

## Chapter 4 Lecture Notes

### Physics 2414 - Strauss

Formulas:

$$\Sigma \mathbf{F} = m\mathbf{a}$$

$$\mathbf{F}_G = m\mathbf{g}$$

$$F_{\text{SF}} \leq \mu_s N$$

$$F_{\text{KF}} = \mu_k N$$

Main Ideas:

1. Newton's Three laws
2. Weight
3. Solving Problems
4. Friction

In this chapter we will study Newton's laws of motion. These are some of the most fundamental and important principles in physics.

### 1. Newton's First Law

**Every object continues in its state of rest or of uniform speed in a straight line unless it is compelled to change that state by a net force acting on the object.**

First note what is *not* stated or implied by Newton's first law.

- This doesn't say that every moving object has a force acting on it.
- This doesn't say that a stationary object has no forces acting on it.

This says that if an object is stationary it will stay stationary, and if it is moving, it will stay moving in a straight line, unless a net force acts on it. Therefore, if an object is stationary or moving in a straight line at a constant velocity, you can be sure that the net force acting on the object is zero. A net force is the vector sum of all the forces on an object. A non-zero net force means that the vector sum of all the forces is not zero.

A book sitting on a table has a net force equal to zero because it is in a state of rest. The table is exerting a force upward and gravity is exerting a force downward, so that the vector sum of the forces is zero. Note that the object exerting a force does not have to be moving, but can be stationary like the table.

Note also that an object that is at rest or an object that is maintaining a constant velocity are equivalent in that both need a force to change them and that in both cases the net force on the object is zero. A net force on an object is not needed to maintain the velocity, only to change it.

Let's look at an example of what Newton's first law implies about the motion of objects. Suppose you were to push a book and let it slide across a table after briefly pushing it. Why does it stop? According to Newton's first law there must be a net force slowing it down, which in this case, is caused by friction. But what if there was no friction? Then what would keep the book going? The answer is that nothing keeps the book going! That's the point. Once the object starts in motion it will continue in motion unless it experiences a net force. It does not take any magic force for the object to continue in motion. The "push" from your hand *only* acts on the book during the brief time your hand is touching the book. It is not the push from your hand that keeps the book moving, but the fact that once the book is set in motion, it will continue in a straight line at the same speed unless a net force acts on it.

The force required to change a body's state of motion is a measure of the inertia of the body. That SI unit of inertia is called "mass". It is harder to change the motion of something with more mass, whether or not there is air resistance, gravity, etc. So even in the vacuum of space, it is harder to change the motion of a spaceship, than a wrench. (There is the force of gravity in space, just not air resistance. More about that later.)

## 2. Newton's Second Law

In chapters one through three we discussed how an object moves when it is experiencing a constant acceleration. However, we never discussed what causes an object to accelerate. Newton's second law gives an explanation for what causes an object to undergo an acceleration. It is the net force applied to the object.

**The acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass. The direction of the acceleration is in the direction of the applied net force.**

$$\mathbf{a} = \Sigma \mathbf{F}/m \quad \text{usually written} \quad \Sigma \mathbf{F} = m\mathbf{a}$$

You should understand what this formula means. Remember that the formulas in physics have a physical meaning. They describe the physical universe. This formula indicates that if the vector sum of **all** the forces **on** an is zero the object will not accelerate. If the vector sum of **all** the forces **on** the object is not zero, the object will accelerate.

To use this formula, we draw a free body diagram showing all of the forces acting on a certain object. The sum of the forces on this object and the mass of this object will determine its acceleration. We do not consider the forces that this object exerts on other objects, but only the forces exerted on the object in question. If all the forces add up (using the rules for adding vectors) to be

zero, then there is no acceleration. If they do not, then there is an acceleration in the direction of the net force. The converse of this is true as well. If an object is accelerating, the net force on it must not be zero. On the right hand side of the equation, always use the mass of the object in question, the object which has the forces acting on it which will cause an acceleration of that object.

