Newton's Laws of Motion

Introduction

Newton's Laws of Motion are a set of laws that describe the motion of objects in physics. They were first proposed in 1687 by Newton, who summarized them based on the experiments and principles developed by his predecessors to explain the relationship between force and the motion of objects. Newton's three laws of motion are the First Law of Motion, the Second Law of Motion, and the Third Law of Motion, which can also be referred to as the Law of Inertia, the Law of Acceleration, and the Law of Action and Reaction, respectively.

Newton's First Law of Motion (Law of Inertia)

Newton's First Law describes that, when an object is not subjected to any force, it tends to maintain its original state of motion, that is, when an object is at rest, if it is not subjected to any force, it will remain at rest. If an object is in motion, if it is not subjected to any force, it will maintain uniform linear motion, which can also be referred to as the Law of Inertia.

Video : STEMonstrations: Newton's First Law of Motion

Sample Problem #1

When an object with a mass of $m = 10\ \mathrm{kg}$ is subjected to a force, and the object is accelerated to a velocity of $v_1 = 20\ \mathrm{m/s}$. If the force is removed, what is the velocity of the object at this time? What is the velocity of the object 3 seconds later?

$Sol.$

Newton's Second Law of Motion (Law of Acceleration)

Newton's Second Law, also known as the Law of Acceleration, describes that when an object is subjected to a force and the sum of the forces is greater than zero, the force will give the object an acceleration, the magnitude of which will be related to the size of the sum of the forces and the mass in the following relationship:

$$\vec{F} = m\vec{a} \tag{1}$$

Unit of Force

Based on the above formula, it's not hard to find that the unit of force can be written as the product of the units of mass and acceleration. Its dimensions are $[\mathrm{M}][\mathrm{L}][\mathrm{T}]^{-2}$, in SI Units, it can be written as $\mathrm{kg} \cdot \mathrm{m} \cdot \mathrm{s}^{-2}$. We can also simplify the unit of force to N (we call it Newton), and the relationship between Newton and the basic unit is $1\mathrm{N} = 1\mathrm{kg} \cdot \mathrm{m} \cdot \mathrm{s}^{-2}$.

Sample Problem #2

Now there is an object with a mass of $2\mathrm{kg}$, which is subjected to a rightward pushing force $F_1 = 10\mathrm{N}$ and a leftward pulling force $F_2 = 5\mathrm{N}$ on a plane, please draw the force diagram of the object and answer the following questions: (a) What is the net force on the object? (b) What is the acceleration produced by the two forces on the object? (c) In addition, the initial velocity of the object is to the left $v_0 = 10\mathrm{m/s}$, at $t = 2\mathrm{s}$, what is the velocity of the object? (d) Following the previous question, what is the displacement Δx of the object from $t = 0\mathrm{s}$ to $t = 4\mathrm{s}$?

Sol.

Sample Problem #3

(a) If the relationship between the position over time of an object with mass m is $x = 3t$, what is the net force on the object?
(b) If the relationship between the velocity over time of the object with mass m is $x = -6t^2 + 2t + 4$, what is the net force on the object?

Sol.

Sample Problem #4

Now there is a particle with a mass of m passing through a parallel plate with a length of L, its velocity is accelerated from v_0 to v_1, if the force on the particle in the parallel plate is a constant, what is the force? What is the acceleration produced by the force?

Sol.

Newton's Third Law of Motion (Law of Action and Reaction)

Newton's Third Law of Motion describes that when two objects interact with each other, the forces that the two objects give to each other will be equal in magnitude and opposite in direction, which can also be referred to as the Law of Action and Reaction.

Sample Problem #5

Suppose there is a ball with a mass of $200\ \mathrm{g}$, which is hit by a bat. During the swing, the velocity of the ball changes from $v_0 = -40\ \mathrm{m/s}$ to $v_1 = 30\ \mathrm{m/s}$. If the duration of the swing is 0.1 seconds, please answer the following questions: (a) If the force exerted by the bat on the ball is constant, what is the magnitude of this force? (b) Following the previous question, how much is the force exerted by the ball on the bat?

Sol.

Sample Problem #6

Suppose a rocket's flight is primarily influenced by gravity and the reaction force from the rocket engine exerted on the air. If the rocket weighs 1000 kg and has an upward acceleration of 10 m/s^2, what is the force exerted by the rocket on the air?

Sol.

Exercises

Exercise #1 [Halliday 5.10]

Sol.

Exercise #2 [Halliday 5.11]

Sol.

Exercise #3 [Halliday 5.19]

Sol.

Exercise #4 [Halliday 5.20]

Sol.

Exercise #5 [Halliday 5.24]

Sol.

Exercise #6 [Halliday 5.90]

Sol.

Solutions

Sample Problem #1

(a) What is the velocity of the object at the time the force is removed?

When the force is removed, the object will continue to move at the same velocity it had at the moment the force was removed, due to Newton's first law of motion (the law of inertia). So, the velocity of the object at this time is $v_1 = 20 \text{ m/s}$.

(b) What is the velocity of the object 3 seconds later?

If no other forces are acting on the object (like friction or gravity), the object will continue to move at the same velocity. So, 3 seconds later, the velocity of the object is still $v_1 = 20 \text{ m/s}$.

Sample Problem #2

(a) What is the net force on the object?

