Chapter 2 Description of motion

Learning outcomes

1) familiar with motion, speed/velocity; displacement/distance and acceleration
2) understanding one dimensional motion; two dimensional motions and 3-dimensional motion
3) apply motion equations to solve problems

Essential Vocabulary (5 – 10 essential vocabulary) (highlighted or bolded)

2.1 what is **motion**? How to describe a motion?

The ball is being passed around on the basketball court; the cars are speeding on the driveway; the students are skipping rope on the playground; The movement of atoms, atomic nuclei and elementary particles is in various forms like translational motion; vibration and rotation. Predicting the motion of objects is one of the most basic goals of physics. In order to achieve this, we need to accurately describe the motion of an object, which is what this section will introduce. Although you may think that you are already familiar with the motion of an object, if you read on, you will find that you are not very clear about some concepts.

What is a motion? The answer to this question is that a motion is a movement in which an object changes its position over time. The change of the spatial position of an object over time is the simplest and most basic form of motion in nature, also called mechanical motion. How to tell if there is a motion or not? For instance, it is commonly believed that houses are motionless, and trees are stationary. In fact, they are moving along with the Earth day in and day out. Another example is that the flight attendants and passengers in a flying airplane are talking and communicating. People outside the airplane think that they are flying with the airplane. But inside the airplane, when the flight attendants and passengers are looking at each other, they could not tell they are flying or moving. Why do people think differently? If you are sitting in the airplane, you and your fellow passengers are relatively motionless to each other. However, after about one hour and a half, all of you would fly from Atlanta to New York. This is because that a motion is a relative term. All objects in nature are in eternal motion, and absolutely stationary objects do not exist. In this sense we say that movement is absolute. However, describing the changes in the position of an object over time is always relative to other objects. We say that houses and trees are stationary, and this is probably not wrong if we choose the earth as the reference. In order to describe a motion, a reference must be chosen. Usually to describe the movement of an object, you must choose some other object as a reference, and observe whether the position of the object changes over time relative to the "other object". Th other object acts as a reference, also called a reference frame.

When describing the motion of an object, the reference frame can be chosen arbitrarily. However, if you choose different reference systems to observe the motion of the same object, the results will be different. Proper selection of the reference system will make the research of the problem simple and convenient. Of course, whenever you mention motion, you should clarify which frame of reference it is relative to. Usually, when discussing the motion of objects on the ground, the ground is used as the reference frame. When the earth is chosen as a reference, all trees and houses are motionless. If the moon is chosen as a reference, all of them are moving along with the Earth. Similarly, on the same flying airplane, if other passengers are chosen as a reference, you are stationary. However, if anything on the ground is chosen as a reference, you are flying with a speed ranging of 880-926 km/h. Commonly, the motion of any objects on Earth in our daily life are referenced to those stationary objects like trees, houses and so on, unless otherwise stated.

2.2 Definitions of Motion Variables.

As aforementioned, a motion is a movement in which an object changes its position over time. What is time? Time is the continued sequence of existence and events that occurs in an apparently irreversible succession from the past, through the present, into the future. The difference between moment and time is that moment refers to a certain instant, which is a point on the time axis, corresponding to position, instantaneous speed, momentum, kinetic energy, etc. While time is the interval between two moments and a section on the timeline, corresponding to process quantities such as displacement, distance, impulse, work, etc.

Displacement and Distance.

Displacement represents the change in the position of a particle in space and is a vector. The displacement is represented by a directed line segment. The magnitude of the displacement is the length of the directed line segment; the direction of displacement is from the initial position to the final position. When an object moves in a straight line, you can use positive and negative displacements. The numerical value of the number represents the magnitude of the displacement. When it takes a positive value, it means that its direction is consistent with the specified positive direction, and vice versa. While the distance is the length of the movement trajectory of the particle in space and is a scalar quantity. Between two determined positions, the distance of an object is not

fixed as it has to do with the specific paths of the particle. Both displacement and distance occur are related to the selection of the reference system. Generally, the magnitude of the displacement is not equal to the distance. The two are equal only when the particle moves in a straight line in one direction.

