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Newton's Laws of Motion

Module Overview

Acknowledgments

This presentation is based on and includes content derived from the following OER resource:

University Physics Volume 1

An OpenStax book used for this course may be downloaded for free at:
https://openstax.org/details/books/university-physics-volume-1

Forces

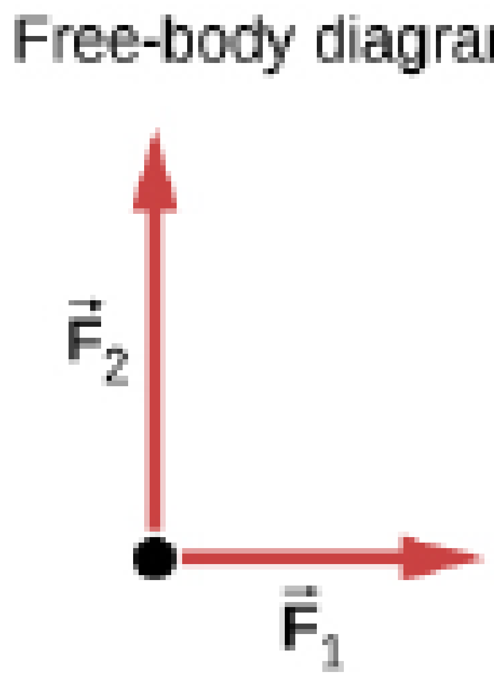
Dynamics is the study of how forces affect the motion of objects and systems. It extends kinematics by giving insight into how motion is produced. The foundations of dynamics are the laws of motion stated by Isaac Newton (1642-1727). These laws apply to objects larger than most molecules when they are moving much slower than the speed of light. This realm of physics is called Newtonian mechanics.

(University Physics Volume 1. OpenStax. Fig. 5.2)

The Working Definition of Force

Dynamics is the study of the forces that cause motion. The intuitive definition of **force** as a push or pull is a useful place to start.

Force has both a magnitude and a direction, making it a vector. We can illustrate all the external forces on an object with a **free-body diagram**. **External forces** are only those forces originating outside the object.



(University Physics Volume 1. OpenStax. Fig. 5.3)

Development of the Force Concept

The forces acting on a body can be broken into two categories: contact forces and field forces.

Contact forces are due to direct contact between objects. These include forces like the push of the Earth on your feet.

Field forces act without the need for physical contact. These include forces like the pull of the Earth on your body. Scientists have discovered only four fundamental force fields in nature: gravity, electromagnetism, the strong nuclear force, and the weak nuclear force. Contact forces are electromagnetic in nature.

Vector Notation for Force

The SI unit of force is called the **newton**. It is the force needed to accelerate a mass of 1 kg by 1 m/s^2. Because force is a vector, it can be written in component form.

The resultant of all the forces on a body is called the **net external force**.

$$\vec{\mathbf{F}} = a\hat{\mathbf{i}} + b\hat{\mathbf{j}} + c\hat{\mathbf{k}}$$

$$\vec{\mathbf{F}}_{\text{net}} = \sum \vec{\mathbf{F}} = \vec{\mathbf{F}}_1 + \vec{\mathbf{F}}_2 + \cdots$$

Newton's First Law

Newton's first law states that "a body at rest remains at rest, or if in motion, remains in motion at constant velocity unless acted on by a net external force."

Our everyday experience suggests that objects tend to come to rest, but this is due to friction. When friction is removed, objects tend to keep moving, as is evident when using a puck on an air-hockey table.

(University Physics Volume 1. OpenStax. Fig. 5.7)

Gravitation and Inertia

Newton's first law is often called the **law of inertia**. **Inertia** is the tendency of an object to resist changes in its motion.

Mass, the measure of the amount of matter in an object, is related to both gravitation and inertia. While inertia is the resistance to change in motion, gravitation is the attraction of two masses to one another. It is a force that is proportional to the mass of the objects involved. Mass gives a measure of both an object's inertia and the gravitational field it creates.