The SI unit of force is  $\text{kg}\cdot\text{m}/\text{s}^2 = \text{Newtons (N)}$ . One Newton is the force required to accelerate one kg one meter per second per second. The British unit of force is the pound. (Note that pounds and kg are not a measure of the same quantity. Pounds is a measure of force, and kilograms is a mass.) The pound is the unit of weight when the acceleration is  $g = 32.1734 \text{ ft/s}^2$ . The unit of mass in the British system is the slug, which is the mass that undergoes an acceleration of  $1 \text{ ft/s}^2$  when a force of 1 pound is applied to it.

In an environment where gravity is different, like on the moon, the weight of an object changes (Newtons or pounds), but the mass stays the same (kg or slugs).  $\text{lbs} = \text{slugs} \times g$ . Using measures of force we find that  $1 \text{ lb} \equiv 4.48 \text{ N}$ .

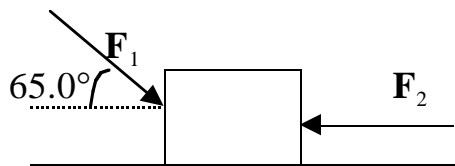
Note that the Newton's first law is a special case of the Newton's second law. When  $\Sigma \mathbf{F} = 0$ ,  $\mathbf{a} = 0$ , and so  $\Delta \mathbf{v} = 0$  because  $\mathbf{a} = \Delta \mathbf{v} / \Delta t$ .

Because the acceleration of an object is one variable in Newton's second law and also in the kinematic equations of chapters 2 and 3, we will often use the kinematic equations to find the acceleration which will be used in Newton's second law, or vice versa, that is, find the acceleration from Newton's second law and use it to solve the kinematic equations.

**Problem:** What is the average net force exerted by a shot putter on a 7.0 kg shot if the shot is moved through a distance of 2.8 m and is released with a speed of 13 m/s?

Also note that the second law is a vector equation. This means that for problems involving two dimensions, Newton's second law actually implies two separate equations. When working with Newton's law in more than one dimension, you must always break down all vectors into their components along different directions and use two equations separately, for example  $\Sigma F_y = ma_y$  and  $\Sigma F_x = ma_x$ . Do not combine forces or accelerations in one direction with forces or accelerations in another direction.

**Problem:** Two forces,  $F_1=45.0 \text{ N}$  and  $F_2=25.0 \text{ N}$  act on a 5.00 kg block sitting on a table as shown. (a) What is the horizontal acceleration (magnitude and direction) of the block? (b) What happens in the vertical direction?



### 3. Newton's Third Law

**Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first.**

It is important to realize that *the equal and opposite forces described by Newton's third law are not exerted on the same body*. For instance, when a nail is hammered, the hammer exerts a force on the nail, which drives the nail into the wood, and the nail exerts an equal and opposite force on the hammer which stops the hammer when it hits the nail. When determining if something will move (like will the nail go into the wood), we must always look only at the forces acting on that object. That is, if you want to determine the motion of the nail, you must consider the force of the hammer on the nail, but you can not consider the force of the nail on the hammer. Newton's third law *always* deals with two different objects, the force object *A* exerts on object *B* is equal and opposite to the force object *B* exerts on object *A*.

Problem: An astronaut who is walking in space pushes on a spaceship with a force of 36 N. The astronaut has a mass of 92 kg and the spaceship has a mass of 11000 kg. What happens?

Problem: Suppose I throw a baseball. My body exerts a force on the baseball and the baseball exerts a force back on my body. How does the force of the ball on my body compare with the force of my body on the ball? Is my body accelerated back? If not, why not?

