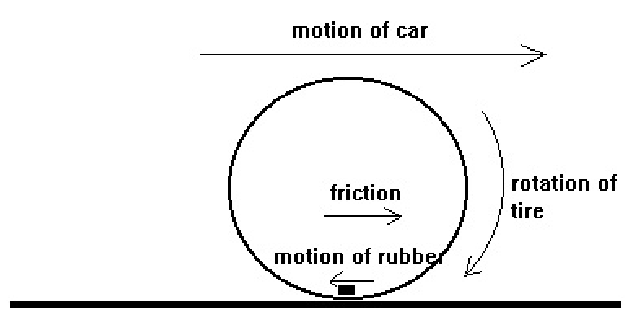
Ch.14: Newton's Second Law and Friction

The Nature of Friction

If we consider resting a brick on a piece of wood on a level surface, commons sense will tell us that the brick will simply stay where it is put. But if we incline the plane slightly and do a force analysis, we will notice that the weight of the brick now has a component down the plane ($mg\sin\theta$) and we would expect the brick to accelerate down the plane. However, common sense also tells us that this is not the case. Another example to consider is a block pushed across a table and released. It will not seem to follow Newton's Laws, it will not continue forever. We know that we have left out an important factor that would make our problems more realistic. That factor is friction. Friction is a reactionary force that can arise from surfaces in contact and opposes the intended relative motion of two objects. This definition is simple on the surface, but requires two comments to clarify its deeper meaning. First, notice that the term reactionary is used and not reaction. This is an important distinction, since we are not talking about action-reaction pairs in this case, we are talking about a force that is only present because of certain circumstances (friction, like all forces is part of an action reaction pair, but it is also reactionary to some other force). Just exactly what we mean by reactionary will be made clearer in the following paragraphs. It should also be noted that we said that friction opposes the relative motion of the two objects in contact and does not necessarily oppose the motion of the entire object. A perfect example of this false paradox is the motion of an automobile. It is the force of friction between the tires and the ground that causes an automobile to move forward, but if we look at the direction of motion of a small piece of rubber on the tire in contact with the ground, we will see that it is attempting to move backwards (see diagram). This is also the same situation that arises when a person walks.



Also notice that the definition says intended motion. Things do not have to move to produce friction, they just have to "try" to move.

A better of way of saying this is that friction will show up opposite the motion that would occur if it wasn't there.

Friction comes in many forms, but most commonly it is divided into solid friction (friction between two solid objects) and fluid friction (between a solid and a liquid or a solid and a gas). Our discussion will focus only on solid friction, with some fluid friction considered at a later date.

Solid friction has many causes, but they can all be summed up by saying that no surface is rigid, no surface is smooth, all particles are attracted to each other, and our knowledge is limited.

By saying that no surface is rigid, we mean that all surfaces "give" a little when another object is placed in contact with it. If we place a brick on a piece of metal, a small indentation forms underneath the brick, and moving the brick requires it to break free from this rut (see diagram).

This effect occurs in <u>all</u> materials, although obviously in different degrees for steel and marshmallows.

Saying the no surface is smooth means exactly that. Even materials that you think are smooth (glass, silver, etc.) are very rough and irregular if you simply look at them under a higher magnification (As a side note, the flawed mirror on the Hubble telescope is incredibly smooth compared to other objects. If it were to be expanded to the size of the state of Texas, the largest bump would the size of a golf ball. However, expanding it further would show it not to be smooth.) If we consider two objects trying to slide across each other and look at them under a magnification that shows their irregularity, we might have a situation like the one shown below. The black and the grey are materials and the white area is the space between them.

Imagine trying to push one of these materials across the other. It would be like trying to push an inverted mountain range across a mountain range. As the peaks hit, they offer resistance and thus slow or prevent the motion. Another interesting thing is that after they pass, there will be little pieces of the white material broken off and imbedded into the grey and visa versa. Think about that next time you rub your hand across a desk. If you imagine filling the white gap with oil, you can begin to see how lubricants work, by keeping the two surfaces apart and allowing the friction between the surfaces and the oil (which is considerably greater) to act instead of the surface-surface friction.

