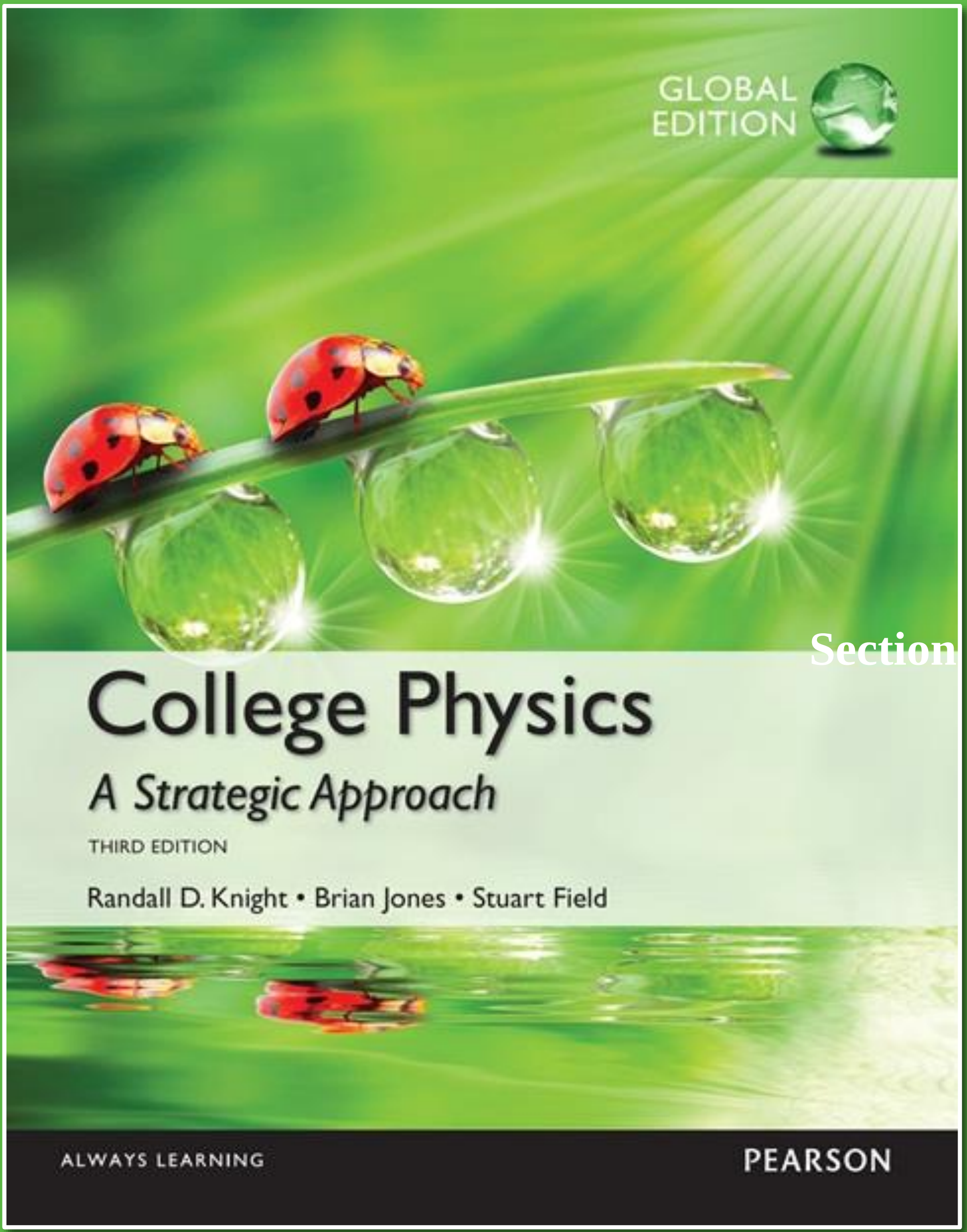


Section

Lecture Presentation

Chapter 10

Energy and Work

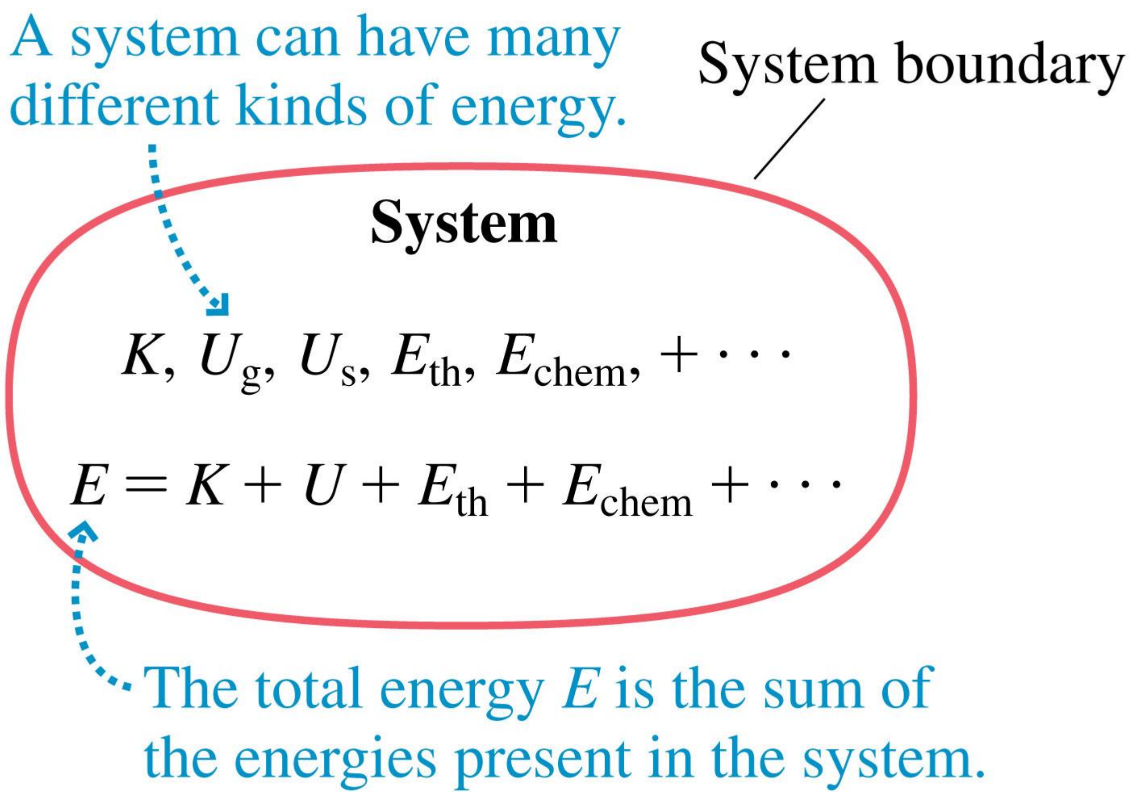
Chapter 10 Energy and work

Section 10.1 The Basic Energy Model
Section 10.2 Work
Section 10.3 Kinetic Energy
Section 10.4 Potential Energy
Section 10.6 Using the Law of Conservation of Energy
Section 10.7 Energy in Collisions
Section 10.8 Power

Section 10.1 The Basic Energy Model

The Basic Energy Model

Every system in nature has a quantity we call its **total energy** E.



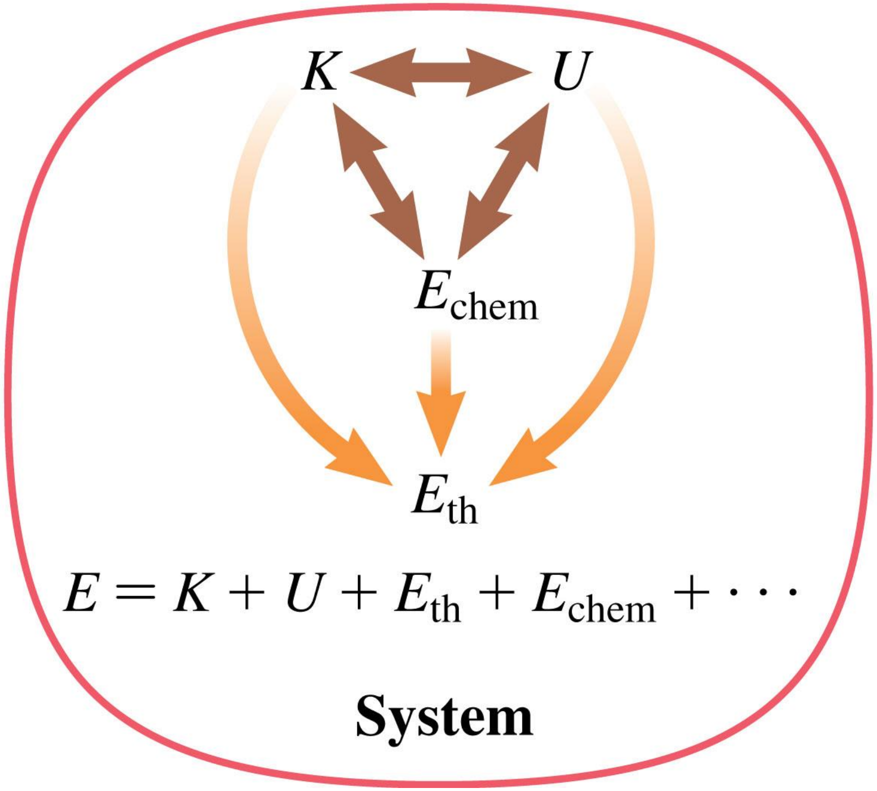
Forms of Energy

Some important forms of energy are

- *Kinetic energy K*: energy of motion.
- *Gravitational potential energy* U_g: stored energy associated with an object's height above the ground.
- *Elastic or spring potential energy* U_s: energy stored when a spring or other elastic object is stretched.
- *Thermal energy* E_{th}: the sum of the kinetic and potential energies of all the molecules in an object.
- *Chemical energy* E_{chem}: energy stored in the bonds between molecules.
- *Nuclear energy* $E_{nuclear}$: energy stored in the mass of the nucleus of an atom.

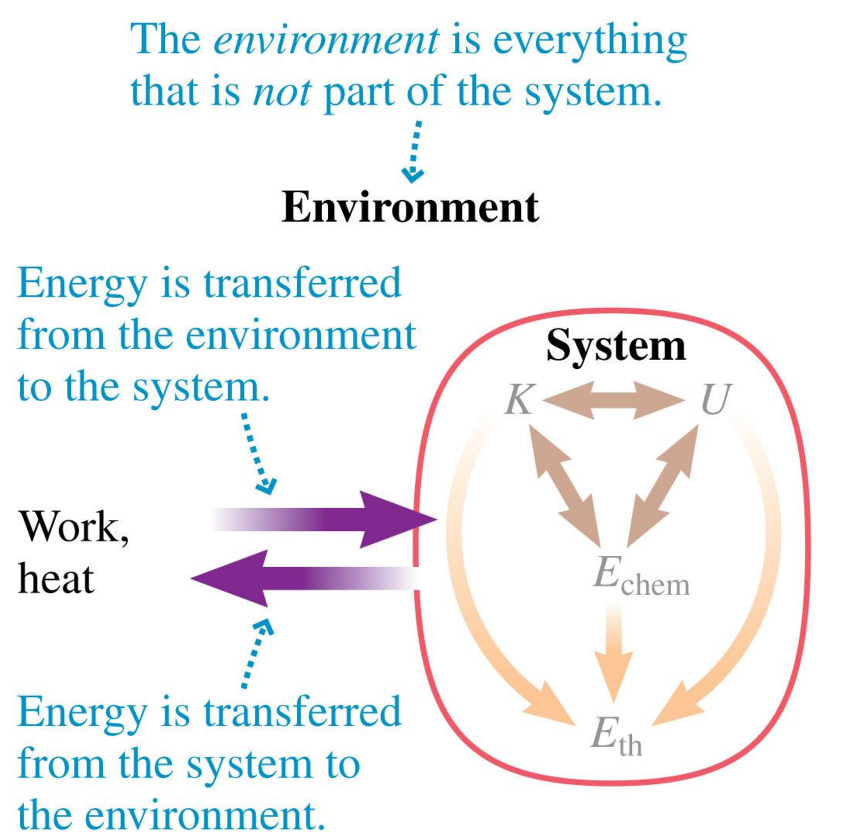
Energy Transformations

Energy of one kind can be *transformed* into energy of another kind within a system.



