Force and Motion

In previous labs, you used a motion detector to measure the position, velocity, and acceleration of different objects. You were not concerned about the "mechanism" that got the object to move, i.e. the forces that acted on the object. In other words, you answered the *kinematic* question "How do objects move?" Now it is time to answer the *dynamic* question "Why do objects move?" From your experiences, you know that force and motion are related. To open a door, you must push or pull on the handle. To stop a car, you must step on the brakes. The *force* of gravity causes the earth to *move* around the sun. The electric *force* causes the electron to *move* around the proton in the Hydrogen atom. In this laboratory you will examine the precise relationship between *force* and *motion*.

Part I.   Two "Force-ometers": The Spring Scale and The Force Probe

Measuring Weight with the Spring Scale

The weight of an object is the force on the object due to gravity. *Calculate* the weight of the masses listed in the table using the theoretical relation between mass and weight.

Examine the spring scale. Hold it in the vertical position with the 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. *Measure* the weight of the masses listed in the table by hanging them from the spring scale.

Mass (g)	Calculated Weight (N)	Measured Weight using spring scale (N)	Measured Weight using force probe (N)
20			
50			
70			
100			

Measuring Weight with the Force Probe

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.

Strain gauges
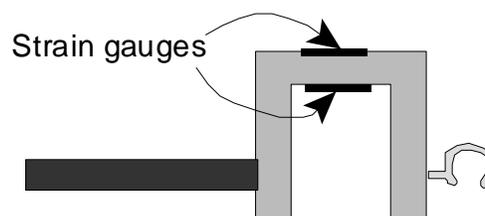
The changes in resistance are converted into changes in voltage that are analyzed by the ULI. The switch on the plastic case lets you choose a 10-N or a 50-N range. Because the weight of the aluminum "C" is enough to change its shape, you will find that the force shown by the probe depends on its orientation. The shape also depends on temperature. To correct for these conditions, you must "zero" the force probe before each measurement.

Start *LoggerPro* and open the file *ForceProbe*. Zero the force probe: click on the *Zero* button (to the right of the Collect button). 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. Report your results in the above table.

Precision of the Spring Scale and the Force Probe

What is the average percent difference between the calculated weight and the measured weight using the spring scale and the force probe? This percent difference provides a measure of the accuracy of the instrument and the error involved in the measurement.

(a) Spring Scale   % error = _____ .

(b) Force Probe   % error = _____ .

Thrust: The Force Exerted on a Propeller-Driven Fan Cart

Examine the fan cart. When the switch is turned on, the motor will turn the propeller at high speed.   <u>DANGER!</u>   Be sure to keep your body and all other objects away from the propeller when it is spinning. 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, there is a force on the **A**ir due to the **P**ropeller: F_{AP}. By Newton's third law, there must exist an equal and opposite force on the **P**ropeller due to the **A**ir: F_{PA}. This force is called *Thrust*. From now on, we will use the word "*thrust*" to denote the force exerted **on** the cart by the air when the propeller is turning.
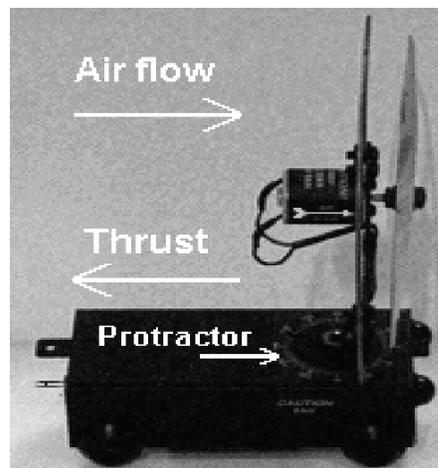
Measuring Thrust with the Spring Scale

When the spring scale is in the horizontal position and nothing is attached to the hook, make sure the scale reads zero. Use the spring scale to measure the thrust 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.

Find the uncertainty in the force by making several (five) measurements. Do each measurement "differently". Try making the measurement at different locations on the track, or on the table. Friction between the cart wheels and the surface can depend on location and affect the reading. Another measurement technique is to gently push and pull the spring scale to loosen the wheels (overcome static friction). The scale reading will oscillate back and forth and settle down to some constant value. The five "different" measurements that you make will give five slightly different values of the force. Record your five force values in the table. Compute the average value. Estimate the uncertainty – the deviation from the average – to be one half of the total spread in your force values: *Uncertainty* ≡ ½ (F_{max} − F_{min}).

