Phys 100: The Physical World
Chapters 6 & 7

Aaron Wirthwein

Department of Physics and Astronomy
University of Southern California

Textbook Sections

Sections 6.1-6.6 (skip section 6.7)

Sections 7.1-7.6 (skip 7.7-7.9)

The Big Ideas of Physics

1. *The laws of physics are "universal."*
2. *Conservation laws constrain interactions.*
3. *Electricity and magnetism are unified.*
4. *Some processes are irreversible.*
5. *Nature is fundamentally probabilistic.*
6. *The laws of physics are frame independent.*

In any system of objects that are isolated from their environment but not from each other, the total momentum and energy of the system will be constant over time. The objects can trade momentum and energy as a result of mutual interactions, but the total momentum and energy will (separately) not change.

Momentum

The concept of momentum has evolved over time with roots in medieval impetus theory. Isaac Newton was the first to develop a mathematical definition of momentum. Every moving object has momentum equal to the product of its mass and its velocity.

$$\text{momentum} = \text{mass} \times \text{velocity}$$

$$p = mv$$

This is why it's hard to answer a question like "would you rather be hit by a truck or shot in the leg?" Even though the truck is very massive and the bullet is very light, the bullet moves very fast and their momenta (plural for momentum) are both large. Momentum, like velocity and force, is a vector quantity, and it points in the same direction as the velocity.

Conceptual Question 1

Two objects are moving directly towards you. Object A has twice the velocity as object B. Which has greater momentum?

(a) Object A

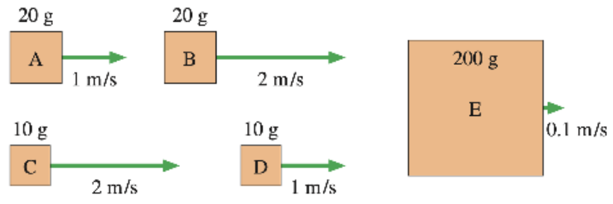
(b) Object B

(c) They have the same momentum.

(d) It's impossible to determine.

Conceptual Question 2

Rank the following objects in terms of their momenta from smallest to greatest:



Revisiting Newton's 2nd law

It's important to understand that mathematical definitions in physics may or may not be intuitive, but they always serve a purpose. Momentum allows us to understand the effect of impact forces and the motion of objects before and after collisions. Under the action of a nonzero net force, an object's velocity will change, and so will its momentum. Newton's second law can equally be phrased as "an object's change in momentum over time is equal to the net force acting upon it."

$$\sum F = \frac{\Delta p}{\Delta t} = \frac{\Delta(mv)}{\Delta t} = m\left(\frac{\Delta v}{\Delta t}\right) = ma$$

assuming the mass is constant, i.e. not changing over time.

Conceptual Question 3

Two trains accelerate from rest by the same force over the same distance on a linear track. Train A has twice the mass of train B. Which has the greater momentum at the end of the track?

(a) Train A

(b) Train B

(c) They have the same momentum.

(d) It's impossible to determine.

Impulse

An impulse is defined as the product of force and time. From Newton's second law, we find that impulse changes momentum.

$$\text{impulse} = \text{change in momentum} = \text{force} \times \text{time}$$

$$\Delta p = F \Delta t$$

You impart twice the impulse to an object by (i) pushing with double the force for the same time, or (ii) pushing with the same force for double the time. Both of these actions will double the change in momentum.

$$\Delta p = \boldsymbol{F} \, \Delta t = F \, \boldsymbol{\Delta t}$$

Conceptual Question 4

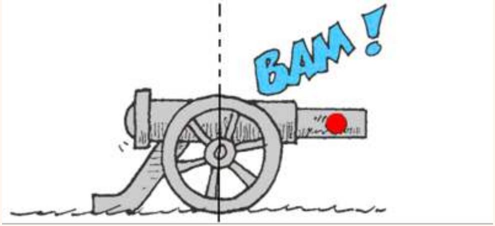
A cannonball shot from a cannon with a long barrel will emerge with greater speed because the cannonball receives a greater

(a) average force

(b) impulse

(c) both of the above

(d) none of the above



Conceptual Question 5

A fast-moving car hitting a haystack or hitting a cement wall produces vastly different results. Compared to the car hitting the haystack, the car hitting the cement wall experiences

(a) the same change in momentum

(b) the same impulse

(c) the same average force

Conceptual Question 6

A 100 gram rubber ball and a 100 gram clay ball are thrown at a wall with equal speeds. The rubber ball bounces, the clay ball sticks. Which object delivers a larger impulse to the wall?