Energy Transfers and Work

- Energy can be *transferred* between a system and its environment through work and heat.
- **Work** is the mechanical transfer of energy to or from a system by pushing or pulling on it.
- **Heat** is the nonmechanical transfer of energy between a system and the environment due to a temperature difference between the two.



Energy Transfers and Work

The athlete does **work** on the shot, giving it kinetic energy, *K*.

The boy does **work** on the slingshot, giving it elastic potential energy, U_s.

The Work-Energy Equation

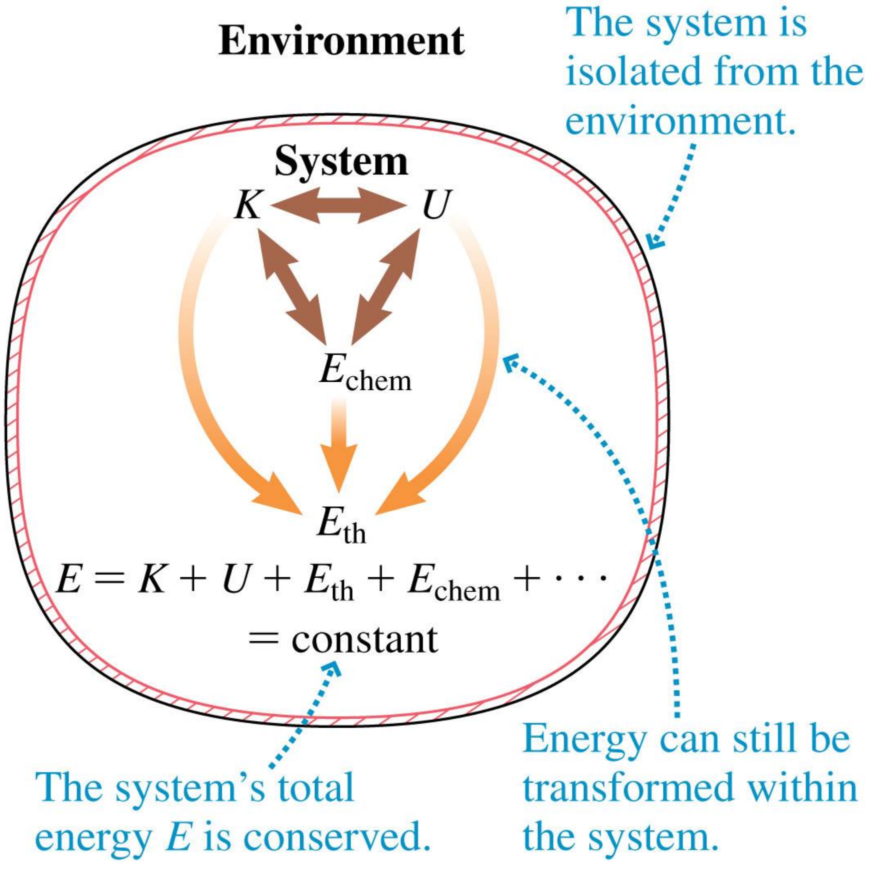
- Work represents energy that is transferred into or out of a system.
- The total energy of a system changes by the amount of work done on it.

$$\Delta E = \Delta K + \Delta U_g + \Delta U_s + \Delta E_{th} + \Delta E_{chem} + \cdots = W$$

- Work can increase or decrease the energy of a system.
- If no energy is transferred into or out of a system, that is an **isolated system**.

The Law of Conservation of Energy

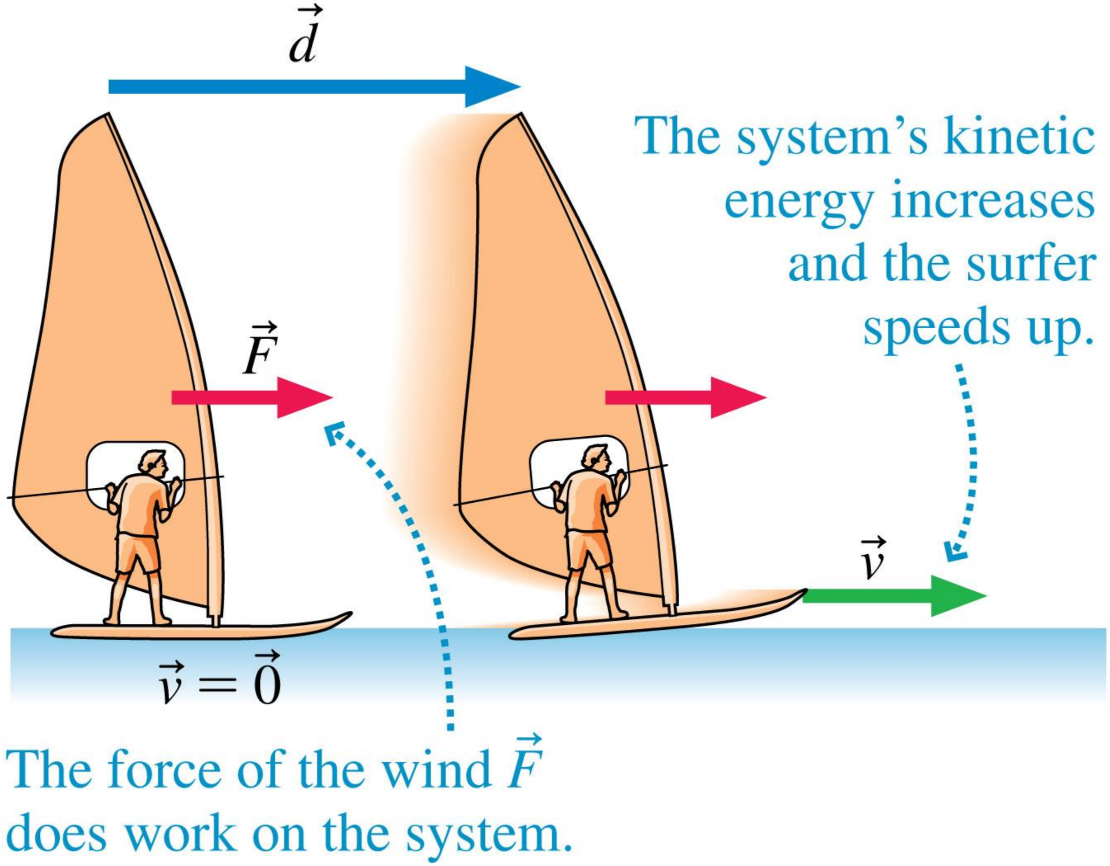
The total energy of an isolated system remains constant.



Section 10.2 Work

Work

Work is done on a system by **external forces**: forces from outside the system.



Calculating Work

$$W = Fd$$

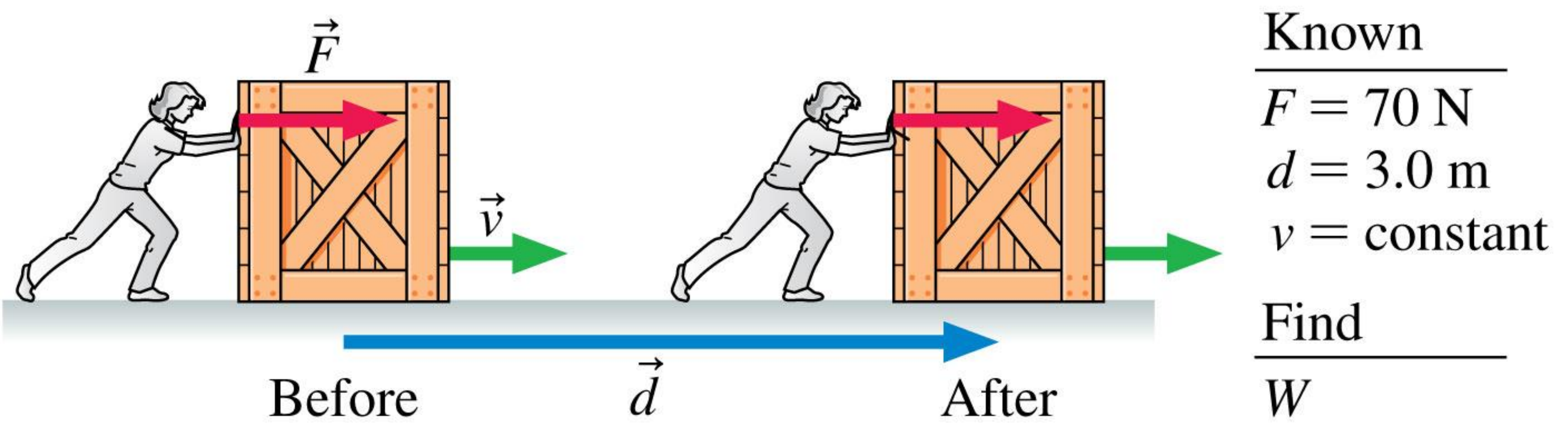
Work done by a constant force $\vec{F}$ in the direction of a displacement $\vec{d}$

- Although both the force and the displacement are vectors, work is a scalar.
- The unit of work (and energy) is:

$$1 \text{ joule} = 1 \text{ J} = 1 \text{ N} \cdot \text{m}$$

Example 10.1 Work done in pushing a crate

Sarah pushes a heavy crate 3.0 m along the floor at a constant speed. She pushes with a constant horizontal force of magnitude 70 N. How much work does Sarah do on the crate?

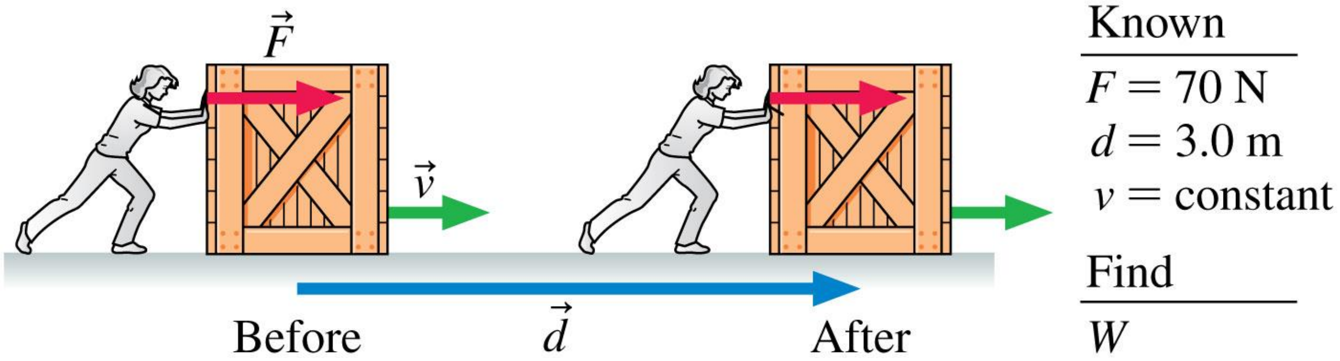


Example 10.1 Work done in pushing a crate (cont.)

PREPARE We begin with the before-and-after visual overview in the figure. Sarah pushes with a constant force in the direction of the crate's motion, so we can use the equation to find the work done.

