PHYS:1200 LECTURE 3 – MECHANICS (2)

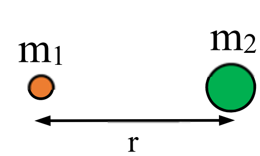
In Lecture 2 we learned that an object will continue in its state of motion unless something acts to change that state. Forces acting on an object can change its state of motion. In Lecture 3 we will consider one of the most common forces that changes the state of motion of objects – **gravity**. We are all subject to the force of gravity that is exerted on us by the earth, so it is really part of our everyday experience. We throw an object upward and it falls back to the ground – this is the effect of the force of gravity acting while the object is going up and coming back down. We will return to this example a little later.

3-1. Newton's Universal Law of Gravity.—First we give some of the basic facts of the law of gravity which was discovered by **Newton** in 1986. Gravity is the force that keeps us on the earth, the moon in its orbit around the earth, and the earth (and all the other planets) revolving around the sun. In fact, gravity holds the entire universe together. Our **weight** is simply **the force of gravity on us by the earth**—the earth is always pulling us downward (actually toward its **center**).

Gravity is a fundamental force of nature and is an example of what is called a **non-contact** force. You do not have to be in contact (touching) with the earth in order for the force to act on us. When we jump us, gravity acts to pull us down. Gravity is an **attractive** (tries to pull them together) force that acts between any two objects (not just between us and the earth) and it depends on the masses of the two objects. The greater the masses, the greater the force. Gravity also depends on how close the objects are to each other – the closer the objects are the greater the force. Newton's law of gravity for 2 masses separated by a distance r is given by:

Newton's Law of Universal Gravitation

$$F = G\frac{m_1 m_2}{r^2},$$



where G is a constant. This formula says that the force between the two masses (which is attractive, i.e., tries to pull them toward each other) depends on the product of the two masses divided by the **square** of their separation r.

You and the person sitting next to you are attracted toward each other by the force of gravity --- you exert an attractive force on the person next to you and the person next to you exerts an attractive force on you. Now you will immediately comment that “I do not feel an attractive force exerted on me by the person sitting next to me.” We are not aware of this force because it is a very, very small force and it is greatly overwhelmed by all the other forces acting on you like the friction between you and your seat. The force is small because the masses involved are relatively small (typically 60 – 100 kg). On the other hand, we definitely feel the force of the earth’s gravity on us (our weight) because the mass of the earth is huge ($6x10^{24}$ kg). We will now explore the effects of gravity on the objects near the earth’s surface.

3-2. The Acceleration Due to Gravity.— When an object falls to earth it is acted on by two forces: gravity and a drag force (air resistance) due to the air molecules hitting it. For objects that fall to earth from a distance of several feet or meters, the effect of air resistance can usually be neglected. To simplify the discussion of gravity, we will just ignore air resistance for now. When an object is dropped it falls to the ground—this is what is called free fall. If a video of the motion of the object is made and analyzed frame by frame we will observe that as it falls it does not maintain a constant speed but its **speed increases as it falls** – the closer it is to the ground the higher its speed. This is an example of what we call **accelerated motion**. Acceleration means increase in velocity and it is a measure of the rate at which the velocity increases – it is the amount of change in velocity divided by the time interval over which the change occurs. In mathematical terms we write for the acceleration a:

Definition of acceleration

$$a = \frac{\Delta v}{\Delta t} \qquad [1]$$

Δv **is read “delta v” and means *the change in velocity*,** and Δt **read “delta t”** is the time interval. This is just the usual meaning of acceleration – when your car accelerates, its speed increases; you push down on the accelerator to go faster.

Example 3.1: suppose an object starts from rest (v = 0) and then is accelerated to a speed of 10 m/s (meters per second) over a time interval of 5 s (seconds); its acceleration is then

$a = \frac{10\,\text{m/s}}{5\,\text{s}} = 2\,\text{m/s per s, or } 2\,\text{m/s}^2$, or, 2 meters per second squared.

Note that an object that moves with a constant speed has an acceleration of zero. Now that we have discussed the general concept of acceleration, we can get back to the specific case of the acceleration due to gravity. If we analyze in detail the video of the falling object (see slide #10) we find that each second that it falls, its speed increases by approximately 10 m/s (the precise number is 9.8, but in this course we will use 10 to keep the arithmetic simple). This is illustrated by the Table in slide #11. Since the speed increases 10 m/s each second, the acceleration is 10 m/s/s = 10 m/s^2. This important parameter is called the **acceleration due to gravity** and is given the special symbol g, so that

Acceleration due to gravity $$g = 9.8\,m/s^2 \simeq 10\,m/s^2 = 32\ ft/s^2\,. \qquad [2]$$

a. Mass and weight.—We can now discuss how to calculate the weight of an object, which recall is just the force of the earth's gravity on it. First of all, we need to emphasize that **weight and mass are not the same!** Weight is a FORCE and mass is a measure of how much matter is in the object--- in everyday language—they are apples and oranges. The mass of an object, which we agreed to measure in kilograms (kg), is a parameter that would be the same regardless of where the object were in the universe. On the other hand, the weight of an object is the force exerted on it by whatever large planet or other celestial body it happens to be near. We have all heard that your weight is less on the moon than on the earth. This is because the mass of the moon is much less than the mass of the earth. (The acceleration due to moon's gravity is 1/6 the acceleration on earth.) An object having a mass m on earth has a **weight** w calculated by multiplying m times g:

weight $$w = m \times g, \text{ or simply } m\,g. \qquad [3]$$

Example 3.2: the weight of an object of mass m = 50 kg is w = 50 kg x 10 m/s^2 = 500 kg m/s^2.