Note the difference between Newton's second law and Newton's third law. **Newton's Second law has to deal with all of the forces acting on a single object. Newton's third law has to do with the forces acting and reacting on two different objects.**

### 4. Force of Gravity and the Normal Force

We know that an object near the surface of the earth will undergo an acceleration  $g = 9.8 \text{ m/s}^2$ . Using Newton's second equation, we see that for a body near the earth, the force of gravity is

$$\mathbf{F} = m\mathbf{a} = m\mathbf{g}$$

since the acceleration of an object near the surface of the earth is  $g$ . This implies that the force acting on an object of mass  $m$  near the surface of the earth is equal to  $mg$  and is directed toward the center of the earth. This is what is often called the object's weight. The weight is the force of the earth (or other celestial body) on the particular object. Remember that the British unit "pounds" is a force, but the SI unit "kilograms" is a mass. So an object of 1 kg near the surface of the earth, has a "weight" of

$$F = mg = (1\text{kg})(9.8 \text{ m/s}^2) = 9.8 \text{ N which is 2.2 pounds.}$$

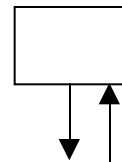
On the moon where the gravity is  $1/6$  of the earth's, the mass will still be 1 kg. Mass never changes no matter what the gravity. However, the weight will now be

$$F = (1\text{kg})(1.6 \text{ m/s}^2) = 1.6 \text{ N which is .37 pounds.}$$

The weight (which is a force) depends on the acceleration of gravity, but the mass is constant no matter what the force of gravity is, even when there is no gravity at all. Remember that even if there is no force of gravity, it still takes more force to accelerate a spaceship of 11000 kg than to accelerate a man of 92 kg at the same rate.

Now suppose an object is placed on a table. What are the forces acting on this object? Certainly gravity is acting on it. But if there was only gravity, then the object would accelerate down by Newton's second law  $\Sigma \mathbf{F} = m \mathbf{a}$ . There must be a force pushing up on the book or it would accelerate down.

This is the force of the table. It pushes up against the book. It is equal and opposite to the force of the earth pulling on the book. It is perpendicular to the table's surface so we call it the **normal** force. Normal means perpendicular. This is **not** the equal and opposite force from Newton's third law because we are dealing with two different forces acting on the same object, the book. What is the equal and opposite force of the earth pulling on the book? It is the book pulling on the earth. (As we will see in chapter 5, the book really does pull up on the earth.)

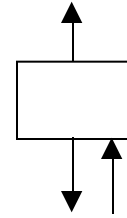


Problem: What is the normal force for a book with a mass of 0.80 kg?

Is the normal force always equal to the weight?

Problem: Suppose I tie a string to the book and lift it with a force of 5.2 N. What is the normal force then?

Problem: If I push down with 5.2 N what is the normal force?

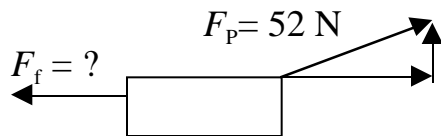


## 5. Solving Problems

There are some basic steps in solving problems using Newton's Laws. (see pages 87 and 100)

1. Draw a diagram
2. Consider only the forces acting on one object at a time and draw a free body diagram.
3. Determine the components of each of the forces and set  $\Sigma F = ma$  in each direction. (If there is no acceleration along a particular direction then  $\Sigma F = 0$  along that direction.)
4. Determine if there are other equations that need to be used (e.g. kinematic equations to get the acceleration).
5. Solve the equations.

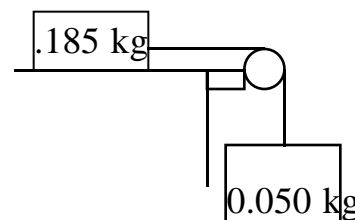
Problem: A man is pulling a wagon at a constant rate of 2 m/s with a force of 52 N with the handle at an angle of  $30^\circ$ . What is the force of friction holding the wagon back?