SOLVE The work done by Sarah is

$$W = Fd = (70\ \text{N})(3.0\ \text{m}) = 210\ \text{J}$$



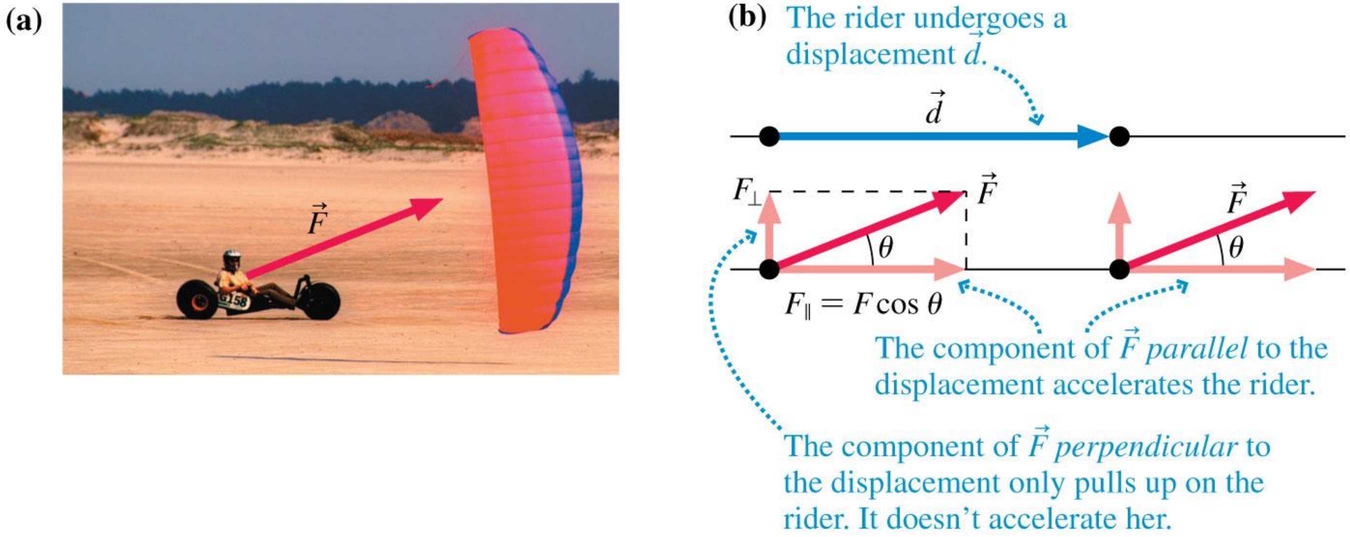
By pushing on the crate Sarah increases its kinetic energy, so it makes sense that the work done is positive.

Force at an Angle to the Displacement

- Only the component of a force in the direction of displacement does work.

$$W = F_{\parallel} d = F d \cos\theta$$

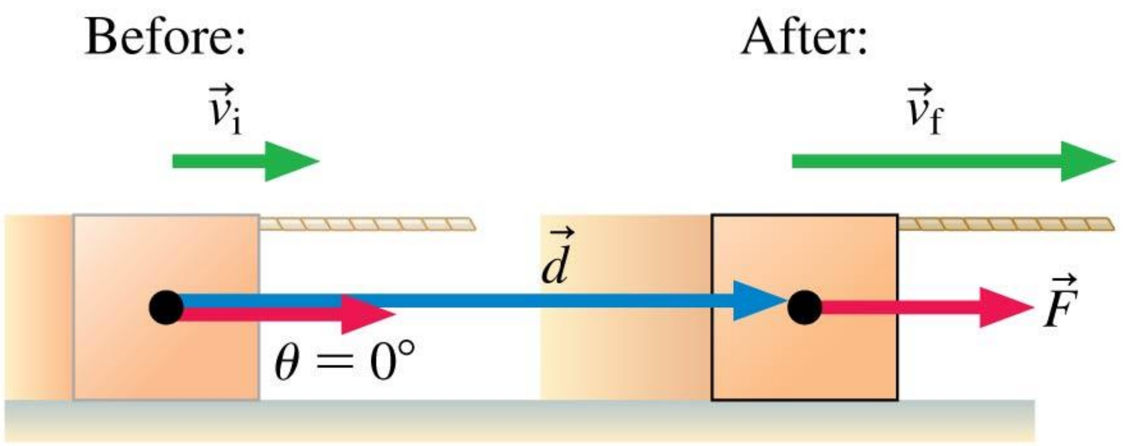
Work done by a constant force $\vec{F}$ at an angle θ to the displacement $\vec{d}$



- If the force is at an angle θ to the displacement, the component of the force, F, that does work is $F\cos\theta$.

Force at an Angle to the Displacement

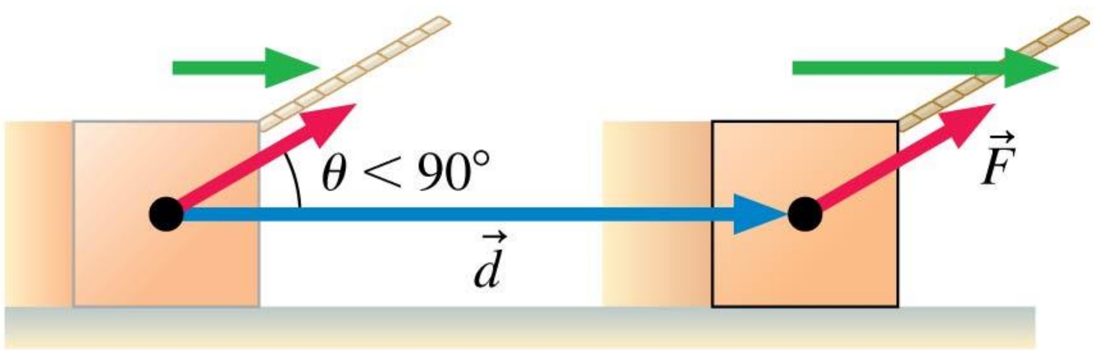
Direction of force relative to displacement | **Angles and work done**



$\theta = 0°$

$\cos\theta = 1$

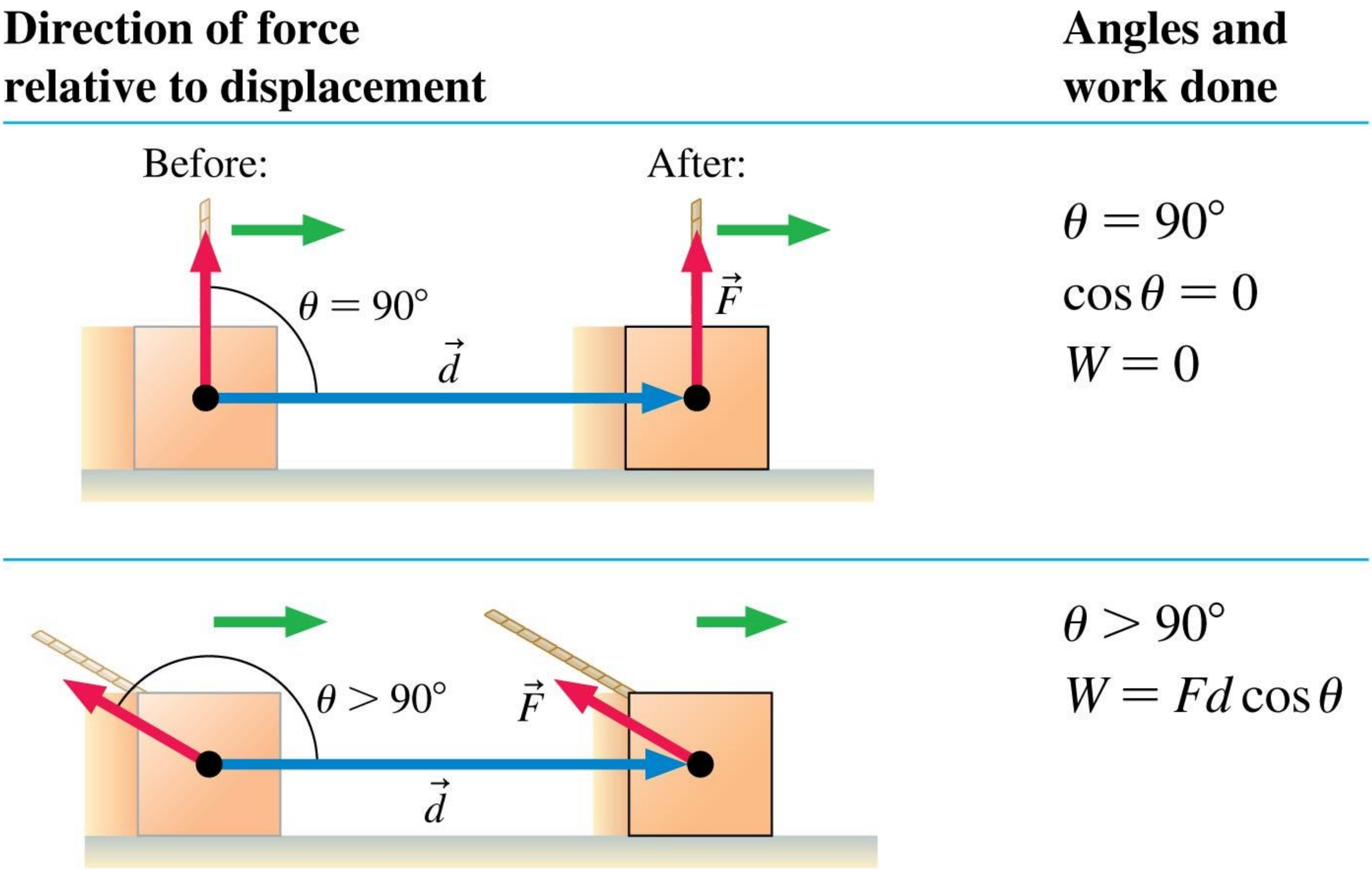
$W = Fd$



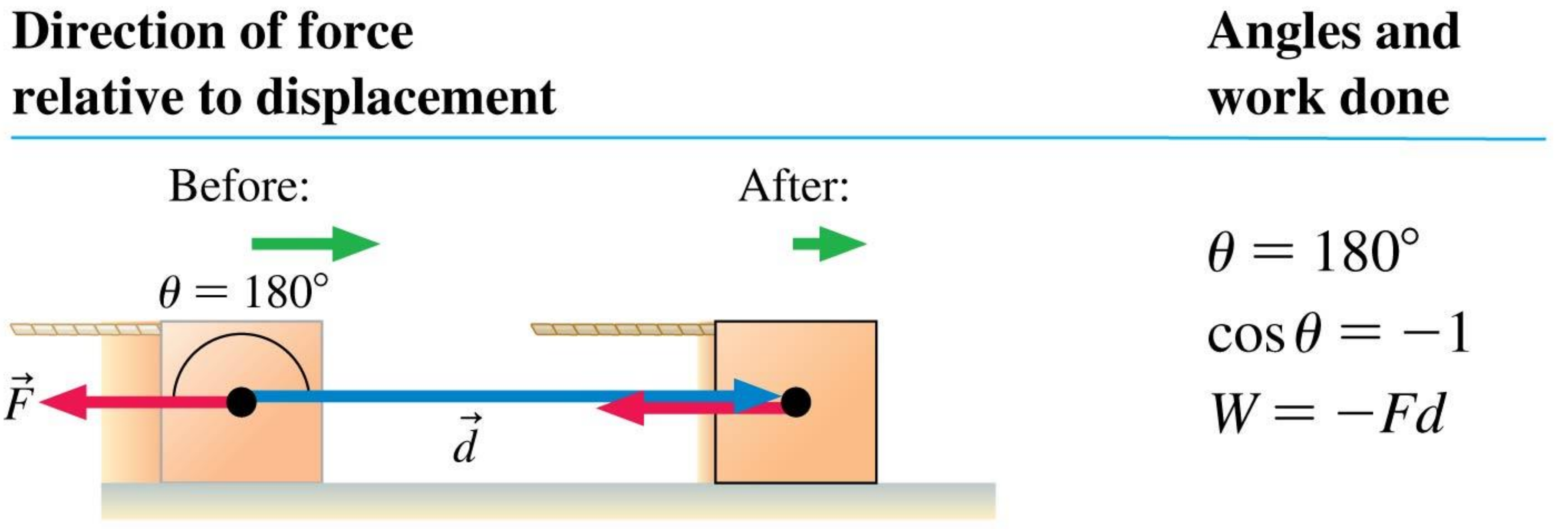
$\theta < 90°$

$W = Fd\cos\theta$

Force at an Angle to the Displacement



Force at an Angle to the Displacement



The sign of W is determined by the angle θ between the force and the displacement.