More specifically, distance is length of path one object covers which depends on the traveling routes. "D" denotes the distance with unit of meters or kilometers. While displacement is a vector describing the change in position of an object from one point to another point. Usually, it is a directed straight segment, connecting the start point with the end point. The vector of displacement has a magnitude and direction.

Speed and Velocity

In order to describe a mechanical motion, not only are physical quantities needed to describe the change in the position of the object, but also physical quantities are essential to describe how fast/slow of the object moves over time, which is called speed.

Speed is defined as how fast an object moves or how fast an object changes its position. Mathematical definition is as follows,

$$\bar{V} = \frac{\Delta D}{\Delta T}$$

In which $\bar{V}$ is called average speed describing the overall speed of the entire journey; ΔD is the change in displacement while ΔT is the elapsed time. In contrast, an instantaneous speed is a speed at any specific moment. While you are driving, when you take a look at your speedometer, the speed is indicated on it showing the instantaneous speed of the moment you took a look. Mathematically, it can be expressed as:

$$v_{\text{limit } \Delta t \to 0} = \frac{\Delta D}{\Delta T}$$

Velocity is a physical quantity that describes the direction and speed of an object's movement. Instantaneous velocity is the velocity at which a moving object passes through a certain moment or position. Its magnitude is called instantaneous speed. Average Velocity is the ratio of the displacement of an object to the time taken during a certain period of time. The average velocity is a vector, and its direction is the same as the displacement direction. While, the average speed is related to the different motion stages of the object, and it is a scalar quantity. The average speed and the average velocity are often not equal. They are equal only when the object moves in a straight line without reciprocation.

Velocity is a vector, which must have a magnitude and direction. So, when considering a speed along a certain direction, you are talking about velocity. Assume there is a circular motion in which an object is moving with a constant rate, is this motion called a uniform speed motion or a uniform velocity motion?

Acceleration

Acceleration is another variable to describe a type of motion. For example, when we are riding a pedal to accelerate the bicycle, the velocity of the object changes over time. The more efforts you exert when pedaling, the faster the speed will increase. When traffic light turns green, the car starts moving, and if you slam the gasoline pedal harder, the velocity will be increased. While driving, if the accelerator is pressed harder, the speed will increase faster. These experiences tell us that the magnitude of acceleration is a result of the increase in speed. Another case is if the speed of an object decreases over time, the motion is called decelerating linear motion, the acceleration is the result of decrease in speed. When the speed is decreasing, the acceleration must be negative and the direction of acceleration is opposite to the direction of velocity.

For instance, the velocity of cars and trains are both increasing, or both are changing. They move at a high different velocity, and their "velocity change" can be the same, but the time taken could be different. The essential difference in two situations is the "rate of velocity change". How fast “the velocity changes" is a concept different from " velocity". If the velocity change of two objects is the same, and the velocity change takes a short time, we call it quicker. If the velocity of two objects changes at different times and the time taken is also different, how to compare the rates of their velocity changes?

When learning velocity, we know that displacement represents a change in position.

To compare how quickly a position changes, the position is divided by time. In the same way, we need to compare how fast the velocity changes, the change in velocity is divided by the time. In physics, the difference between the change in velocity and the time it takes for this change to occur is Ratio, which is called acceleration. Acceleration describes as how fast/slow the velocity of an object changes over time. The velocity refers to how fast an object moves in a certain direction. Acceleration is defined as the rate at which velocity changes over time. Mathematically,

$$a = \frac{\Delta v}{\Delta t} = \frac{v_2 - v_1}{t_2 - t_1}$$

In which v_1 and v_2 refer to the initial velocity and the final velocity, respectively. The unit of acceleration is $\frac{m}{s^2}$. The unit of velocity is m/s. They have different units, and have different meanings.

Nowadays, camera technology is so advanced that digital cameras can take multiple photos per second. By using multiple exposures to record the movement of objects in photos, we will get the following constant speed and acceleration.

