Force and Motion

Introduction
In previous labs, you have used a motion detector to display position-time and velocity-time graphs of the motion of different objects. You were not concerned about how you got the object to move, i.e., what forces acted on it. From your experiences, you know that force and motion are related in some way. To open the door to a classroom, you must push or pull on the door; to stop a car you must step on the brakes. Exactly how is force related to the quantities you have used to describe motion—position, velocity, and acceleration? In this laboratory you will examine how forces affect motion.

Questions
1. What is the weight of a 100-g mass?

2. Suppose that you exert the same force (0.5 N) on objects with different masses ($m$) and measure their accelerations ($a$). If you graph $a$ versus $1/m$ you should get a straight line. What is the slope of that line? (Hint: rearrange $F_{net} = ma$ first so that the left-hand side is $a$.)

How the Force Probe Works
The force probe consists of a rigid block of aluminum cut in the shape of the letter “C.” Fastened to the inside and outside of the block are thin electrical resistors called strain gauges. When a force is exerted on the block it bends slightly. The gauges on the inside of the “C” are stretched, raising their resistance while those on the outside are compressed, lowering their resistance. The changes in resistance are converted into changes in voltage that are analyzed by the ULI. The switch on the plastic case lets you choose a 10-N or a 50-N range. Because the weight of the aluminum “C” is enough to change its shape, you will find that the force shown by the probe depends on its orientation. The zero level may also depend on the room temperature. For these reasons, you should “zero” the probe before you make a measurement.

IMPORTANT!!!
FORCE PROBE MUST BE ZEROED BEFORE EACH MEASUREMENT.
Part I
Measuring Forces

Equipment
- Spring scale (1 N)
- Weight hanger (50 g), 20-g hanging mass. 20- and 50-g slotted masses
- Grooved aluminum track with end pulley
- Fan cart
- Meter stick
- Computer with ULI, force probe, and file ForceProbe.

Mass and Weight
1. You know that Earth exerts a downward force (weight) on all masses. Examine the spring scale. Hold it vertically, hook downward. With nothing attached to the hook, the scale should read zero. Does it? If not, consult your instructor for instructions on "zeroing" the scale.
2. Find the weight of the masses listed in this table by hanging them from the scale. Compare the weight given by the scale with the calculated weight. If you do not know how to calculate the weight of a given mass, consult your textbook.

<table>
<thead>
<tr>
<th>Mass (g)</th>
<th>Calculated weight (N)</th>
<th>Measured weight using scale (N)</th>
<th>Measured weight using force probe (N)</th>
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</thead>
<tbody>
<tr>
<td>20</td>
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<tr>
<td>50</td>
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<td>70</td>
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<td>100</td>
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Calibrating the Force Probe
1. Start LoggerPro and open the file ForceProbe. Click on the Zero button to the right of Collect before you make each measurement.
2. Select the 10N range on your force probe. Click on Collect and find the weights of the same set of masses that you used above. The Table Window shows the numerical values. If the probe and calculations disagree by more than 10%, remove all hanging masses and click on Zero and measure again. If that fails, check with your instructor and calibrate the probe.
Thrust: The Force Exerted on a Propeller-driven Fan Cart

1. Examine the fan cart. When the switch is turned on, the motor will turn the propeller at high speed, pushing air in the direction shown. DANGER! Be sure to keep your body and all other objects away from the propeller when it is moving. Make sure that the propeller unit is turned so that it faces the shorter end of the cart as shown to the right. The protractor on the cart body should read “180 deg.”

   When the propeller is turning, it pushes air in the direction shown. That is, the propeller exerts a force on the air. As a result, the air then exerts a force on the propeller. This force is called Thrust. From now on, we will use the word thrust to mean the force exerted on the cart by the air when the propeller is turning.

2. Use the spring scale to measure the thrust of the fan cart when the switch is set to both low and high speed. Be sure to turn the motor off immediately after you finish the measurement so that the batteries will remain fresh for your later experiments. Estimate the uncertainty in this measurement by making several measurements or by using your measurements of the weights of hanging masses to determine the precision of the measuring instrument.

3. Use the force probe and ULI to measure the car’s thrust. Mount the probe on the cart by attaching it to the bracket and hold the hook with your fingers. Summarize all your measurements in this table:

<table>
<thead>
<tr>
<th>Motor Speed</th>
<th>Thrust ± Uncertainty</th>
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<tbody>
<tr>
<td></td>
<td>Spring scale (N)</td>
</tr>
<tr>
<td>Low</td>
<td></td>
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<tr>
<td>High</td>
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Questions

1. Explain how you arrived at the uncertainty in the values of the thrust.

2. Which set of measurements is more accurate? What makes you say so?

Part II
Force, Mass, and Acceleration

Equipment
- Aluminum track with end pulley
- Selection of weights
- Propeller-driven fan cart
- Computer with ULI, motion detector, force probe, file ForceVelAcc, DistVelAcc.
A. Pushing and Pulling the Cart: The Shape of v, a, and F

Place the fan cart on the track as shown. The force probe should be mounted on the bracket attached to the cart. Open the file ForceVelAcc. Zero the force probe by clicking on the Zero button. The fan motor should be off. Your hand will be the only horizontal force on the cart. Click the Collect button. Hold on to the hook on the force probe. When you hear the motion sensor begin to click, quickly pull the cart away from the motion sensor, then quickly stop it. Quickly push it back toward the detector, and again quickly stop it. Quickly pull and push a couple more times before the motion sensor stops collecting data. Notice the word “quickly”. Make quick changes in the velocity of the cart. Do not twist the probe. Print the graph window.