When we say that all objects are attracted by forces, we mean that the surface particles of any material will feel a force of attraction from the surface particles of any other material to which they get close. The two materials are in fact pulled together by these forces and the "bonds" that form must be overcome in order to move or separate the materials. These bonds are formed by the so called Van der Waals forces that were probably mentioned in your chemistry class. Van der Waals forces are today believed to be one of the major causes of friction, and their effect can be seen if we manage to eliminate the other effects (as much as possible). For example, if we take two very rigid surfaces and make them smoother and smoother, the friction will generally decrease. However, there will come a point where making them any smoother will actually result in an increase in the amount of friction because the particles are allowed to get so close together that the Van der Waals forces increase tremendously.

The final cause of friction is simply unknown. There is much that we don't know or understand about how friction works and there is much research that needs to be done.

It should be remembered that friction is not necessarily a bad thing. In fact, at times it is indispensable. Without friction we could not drive a car (or stop a moving car!), we could not walk, we could not write, and any slight disturbance would send a piece of furniture sliding across the floor. Friction is a useful part of our universe.

Now that we understand some of the causes of solid friction, we should turn our attention to some of the factors that do and do not affect friction. Friction is of course dependent on the nature and types of the materials in contact. Each and every different pair of materials will generate its own amount of friction. For instance, dragging a brick across fabric will result in a different amount of friction than dragging a brick across wood.

Surprisingly, solid friction is practically independent of surface area in contact. If we pull a rectangular brick across a block of wood, we will generate the same amount of friction regardless of the side that we put face down. This means that as far as traction goes, tire width has no effect on performance. Bicycle tires will do as well as balloon tires do. Sports and race cars have large, wide tires for reasons other than traction (please remember, however, that in this comparison we are comparing tires made of the same materials with all of the properties the same, other than size).

What may also seem surprising is that solid friction is unaffected by velocity. A brick being dragged at 3 m/s will be affected by the same amount of friction as the same brick being dragged at 30 m/s. It is also worth mentioning that the two factors that do not affect solid friction (surface area and velocity) are the same two factors that most affect fluid friction.

Temperature will also affect solid friction to a small, unpredictable degree. In some cases it will increase it (by expanding the irregularities and reducing the rigidity) and in some cases it will decrease it (by reducing the effects of the Van der Waal's forces).

Most importantly, friction depends on the force that is pushing the two objects together. Many books say that friction is dependent on the weight of the object being moved, but in fact it is dependent on the contact force or the normal force on the object. Since normal force is often not equal to the weight, it is more correct to say the latter. In fact, solid friction is directly proportional to the normal force. Thus the formula that gives us the value of the force of friction on an object is:

$$F_f=\mu N.$$

Where μ is called the coefficient of friction for the two materials in contact. As was stated earlier, every different pair of materials will result in a different amount of friction, thus there is a different μ for each pair of materials. In actuality, the different μ are measured experimentally and there is no theoretical way to arrive at their values. The equation above is really a definition for μ, not for the force of friction. The astute student will notice that μ has no units, it is a ratio quantity ($\mu = F_f/N$) thus is unitless. Also, notice that the equation above is not a vector equation, if it were, then friction would point in the direction of the normal force and we know that is not the case. The above equation is only for the magnitude of the force of friction and its direction is given logically as opposite to the direction of intended motion. Notice that this means friction will always act <u>parallel</u> to the surfaces in contact.

There are really four types of solid friction; static, starting, kinetic (or sliding), and rolling friction. We will limit our discussion to the first three. In order to investigate these types of friction, it is best to simply do some problems regarding each type and draw some conclusions. The first example shows us some interesting things about static friction.

EX EF.) Imagine a box weighing 10 N resting on the floor. Suppose you attempt to push the box with a force of 3 N and it does not move. What is the force of friction and what is the coefficient of static friction in this case? If you push with 5 N and it still does not move, what forces have changed?

This example illustrates an interesting fact, and that is that μ_s (the coefficient of static friction) changes as the force applied changes. The friction adjusts itself to the particular situation. This is exactly what was meant earlier when we said that friction was a reactionary force. As the applied force increases, more friction is needed to maintain equilibrium, and this friction arises from an increase in μ (not really, but it is helpful to think of it in that way). If there is no applied force, there is no μ, and thus no friction. But common sense tells us that if we push hard enough, the block will accelerate. This can only be explained by saying that μ_s cannot increase forever. There must exist some maximum value for the coefficient and that maximum value is called the starting coefficient (that is what is usually given as μ_s since we cannot really give a value for the static coefficient except in very particular circumstances). Thus the starting coefficient (μ_s) of friction is defined as the maximum value of the static coefficient for a particular set of materials.

