Chapter 4 : Force and Newton's Laws of Motion

4.1 Force and Mass

4.2 Newton's Laws of Motion

4.3 Applications of Newton's Laws

4.4 Friction and Drag

4.5 Newton's Laws and Uniform Circular Motion

•**Dynamics:** is the study of forces that cause changes in motion. It can also be referred to as Newtonian Dynamics. It is a branch of Classical Mechanics.

•**Classical Dynamics** describes the relationship between the motion of objects in our everyday world and the forces acting on them.

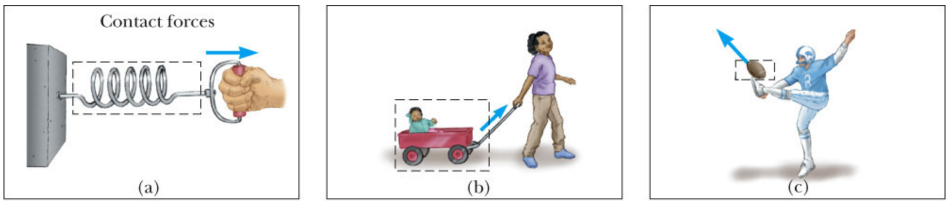
•Conditions when Classical Mechanics does not apply
- •Very tiny objects (< atomic sizes)
- •Objects moving near the speed of light

From Wikipedia: The study of the motion of bodies is an ancient one, making classical mechanics one of the oldest and largest subjects in science, engineering and technology. Classical mechanics describes the motion of macroscopic objects, from projectiles to parts of machinery, as well as astronomical objects, such as spacecraft, planets, stars, and galaxies. Besides this, many specializations within the subject deal with gases, liquids, solids, and other specific sub-topics.

4.1 Force and Mass

Force

- Commonly imagined as a push or pull on some object.
- Force is a **Vector** quantity
- May be a **contact force** or a **field force**



4.1 Force and Mass

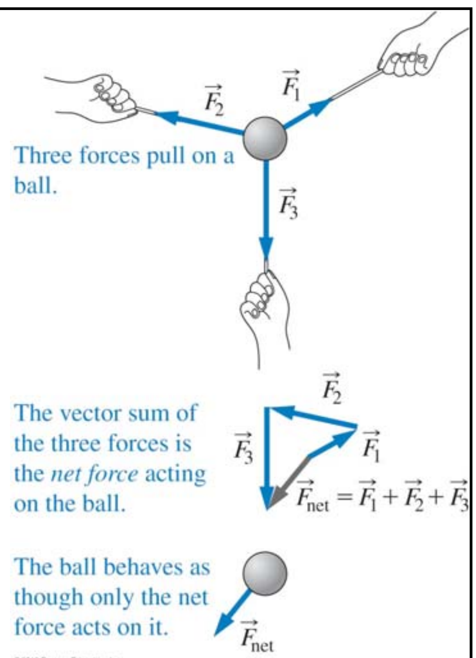
Mass

- Mass is the measure of how hard it is to change an object's velocity.
- It is also the measure of the quantity of matter in an object (scalar quantity, SI unit is kg)

Net Force and Force Diagram

- The **net force** on an object is the sum of all the individual external forces:

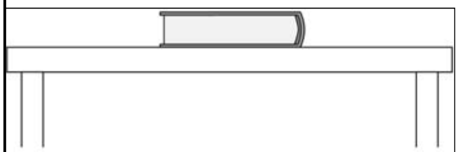
$\boldsymbol{F}_{net} = \boldsymbol{F}_1 + \boldsymbol{F}_2 + \boldsymbol{F}_3$



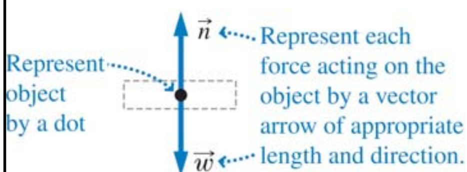
4.2 Newton's Laws of Motion

Newton's First Law

•An object at rest remains at rest, and an object in motion remains in motion with constant velocity, unless acted upon by a nonzero **net force**.