The units for weight is the combination of the mass unit multiplied by the acceleration unit or kg m/s^2. Since weight is just a specific example of a force, kg m/s^2 is the general unit for any force in our scientific system of units. Sometimes, a unit formed by the combination of other units is given a special name; in this **case 1 kg m/s^2 is given the name 1 Newton (N)**, in honor of Sir Isaac Newton. So in the above example, the weight of the 50 kg object is 500 N.

In the system of units used in the US (called the English system, even though it is not used anymore in the UK) (Liberia and Burma still use the English system also) weight is measured in the British force unit of **pounds** (lb), with the conversion that 1 N = 0.225 lb. Often, a person's weight might be quoted as the equivalent mass in kg. The reason for using kg for weight is that even though mass and weight are not the same, your weight is uniquely determined by your mass, so you can compare weights by comparing masses – if object B has twice the mass as object A, it also weights twice as much. A mass of 1 kg has a weight of mg $\approx$ (1 kg) (10 m/s^2) = 10 N. Using the conversion 1 N = 0.225 lb, 10 N $\approx$2.2 lb, so we say that 2.2 lb is approximately equivalent to 1 kg. (the symbol $\approx$ means approximately equal to)

Example 3.3: What is the "weight" in kg of a 150 lb person?

Solution- $\mathrm{w} = 150\ lb \times \frac{1 kg}{2.2\ lb} = 68\ kg$. Note that I put weight in quotation marks because kg is a unit of mass and weight is a unit of force. What is meant here is that a 150 lb person has an equivalent mass of 68 kg. A 68 kg mass has a weight of approximately 680 N.

How is weight measured? On a scale—what is a scale? If you hang an object from a spring it stretches the spring. So the amount that the spring is stretched can be calibrated so that it gives a weight measurement. Springs are interesting objects in themselves which we will discuss in a later lecture.

*b. Galileo's experiments on free fall.***—** Galileo performed the first experiments on gravity, supposedly by dropping various objects from the Leaning Tower of Pisa, although historians are still arguing about whether or not this is truth or legend. What is clear is that wherever he did the experiments, he came to the correct conclusions about free fall. Now to fully appreciate Galileo's contributions to the science of motion, we need to realize that the clock as we know it was not yet invented in his time. The fact that he was able to get the physics correct without an instrument that accurately measured time is quite remarkable. Galileo was an ingenious fellow! How did he measure time? Galileo was trained as a physician and he knew that the heart beat (pulse) was a regular phenomenon – so he could use his own pulse as a stop watch. (A normal male has a heart rate of 60 – 100 beats per minute.) He also realized that an object tied to the end of a string (pendulum) would swing back and forth at regular intervals of time, and the shorter the string, the shorter the time. So each swing of the pendulum is a "tick" of a clock. Galileo dropped various objects (different masses) from various heights and measured how long it took them to reach the ground. The conclusions from his experiment were:

GALILEO: All objects, regardless of their mass, and in the absence of air resistance, fall to earth with the same acceleration g = 10 m/s^2.

This will be shown in class by a demonstration in which a feather and a 25 cent coin fall in a glass cylinder in which the air was pumped out, thus essentially eliminating air resistance. (This experiment was also performed on the moon (where there is no air) by Cmdr. David Scott on the Apollo 15 mission.)

To obtain quantitative results from his free-fall experiments, Galileo made us of inclined planes (slide # 19). He realized that an object sliding down an **inclined plane** was still falling under the influence of gravity, but the effect of gravity would be reduced depending on the angle of the plane relative to the horizontal. (To reduce the effect of friction between the object and the plane, Galileo used spherical objects that rolled down the plane nearly frictionlessly. We can perform experiments today using the air track that is tilted.) For example, if the plane of the incline is tilted relative to the horizontal by 30 degrees, the effect of gravity is reduced by a factor of 2, that is the *"effective g"* = g/2 = 5 m/s^2. The advantage of using the inclined plane was that the time for the object to reach the bottom of the plane was longer than the case in which the object fell straight down from the same height as the top of the plane. This meant that the time was longer and therefore could be measured more accurately. From these experiments, Galileo was able to obtain a mathematical relation for the distance that an object fell as a function of time. This will be discussed in the next lecture.

c. Up and down: the effect of gravity.—You toss a ball straight up, it continues to move upward until it reaches its highest point, then falls back down. What is the effect of gravity as the ball rises and then as it falls back down? First, we must realize **that the force of gravity on an object near the earth (i.e., its weight) always acts in the downward direction** (technically toward the center of the earth, but locally we think of the earth as flat so the force is down.) When you toss a ball upward, you give it some initial upward speed. The downward force of gravity then acts to slow the ball down (reducing its speed) as it rises, until it reaches its highest point where it is instantaneously at rest, i.e., $v = 0$ at the very top of the ball's path. Gravity then continues to pull the ball downward from its highest point, and as it falls its speed increases. Keep in mind that weight is a force and forces cause changes in velocity. **On the way up the velocity decreases, on the way down velocity increases, but the force (weight) always acts downward.**