Inertial Reference Frames

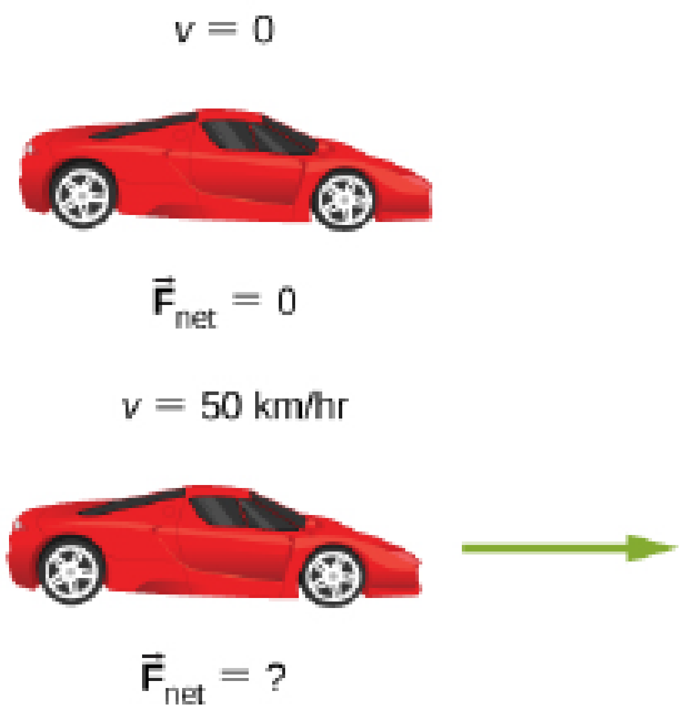
An **inertial reference frame** is a reference frame where a body that experiences zero net force has a constant velocity. Thus, an inertial reference frame is a reference frame where Newton's first law is valid. A reference frame moving at constant velocity relative to an inertial frame is also inertial. A reference frame accelerating relative to an inertial frame is not inertial.

In practice, a point on the Earth's surface is almost always considered inertial, despite the fact that it rotates with respect to the Sun and the most distant stars. The deviation of the Earth from a true inertial frame is smaller than 1 part in 250.

Newton’s First Law and Equilibrium

Newton’s first law can be expressed mathematically as a vector equation, $\vec{\mathbf{v}} = \text{constant when } \vec{\mathbf{F}}_{\text{net}} = \vec{\mathbf{0}}$.

Note that whether an object is at rest or moving at a constant, non-zero velocity, the net force is still the same – zero. For a car at constant velocity, the force of the tires propelling it and the friction it experiences are equal.