QuickCheck 10.4

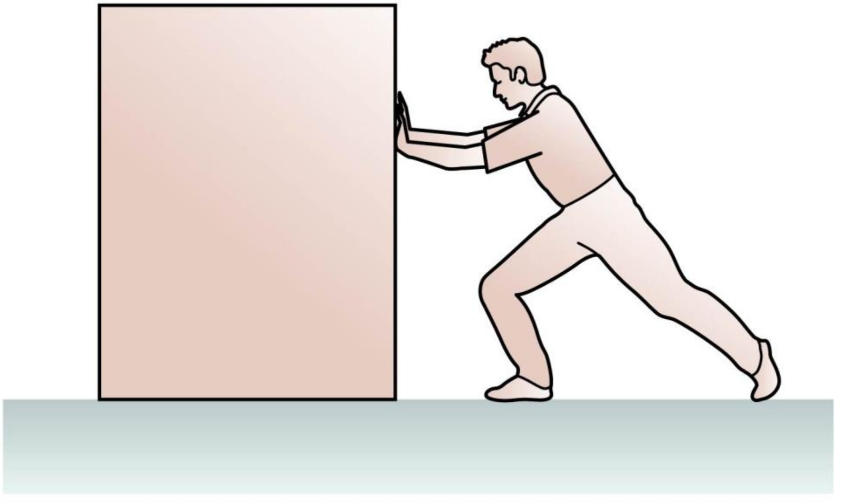
- A crane lowers a girder into place at constant speed. Consider the work W_g done by gravity and the work W_T done by the tension in the cable. Which is true?

A. $W_g > 0$ and $W_T > 0$
B. $W_g > 0$ and $W_T < 0$
C. $W_g < 0$ and $W_T > 0$
D. $W_g < 0$ and $W_T < 0$
E. $W_g = 0$ and $W_T = 0$

QuickCheck 10.5

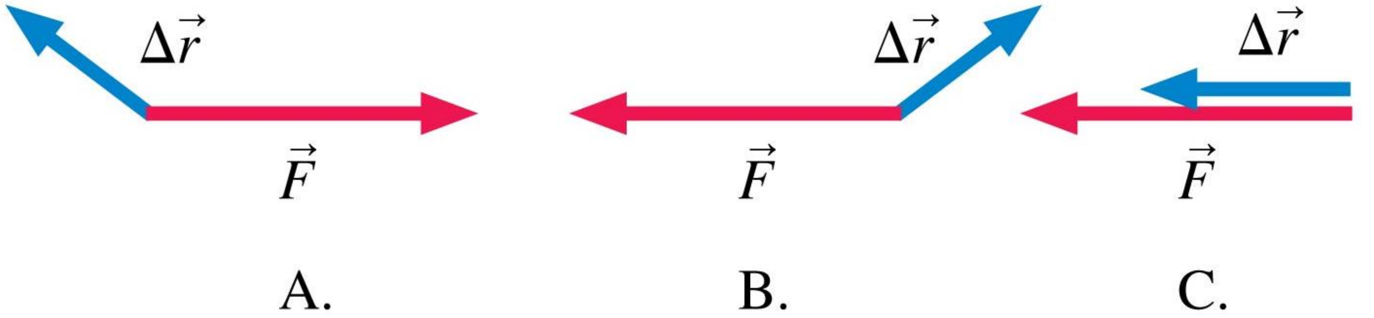
- Saud pushes the box to the left at constant speed. In doing so, Saud does _______ work on the box.

A. positive
B. negative
C. zero



QuickCheck 10.6

- A constant force $\vec{F}$ pushes a particle through a displacement $\Delta\vec{r}$. In which of these three cases does the force do negative work?



D. Both A and B.

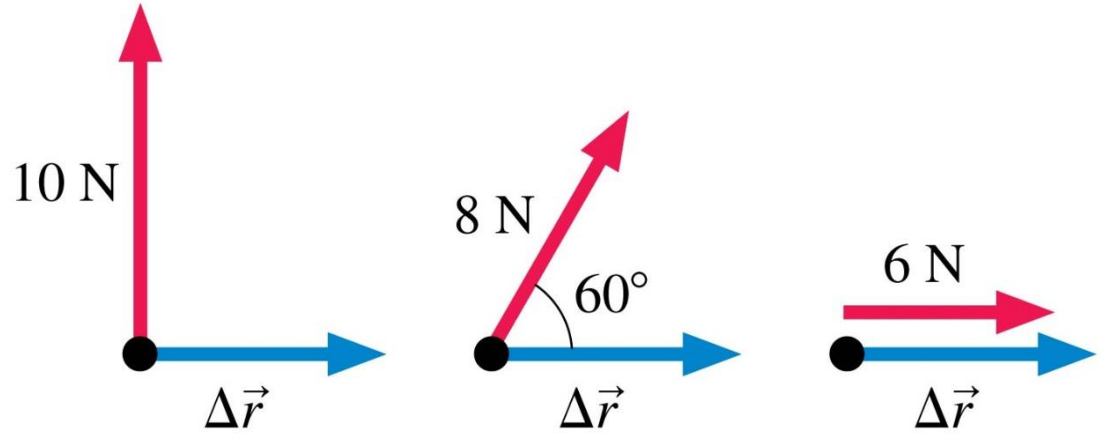
E. Both A and C.

QuickCheck 10.7

- Which force below does the most work? All three displacements are the same.

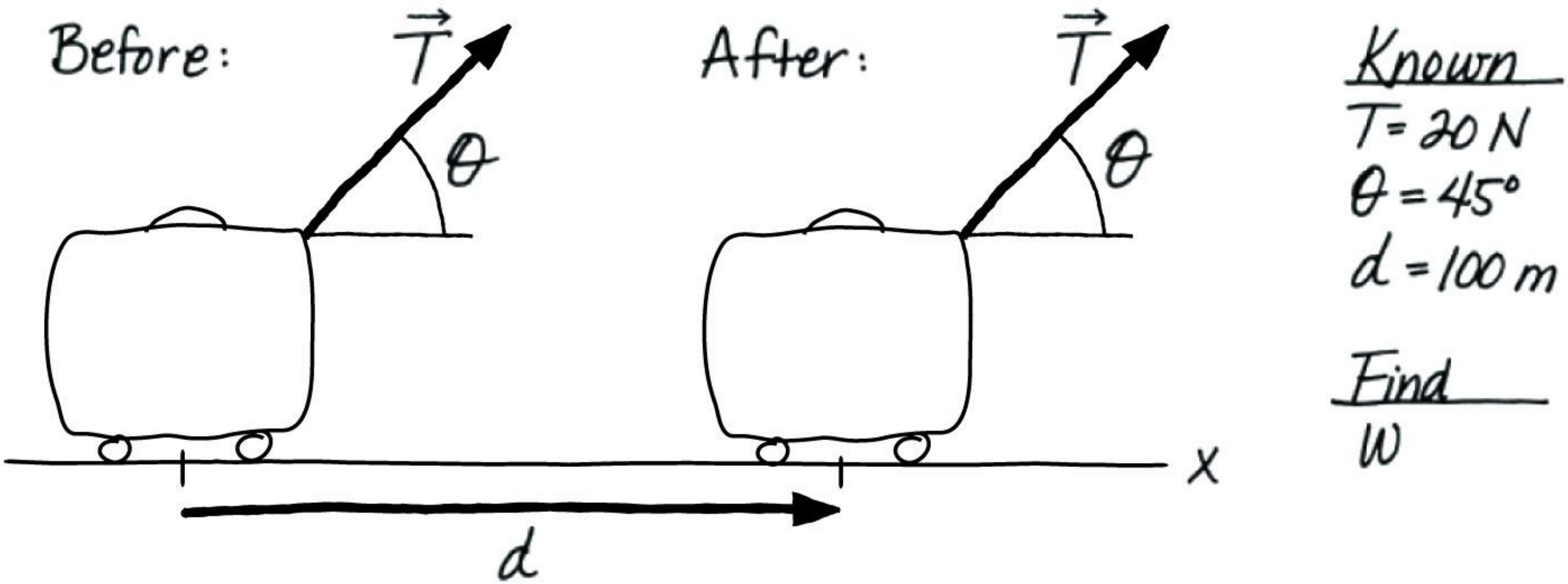
A. The 10 N force.
B. The 8 N force
C. The 6 N force.
D. They all do the same work.

$\sin 60° = 0.87$
$\cos 60° = 0.50$



Example 10.2 Work done in pulling a suitcase

A strap inclined upward at a 45° angle pulls a suitcase through the airport. The tension in the strap is 20 N. How much work does the tension do if the suitcase is pulled 100 m at a constant speed?



Example 10.2 Work done in pulling a suitcase (cont.)

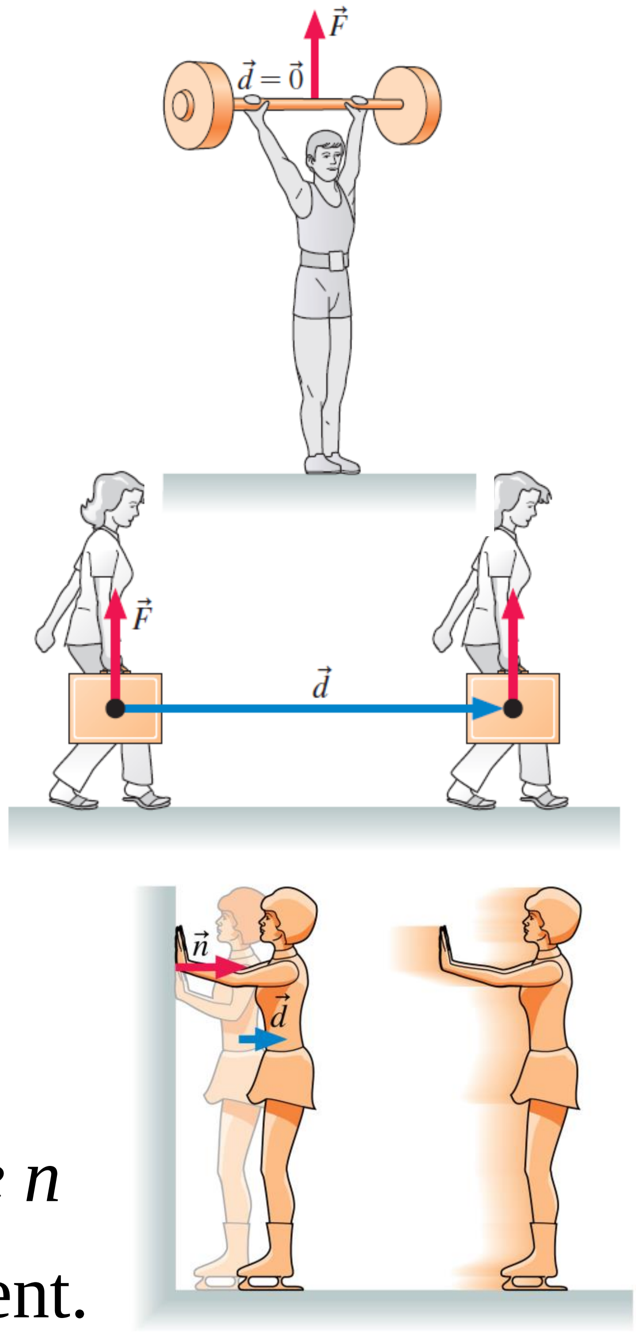
PREPARE Since the suitcase moves at a constant speed, there must be a rolling friction force (not shown) acting to the left.