EX EG.) What is the maximum frictional force that can exist on a 23 N block on a surface with a coefficient of starting friction of 0.63.

EX EH.) Suppose a 30 kg block was resting on a floor with a coefficient of starting friction of 0.46. If a person tried to push the box with a force of 100 N, would it move? What would happen if the person pushed with a force of 150 N?

The above example illustrates a trap that is easy to fall into. We must remember that μ_s is only good for cases where the object is at rest. You may recall that there was a different category called kinetic friction and this covers moving objects. Therefor, we cannot determine the acceleration from a problem that only states μ_s. We can only determine whether or not the object the object will move. A simple set of rules can be determined that will tell us whether or not the object does indeed move. If we assign the direction of intended motion as positive, and use the coefficient of starting friction, then:

If $\Sigma F<0$, the object will not move.

If $\Sigma F>0$, the object will move.

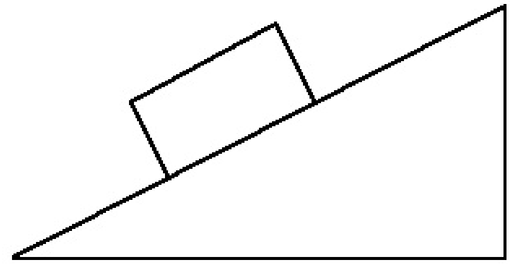
If $\Sigma F=0$, the object will not move (the cut off point).

Because we can't use $\Sigma F=ma$ for these problems, it is often convenient to write these as:

$\Sigma F=?$

because we are only interested in whether or not the above term is positive or negative. Beyond the sign of our answer, however, it is important to remember that the answer has no actual physical significance.

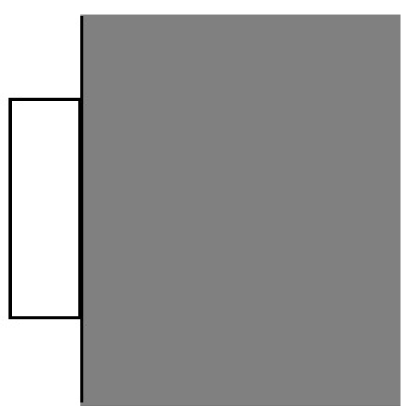
EX EI.) A 16 kg block is placed on a plane and the plane is raised until the block begins to move. At that point, the angle between the plane and the horizontal is 36°. What is the coefficient of starting friction?



EX EJ.) Use the above formulas to determine a formula that will simply tell you when a block on an incline will begin moving.

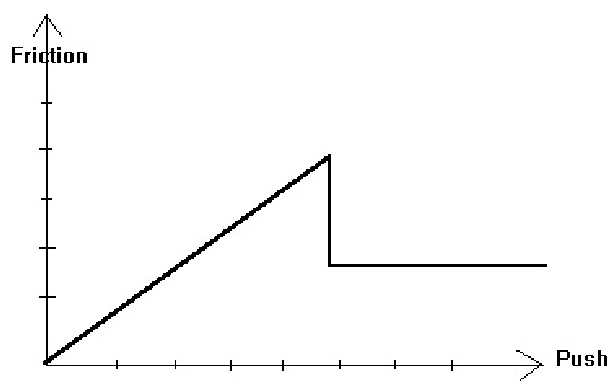
Remember, the above formula only holds true for situations that match the conditions in the previous problems. Now another example of how this works in a slightly different situation.

EX. EK.) Suppose a refrigerator magnet that has a mass of 75 g and can exert a pull of 2.0 N is placed on a refrigerator that has a coefficient of friction 0.4. Will it stick or slide down?



The refrigerator is a perfect example of a situation where the normal force in a friction problem is not even related to the weight and thus the friction is not related to the weight. Also, it is interesting to note that without friction, refrigerator magnets would not work at all. If there was no upwards force, then regardless of how strong a magnet was, it would slide down a refrigerator.

The previous examples are all excellent cases of how to solve problems involving static friction, but we must remember that these problems only tell us whether or not something will move, and tell us nothing about how it will move. We have already stated that there is a different coefficient for moving objects compared to objects standing still, and that coefficient is called the coefficient of sliding friction or the coefficient of kinetic friction (μ_k). If you have ever tried to move a box across a rough floor, you may have noticed that you push and push and then once it is moving it is easier to keep moving. The reason is that the μ_k is always less than the μ_s. In short, the friction as you push gets higher and higher and then, once the box begins to accelerate, the friction drops and remains at a constant value (see graph).