(a) The clay ball delivers a larger impulse because it sticks.
(b) The rubber ball delivers a larger impulse because it bounces.
(c) They deliver equal impulses because they have equal momenta.
(d) Neither delivers an impulse to the wall because the wall doesn't move.

Collisions

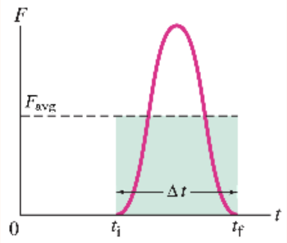
A collision is a brief interaction between two objects that strike each other. A tennis ball colliding with the ground and rebounding appears instantaneous to us, but high-speed photography reveals that the ball spends time touching the ground and deforms significantly during the collision (video link).

The duration of a collision depends on the materials from which the objects are made, but 1 to 10 ms is typical for many elastic objects like rubber. The harder the objects, the shorter the contact time. For instance, a collision between two steel balls lasts less than $200\ \mu\mathrm{s}$ (microseconds).

Macroscopic objects deform throughout a collision. At the microscopic level, molecular bonds behave like tiny springs. They compress upon contact and re-expand as the object rebounds.

Impulsive Forces

An impulsive force is a large force exerted over a small period of time that significantly changes an object's motion. Impulsive forces vary throughout collisions, but we can estimate their effect by taking a time average. The net force on an object is dominated by the impulsive force during a collision.



During a collision, the impulse is simply the average force multiplied by the time interval of the collision.

$$\Delta p = \text{average force} \times \text{time of collision}$$

Example 1

A 150 gram baseball is thrown to the left with a speed of 20 m/s. It is hit straight back toward the pitcher at a speed of 40 m/s. High-speed photography reveals the interaction between the ball and the bat occurs during a time interval of 3.0 ms (video link). What impulse is delivered to the ball and what average force does the bat exert on the ball?

Example 2

(a) What is the impulse experienced by a person landing on firm ground after jumping from a table? Make an estimate using reasonable everyday numbers. (b) Then estimate the average force exerted on the feet by the ground if this person lands stiff-legged, and (c) lands while bending their legs. With stiff legs, assume the body moves 1 cm during impact, and when the legs are bent, about 50 cm. Hint: The net force on the person is the vector sum of gravity and the force exerted by the ground.

Reducing Impact Forces

An impulse is the product of force and duration; the same impulse can be achieved by a large force acting over a short duration or a weaker force acting over a longer duration. Lengthening collision times reduces the impact forces necessary to cause a given change in momentum.

Your car is designed with crumple zones to increase the duration of a head-on collision so as to reduce the impact force on passengers. Seat belts and air bags also bring occupants to rest over a longer interval of time.

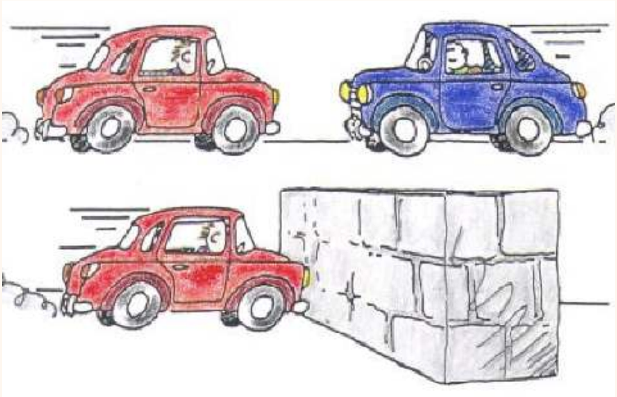
Similarly, a bike helmet is filled with a crush-able material that, in an accident, brings the rider's head to rest more slowly than in a direct impact with the road. Woodpeckers have spongy, elastic bones in their skulls that spread out the impact of hammering on tree trunks.

Crashing Cars

Click here to watch video. (4:58)

Conceptual Question 7

Which is more damaging: driving into a massive concrete wall at 50 mph, or driving at the same speed into a head on collision with an identical car traveling toward you at the same speed?