SOLVE We can use Equation 10.6 , with force $F = T$, to find that the tension does work:

$$W = Td \cos \theta = (20 \text{ N})(100 \text{ m})\cos 45° = 1400 \text{ J}$$

The tension is needed to do work on the suitcase even though the suitcase is traveling at a constant speed to overcome friction. So it makes sense that the work is positive. The work done goes entirely into increasing the thermal energy of the suitcase and the floor.

Forces That Do No Work



A force does no work on an object if

- The object undergoes no displacement.
- The force is perpendicular to the displacement.

- The part of the object on which the force acts undergoes no displacement (even if other parts of the object do move):

The wall does no work on her, because

the point of her body on which *the force n*

acts (her hands) undergoes no displacement.

Section 10.3 Kinetic Energy

Kinetic Energy

- Kinetic energy is energy of motion.

$$K = \frac{1}{2}mv^2$$

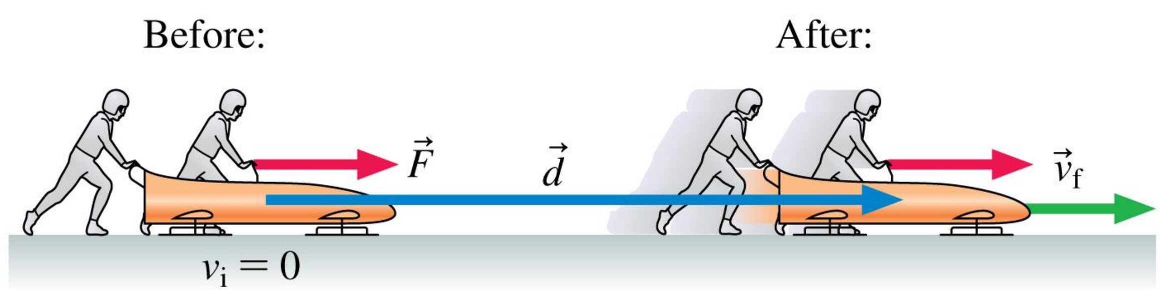
Kinetic energy of an object of mass m moving with speed v

Example 10.5 Speed of a bobsled after pushing

A two-man bobsled has a mass of 390 kg. Starting from rest, the two racers push the sled for the first 50 m with a net force of 270 N. Neglecting friction, what is the sled's speed at the end of the 50 m?

Example 10.5 Speed of a bobsled after pushing (cont.)

PREPARE Because friction is negligible, there is no change in the sled's thermal energy. And, because the sled's height is constant, its gravitational potential energy is unchanged as well. Thus the work-energy equation is simply $\Delta K = W$. We can therefore find the sled's final kinetic energy, and hence its speed, by finding the work done by the racers as they push on the sled. The figure lists the known quantities and the quantity v_f that we want to find.



Known	
$m = 390$ kg	$F = 270$ N
$d = 50$ m	$v_i = 0$ m/s

Find: v_f

The work done by the pushers increases the sled's kinetic energy.

Example 10.5 Speed of a bobsled after pushing (cont.)

SOLVE From the work-energy equation, the change in the sled's kinetic energy is $\Delta K = K_f - K_i = W$. The sled's final kinetic energy is thus

$$K_f = K_i + W$$

Using our expressions for kinetic energy and work, we get

$$\frac{1}{2}mv_f^2 = \frac{1}{2}mv_i^2 + Fd$$

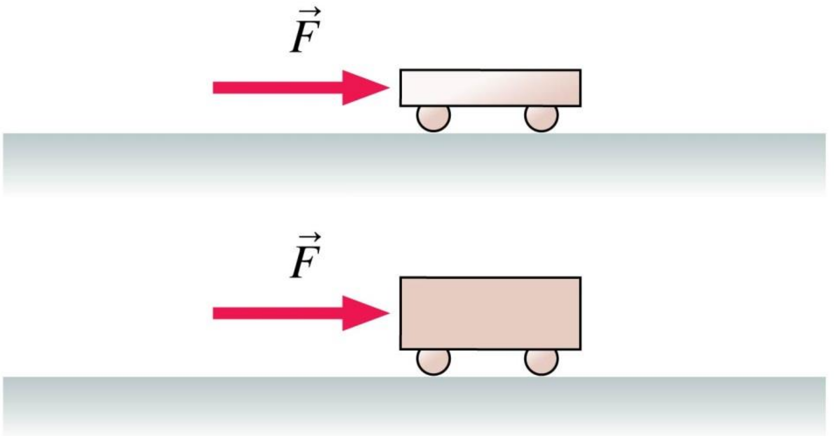
Because $v_i = 0$, the work-energy equation reduces to $\frac{1}{2}mv_f^2 = Fd$.

We can solve for the final speed to get

$$v_f = \sqrt{\frac{2Fd}{m}} = \sqrt{\frac{2(270\text{ N})(50\text{ m})}{390\text{ kg}}} = 8.3\text{ m/s}$$

QuickCheck 10.10

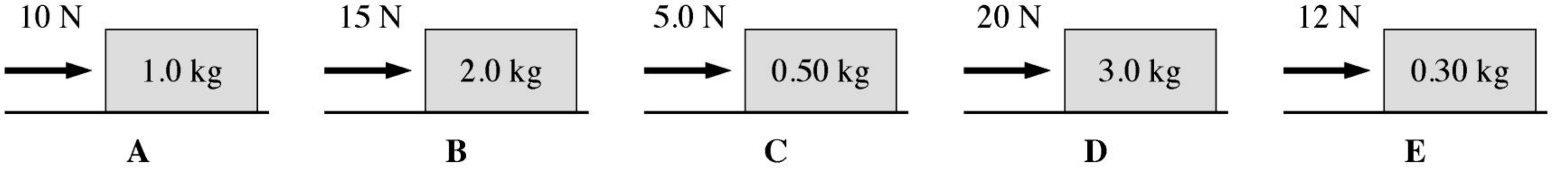
- A light plastic cart and a heavy steel cart are both pushed with the same force for a distance of 1.0 m, starting from rest. After the force is removed, the kinetic energy of the light plastic cart is ________ that of the heavy steel cart.



A. greater than
B. equal to
C. less than
D. Can’t say. It depends on how big the force is.

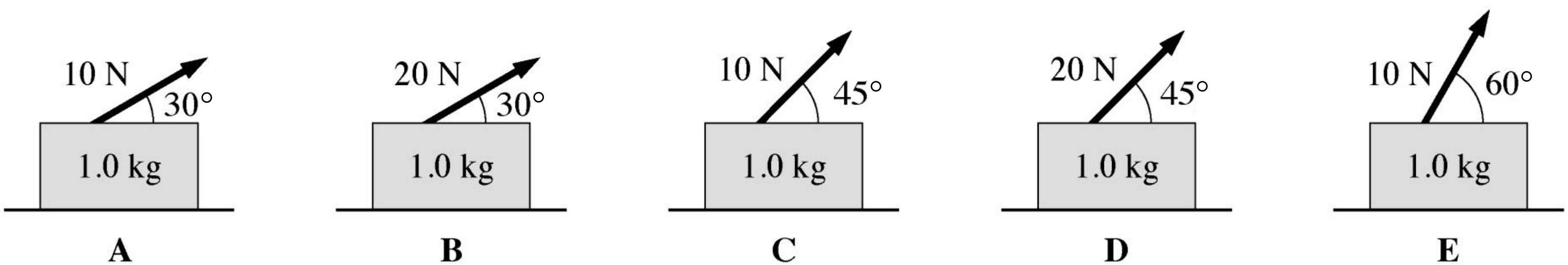
QuickCheck 10.11

- Each of the boxes shown is pulled for 10 m across a level, frictionless floor by the force given. Which box experiences the greatest change in its kinetic energy?



QuickCheck 10.12

- Each of the 1.0 kg boxes starts at rest and is then is pulled for 2.0 m across a level, frictionless floor by a rope with the noted force at the noted angle. Which box has the highest final speed?

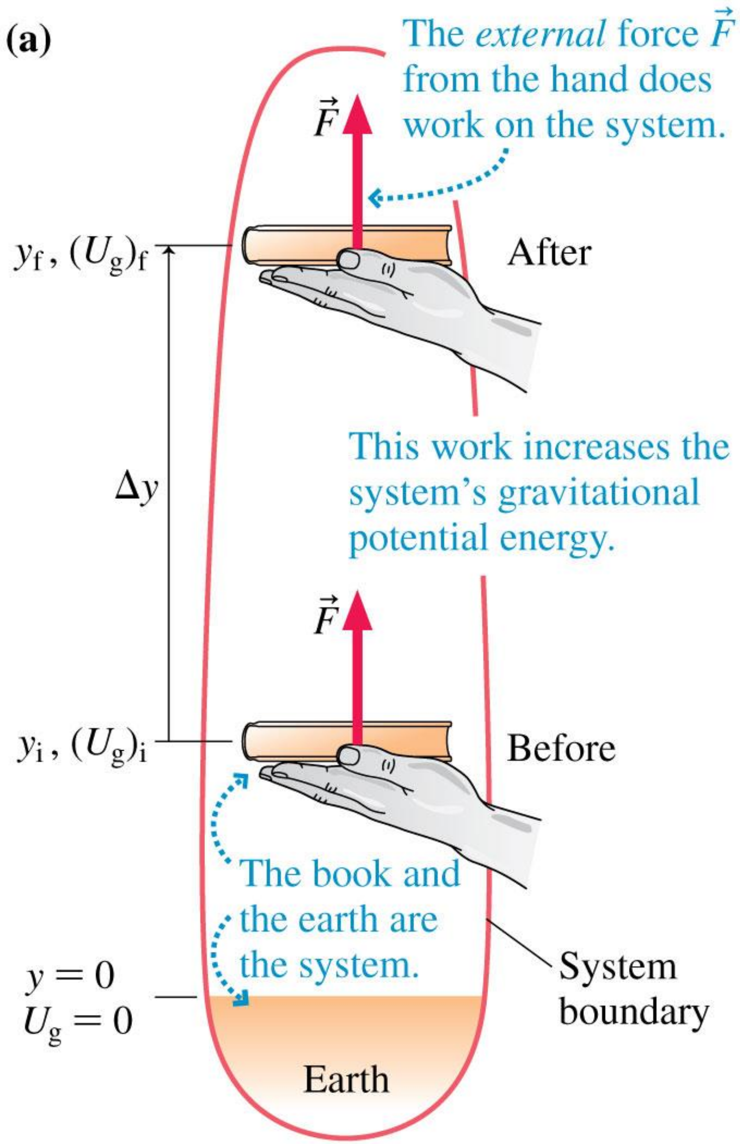


Section 10.4 Potential Energy

Potential Energy

- Potential energy is stored energy that can be readily converted to other forms of energy, such as kinetic or thermal energy.
- Forces that can store useful energy are **conservative forces**:
  - Gravity
  - Elastic forces
- Forces such as friction that cannot store useful energy are **nonconservative forces**.