It remains at this constant value, you remember, because we said that solid friction does not depend on speed. This also means that once an object reaches it's breaking point, it will begin to move, the friction will go down, and the force that previously was just barely enough to move it will become a force strong enough to accelerate the object. Notice how illogical it would be if $\mu_k > \mu_s$. An astute student would be able to explain what craziness would occur. (One way to think about the fact that μ_s acts until it is overcome is to consider that it is similar in concept, but not detail, to the behavior of heating a material through a phase change. The material will continue to absorb heat, but the temperature will not rise until the material completely changes phase. Then it continues unabated.) Now we also have a way to calculate the acceleration, by using a different coefficient of friction for the part of the problem that involves motion.

EX EL.) A 20 kg block rests on a surface with a starting coefficient of 0.4 and a kinetic coefficient of 0.3. It is pushed by a 80 N force.

a.) Show that it will move.

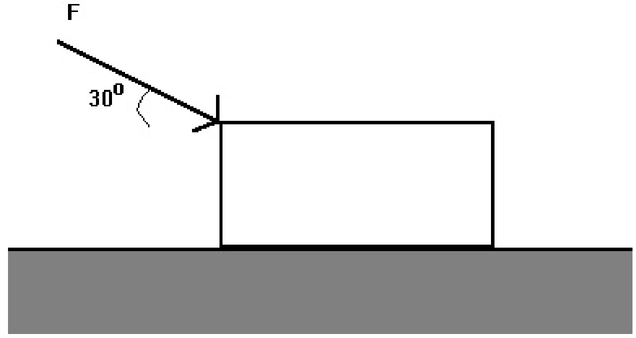
b.) Determine acceleration.

c.) If this force acts for 16 seconds, what will be the velocity of the block at the end of this time?

d.) Suppose after the 16 seconds are up, the force stops. How long will it take for the block to come to rest?

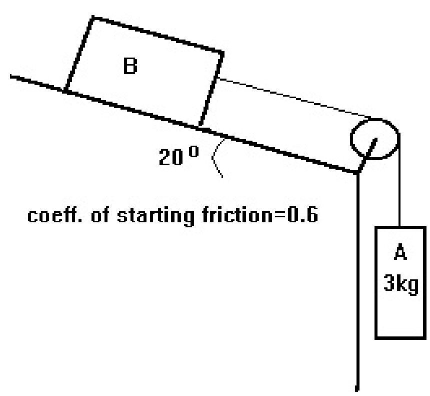
The above problem is important, because each section shows a different aspect of friction. Parts a and b are obvious, while part c shows us how to incorporate our equations of motion into the friction problem and part d clears away a major misconception (remember, just because something is moving, it does not necessarily follow that there is a force pushing it).

EX EM.) Consider a 60 kg block being pushed as shown below. If the force is 400 N and the kinetic coefficient is 0.2, what is the resulting acceleration?



Once again, we have a perfect example of a situation where the normal force is not equal to the weight of the object, but instead is affected by other forces in the problem. You should always "solve" for the normal force instead of assuming it's value (unless, of course, the problem is very simple and obvious). The last example in this section will show us how to do a rather involved force problem that takes friction into account.

EX EN.) On the setup below, what is the minimum value for the weight of block B such that we have equilibrium?



Fluid Friction

All of our previous results hold for solid friction only, not for fluid friction. Although we are not going to look into fluid friction numerically, it would be a good idea to take a few minutes and take a look at how fluid friction behaves conceptually.

First of all, as stated before, the factors that affect fluid friction the most are the two factors that do not affect solid friction at all: velocity and surface area. It turns out that fluid friction is proportional to the surface area of the object that presents itself in the direction of motion (in other words, the cross sectional area of the object taken in a plane perpendicular to the direction of motion) and proportional to the velocity squared. The fact that the dependence is on the velocity is something that causes fluid friction to be a fairly complicated subject. Since the forces depend on the velocity and the acceleration depends on the forces, this means that the acceleration depends on the velocity. As the object changes, the velocity changes and then the acceleration changes with it. Recall that all our previous discussions were focused on cases where the acceleration was constant. Dealing with a changing acceleration requires that we use calculus to derive any meaningful equations that we might use. You can imagine the complications that arise when you have fluid friction in two directions (as in the case of a realistic treatment of projectiles).