Law of Conservation of Momentum

In the last conceptual question, Newton's third law explains why the impulses delivered to each car must be equal and opposite– this is true even when the cars have unequal speeds.

When there are no external forces, the total momentum of the two cars, or any two colliding objects, will be constant. In other words, it will not change before and after the collision, but some momentum from one car may be transferred to the other.

In the absence of external forces,
the total momentum of a system remains unchanged.

$$\Delta p_A = -\Delta p_B \rightarrow \Delta p_A + \Delta p_B = 0$$

$$\Delta (p_A + p_B) = 0$$

Conservation of Momentum in Space

Click here to watch video. (1:59)

Conceptual Question 8

A compact car and a large truck collide head-on and stick together. Which undergoes the larger momentum change?

(a) Car

(b) Truck

(c) The momentum change is the same for both vehicles

(d) Can't tell without knowing the final velocity of combined mass

Conceptual Question 9

Freight car A is moving toward identical freight car B that is at rest. When they collide, both freight cars couple together. Compared with the initial speed of freight car A, the speed of the coupled freight cars is

(a) the same

(b) half

(c) twice

(d) none of the above

Conceptual Question 10

Suppose that two ice skaters are standing face to face, motionless on the ice. They push each other and thus slide away from each other on the ice (their motion can be considered frictionless). The total change in momentum of the system of the two ice skaters is

(a) positive, since both are now moving with some velocity.

(b) zero, since there are no external forces acting on the skaters.

(c) negative, since they are moving away from each other.

(d) impossible to determine since we don't know their masses and thus the gravitational forces.

Example 3

Squid rely on jet propulsion when a rapid escape is necessary. A $1.5\ \mathrm{kg}$ squid at rest slowly pulls $100\ \mathrm{g}$ of water into its mantle, then, with a strong muscular contraction, ejects this water at a remarkable $45\ \mathrm{m/s}$. How fast is the squid moving immediately after this ejection?

Rocket Propulsion

Click here to watch video. (4:04)

Example 4

In a laboratory experiment, a 200 gram air-track glider and a 400 gram air-track glider are pushed toward each other from opposite ends of the track. The gliders have Velcro tabs on the front and will stick together when they collide. The 200 gram glider is pushed with an initial speed of 3.0 m/s. The collision causes it to reverse direction at 0.40 m/s. What was the initial speed of the 400 gram glider?

Work and Energy

We loosely define energy as the ability of a system to do work or heat, however, it is best characterized by its total conservation and the many forms that it can take: mechanical energy, kinetic energy, potential energy, thermal energy, chemical energy, nuclear energy, and light energy (radiation), to name a few.

Viewing dynamical processes as energy conversions provides insight and simplifies many problems. We will learn that the principle of energy conservation, much like the principle of momentum conservation, can be derived from Newton's laws and used to predict outcomes even when the situation is difficult to analyze with Newton's laws directly.

Work in Physics

Work has a precise definition in physics, and your intuitive notion serves only as a guide. Forces do work by (i) moving an object and (ii) having a component that is in the same or opposite direction to the motion. When the force is constant and the motion is in a straight line in the direction of the force,

$$\text{work} = \text{force} \times \text{distance}$$

$$W = Fd$$

Work is measured in units of Joules (J) where $1\ \mathrm{J} = 1\ \mathrm{N} \cdot \mathrm{m}$. Work can also be negative, and this happens when there is a component of the force in the opposite direction of the motion. When a force acts at right angles to the displacement, with no component in the direction of motion, no work is done.

Conceptual Question 11

If you push against a stationary wall for several minutes, you do no work

(a) on the wall

(b) at all

(c) both of the above

(d) none of the above

Power

In physics, power is the rate at which work is done over time:

$$\text{power} = \frac{\text{work done}}{\text{time}}$$

Power is measured in Watts (W) where 1 W $=$ 1 J$/$s. Another common unit is the horsepower (hp): 1 hp $=$ 746 W.

Power plants do electrical work at a rate of about 1,000-10,000 Megawatts (1 MW $= 10^6$ W). The largest power plant in the world, the Three Gorges Dam in China, is a hydroelectric power plant which has a power rating of 18,000 MW! Elite athletes are capable of sustaining 5-7 W$/$kg of body mass for extended periods of time. If you've ever used a rowing machine or a bicycle equipped with a power meter, you may already be familiar with the concept of power.