The sequence photo recording reveals a motion with uniform velocity; a motion with positive acceleration and a motion with negative acceleration as shown:

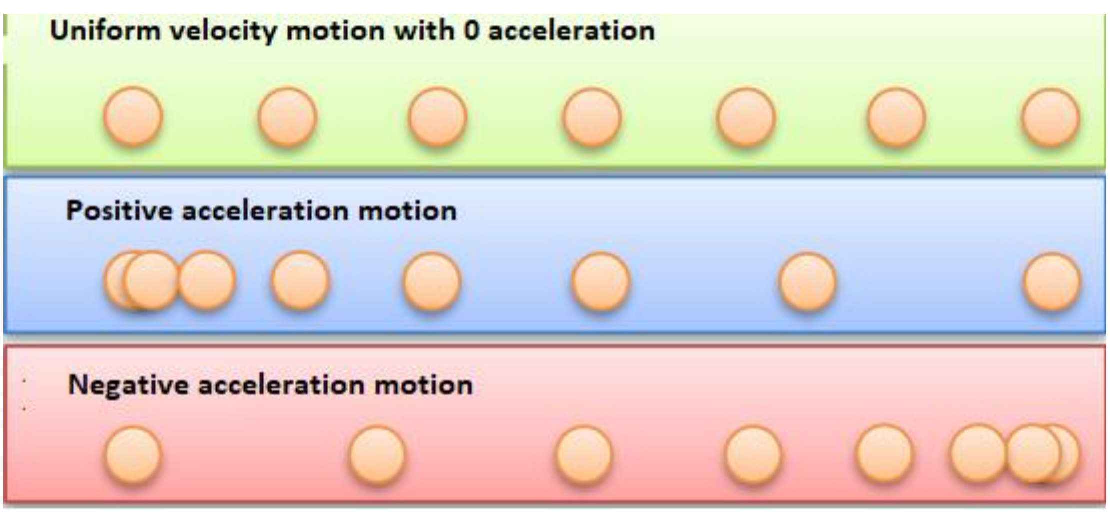


Figure 2.1 the sequence of photos of accelerated motions, Adapted from McCraw hill publishing company

Example 1:

A bike accelerates from rest to 1.0 m/s in 30 seconds, what is its acceleration?

Solutions:

According to the definition of an acceleration

$$a = \frac{\Delta v}{\Delta t} = \frac{v_2 - v_1}{t_2 - t_1}$$

In this example, $v_1 = 0,$ as it is from rest; $v_2 = 1.0\frac{m}{s}$, and $\Delta t = 30\ seconds$;

Therefore, plug all given variables in:

$$a = \frac{1.0\frac{m}{s} - 0}{30\ s} = \boxed{0.033\bar{3}\frac{m}{s^2}}$$

Example 2:

A car moves with 30 $\frac{m}{s}$ and comes to a stop in 20 minutes, what is its acceleration?

Solution:

Given $v_1 = 30\ \frac{m}{s};\ v_2 = 0$ as it comes to a stop; and $t = 20\ minutes$.

Since the time is in second in those velocities, $t = 20\ minutes$ has to be converted into seconds.

Given 1 $minute = 60\ seconds;$ such that,

$$t = 20\ minutes = 20\ minutes * 60\frac{seconds}{minutes} = 1200\ seconds$$

Then according to the formula of acceleration:

$$a = \frac{\Delta v}{\Delta t} = \frac{v_2 - v_1}{t_2 - t_1}$$

Plug all given variables into the equation:

$$a = \frac{0 - 30\frac{m}{s}}{1200s}$$

$$a = \boxed{-\,0.025\frac{m}{s^2}}$$

The answer is a negative number, which means the deceleration in this case.

2.3 Types of Motion

There are several types of motion, which can be categorized as one-dimensional motion, two-dimensional motion and 3-dimensional motion.

a. One dimensional motion, free fall and air resistance

In order to investigate a one-dimensional motion of objects and particles, the location of the object is needed to be recorded. We can imagine one dimensional motion when walking along a straight street (straight line). Even you walk forward or backward as long as stay in a straight line, it is still a one-dimensional motion as one-dimensional motion is restricted to this straight line, just like a train can only travel on rails. To measure the movement of an object in one-dimensional space, we must first define the one-dimensional coordinate system and vector table. Figure 2.2 is a one-dimensional coordinate system. This route is directional with the arrow points to both directions. It means that going to the right is the positive (+) direction, and conversely going to the left is the reverse arrow, which is the negative (-) direction.