Gravitational Potential Energy



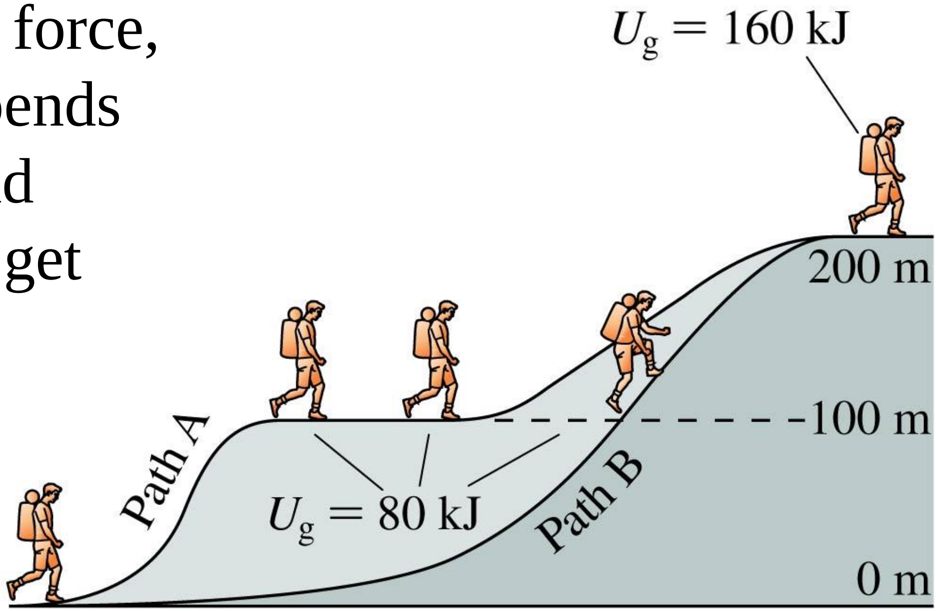
The change in gravitational potential energy is proportional to the change in its height.

Gravitational Potential Energy

$$U_g = mgy$$

Gravitational potential energy of an object of mass m at height y (assuming $U_g = 0$ when the object is at $y = 0$)

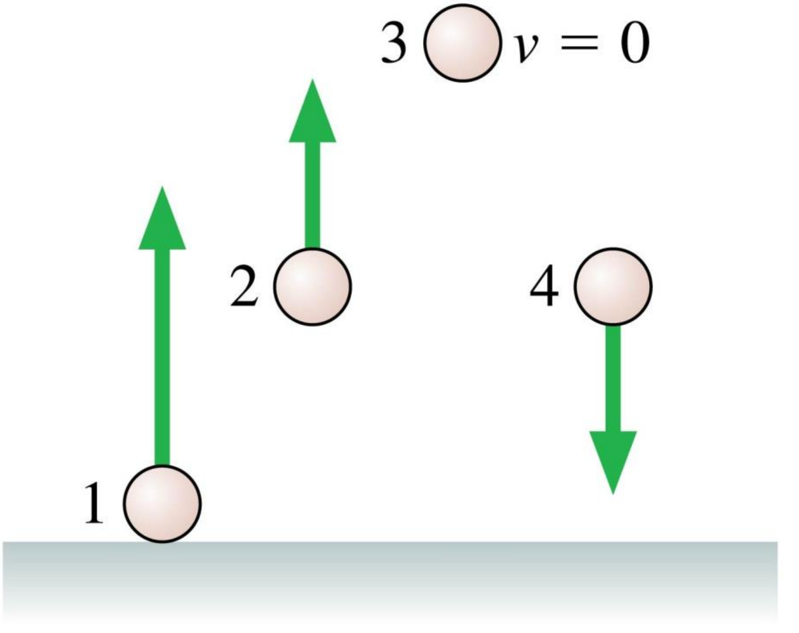
- We can choose the reference level where gravitational potential energy $U_g = 0$ since only changes in U_g matter.
- Because gravity is a conservative force, gravitational potential energy depends only on the height of an object and not on the path the object took to get to that height.



QuickCheck 10.13

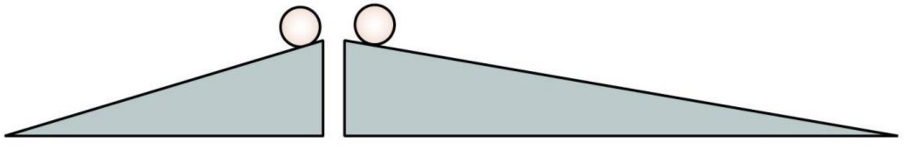
- Rank in order, from largest to smallest, the gravitational potential energies of the balls.

A. $1 > 2 = 4 > 3$
B. $1 > 2 > 3 > 4$
C. $3 > 2 > 4 > 1$
D. $3 > 2 = 4 > 1$



QuickCheck 10.14

- Starting from rest, a marble first rolls down a steeper hill, then down a less steep hill of the same height. For which is it going faster at the bottom?

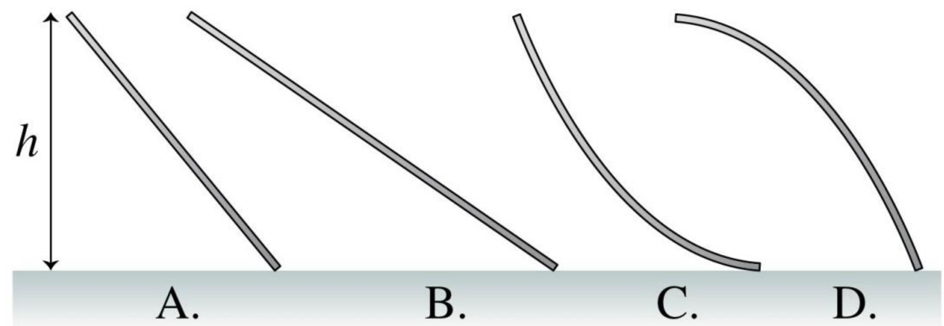


A. Faster at the bottom of the steeper hill.
B. Faster at the bottom of the less steep hill.
C. Same speed at the bottom of both hills.
D. Can’t say without knowing the mass of the marble.

QuickCheck 10.15

- A small child slides down the four frictionless slides A–D. Rank in order, from largest to smallest, her speeds at the bottom.

A. $v_D > v_A > v_B > v_C$
B. $v_D > v_A = v_B > v_C$
C. $v_C > v_A > v_B > v_D$
D. $v_A = v_B = v_C = v_D$



Section 10.6 Using the Law of Conservation of Energy

Using the Law of Conservation of Energy

- We can use the law of conservation of energy to develop a before-and-after perspective for energy conservation:

$$W = \Delta E = \Delta K + \Delta U_g$$

$$K_f + (U_g)_f = K_i + (U_g)_i + W$$

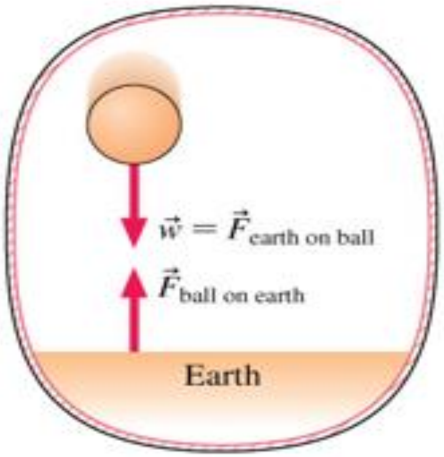
- This is analogous to the before-and-after approach used with the law of conservation of momentum.
- In an **isolated system**, $W = 0$:

$$K_f + (U_g)_f = K_i + (U_g)_i$$

Choosing an Isolated System

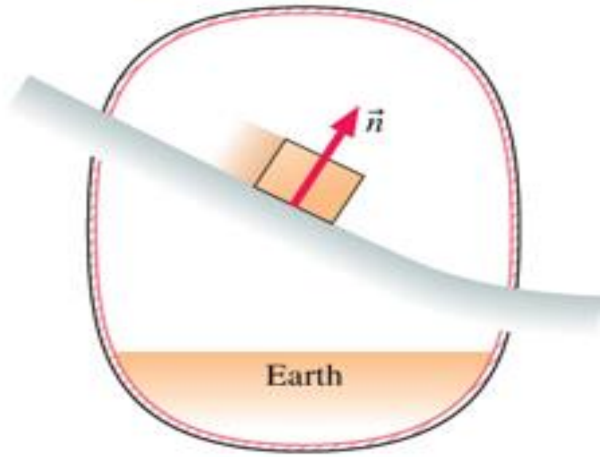
TABLE 10.2 Choosing an isolated system

An object in free fall



We choose the ball *and* the earth as the system, so that the forces between them are *internal* forces. There are no external forces to do work, so the system is isolated.

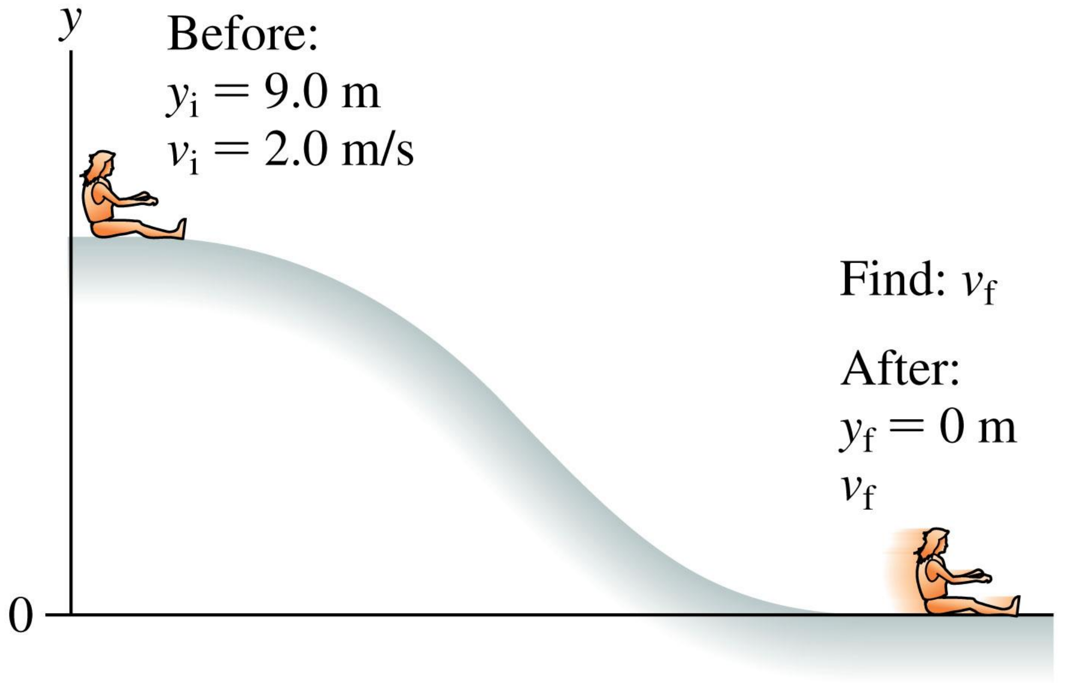
An object sliding down a frictionless ramp



The external force the ramp exerts on the object is perpendicular to the motion, and so does no work. The object and the earth together form an isolated system.

Example 10.11 Speed at the bottom of a water slide

While at the county fair, Sarah tries the water slide, whose shape is shown in the figure. The starting point is 9.0 m above the ground. She pushes off with an initial speed of 2.0 m/s. If the slide is frictionless, how fast will Sarah be traveling at the bottom?



Example 10.11 Speed at the bottom of a water slide (cont.)

PREPARE Table 10.2 showed that the system consisting of Sarah and the earth is isolated because the normal force of the slide is perpendicular to Sarah's motion and does no work. If we assume the slide is frictionless, we can use the conservation of mechanical energy equation.

SOLVE Conservation of mechanical energy gives

$$K_f + (U_g)_f = K_i + (U_g)_i$$

or

$$\frac{1}{2}mv_f^2 + mgy_f = \frac{1}{2}mv_i^2 + mgy_i$$

Example 10.11 Speed at the bottom of a water slide (cont.)