Examine the shapes of your three graphs. Which graph – velocity or acceleration – most closely resembles the force graph? Justify your answer on your graphs by clearly labeling the matching trends.

According to theory, how is velocity or acceleration of the cart related to the force exerted on it?

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B. Finding the Force by Observing the Motion: F, ma, and F = ma

Carts and Quarks, Air Tracks and Atom Smashers

We have seen how force can be measured by a mechanical spring scale or an electronic strain gauge (force probe). These force-ometers have been calibrated to convert a length quantity (stretch or bend) into a force value in Newtons. Since the mass remained at rest while measuring the force with these instruments, this is a “static method” of measuring force.

The static method is convenient for measuring force, but it does not answer the deep question: What is force? The precise meaning of force is given by the fundamental relation $F = ma$. This relation provides a “dynamic method” to measure force. If you observe a mass $m$ moving with an acceleration $a$, then you can rigorously conclude that the net force on the mass is $ma$. The value of force is determined by the change in the velocity. The key word here is “change”. Constant velocity is synonymous with zero force. Changing velocity is proportional to force. F is the cause, $\Delta v$ is the effect.

If you own a meter stick, a stop watch, and a mass scale, then you are in business to measure the force acting on any moving object. Here is the dynamic recipe for measuring force:

1. Measure $\Delta v$. 2. Measure $\Delta t$. 3. Measure $m$. 4. Compute $m\Delta v/\Delta t$. 5.
The motion quantity \( m \Delta v / \Delta t \) gives the value of the force acting on the mass \( m \). If the force is not constant, then the changes \( \Delta t \) and \( \Delta v \) must be tiny (infinitesimal) quantities and the acceleration \( \Delta v / \Delta t \) will depend on time.

It should be emphasized that the dynamic measurement of force based on the relation, \( \text{force} \sim \text{change in velocity} \), is far more fundamental and universal than the static method based on the relation, \( \text{force} \sim \text{stretch of spring} \). Whoever calibrated the spring scale to measure force did so by using the basic law \( F = ma \).

All the basic laws of physics that describe the fundamental forces of nature are deduced by observing the motion of matter. Newton deduced the law of gravity by finding the change in velocity of a planet moving in an elliptical orbit. The electromagnetic force is deduced by observing the change in velocity of electric charges (currents) moving in electric and magnetic fields. Instead of air tracks, high-energy physicists use atom smashers to study the motion of elementary particles such as protons, electrons, muons, neutrinos, quarks, etc. The particles are accelerated to near light speed and then allowed to collide with each other. The quantum (nuclear) force between particles is deduced by monitoring the change in velocity and other processes of “change”, such as radioactive decay and matter-antimatter annihilation.

The program of mechanics – classical or quantum – is to observe motion and deduce force. In this experiment, you will observe the motion of a fan cart to find the force of propulsion.

**Measuring Thrust with a Stopwatch**

First make sure the track is level. Turn the fan motor on low speed. CAUTION - fan blade! Release the fan cart from rest and measure the time \( t \) it takes – using a stop watch – to traverse the length \( L \) of the track. Compute the acceleration \( a \) of the cart from the values of \( t \) and \( L \). Repeat this measurement five times and record your results in the table below.

Measure the mass of the cart using the mass scale: \( m = \) ____________ kg.

**Low Thrust Motion Table**

<table>
<thead>
<tr>
<th>L (m)</th>
<th>t (s)</th>
<th>a (m/s²)</th>
<th>ma (N)</th>
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Show a sample calculation of \( a \) and \( ma \):

Compute the average value of \( ma \). Estimate the uncertainty from the spread in your five values of \( ma \): Uncertainty = \([ma \text{ (min)} + ma \text{ (max)}] / 2\).

For Low Thrust, \( ma = \) ____________ \( \pm \) ____________ N.

Now turn the fan motor on high speed (caution), measure the motion, and compute \( ma \) as before.
**High Thrust Motion Table**

<table>
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For High Thrust, \( ma = \_\_\_\_\_\_\_ \pm \_\_\_\_\_\_\_ N \).

**Comparing ma and F**

Compare your values of the force quantity \( F \) measured with a force meter (spring scale, force probe) and your values of the motion quantity \( ma \) measured with a stopwatch. Can you conclude that \( F \) is equal to \( ma \)? Remember: the equality of experimental numbers hinges on the magnitude of the experimental uncertainties.

**Part III. Designing a Constant Velocity Ramp**

Your goal is to figure out how much the track needs to be tilted so that the air cart moves up the track under high thrust with a *constant* speed of 5.0 cm/s.

**Theory**

Work out the theory in the space below. Include a force (free body) diagram and a picture of the ramp showing the relevant parameters (length, height, angle, etc.). Based on your measured value of the thrust, calculate the predicted height (\( H \)) of the ramp from the theoretical equations of Newton.
Theoretical $H = \underline{\text{\hspace{1cm}}} \text{cm}$.

**Experiment**

Elevate the track according to your predicted height. Turn the motor on high speed and nudge the cart to give it the desired initial speed. Use the motion sensor to record the velocity of the cart during its entire trip from the bottom to the top of the ramp. Print the graph and the table of the velocity data.

**Conclusion**

Compare theory with experiment. Does the velocity of the cart stay constant according to the design specs? Does it merely fluctuate, say between 4 cm/s and 6 cm/s? If there is an acceleration or deceleration of the cart, can you eliminate it by slightly increasing or decreasing the amount of tilt? Are there any systematic errors (due to forces not included in your theoretical analysis) that could explain this unwanted acceleration and corresponding tilt correction factor?