However, there are still some interesting conclusions that can be discussed from a conceptual point of view regarding fluid friction. The first has to do simply with the v^2 dependence on velocity. Since the dependence is a square relation, increasing the velocity slightly can greatly increase drag (as fluid friction is sometimes called). Doubling velocity will bring a fourfold increase in drag. Simply going from 40 mph to 45 mph in a car causes your drag to increase 30%. This explains why vehicular traffic at high speeds can be very difficult. In order to double the speed of an airplane, you would need an engine 4 times as powerful, not just twice as powerful. Small increases in speed require great increases in expenditure in fuel. This is part of the reason why going above the speed limit in a car often greatly reduces your gas mileage (the other part is that car are mechanically geared for efficiency at some certain speed, usually the prevailing highway speed limit). It is interesting to note, while on the subject of automobiles, that improving gas mileage is often best done by improving the aerodynamics of the car. There are three factors that come into play in auto efficiency: the efficiency of the engine, the standard (solid on solid) friction in the car and the air drag. The "standard" friction is basically a constant for vehicles regardless of speed and the efficiency of the engine can be manipulated slightly. Great increases come from shape modification that prove more aerodynamic.

If we approach the matter from a conceptual view, however, we can make some interesting observations.

EX EO: In a previous section, we discussed the acceleration, velocity and forces on a skydiver. Redo that discussion in terms of fluid friction.

The above discussion leads us to the concept of terminal velocity. Since (in most, but not all cases), we have velocity that is increasing, the air resistance will increase, the net force will decrease and eventually it will reach zero. When this happens, the velocity will remain constant from that point on. This occurs when the air resistance has increased to equal the weight of the object and it is called the terminal velocity. Since this occurs when the air resistance equals the weight, for cases where other factors are equal (especially the important factor of surface area), heavier objects will have a greater terminal velocity. In fact, the relation is linear, meaning that an object with double the mass will have double the terminal velocity (once again, this is if other factors are equal). With this in mind, the student can now explain one of the many relations determined in the first lab.

Although we have been discussing terminal velocity in terms of air resistance, we should not forget that objects will have terminal velocities in liquids as well. Often, objects will reach their terminal velocities in fluids very quickly. Consider dropping a penny in a swimming pool or a marble into a jar of maple syrup. The concepts are the same, the fluid is different.

Before we close this subject, it is important to note that our treatment of fluid friction has not been a treatment of "air resistance" since factors other than fluid friction might come into play. In the case of a car, for example, there is a suction effect that resists the motion of the car as the air spirals around the back of the vehicle. Fluid dynamics is an extremely complicated subject that is still not completely understood.

Assignment #14

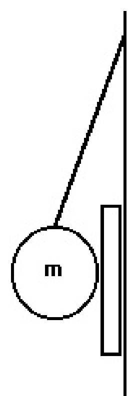
1.) If we push a 400 N box with a force of 75 N on a level floor with a coefficient of friction of μ_s=0.3, will it move?

2.) Imagine a 150 N box resting on an incline plane with a coefficient of static friction of 0.8. If the incline has an angle of 30^0, how hard would a person have to push up the incline to get it to move? How hard would they have to push down the incline?

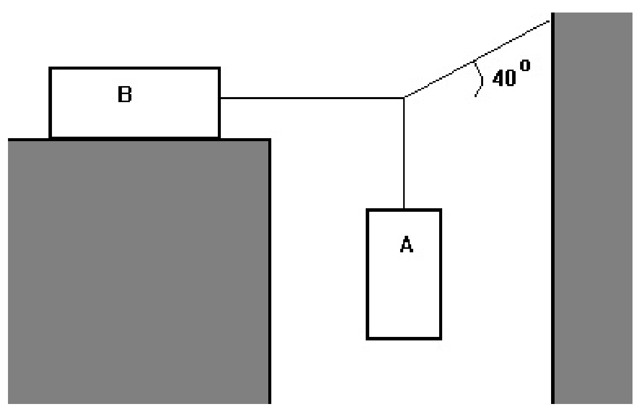
3.) If a 400 N crate is resting on a floor (μ_s = 0.4) and you wish to pull it by a rope, how much would you have to pull, just to get it moving, if the rope was to make an angle of -35^0 with the horizontal? What if you were to make an angle of 35^0 with the horizontal? What about 70^0? Comment on your answers.

