and record it in the first line of Table II. Call it m_c. Hook the string with weights at one end to the cart. Make sure the string sits nicely on the pulley every time before you do the measurement. Begin with the weight marked as "50 g" which is enough to pull the cart smoothly along the rail. Let us call the mass of the weight m_w. Record m_w in Table IIA. Run the program again. Hold the cart about one-half meter from the motion detector. Press the ENTER button on your calculator immediately after releasing the cart. The screen will not show anything until the CBR finishes taking data. Also, the detector is measuring the velocity, as well as displacement. In other words, make sure the plot that appears on the calculator screen is actually a v-t plot. To do this, press Enter after seeing the graph and go to the velocity graph.

You may want to experiment several times before you take the final data. The data taking rate can be changed by choosing the main menu and adjusting the time. The v-t plot will not be a single straight line because of the changing forces when you just release the cart and when the weight hits the floor. You have to determine the section of the v-t plot during which the cart is accelerated constantly by the weight. You can find out the beginning and terminating time of this period by moving the little cursor on the screen with the left and right arrow. The number on the screen tells you the time corresponding to the cursor position. Record these two time readings in the t column of Table IIA. Determing the velocity of the cart corresponding to the time you have just recorded. Enter the readings in the v column of Table IIA.

Calculate the acceleration from your data in Table IIA. You can also estimate the acceleration from m_c and m_w, with the equation you have derived from the Prelab.

Acceleration from data:______________________________________

Acceleration estimated from m_c and m_w:____________________________________

If these two values agree with each other reasonably well, you can continue the experiment by adding a little more weight to m_w. As you add more weight, the cart will accelerate faster. Do not forget that you have control of the data-taking rate. Repeat the experiment. Enter your data in Table IIB and repeat this for different weights until you fill Tables IIA to IIE.

IV. Data sheets. Experiment 5

Name ______________________________ Date _______________

Table I.

t (s)	x (m)

Table II.

Mass of cart, m_c = ____________________kg

IIA.

Mass of weight, m_w = ___________________kg

t (s)	v (m/s)

a **= ___________________________m/s²**

IIB.

Mass of weight m_w = ____________________kg

t (s)	*v* (m/s)

a = ____________________________ m/s^2

IIC.

Mass of weight m_w = ____________________kg

t (s)	*v* (m/s)

a = ____________________________ m/s^2

IID.

Mass of weight m_w = ____________________kg

t (s)	*v* (m/s)

a = ____________________________ m/s^2

IIE.

Mass of weight, m_w = ____________________kg

t (s)	*v* (m/s)

a = _________________________ m/s^2

V. Questions

1. For the experiment on Newton's First Law, plot your data on an *x*-*t* graph. Does the graph show that the cart was moving with constant velocities in both the forward and backward directions?

2. From the *x*-*t* graph, calculate the velocity when the cart was moving (i) forward, and (ii) backward. What has happened in between? How does this event register in the *x*-*t* plot?

3. Did the cart bounce back slower or faster? Is this always the case? Discuss your answer with your friends and the laboratory instructor.

4. Explain why it is important to make sure that the rail is horizontal in this experiment. What will happen to the *x*-*t* graph if the rail is not horizontal?

5. Calculate the acceleration using the data in each of Tables IIB to IIE. Plot a versus $m_w/(m_c + m_w)$. Do you expect to have a straight line according to the equation you derived in the Prelab? If you have a straight line, estimate the slope of the straight line.

6. Estimate the value of g from your graph.

7. If your measured value of g is too far away from the expected value of 9.8 m/s^2, discuss possible reasons for the error.

8. Explain in general how you can estimate the horizontal force acting on the cart by the string from your data. Give an actual calculation using the data in Table IIA. Should this force equal to the weight of the hanging mass? Explain your answer.

9. Explain why the cart and the weight have the same magnitude of acceleration, even though the directions are different.