Example 5

A farmer hitches her tractor to a sled loaded with firewood and pulls it a distance of 20 m along level ground. The total weight of sled and load is 15,000 N. The tractor exerts a constant 3000 N force in the same direction as the displacement. A 3000 N friction force opposes the sled's motion. (a) Find the net force on the sled and determine its acceleration. (b) Find the work done by each force acting on the sled and the total work done by all the forces. (c) If the tractor pulls the sled a distance of 20 m in 20 s, what was the average power produced by the tractor?

Kinetic Energy and the Work-Energy Theorem

Kinetic energy is the energy of motion–it is the work required to accelerate an object with mass m from rest to a speed v, or equivalently, the work the object can do while being brought to rest. For technical reasons, it is defined as one-half the mass of the object times the square of its speed:

$$\mathrm{KE} = \frac{1}{2}mv^2$$

The work-energy theorem states that any change in kinetic energy of an object is equal to the work done on the object.

work = change in kinetic energy

$$W = \Delta\mathrm{KE}$$

Conceptual Question 12

A fast-moving crate slides across a factory floor subject to a known frictional force. The crate slows down and eventually stops. Which of the following equations most directly determines the stopping distance?

(a) $F = ma$

(b) $Ft = \Delta(mv)$

(c) $\mathrm{KE} = \frac{1}{2}mv^2$

(d) $Fd = \frac{1}{2}mv^2$

Conceptual Question 13

The work done in bringing a moving car to a stop is the force of tire friction times the stopping distance. If the initial speed of the car is doubled, the stopping distance is

(a) reduced

(b) about the same

(c) doubled

(d) none of the above

Concept of Potential Energy

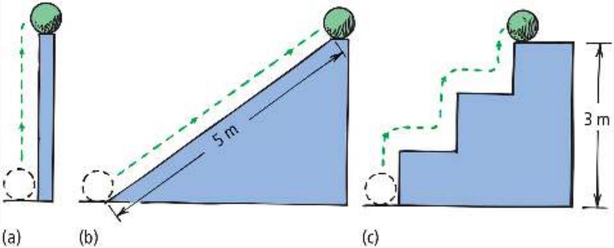
Energy can be stored in both elastic and gravitational systems. If you pick up a rock and release it, the rock will gain kinetic energy on its way down equal to the work you did picking it up. Positive work done by you is negative work done by gravity. If you throw a ball against a wall, elastic potential energy is stored when the ball compresses due to the force from the wall, and that energy is transformed to kinetic energy as the ball rebounds. Potential energy is stored energy.

More specifically, potential energy is the energy stored in a system, by doing work on it, that is associated with the relative positions of its components. Potential energy is not something a body has by itself but is rather associated with interaction of two or more bodies.

Gravitational Potential Energy

Gravitational potential energy of an object above the Earth's surface is equal to the (minimum) work done to lift the object. The work done is completely independent of the path and only depends on the elevation! As an equation,

$$\text{gravitational PE} = \text{weight} \times \text{height}$$
$$\mathrm{PE} = mgh$$



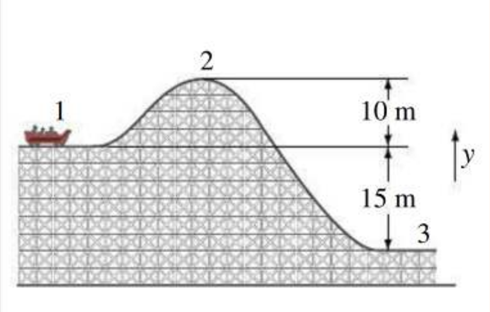
Example 6

Changes in gravitational potential energy do not depend on the chosen reference point. Consider a $10,000\text{-N}$ roller-coaster car moving from point 1 to point 2 and then to point 3 (see figure below).

(a) What is the PE at points 2 and 3 relative to point 1?

(b) What is the change in PE when the car goes from 2 to 3?

(c) Repeat parts (a) and (b), but let point 3 be the reference point.