Thrust Measured with Spring Scale

						Average ± *Uncertainty*
F(N) *Low Thrust*						±
F(N) *High Thrust*						±

Measuring Thrust with the Force Probe

Now use the force probe to measure the thrust. Mount the probe on the cart by attaching it to the bracket and hold the hook with your fingers. Remember to zero the probe. Instead of five values of F, the force probe collects hundreds of values of F (about ten values per second). Find the thrust by averaging [use the *STATS* icon] over all these F values. The *standard deviation* away from the average value provides a measure of the *uncertainty* in the measured force. Record the average force and its uncertainty:

Thrust Measured with Force Probe

F(N) *Low Thrust*	±
F(N) *High Thrust*	±

Compare the measured values of the low and high thrust using the spring scale with those measured using the force probe. What are the percent differences? If they differ by more than 10%, consult with your instructor.

Part II.   The Pillars of Dynamics: Force , Mass , Acceleration

A. Pushing and Pulling the Cart: Comparing the "Shapes" of v, a, and F

Place the cart on the track:
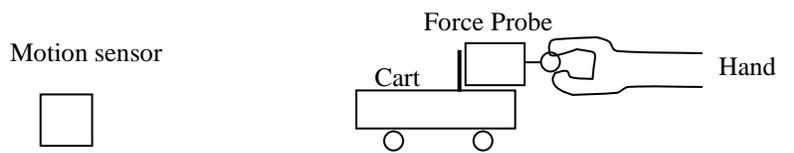
The force probe should be mounted on the bracket attached to the cart.   Open the file *ForceVelAcc*. Zero the force probe by clicking on the Zero button. The fan motor should be **off**. Your hand will be the only horizontal force on the cart. Click the Collect button. Hold on to the hook attached to the force probe. When your hear the motion sensor start to click, *quickly* pull the cart away from the motion sensor over a distance of about one meter. Stop briefly. Push the cart back *quickly* about one-half meter, stop briefly, then push back *slowly* the remaining one-half meter. Stop. Do not twist the hook. Print the graph.

Examine the shapes of your three graphs (v, a, F). Which graph – velocity or acceleration – most closely resembles the force graph?

Justify your answer on your printed graphs *by clearly labeling some of the matching trends* – those regions where the two matching graphs are "in sync" (both reach a maximum, both reach a minimum, both have a little bump, both go through zero, etc.)

According to pure theory, which motion quantity, velocity v or acceleration a, is the net force F related to *most simply*? What is the mathematical relation between F and a?   Between a and v?

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, Δv is the effect.

If you own a meter stick, a stopwatch, 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 Δv.   2. Measure Δt.   3. Measure m.   4. Compute mΔv/Δt.

The motion quantity mΔv/Δt gives the value of the force acting on the mass m. If the force is not constant, then the changes Δt and Δv are replaced by the infinitesimal quantities dt and dv, and the force mdv/dt will depend on time.

It should be emphasized that the dynamic measurement of force based on the relation,   *force ~ change in velocity*, is far more fundamental and universal than the static method based on the relation, *force ~ stretch of spring*. Whoever calibrated the spring scale to measure force did so by using the gold standard meaning of force: $F = ma$.

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 fan carts and air tracks, high-energy physicists use atom smashers to study the motion of sub-atomic 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 their *change in velocity* and other processes of "*change*", such as radioactive decay, emission of photons, and creation of matter-antimatter.

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 deduce the force of propulsion.

Measuring Thrust with a Stopwatch

First make sure the track is level using the leveler. 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 *stopwatch* – 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

L (m)	t (s)	a (m/s^2)	ma (N)

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$_{max}$ − ma$_{min}$) / 2.

For Low Thrust ,   ma = _____ ± _____ N .

Now turn the fan motor on high speed (CAUTION), measure the motion, and compute ma as before.

High Thrust Motion Table

| L (m)	t (s)	a (m/s^2)	ma (N)

For High Thrust ,   ma = _____ ± _____ N .

Comparing ma and F

In Part I, you measured the *force quantity F* with a spring scale and strain gauge. In Part II, you measured the *motion quantity ma* with a stopwatch, meter stick, and mass scale. The big question is this:

Is F equal to ma ?

Remember, since an experimental value (*number ± uncertainty*) is really a *range* of numbers, "comparing two values" really means "comparing two ranges".