The net force is the vector sum of all forces acting on the object. In this case, it's the difference between the rightward pushing force and the leftward pulling force.

$$F_{net} = F_1 - F_2 = 10\text{N} - 15\text{N} = -5 \text{ N} \tag{1}$$

(b) What is the acceleration produced by the two forces on the object?

The acceleration is the net force divided by the mass of the object, according to Newton's second law.

$$a = \frac{F_{net}}{m} = \frac{-5\text{N}}{2\text{kg}} = -2.5 \text{ m/s}^2 \tag{2}$$

(c) In addition, the initial velocity of the object is to the left $v_0 = 10 \text{ m/s}$, at $t = 2 \text{ s}$, what is the velocity of the object?

The velocity at any time can be found by adding the product of the acceleration and time to the initial velocity. Since the initial velocity is to the left, we take it as negative.

$$v = v_0 + at = -10\text{m/s} - 2.5\text{m/s}^2 \times 2\text{s} = -15 \text{ m/s} \tag{3}$$

(d) Following the previous question, what is the displacement Δx of the object from $t = 0\ \mathrm{s}$ to $t = 4\ \mathrm{s}$?

The displacement can be found by integrating the velocity function from 0 to 4 seconds. Since the velocity is constant, this is simply the product of the velocity and time.

$$\Delta x = v_0 t + \frac{1}{2} a t^2 = -45\ \mathrm{m} \tag{4}$$

Sample Problem #3

(a) If the relationship between the position over time of an object with mass m is $x = 3t$, what is the net force on the object?

The velocity of the object is the derivative of the position with respect to time, which is $v = dx/dt = 3$. The acceleration of the object is the derivative of the velocity with respect to time, which is $a = dv/dt = 0$. According to Newton's second law, the net force on the object is the product of the mass and the acceleration, which is $F_{net} = m \times a = m \times 0 = 0$.

$$F_{net} = m \times a = m \times 0 = 0 \tag{5}$$

(b) If the relationship between the velocity over time of the object with mass m is $v = -6t^2 + 2t + 4$, what is the net force on the object?

The velocity of the object is the derivative of the position with respect to time, which is $v = dx/dt = -12t + 2$. The acceleration of the object is the derivative of the velocity with respect to time, which is $a = dv/dt = -12$. According to Newton's second law, the net force on the object is the product of the mass and the acceleration, which is $F_{net} = m \times a = m \times (-12t + 2)$.

$$F_{net} = m \times a = m \times -12 = -12m \tag{6}$$

Sample Problem #4

The acceleration produced by the force?

The force on the particle can be found using the second law of motion and the equation of motion. The acceleration can be found using the equation $v_1^2 = v_0^2 + 2aL$. Substituting this acceleration into the second law gives the force.

$$a = \frac{v_1^2 - v_0^2}{2L} \tag{7}$$

The force on the particle?

The force on the particle can be found using the second law of motion and the equation of motion.

$$F = m \times a = m \times \frac{v_1^2 - v_0^2}{2L} \tag{8}$$

Sample Problem #5

(a) If the force exerted by the bat on the ball is constant, what is the magnitude of this force?

The force on the ball can be found using the second law of motion and the equation of motion. The acceleration can be found using the equation $v_1 = v_0 + at$. Substituting this acceleration into the second law gives the force.

$$F = m \times a = m \times \frac{v_1 - v_0}{t} = 140.0\,N \tag{9}$$

(b) Following the previous question, how much is the force exerted by the ball on the bat?

According to Newton's third law, the force exerted by the ball on the bat is equal in magnitude and opposite in direction to the force exerted by the bat on the ball.

$$F_{\text{BallOnBat}} = -F_{\text{BatOnBall}} = -140.0\,N \tag{10}$$

Sample Problem #6

Suppose a rocket's flight is primarily influenced by gravity and the reaction force from the rocket engine exerted on the air. If the rocket weighs 1000 kg and has an upward acceleration of 10 m/s², what is the force exerted by the rocket on the air?

Solution:

To find the force exerted by the rocket on the air, we need to consider both the gravitational force and the net force required to achieve the given acceleration.

$$F_{net} = m \cdot a = 1000\,\mathrm{kg} \cdot 10\,\mathrm{m/s}^2 = 10000\,\mathrm{N} \tag{11}$$

The gravitational force acting on the rocket is:

$$F_{gravity} = m \cdot g = 1000\,\mathrm{kg} \cdot 9.8\,\mathrm{m/s}^2 = 9800\,\mathrm{N} \tag{12}$$

The total force exerted by the rocket on the air is the sum of the net force and the gravitational force:

$$F_{total} = F_{net} + F_{gravity} = 10000\,\mathrm{N} + 9800\,\mathrm{N} = 19800\,\mathrm{N} \tag{13}$$

Exercise #1 [halliday 5.10]

$-7.98\ \mathrm{N}$

Exercise #2 [halliday 5.11]

$+9.0\ \mathrm{m/s^2}$

Exercise #3 [halliday 5.19]

$1.2 \times 10^5\ \mathrm{N}$

Exercise #4 [halliday 5.20]

6.8×10^3 N

Exercise #5 [halliday 5.24]

If take right as positive, (a) 0 N ; (b) 20 N ; (c) -20 N ; (d) -40 N ; (e) -60 N

Exercise #6 [halliday 5.90]

(a) $1.2 \times 10^2\ \mathrm{m/s^2}$; (b) $12g$; (c) 1.4×10^8 N ; (d) 4.2 year