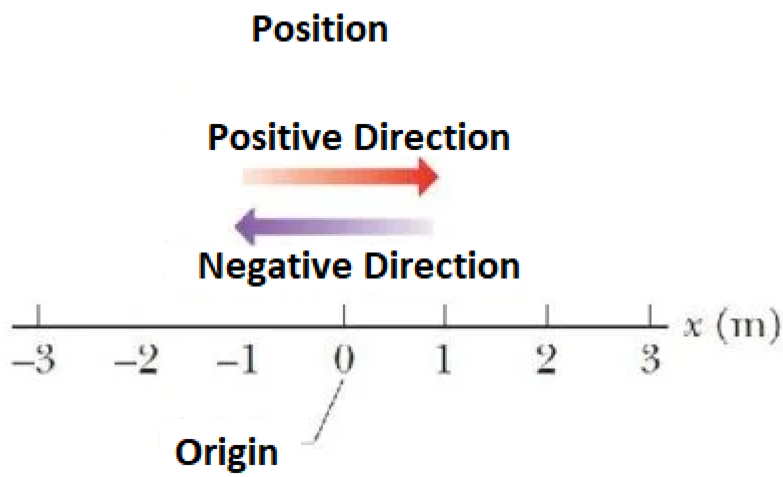


Figure 2.2 one-dimensional motion is along x-axis.

Furthermore, this route must have an origin 0 and units of the same size - 1 unit of length.

A free fall is another one-dimensional motion with a constant acceleration. Over time, the y direction position is changing as shown in the figure 2.3.

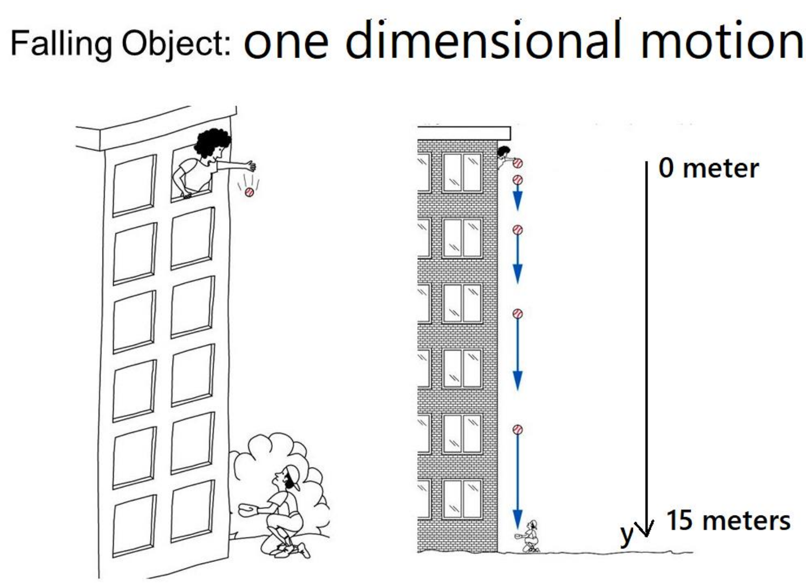


Figure 2.3 A free fall motion is one dimensional motion. Adapted from McGraw Hill publishing companies

Over time, only x coordinate or y coordinate of an object keeps changing. It is called one dimensional motion or an object moves along a straight line. In this one-dimensional motion, all motion equations