Do we have a nonzero net force?



(b) Force diagram for book

Question:

A hockey puck slides on ice at constant velocity. What is the *net* force acting on the puck?

Zero

If you give the book on the table a push, it slides and then it stops. It means there is a **net force** not equal to zero!

Question 4.1 Cart on Track I

Consider a cart on a horizontal frictionless table. Once the cart has been given a push and released, what will happen to the cart?

a) slowly come to a stop
b) continue with constant acceleration
c) continue with decreasing acceleration
d) continue with constant velocity
e) immediately come to a stop

Question 4.2 Cart on Track II

We just decided that the cart continues with constant velocity. What would have to be done in order to have the cart continue with constant acceleration?

a) push the cart harder before release

b) push the cart longer before release

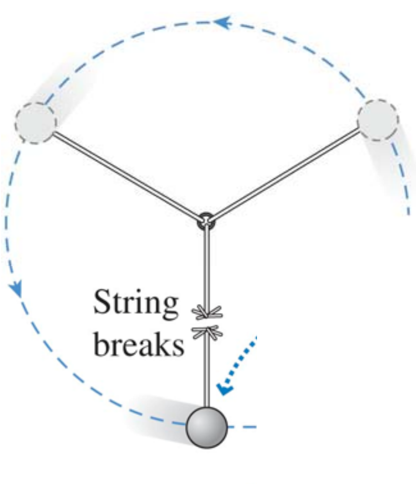
c) push the cart continuously

d) change the mass of the cart

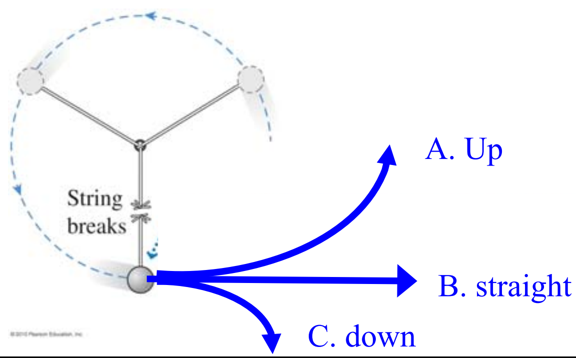
e) it is impossible to do that

Conceptual Example 4.1

An astronaut attaches a ball on a string and whirls it around in a circle. The string breaks. Describe the subsequent path of the ball.



An astronaut attaches a ball on a string and whirls it around in a circle. The string breaks. Describe the subsequent path of the ball.



4.2 Newton's Laws of Motion

Weight and Gravitational Acceleration

Weight

The magnitude of the gravitational force acting on an object of mass *m* near the Earth's surface is called the weight **w** of the object:

$$\vec{w} = m\vec{g} \quad \text{(Weight of an object with mass } m\text{; SI unit: N)} \qquad (4.1)$$

this is a special case of Newton's Second Law

g is the acceleration due to gravity

4.2 Newton's Laws of Motion

Newton's Second Law of Motion

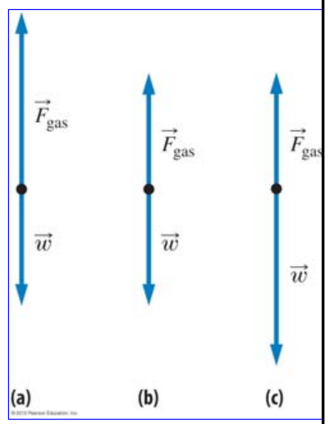
•The acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass.

$\mathbf{a} = \mathbf{F}_{\mathbf{net}} / \mathrm{m}$ or $\mathbf{F}_{\mathbf{net}} = \mathrm{m} \times \mathbf{a}$; SI units N (Newton) or kg × m/s^2.

Forces cause *changes* in motion

But motion can occur in the absence of forces!

Question (p. 74): A rocket of weight w is accelerating straight up just after launch. The exhaust gases exert a force F_{gas} on the rocket. Which is the correct force diagram for the rocket?



Question 4.24 Going Up I

A block of mass *m* rests on the floor of an elevator that is moving upward at constant speed. What is the relationship between the force due to gravity and the normal force on the block?