Taking $y_f = 0$ m, we have

$$\frac{1}{2}mv_f^2 = \frac{1}{2}mv_i^2 + mgy_i$$

which we can solve to get

$$v_f = \sqrt{v_i^2 + 2gy_i}$$

$$= \sqrt{(2.0\text{ m/s})^2 + 2(9.8\text{ m/s}^2)(9.0\text{ m})} = 13\text{ m/s}$$

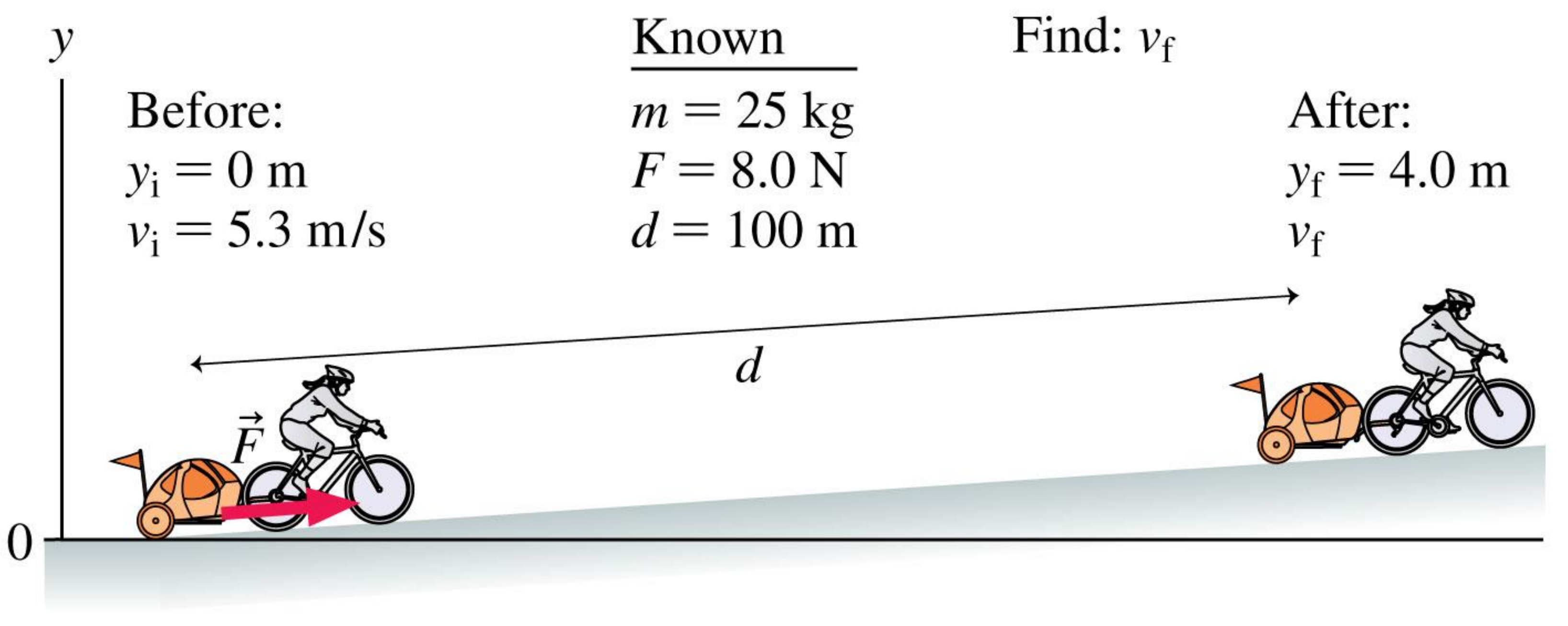
Notice that the shape of the slide does not matter because gravitational potential energy depends only on the *height* above a reference level.

Example 10.13 Pulling a bike trailer

Mounira pulls her daughter Sarah in a bike trailer. The trailer and Sarah together have a mass of 25 kg. Mounira starts up a 100-m-long slope that's 4.0 m high. On the slope, Mounira's bike pulls on the trailer with a constant force of 8.0 N. They start out at the bottom of the slope with a speed of 5.3 m/s. What is their speed at the top of the slope?

Example 10.13 Pulling a bike trailer (cont.)

PREPARE Taking Sarah and the trailer as the system, we see that Mounira's bike is applying a force to the system as it moves through a displacement; that is, Mounira's bike is doing work on the system. Thus we'll need to use the full version of Equation 10.18, including the work term W.



Example 10.13 Pulling a bike trailer (cont.)

SOLVE

$$W = \Delta E = \Delta K + \Delta U_g$$

$$K_f + (U_g)_f = K_i + (U_g)_i + W$$

Or

$$\frac{1}{2}mv_f^2 + mgy_f = \frac{1}{2}mv_i^2 + mgy_i + W$$

Example 10.13 Pulling a bike trailer (cont.)

Taking $y_i = 0$ m and writing $W = Fd$, we can solve for the final speed:

$$v_f^2 = v_i^2 - 2gy_f + \frac{2Fd}{m}$$

$$= (5.3\text{ m/s})^2 - 2(9.8\text{ m/s}^2)(4.0\text{ m}) + \frac{2(8.0\text{ N})(100\text{ m})}{25\text{ kg}}$$

$$= 13.7\text{ m}^2/\text{s}^2$$

from which we find that $v_f = 3.7$ m/s. Note that we took the work to be a positive quantity because the force is in the same direction as the displacement.

ASSESS A speed of 3.7 m/s seems reasonable for a bicycle's speed. Sarah's final speed is less than her initial speed, indicating that the uphill force of Mounira's bike on the trailer is less than the downhill component of gravity.

Energy and Its Conservation

Kinetic energy is the energy of motion.

$$K = \frac{1}{2}mv^2$$

Mass (kg)

Velocity (m/s)

Gravitational potential energy is stored energy associated with an object's height above the ground.

$$U_g = mgy$$

Free-fall acceleration

Mass (kg)

Height (m) above a reference level $y = 0$

For an *isolated system*, the **law of conservation of energy** is

$$\underbrace{K_f + (U_g)_f + (U_s)_f + \Delta E_{th}}_{\text{Final total energy}} = \underbrace{K_i + (U_g)_i + (U_s)_i}_{\text{Initial total energy}}$$

A system's final total energy, including any increase in its thermal energy, is equal to its initial energy.

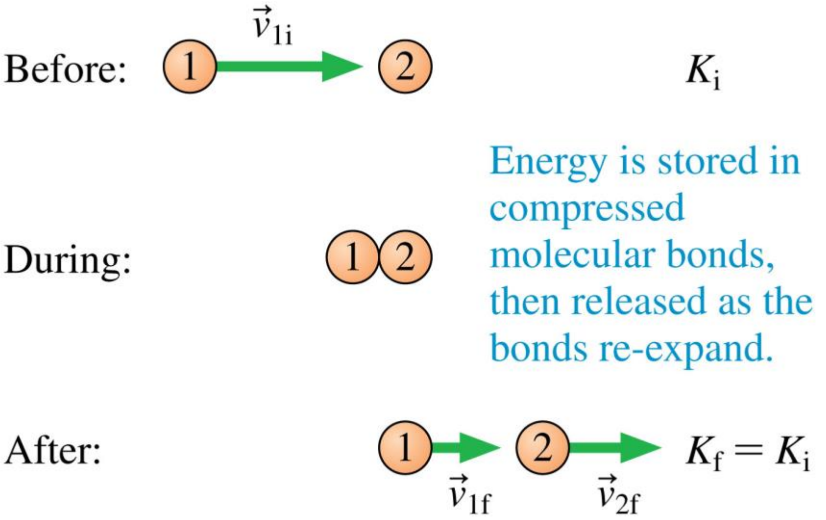
Section 10.7 Energy in Collisions

Energy in Collisions

- A collision in which the colliding objects stick together and then move with a common final velocity is a **perfectly inelastic collision**.
- A collision in which mechanical energy is conserved is called a **perfectly elastic collision**.
- While momentum is conserved in all collisions, mechanical energy is only conserved in a perfectly elastic collision.
- In an inelastic collision, some mechanical energy is converted to thermal energy.

Elastic Collisions

Elastic collisions obey conservation of momentum and conservation of mechanical energy.



$$\text{Momentum: } m_1 v_{1i} + 0 = m_1 v_{1f} + m_2 v_{2f}$$

$$\textit{Energy}\text{: } \frac{1}{2} m_1 v_{1i}^2 + 0 = \frac{1}{2} m_1 v_{1f}^2 + \frac{1}{2} m_2 v_{2f}^2$$

Elastic Collisions

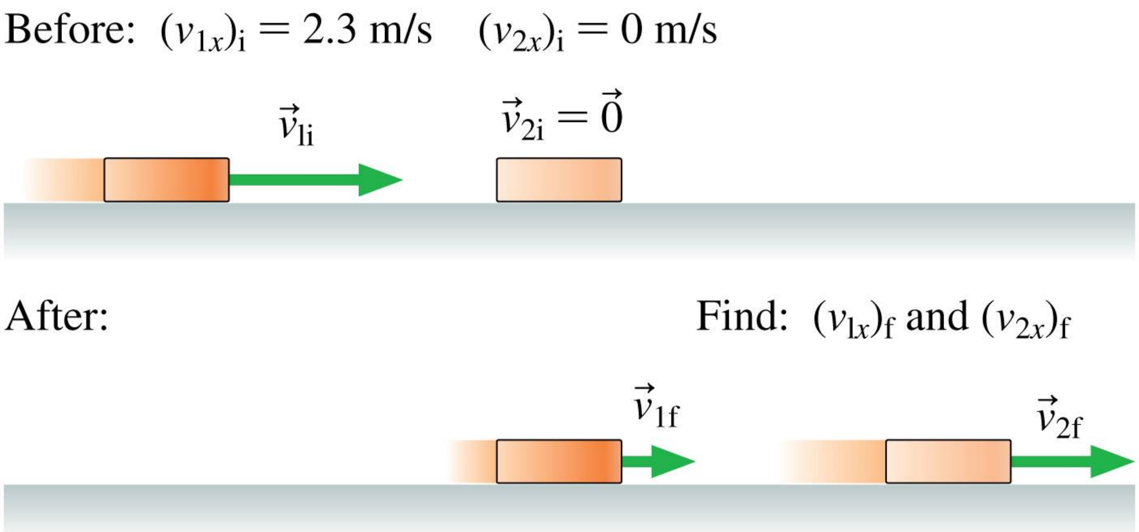
$$\left.\begin{aligned} m_1\left(v_{1i}^2 - v_{1f}^2\right) &= m_2 v_{2f}^2 \\ m_1\left(v_{1i} - v_{1f}\right) &= m_2 v_{2f} \end{aligned}\right\} \Rightarrow v_{1i} + v_{1f} = v_{2f} \text{ (The ratio of the two equations)}$$

$$\left.\begin{aligned} v_{1i} + v_{1f} &= v_{2f} \\ v_{1i} - v_{1f} &= \frac{m_2}{m_1} v_{2f} \end{aligned}\right\} \Leftrightarrow \left\{\begin{aligned} v_{1f} &= \frac{m_1 - m_2}{m_1 + m_2} v_{1i} \\ v_{2f} &= \frac{2m_1}{m_1 + m_2} v_{1i} \end{aligned}\right.$$

Example 10.16 Velocities in an air hockey collision

On an air hockey table, a moving puck, traveling to the right at 2.3 m/s, makes a head-on collision with an identical puck at rest. What is the final velocity of each puck?

Example 10.16 Velocities in an air hockey collision (cont.)



PREPARE The before-and-after visual overview is shown in the figure. We've shown the final velocities in the picture, but we don't really know yet which way the pucks will move. Because one puck was initially at rest, we can use the equations to find the final velocities of the pucks. The pucks are identical, so we have $m_1 = m_2 = m$.

Example 10.16 Velocities in an air hockey collision (cont.)

SOLVE We use Equations of slide 66 with $m_1 = m_2 = m$ to get

$$\begin{cases} v_{1f} = \dfrac{m-m}{m+m} v_{1i} = 0 \\ v_{2f} = \dfrac{2m}{m+m} v_{1i} = v_{1i} = 2.3 \text{ m/s} \end{cases}$$

The incoming puck stops dead, and the initially stationary puck goes off with the same velocity that the incoming one had.