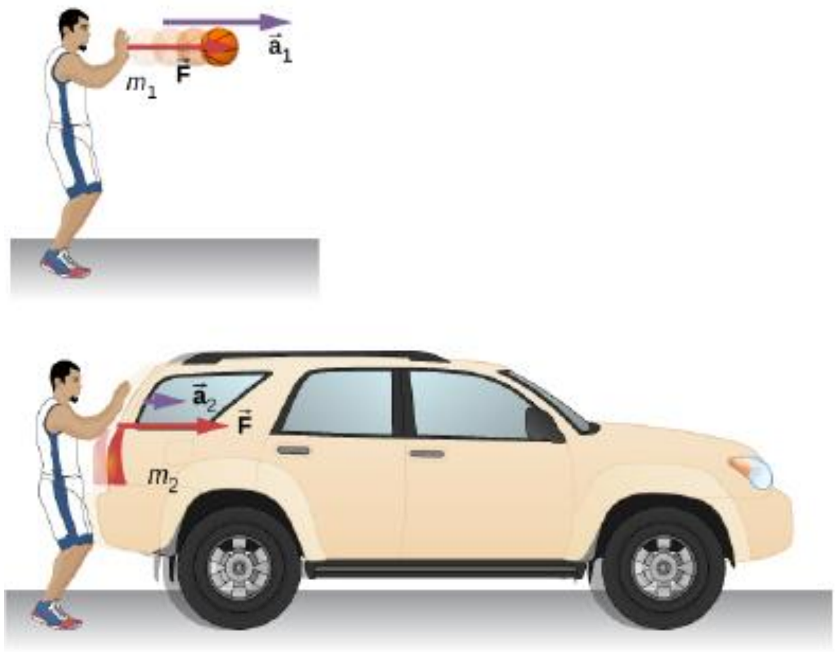


(University Physics Volume 1. OpenStax. Fig. 5.9)

Newton’s Second Law

The acceleration of an object or system is proportional to the net external force it experiences, $\vec{\mathbf{a}} \propto \vec{\mathbf{F}}_{\text{net}}$. In addition, the object’s acceleration is inversely proportional to its mass, $\vec{\mathbf{a}} \propto \frac{1}{m}$.

These relationships are captured by **Newton’s second law** of motion, $\vec{\mathbf{F}}_{\text{net}} = m\vec{\mathbf{a}}$.



(University Physics Volume 1. OpenStax. Fig. 5.11)

Newton's Second Law and Momentum

Newton's second law can be split into three component equations.

An object's **momentum** is the product of its mass and velocity, $\vec{\mathbf{p}} = m\vec{\mathbf{v}}$. Newton's second law can also be written in terms of momentum.

$$\sum \vec{\mathbf{F}}_{\mathrm{x}} = m\vec{\mathbf{a}}_{\mathrm{x}}$$

$$\sum \vec{\mathbf{F}}_{\mathrm{y}} = m\vec{\mathbf{a}}_{\mathrm{y}}$$

$$\sum \vec{\mathbf{F}}_{\mathrm{z}} = m\vec{\mathbf{a}}_{\mathrm{z}}$$

$$\vec{\mathbf{F}} = \frac{d\vec{\boldsymbol{p}}}{dt}$$

Weight and Gravitational Force

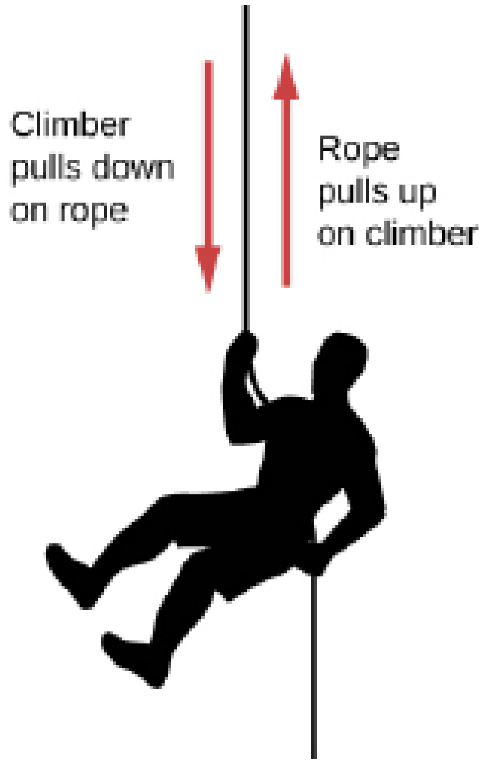
The unit of force is the newton, $1\ \mathrm{N} = 1\ \mathrm{kg} \cdot \mathrm{m/s}^2$. One newton is about 0.255 pounds, so a 1-pound bag of flour weighs about 4 newtons.

Gravity creates a constant acceleration on an object, $\vec{\mathbf{g}}$. Applying this to Newton's second law shows that the force of the weight of an object points in the direction of the acceleration due to gravity, $\vec{\mathbf{w}} = m\vec{\mathbf{g}}$. When the net external acceleration on an object is due only to gravity, we say that the object is in **free fall**.