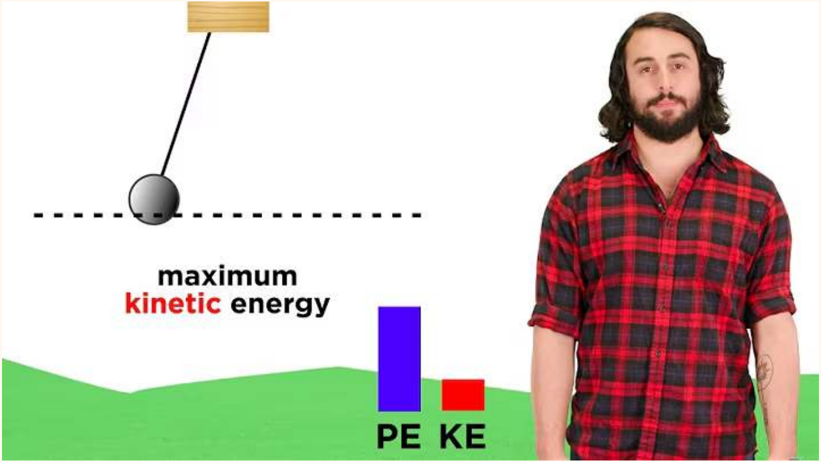


Law of Conservation of Energy

Energy cannot be created or destroyed; it can be transferred from one object to another or transformed from one form into another, but the total amount of energy never changes.

Consider the system of a bow, an arrow, and the Earth. In drawing the bow, we do work on the system and give it potential energy. When the bowstring is released, most of the potential energy is transferred to the arrow as kinetic energy and some as heat to the bow. As the arrow rises higher into the air, the kinetic energy of the arrow decreases as the potential energy increases. Some energy is lost due to air resistance, causing the arrow and the surrounding air to warm up slightly. As the arrow falls, the kinetic energy increases as the potential energy decreases until it finally lands in the target, where its kinetic energy decreases as friction mediates an energy transfer by heat.

Conservation of Energy



Click here to watch video. (5:19)

Conceptual Question 14

Suppose the potential energy of a drawn bow is 50 joules and the kinetic energy of the shot arrow is 40 joules. Then

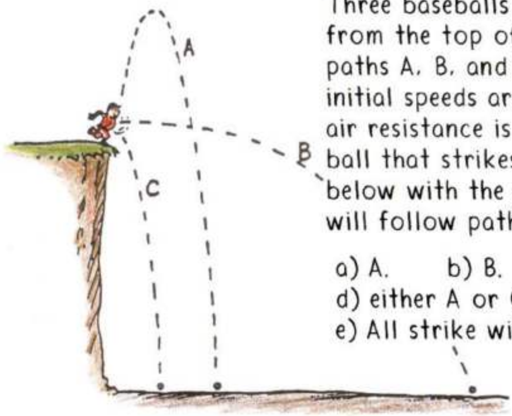
(a) energy is not conserved in this process

(b) 10 J go to warming the bow

(c) 10 J go to warming the target

(d) 10 J are stored in the arrow

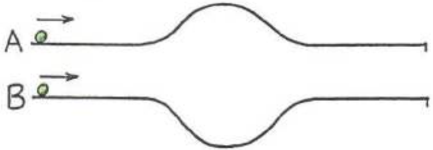
Conceptual Question 15



Three baseballs are thrown from the top of the cliff along paths A, B, and C. If their initial speeds are the same and air resistance is negligible. The ball that strikes the ground below with the greatest speed will follow path

a) A. b) B. c) C.
d) either A or C.
e) All strike with the same speed.

Conceptual Question 16



Two smooth tracks of equal length have "bumps"—A up and B down, both of the same curvature. If two balls start simultaneously with the same initial speed, the ball to complete the journey first is along

a) Track A. b) Track B. c) ... both take the same time.

If the initial speed = 2 m/s, and the speed of the ball at the bottom of the curve on Track B is 3 m/s, then the speed of the ball at the top of the curve on Track A is

d) 1 m/s. e) > 1 m/s. f) < 1 m/s.

Types of Collisions

1. An elastic collision occurs when colliding objects rebound without lasting deformation or any generation of heat. Momentum and kinetic energy are conserved before and after an elastic collision takes place in an isolated system.

2. Most collisions are inelastic–only momentum is conserved in an isolated system. Some kinetic energy is lost to other forms like heat, sound, or deformation. In perfectly inelastic collisions, two objects stick together after the collision. An explosion is like a perfectly inelastic collision in reverse.

Conceptual Question 17

A massive truck and an indestructible bumble bee travel toward each other with equal speeds v. After an *elastic collision*, the speed of the bee is

(a) v

(b) $2v$

(c) $3v$