4.) If you placed an empty coffee cup on a slanted surface and began to pour coffee into it, would it begin to slide down the incline at some point? Support your answer with formulas. (R9)

5.) In the diagram below, a mass is attached to a cord that makes an angle of 15 degrees with the wall. In between the mass and the wall a book is placed. If the book has a mass of 1.0 kg. and the coefficient of static friction between the book and the wall is 0.35, what is the minimum value of the mass needed to hold the book in place ? (R6*)



6.) What is the minimum weight of block B in the setup below required to maintain equilibrium? Block A weighs 400 N and the coefficient of static friction on the horizontal surface is 0.35. (R8*)



7.) A 200 N force is used to pull a 420 N box at a constant speed across a floor by means of a rope that makes an angle of 35 degrees up from the horizontal. What is the coefficient of sliding friction? (R1)

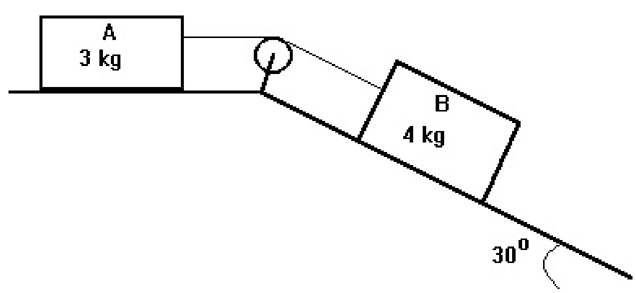
8.) A 200 N force is used to pull a 420 N crate at a constant speed across a floor by means of a rope that makes an angle of 35 degrees down from the horizontal. What is the coefficient of sliding friction? (R2)

9.) A 5.0 kg block slides down an incline plane (coefficient of sliding friction = 0.30) that makes an angle of 40 degrees with the horizontal. How long does it take to reach the bottom ? (distance = 5.0 m) (R4)

10.) A 20 kg block is projected up an incline that makes an angle of 50^0 and has a coefficient of kinetic friction of 0.5. If it is projected up the incline with a velocity of 4 m/s, with what speed will it return to the bottom (careful, this is a fairly involved problem).

11.) In the problem above, using the coefficient of sliding friction given, the minimum angle for which the block would slide down is approximately 27^0 (found using $\tan\theta = \mu$, as proven in the chapter). However, if the plane was set at 27^0 the block would not slide down. In fact, the block would probably not slide down even at 30^0. Explain in detail why.

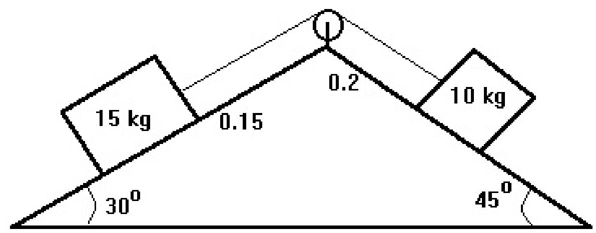
12.) In the setup below, the incline is frictionless and the horizontal section has a coefficient of kinetic friction of 0.4. What is the acceleration of block A? (R10)



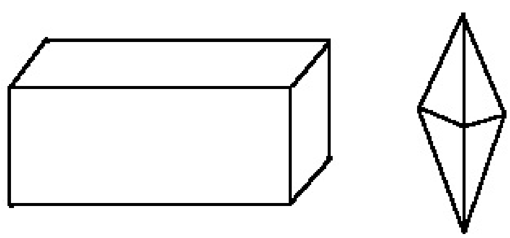
13.) Consider the set up as shown below. Using the quantities given (the coefficients of kinetic friction are next to each incline), determine:

a.) Which block will slide up and which block will slide down.
b.) The acceleration of the system.

WARNING: There is more to this problem than meets the eye.



14.) The diagram below shows two objects. The object on the right is light and the object on the left is heavy. Which will have a greater terminal velocity? Why can't this question be answered?



15.) Make a rough sketch of the following quantities (all on the same graph) versus time: acceleration, net force, velocity, air resistance for a ball thrown straight up in the air. Do two separate graphs, one for the ball going up, the other for the ball going down. Which motion takes more time, going up or coming down?

16.) Describe the motion of an object thrown straight down from a plane at a velocity greater than its terminal velocity. Describe the forces, the acceleration, the velocity and the air resistance.