Note the difference between mass and weight. Mass is a fixed property of an object. Weight is the force exerted by the nearest large mass. For example, a 1-kg mass weighs more on Earth than on the Moon.

Newton’s Third Law

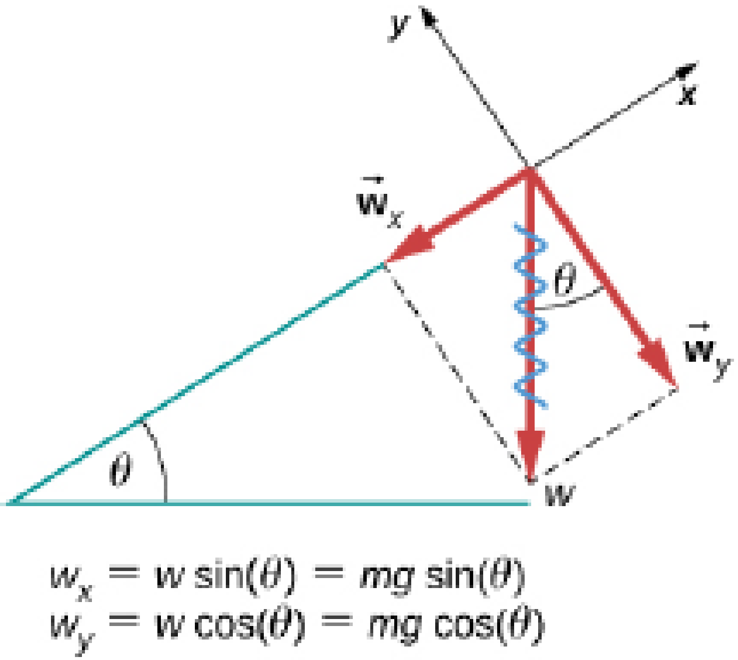
Newton’s third law states: Whenever one body exerts a force on a second body, the first body experiences a force that is equal in magnitude and opposite in direction to the force that it exerts. Mathematically, if a body A exerts a force $\vec{\mathbf{F}}$ on body B, then B simultaneously exerts a force $-\vec{\mathbf{F}}$ on A. In vector equation form, $\vec{\mathbf{F}}_{\mathrm{AB}} = -\vec{\mathbf{F}}_{\mathrm{BA}}$.



(University Physics Volume 1. OpenStax. Fig. 5.17)

Normal Force

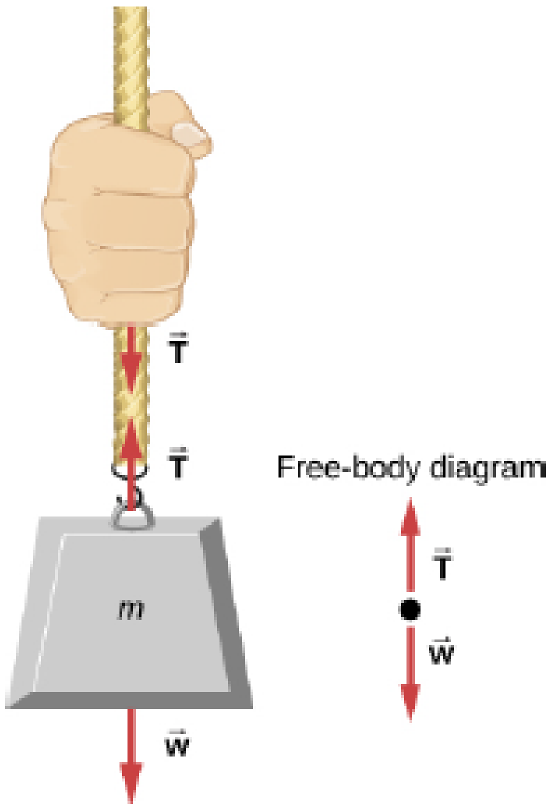
The force a fixed object exerts on another to counteract gravity is called the **normal force**, $\vec{\mathbf{N}}$. On a horizontal surface, the normal force is simply equal to the gravitational force, $\vec{\mathbf{N}} = -m\vec{\mathbf{g}}$. On an incline, the normal force is reduced by depending on the angle of the incline, $N = -mg\cos\theta$.