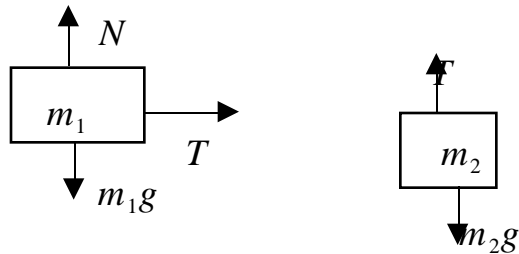
Problem: If the wagon has a mass of 12 kg, what is the normal force?

When working with more than one object. Draw free body diagrams of all the objects separately, write equations from each from body diagram, and look for relationships between the different objects.

PROBLEM: Consider a block on a frictionless table with a mass hanging down as shown .  
 (a) What is acceleration and tension in the cord?  
 (b) How long will it take the block on top to move 0.70 m?

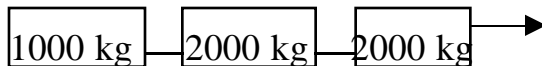


Look at block falling down draw a free body



The tensions must be the same and the accelerations must be the same, so for block 1 tension and acceleration are in the same direction.

Problem: A train is given an acceleration of  $5 \text{ m/s}^2$ . What is the tension between the two cars with a mass of 2000 kg.



## 6. Friction and Inclines

In most cases we need to include friction. For many surfaces the force of sliding friction is proportional to the normal force. That is, as the normal force increases, the force of friction increases linearly. When this is true, we write  $F_{\text{fr}} \propto F_N$  with the proportionality constant called  $\mu_k$ , **the coefficient of kinetic friction**. This is the friction when the object is moving.

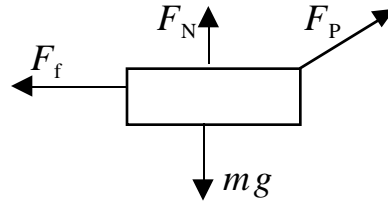
$$F_{\text{KF}} = \mu_k F_N.$$

If I push a table and it doesn't move, there must also be a force pushing back. That force comes from friction, as well. It is the friction when the object is not moving, or static, called the coefficient of static friction. It is always greater than or equal to the coefficient of kinetic friction. It is often harder to start something sliding than to keep it sliding, due to the difference in these coefficients.

$$F_{\text{SF}} \leq \mu_s F_N.$$

Problem: A 20 kg sled is being pulled across a horizontal surface at a constant velocity. The pulling force has a magnitude of 80.0 N and is directed at an angle of  $30.0^\circ$  above the horizontal. Determine the coefficient of kinetic friction.

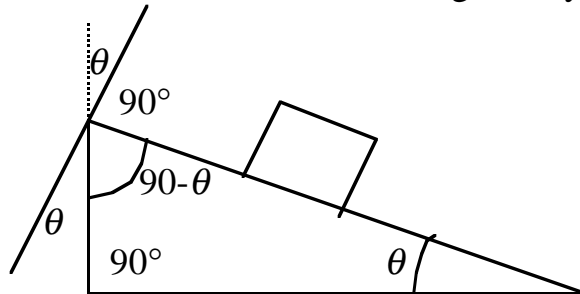
We know that  $F_f = \mu_k F_N$  or  $\mu_k = F_f / F_N$  so to solve the problem, we need to find what  $F_f$  and  $F_N$  are.



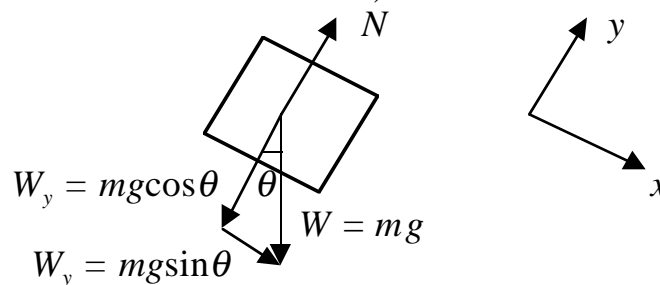
Many problems involving friction also involve surfaces at an incline. In such a case it is almost always a good strategy to set one axis parallel to the surface and one axis perpendicular to the surface. Why? Because the acceleration is along the surface. Along the direction perpendicular to the plane, then  $\Sigma F = ma = 0$ , and all of the acceleration is along the surface parallel to the plane.