17.) Decipher: "Abstention from any aleatory undertakings precludes a potent escalation of a lucrative nature." (DNCTHWG)

<u>Lab #11 - Kinetic Friction</u>

The purpose of this lab is to learn to evaluate the coefficient of kinetic friction for a moving object. We will do so by using a kinematics cart and measuring the acceleration caused only by friction. If we start the cart by releasing the plunger, it will travel across the floor and accelerate (negatively) to a stop because of friction. If we know the distance and the time of travel, we can evaluate the acceleration (by using our equations of one dimensional motion and substituting the v_i with our v_f of zero (why can we do this?)). Once we have the acceleration, we can determine the force from Newton's Second Law and by doing a force analysis, we can determine the coefficient of friction.

Procedure:

1.) Set a dynamics cart on a long, smooth surface and place it, with plunger set, up against a brick.
2.) Release the plunger and start the stop watch at the same time, stopping the watch when the cart comes to a complete stop.
3.) Measure the distance traveled and record this along with the time in the chart below.
4.) Repeat this five times.

Trial	Time	Distance	Acc.
1			
2			
3			
4			
5			
	Average	Accel.	

5.) Determine the acceleration for each trial and the average acceleration.
6.) Repeat the entire process by having the cart transverse the same track in the opposite direction.

Trial	Time	Distance	Acc.

1			
2			
3			
4			
5			
	Average	Accel.	

Analysis and Conclusions: By doing a force analysis, determine the coefficient of friction for the car in each direction. Was there a difference? Also explain (in your theory!) why we were allowed to use our equation of motion substituting final velocity for initial (consider symmetry for the answer).

Lab Extension #3 - Correcting for Inherent Errors

Sometimes in a laboratory setting, there will be problems with the lab that simply cannot be eliminated. A perfect example of this would be doing some sort of chemistry lab involving gas collection on a humid day. In that case, some water vapor would get into the collected sample. This problem is easily solved, however, since you can determine the vapor pressure of water and in essence subtract the effect from your results. Other problems are not so easily resolved.

Imagine that the floor in the physics lab was not level, but slanted. In that case, the slant of the floor would cause an extra acceleration (either positive or negative, depending on which way the floor sloped) to your cart. Determining if this was a factor in your lab requires a brilliant and ingenious method.

This technique involves doing the experiment twice, once when the factor is working with the experiment and once when it is working against it. This is the reason we did the experiment once in each direction. The way we determine the effect of the floor angle is to do a force analysis on the cart (including the slant of the floor) once for each direction. Inputting all the know information into these two equations will give you two equations with two unknowns (μ, the coefficient of kinetic friction and θ, the angle of the floor). Using these two equations you can solve for both of these unknowns.

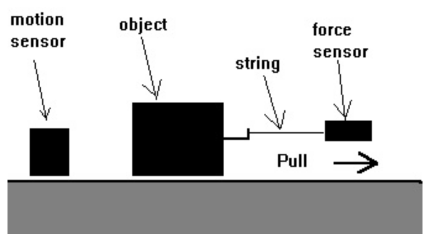
Do so for this lab and answer the following questions. What percent error did the floor angle cause in this lab? Was this significant? What percent of the acceleration did the floor angle cause in this lab? What was the angle of the floor?

Activity #15 - Static and Kinetic Friction

In this activity, you will use a computer interface to investigate the relationship between frictional forces and velocity. This will be done using a force sensor and a motion sensor and graphing velocity versus force while a large, heavy object is dragged across the table.

Procedure:

1.) Place a large, heavy (2-3 kg) object on the desk and attach a string (or other contrivance) to it so that it can be dragged by the hook on the force sensor.



2.) After being sure the sensors are calibrated, begin the experiment by turning on the sensors and gradually increasing the pull on the force sensor until the object moves about one meter across the table.

3.) There time interval measured should be about equally distributed between the object standing still and the object moving. You should also attempt to pull the object at a roughly constant velocity across the table.

4.) Manipulate the graphs so that you end up with a graph of velocity versus force for the experiment.

5.) Repeat the above procedure, this time pulling the object more sharply, resulting in a shorter time standing still and a more accelerated motion across the table.

Conclusions: By examining the graphs and using your knowledge of the behavior of frictional forces, draw as many conclusions as possible regarding the experiment. Do the graphs support the concepts discussed in this chapter? Give specific examples of how this is shown by referring to specific parts of the graph and specific concepts.