Section 10.8 Power

Power

- **Power** is the rate at which energy is transformed or transferred.

$$P = \frac{\Delta E}{\Delta t}$$

Power when an amount of energy ΔE is transformed in a time interval Δt

$$P = \frac{W}{\Delta t}$$

Power when an amount of work W is done in a time interval Δt

- The unit of power is the **watt**:

$$1 \text{ watt} = 1 \text{ W} = 1 \text{ J/s}$$

Output Power of a Force

- A force doing work transfers energy.
- The rate that this force transfers energy is the **output power** of that force:

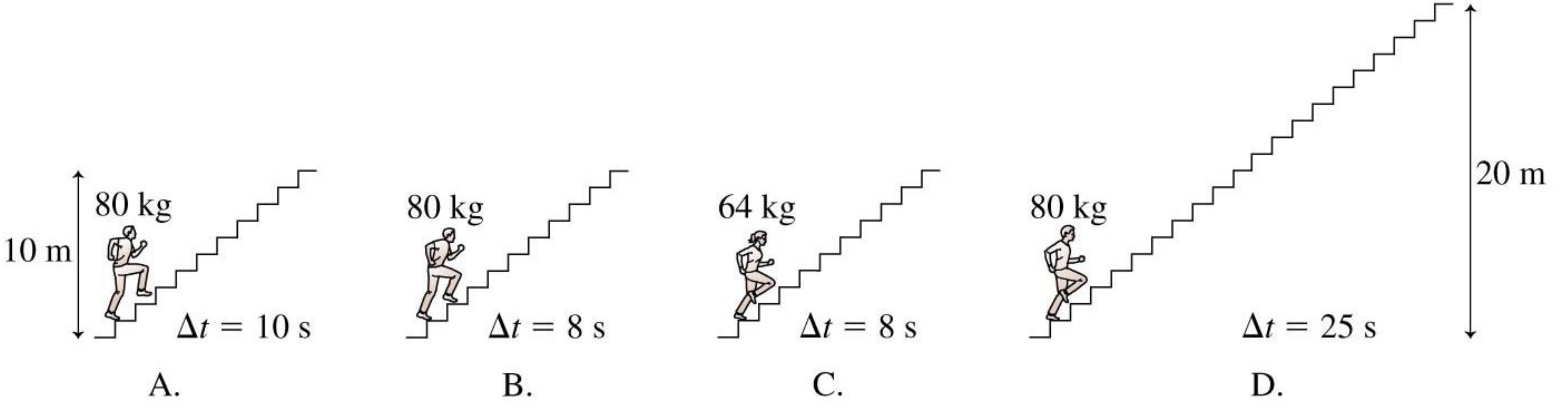
$$P = \frac{W}{\Delta t} = \frac{F\Delta x}{\Delta t} = F\frac{\Delta x}{\Delta t} = Fv$$

$$P = Fv$$

Rate of energy transfer due to a force F acting on an object moving at velocity v

QuickCheck 10.20

- Four students run up the stairs in the time shown. Which student has the largest power output?



QuickCheck 10.21

- Four toy cars accelerate from rest to their top speed in a certain amount of time. The masses of the cars, the final speeds, and the time to reach this speed are noted in the table. Which car has the greatest power?

Car	Mass (g)	Speed (m/s)	Time (s)
A	100	3	2
B	200	2	2
C	300	2	3
D	600	1	3
E	400	2	4

Example 10.18 Power to pass a truck

Your 1500 kg car is behind a truck traveling at (27 m/s).

To pass the truck, you speed up to (34 m/s) in 6.0 s.

What engine power is required to do this?

PREPARE Your engine is transforming the chemical energy of its fuel into the kinetic energy of the car. We can calculate the rate of transformation by finding the change ΔK in the kinetic energy and using the known time interval.

Example 10.18 Power to pass a truck (cont.)

SOLVE We have

$$K_{\mathrm{i}} = \frac{1}{2}mv_{\mathrm{i}}^2 = \frac{1}{2}(1500\ \mathrm{kg})(27\ \mathrm{m/s})^2 = 5.47 \times 10^5\ \mathrm{J}$$

$$K_{\mathrm{f}} = \frac{1}{2}mv_{\mathrm{f}}^2 = \frac{1}{2}(1500\ \mathrm{kg})(34\ \mathrm{m/s})^2 = 8.67 \times 10^5\ \mathrm{J}$$

so that

$$\Delta K = K_{\mathrm{f}} - K_{\mathrm{i}}$$

$$= (8.67 \times 10^5\ \mathrm{J}) - (5.47 \times 10^5\ \mathrm{J}) = 3.20 \times 10^5\ \mathrm{J}$$

To transform this amount of energy in 6 s, the power required is

$$P = \frac{\Delta K}{\Delta t} = \frac{3.20 \times 10^5\ \mathrm{J}}{6.0\ \mathrm{s}} = 53{,}000\ \mathrm{W} = 53\ \mathrm{kW}$$

Reading Question 10.1

If a system is *isolated*, the total energy of the system

A. Increases constantly.
B. Decreases constantly.
C. Is constant.
D. Depends on the work into the system.
E. Depends on the work out of the system.

Reading Question 10.2

Which of the following is an energy transfer?

A. Kinetic energy
B. Work
C. Potential energy
D. Chemical energy
E. Thermal energy

Reading Question 10.3

If you raise an object to a greater height, you are increasing

A. Kinetic energy.
B. Heat.
C. Potential energy.
D. Chemical energy.
E. Thermal energy.

Reading Question 10.4

If you hold a heavy weight over your head, the work you do

A. Is greater than zero.
B. Is zero.
C. Is less than zero.
D. Is converted into chemical energy.
E. Is converted into potential energy.

Reading Question 10.5

The unit of work is

A. The watt.
B. The poise.
C. The hertz.
D. The pascal.
E. The joule.

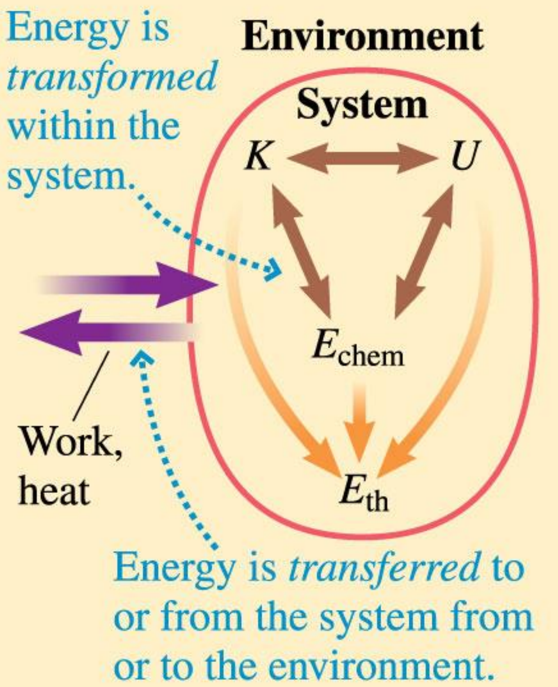
Summary: General Principles

Basic Energy Model

Within a system, energy can be **transformed** between various forms.

Energy can be **transferred** into or out of a system in two basic ways:

- **Work:** The transfer of energy by mechanical forces
- **Heat:** The nonmechanical transfer of energy from a hotter to a colder object



Summary: General Principles

Conservation of Energy

When work W is done on a system, the system's total energy changes by the amount of work done. In mathematical form, this is the **work-energy equation:**

$$\Delta E = \Delta K + \Delta U_g + \Delta U_s + \Delta E_{th} + \Delta E_{chem} + \cdots = W$$

A system is **isolated** when no energy is transferred into or out of the system. This means the work is zero, giving the **law of conservation of energy:**

$$\Delta K + \Delta U_g + \Delta U_s + \Delta E_{th} + \Delta E_{chem} + \cdots = 0$$

Summary: General Principles

Solving Energy Transfer and Energy Conservation Problems

PREPARE Draw a before-and-after visual overview.

SOLVE

- If work is done on the system, then use the before-and-after version of the work-energy equation:

$$K_f + (U_g)_f + (U_s)_f + \Delta E_{th} = K_i + (U_g)_i + (U_s)_i + W$$

- If the system is isolated but there's friction present, then the total energy is conserved:

$$K_f + (U_g)_f + (U_s)_f + \Delta E_{th} = K_i + (U_g)_i + (U_s)_i$$

- If the system is isolated and there's no friction, then mechanical energy is conserved:

$$K_f + (U_g)_f + (U_s)_f = K_i + (U_g)_i + (U_s)_i$$

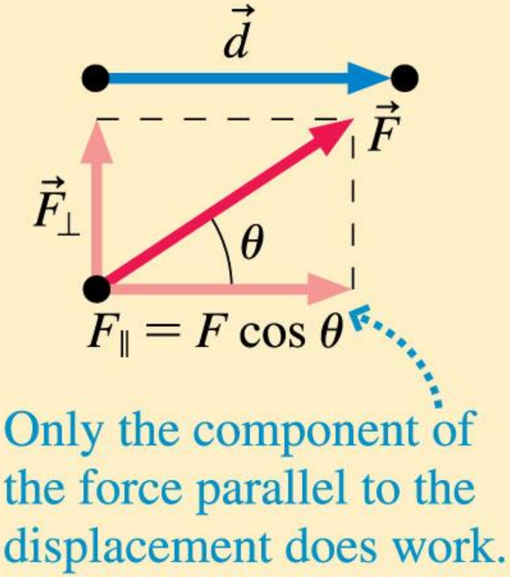
ASSESS Kinetic energy is always positive, as is the change in thermal energy.

Summary: Important Concepts

Work is the process by which energy is transferred to or from a system by the application of mechanical forces.

If a particle moves through a displacement $\vec{d}$ while acted upon by a constant force $\vec{F}$, the force does work

$$W = F_{\parallel}d = Fd\cos\theta$$



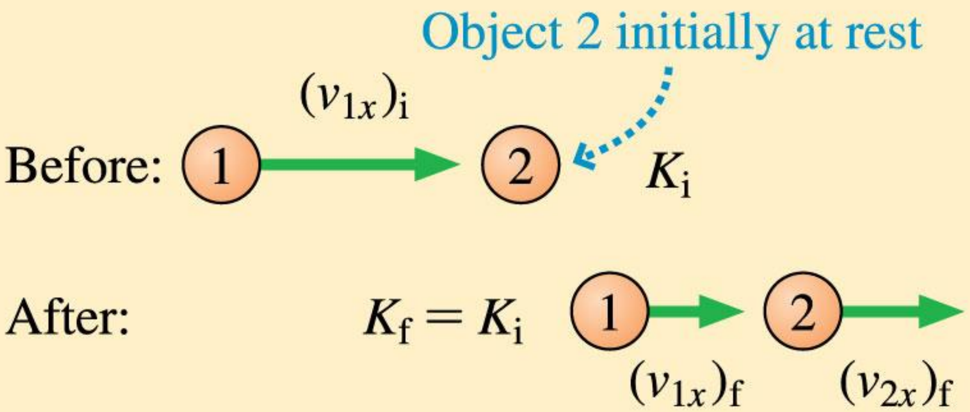
Summary: Applications

Perfectly elastic collisions

Both mechanical energy and momentum are conserved.

$$(v_{1x})_f = \frac{m_1 - m_2}{m_1 + m_2}(v_{1x})_i$$

$$(v_{2x})_f = \frac{2m_1}{m_1 + m_2}(v_{1x})_i$$



Summary: Applications

Power is the rate at which energy is transformed . . .

$$P = \frac{\Delta E}{\Delta t}$$

- ΔE: Amount of energy transformed
- Δt: Time required to transform it

. . . or at which work is done.

$$P = \frac{W}{\Delta t}$$

- W: Amount of work done
- Δt: Time required to do work