Problem/Demonstration: Calculate the acceleration of gravity using an inclined plane and an air track.

Consider an object on a inclined plane tilted at an angle of  $\theta$ . Note that the angle between the normal and the vertical is also given by  $\theta$ .



We draw a free body diagram for the case when there is no friction between the object and the surface. Inclined plane problems are usually easier to solve if we chose the “x” axis along the incline. (In general, always chose the direction of acceleration as one of the axes).



Since the acceleration is along this  $x$  axis, let's look at the forces in that direction.

$$\Sigma F = ma$$

$$mg \sin \theta = ma$$



If we know  $a$  and  $\theta$ , we can use this to measure  $g$ ! Using kinematic equations in that  $x$  direction gives

$$x - x_0 = vt + (1/2)at^2, \text{ or with } v_0=0, \\ a = 2(x - x_0)/t^2.$$

Plugging this into  $\Sigma F = ma$  from above gives

$$mg \sin\theta = m 2(x - x_0)/t^2 \\ g = 2(x - x_0)/t^2 \sin\theta$$

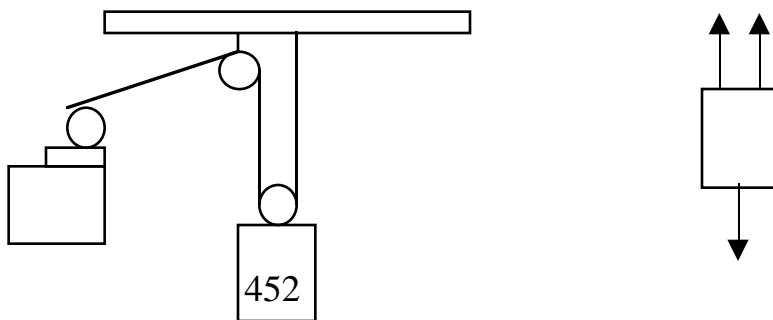
**Problem:** An 18.0 kg box is released on a  $37.0^\circ$  incline and accelerates down the incline at  $0.270 \text{ m/s}^2$ . Find the coefficient of friction and the frictional force.



Friction is not always a force that will slow something down. Sometimes friction is the force that causes things to go. Think of an example like a car driving along the road, or a dog standing up in the back of a pickup truck.

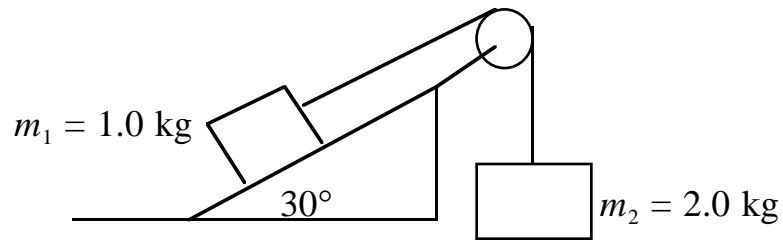
## 7. Solving Some Harder Problems

**Problem:** An electric motor is lowering a 452 kg crate with an acceleration of  $1.60 \text{ m/s}^2$ . What is the tension in the cord?



The only tricky part of this is to realize that all of the cords have the same tension, so the free body diagram looks like this and (with tension in the opposite direction from the acceleration).

**Problem:** Given the following situation with  $\mu_k = 0.50$ , what is the acceleration of  $m_1$  and  $m_2$ ?



**Problem:** A 3.0 kg mass hangs at one end of a rope that is attached to a support on a railroad car. When the car accelerates to the right, the rope makes an angle of  $4.0^\circ$  with the vertical. Find the acceleration of the car.