apply. For instance, a Free fall is another one-dimensional motion with a constant acceleration. It is a common observation that a stone falls more quickly than a leaf. In history, Aristotle believed that the speed of an object falling is related to its weight. Heavy objects fall quickly. His conclusion is in line with people's common sense. For the next two thousand years, everyone regarded it as a classic.
Galileo believed that according to Aristotle "heavy objects fall faster", the conclusions will lead to conflicting conclusions. For example, suppose a large rock is with a falling speed of 8 m/s, while a small stone is falling with 4 m/s. When two stones are tied together, the big stone will be dragged by the small stone and slow down, and the entire object will be falling with a speed less than 8 m/s. however, after tying two stones together, the whole system should be faster than 8m/s as it has more weight. This contradictory conclusion illustrates Aristotle's "heavy objects" is not correct. According to careful analysis, Galileo believed that there is only one possibility for the motion of falling objects: heavy objects and light objects; the body should fall equally fast. It can be seen from the experiment that after the air in the glass tube is extracted, there is no air resistance, light objects fall equally fast as heavy objects. In real life, the reason why people see objects falling at different speeds is because of the effect of air resistance. If there is no air resistance, all objects fall with the same rates. Please refer to you-tube demonstration of a lead ball and feather falling in vacuum. https://www.youtube.com/watch?v=E43-CfukEgs.

A motion that starts from rest and falls only under the influence of gravity is called free fall assuming there is no air resistance. Near the surface of the earth, it is a constant accelerated motion with g =9.81m/s^2.

Why do free falls have a constant acceleration? It is related to the fact that all objects are subject to external forces, which are equally affected by gravity and produce gravitational acceleration. All objects on the earth are affected by an external force resulting in the same magnitude of gravitational acceleration toward the center of the earth. The acceleration due to gravity on the earth's surface is approximately 9.81 (m/s^2) if air resistance is neglected, all objects will fall freely and reach the ground at the same pace.

The characteristics of free fall are the following:

1) The object’s speed increases with time, and the speed is directly proportional to time;

According to the definition of acceleration :

$$a = \frac{\Delta v}{\Delta t} = \frac{v_2 - v_1}{t_2 - t_1}$$

In the free fall motion, a=g=$\frac{v_2-v_1}{t}$; Due to its initial speed v_1 =0,

Then $g = \frac{v_2}{t}$; then $v_2 = g * t$ by changing the form, which interprets why the speed is increasing over time.

2) The displacement of free fall increases with time and is proportional to the square of time;

We previously learned that $D = \bar{v} * t$, in which $\bar{v} = \frac{v_1+v_2}{2}$ is the average speed.

Then in free fall motion, due to the fact that v_1 =0 and $v_2 = g * t$

Then

$$D = \frac{1}{2}(v_1 + v_2) * t = \frac{1}{2} * g * t^2$$

3) Free fall motion is a uniformly accelerated linear motion with an initial velocity of zero and acceleration g.

Example 3

A rock is dropped on the edge of a cliff and after 5 seconds it lands the ground. How high is this cliff?

Analysis: this is a free fall motion. In the reality, in order to simplify the situation, air resistance can be neglected. Then this is a free fall motion with a constant acceleration g=9.81m/s^2.

Solution:

According to the free fall formula:

$$d = \frac{1}{2} * g * t^2$$

Then with $g = 9.81\ \frac{m}{s^2}$

$$t = 5\ seconds$$

Plugging those given variables into the equation

$d = \frac{1}{2} * 9.81 * 5^2$= $\boxed{\text{122.63 meters}}$

Example 4:

A backpack falls off a 1.0-meter-high book shelf, how long does it take to reach the floor?

Analysis: this is a free fall motion with a constant acceleration $g = 9.81\ \frac{m}{s^2}$; the height of a book shelf is given which is the vertical distance with $d = 1.0\ meter$.

Then $d = \frac{1}{2} * g * t^2$

Next plugging all given variables into the equation:

$$1.0 = \frac{1}{2} * 9.81 * t^2$$

Both sides are divided by $\frac{1}{2} * 9.81$

$$t^2 = \frac{1}{\frac{1}{2} * 9.81} \cong 0.204$$

Then $t = \sqrt{0.204} \cong \boxed{0.452\ seconds}$

b. Two-dimensional motion--projectile motion and circular motion

In a volleyball match, have you ever felt sorry for a volleyball going off the net or out of bounds? If a player hits the ball in a horizontal direction, what factors need to be considered to make the volleyball pass the net without going out of bounds, regardless of air resistance? How to estimate the speed of a ball when it hits the ground? After the ball is thrown out, the magnitude and direction of its displacement relative to the throwing point are keeping on changing, describing a parabola path, in which both x and y coordinates are varying as shown in Figure 2.4. If both x and y coordinates of an object changes Over time, the motion is called two -dimensional motion. The typical one is called a projectile motion.