Display your results for F and ma on the following *range diagram*. For F, use your values measured with the spring scale, which should be the 'same' as those measured with the force probe. Remember that an experimental value, such as 0.30 ± 0.04 N, is displayed on the range diagram as a horizontal line segment from 0.26 to 0.34 N. Fill in the axis labeled "Newtons".

Low Thrust

F

ma

Newtons

High Thrust

F

ma

Newtons
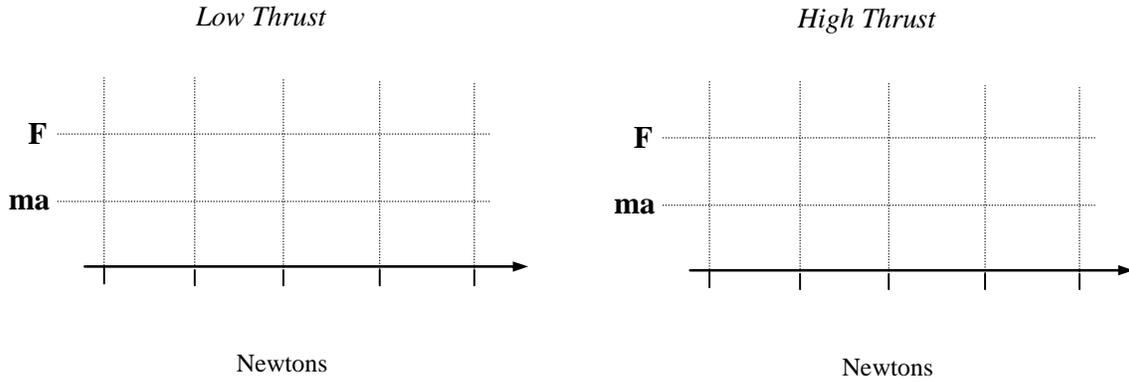
Conclusion

Use the results displayed on your experimental range diagram to rigorously answer the deep question: Is **F** equal to **ma** ?

Testing the Mass Factor in F = ma

Theoretical Prediction
If you double the mass of the cart <u>from m to 2m</u> , while keeping the force on the cart constant, then the acceleration of the cart will change

from *a* to _____ .

Experimental Test of Prediction
Add weight to your cart so that its mass doubles (from m to 2m). Keep the thrust on high. Measure the acceleration. Report your results.

a (mass m)   =   _____ m/s^2 .   (from previous table)

a (mass 2m) =   _____ m/s^2 .

Do your experimental results verify your theoretical prediction? Explain.

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. Draw a force (free body) diagram. Set up **F** = m**a**. Based on your *measured* value of the thrust, *calculate* the required height H of the ramp by solving the equation of motion. Show *all* your work.

Here is a picture of the ramp geometry. Examine your ramp to see which parts of the ramp touch the table and the block. Note that the hypotenuse of the right triangle that contains θ and H is <u>not</u> the length of the track.
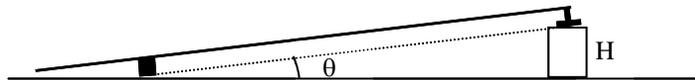
Theoretical H = _____ *cm* .

Experiment

Again make sure that the track is level. Elevate the track according to your predicted height. To achieve the precise value of H to the *tenths of a centimeter*, place *thin metal plates* on top of the wooden blocks. Open the file *Moving Along*. Change the vertical axis to be the velocity v of the cart (instead of position x). Change the velocity scale so that it goes from v(min) = 0.0 *m/s* to v(max) = 0.10 *m/s*.

Turn the motor on high speed and nudge the cart to give it the desired initial speed of 5.0 *cm/s*. Use the motion sensor to record the velocity of the cart during its entire trip from the bottom to the top of the ramp.   Make sure that your graph *clearly displays the up and down fluctuations in* v(t) around the desired value of v = 0.05 *m/s*.   Print the graph.

Compare Theory with Experiment

Does the velocity of your cart stay constant at 5 *cm/s* according to the design specs? How much does it fluctuate, i.e. does it vary between 4 *cm/s* and 6 *cm/s* ?

If there is an acceleration or deceleration of the cart, try to eliminate it by *slightly* increasing or decreasing the amount of tilt by adding or removing the thin metal plates. How many plates does it take?

What is the percent difference between the theoretical H and the actual H that achieves the constant-velocity motion?

Are there any *systematic errors*, i.e. due to forces not included in your theoretical analysis, that could explain this unwanted acceleration and corresponding tilt correction factor?