(University Physics Volume 1. OpenStax. Fig. 5.23)

Tension

Tension, $\vec{\mathbf{T}}$, is the force along the length of a medium. Flexible connectors like ropes and cables can only pull along their lengths. When a rope is used to hold a weight at rest or any constant velocity, the tension in the rope is equal to the weight of the mass, $\vec{\mathbf{T}} = -m\vec{\mathbf{g}}$.

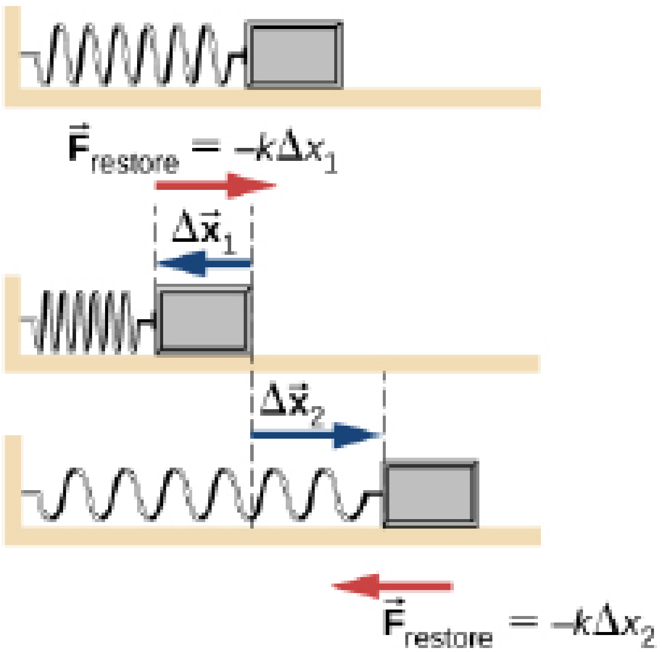


(University Physics Volume 1. OpenStax. Fig. 5.24)

Friction and Spring Force

Friction is a contact force that opposes the motion of an object.

The **spring force** is the restoring force exerted by a spring when it is stretched from its equilibrium. The force exerted by the spring is proportional to the displacement from equilibrium and the stiffness, k, of the spring, $\vec{\mathbf{F}} = -k\vec{\mathbf{x}}$.



(University Physics Volume 1. OpenStax. Fig. 5.29)

Real Forces and Inertial Frames

Real forces are forces that have a physical origin, like the gravitational force the Earth exerts on each of us.

Fictitious forces arise because an observer is in a non-inertial reference frame, which either rotates or accelerates linearly. Examples of fictitious forces are the outward force experienced on a rotating merry-go-round and the force in the direction opposite the motion when a car rapidly accelerates.

If a force under consideration has no reaction force, then it is a fictitious force.

Drawing Free-Body Diagrams

Drawing a free-body diagram is a very useful technique for understanding the dynamics of a physical system. There are just a few steps for drawing a free-body diagram.

- Draw a simple diagram of the object. If rotation is not being considered, the object can be represented as a point.
- Draw all forces acting on the object as vectors. Do not include forces the object exerts on its environment.
- Split each force into x- and y-components. Draw a squiggly line through the original line force to show that it is no longer in play.
- Draw a separate free-body diagram for each object under consideration.

How to Study this Module

- Read the syllabus or schedule of assignments regularly.
- Understand key terms; look up and define all unfamiliar words and terms.
- Take notes on your readings, assigned media, and lectures.
- As appropriate, work all questions and/or problems assigned and as many additional questions and/or problems as possible.
- Discuss topics with classmates.
- Frequently review your notes. Make flow charts and outlines from your notes to help you study for assessments.
- Complete all course assessments.