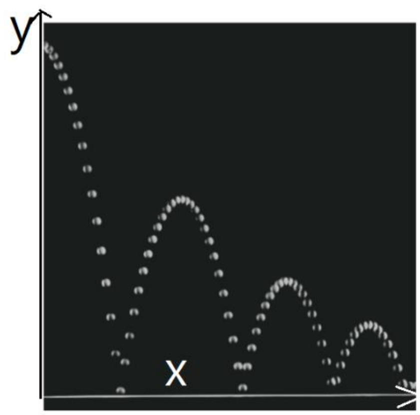


Figure 2.4, a projectile motion of a ball, adapted from McCraw Hill publishing company

A projectile motion is a compound motion, which can be viewed as that a uniform straight-line motion is in the horizontal direction, and the vertical direction is a free-falling motion. When an object is in projectile motion, it is only affected by gravity if we ignore the air resistance. Therefore, the acceleration of projectile motion is always the acceleration of gravity g. If the acceleration is constant, the amount of velocity change is the same in equal time, that is, and the direction of velocity change is always vertical downward. Projectile motion must be a uniformly variable motion. If the direction of the initial velocity and the direction of gravity are on the same straight line, the object will make a uniform linear motion with an acceleration of g; if the direction of the speed and the direction of gravity are not on the same straight line, the object will move in a curve with a uniform speed, and the acceleration of the object is also g. This is because the object is only affected by gravity, its acceleration is constant g, and its direction is vertically downward as showed in figure 2.5.

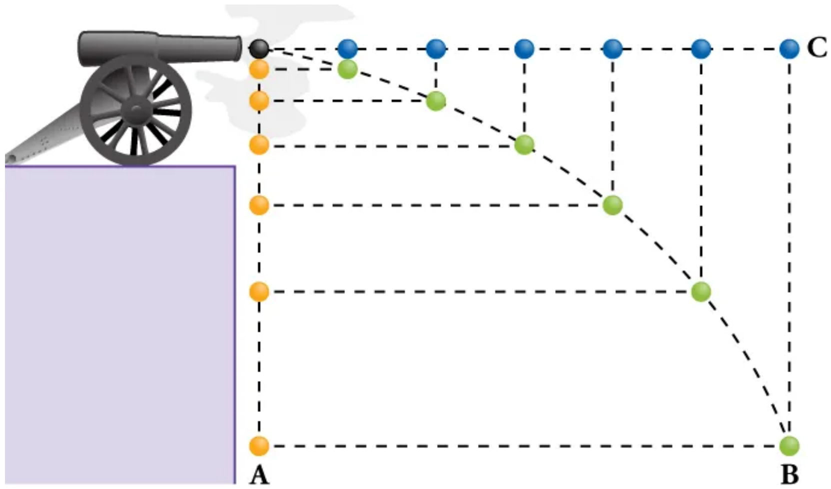


Figure 2.5 a Projectile motion can be viewed as two one dimensional motions. Adapted from OpenStax.

Another typical 2-dimensional motion is a circular motion in which an object moving along a circular path with x and y coordinates keep changing over time. For instance, lots of planets are orbiting around the Sun which can be viewed as a circular motion as shown in Figure 2.6. It is an accelerated motion as the centripetal force is applied to keep the object moving in the orbit.

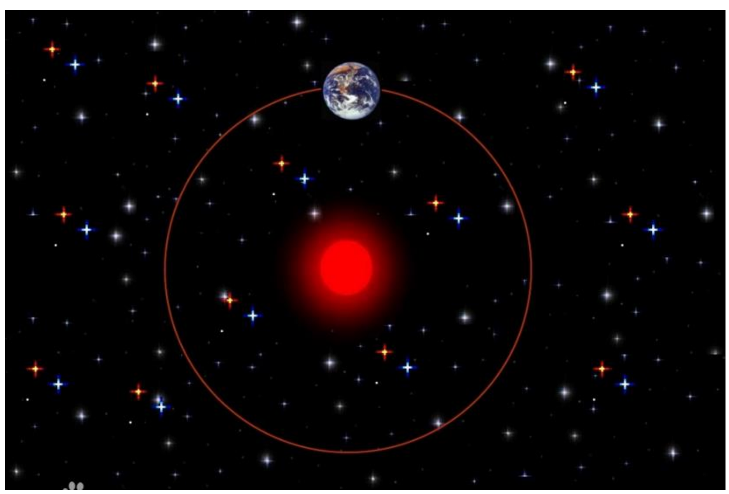


Figure 2.6 A circular motion in the galaxies, adapted from McCraw Hill publishing campany

When a particle moves circularly, so to speak, its trajectory is a circle, which is called circular motion. During the motion, the magnitude of the velocity remains unchanged but only the direction changes. Such circular motion is called uniform circular motion. Strictly speaking, uniform circular motion should be called uniform speed circular motion, not uniform velocity circular motion as the direction of the velocity keeps on changing all the time.

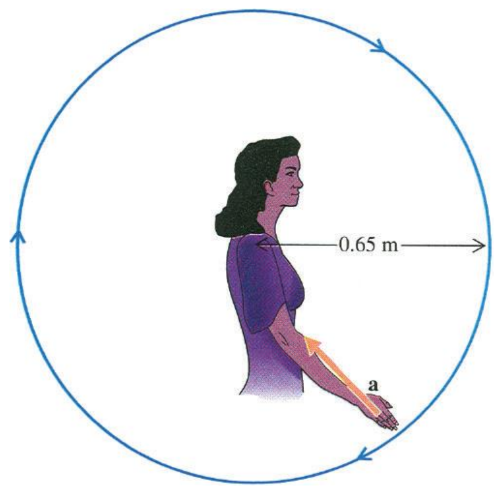
In terms of the nature of motion, a uniform circular motion is a variable-speed motion (the v direction changes all the time), and it is an accelerated motion (the direction changes all the time). If an object performs a uniform circular motion, then the force must be unbalanced, and there must be an external force to provide as a centripetal force which holds the object on the circular path.

Mathematically the acceleration caused by a centripetal force is defined as:

$$a = \frac{v^2}{r}$$

In which v is velocity and r being a radius of the circle.

Example: Extending your arm and rotating it in a vertical circle. Suppose the length of your arm is 60 cm, and the speed of rotating is 0.05 m/second. Find the acceleration of this circular motion?



Solution:

Given r=60cm =0.6 m

V=0.05m/s

Then

$$a = \frac{v^2}{r}$$

$$a = \frac{0.05^2}{0.6} \cong \boxed{0.0042\frac{m}{s^2}}$$

3-dimentional motion

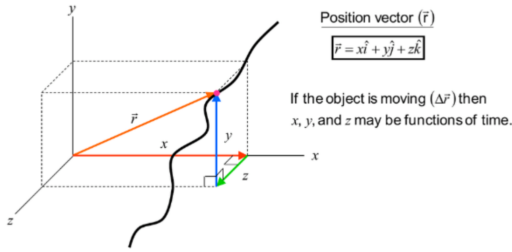


Figure 2.7 a 3-dimensional motion with coordinates of x, y and z changing over time. Picture adapted from: https://studylib.net/doc/12116283/general-two-and-three-dimensional-motion-%EF%80%A8-%EF%80%A9-%EF%81%B2

When particles move along an arbitrary-shaped trajectory in three-dimensional space, vectors are usually used to describe each kinematic quantity. In this case, the kinematic quantities such as position, displacement, velocity and acceleration are defined similarly to the case of one-dimensional motion. When an object moves along an arbitrarily shaped trajectory, it is convenient to use vectors to describe the motion. In order to use vectors to describe the movement of particles, draw a directed line segment from the origin of the coordinates to the location of the particle, which is called the position vector of the particle, referred to as the position vector, represented by $\vec{r}$. Using the composition rule of vectors, the position vector can be decomposed into a combination of three component vectors along each coordinate axis:

$$\vec{r} = \vec{x} + \vec{y} + \vec{z}$$

where x ,y and z are the coordinates of the particle's location. This expression is called the analytic expression of the position vector. It can be seen from this expression that the position vector is related to the choice of the coordinate system and determined by 3 coordinates.

Summary

In physics, motion is the fundamental phenomenon about an object changing its position over time.

There are lot of variables to describe a motion. Understanding the reference is important to a motion. Modern physics believes that because of no absolute frame of reference, Newton's concept of absolute motion cannot be determined. As such, everything in the universe can be considered to be in motion.

Motion applies to various physical systems: objects, bodies, matter particles, matter fields, radiation, radiation fields, radiation particles, curvature, and space-time.

Exercises

1. In the equation V=D/T; in which V represents

   A. average speed.

   B. instantaneous speed.

   C. final speed.

   D. constant speed

2. A car with initial speed 10 m/s, will be accelerated with 1.2m/s^2 for 5 seconds, what is its final speed?

a. 15 m/s

c. 35 m/s

b. 32 m/s

d. 16 m/s

3. If you consider the total distance and total time for a trip, you are calculating a(an)

   A. instantaneous speed.
   B. constant speed.
   C. average speed.
   D. nonuniform speed

4. A rock is dropped from a building and lands on the ground after 3 seconds. What is the height it falls from? assuming there was no air resistance and with g =9.81m/s^2.

a. 44.15 m

c. 16.45 m

b. 23.11 m

d. 24.5 m

5. If an object is uniformly moving, it means it has no acceleration.

a) sometimes

b) all the time

c) don’t know

d) depends on the situation

6. When a car is moving with 0.1 m/s^2 from rest to reach 4.0 m/s, how long does it take?

a. 20 s

b. 40 s

c. 15 s

d. 25s

7. A heavy object and a light object are dropped from rest at the same time on a planet with no air (vacuum). The heavier object will reach the ground

A. before the lighter object.

B. at the same time as the lighter object.

C. after the lighter object.

D. It depends on the shape of the object.

8. A ball is dropped from 150 meters high, how long it takes to reach the floor?

a. 5.53s

b. 2.5 s

b. 23s

d. 10 s

9. A bicycle and its rider with a speed of 6 m/s, comes to a stop in 5 seconds, what is their acceleration?

a.1.2 m/s^2

b.5.3 m/s^2

c.12 m/s^2

d.16 m/s^2

10. Ignoring air resistance, the velocity of a falling object

A. is constant.

B. is constantly increasing.

C. increases for a while, then becomes constant.

D. depends on the mass of the object

Problems:

1. A bicycle moves down a steep slope with a speed of 3 m/s, and when it reaches the bottom of the slope after 3 seconds, the speed becomes 12 m/s, what is its acceleration?

2. A snail starts crawling from rest after 0.2 s, and Obtains a speed of 0.002 m/s, what is its acceleration?

3. As a train was speeding away from the station, it takes 100 s increases the speed from 72 km/h to 144 km/h, what was its acceleration?

4. An object moves with a speed of 20 m/s, and then starts to decelerate. After 2 minutes, it comes to a stop, find the acceleration of the object.

5. A car traveling at a speed of 18 m/s, after braking, it keeps on moving another 36 meters in 3 seconds, what was its acceleration?

6. A cyclist travels along a long path with an initial speed of 5 m/s with an acceleration of 0.4 m/s^2, After 5 s, how far has he traveled?

7. if a car is moving with 20 m/s and doubles its speed in 20 seconds, what is its acceleration?
8. A car is braked to a stop in 20 seconds with an acceleration of -1.20 m/s^2, what was its initial speed?
9. what is the distance the car travels if a car with initial speed 10 m/s, will be accelerated with 1.2m/s^2 for 5 seconds?
10. A car traveling from rest begins to be accelerated at 12 m/s in the first 5 s. What is its acceleration?

References:

1. https://en.wikipedia.org/wiki/Science.

2. https://collegedunia.com/exams/motion-definition-types-examples-physics-articleid-949

3. https://www.youtube.com/watch?v=E43-CfukEgs.