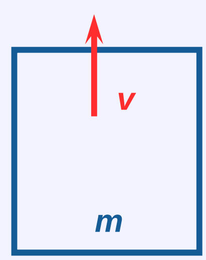
a) $N > mg$

b) $N = mg$

c) $N < mg$ (but not zero)

d) $N = 0$

e) depends on the size of the elevator



Question 4.6 Going Up II

A block of mass *m* rests on the floor of an elevator that is accelerating upward. What is the relationship between the force due to gravity and the normal force on the block?

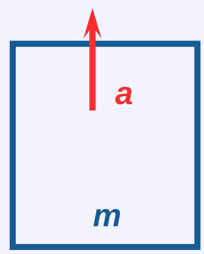
a) $n > mg$

b) $n = mg$

c) $n < mg$ (but not zero)

d) $n = 0$

e) depends on the size of the elevator



4.3 Applications of Newton's Laws

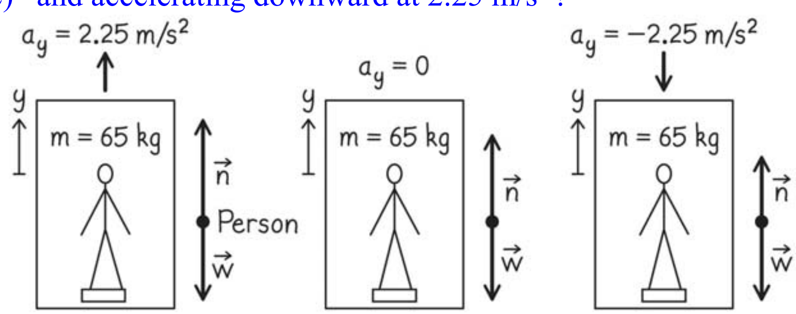
Solve Example 4.7 at home:

The scale measures the normal force between the scale and what is on it. What is the scale reading when the elevator is

a) accelerating upward at 2.25 m/s^2 ?

b) moving with constant velocity

c) and accelerating downward at 2.25 m/s^2 ?



(a) Accelerating upward (b) Constant velocity (c) Accelerating downward

Do problem 58 at home.

4.2 Newton's Laws of Motion

Weight and Gravitational Acceleration

Weight

Weight is **not** an inherent property of an object. Mass **is** an inherent property.Weight depends upon location.

In a free-fall, weight is the only force acting on the object, giving a net force $\mathbf{F}_{net} = \mathbf{w}$.

Mass, Inertia, and Newton's Law

Inertia is the tendency of an object to continue in its original motion.

Question 4.4 Newton's First Law III

You put your book on the bus seat next to you. When the bus stops suddenly, the book slides forward off the seat. Why?

a) a net force acted on it

b) no net force acted on it

c) it remained at rest

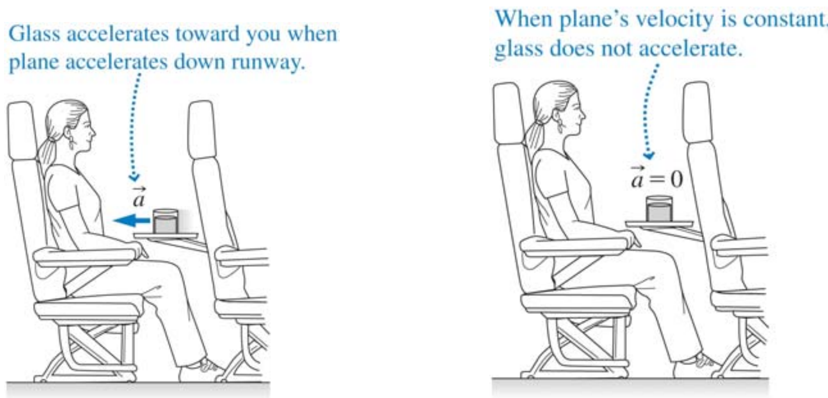
d) it did not move, but only seemed to

e) gravity briefly stopped acting on it

4.2 Newton's Laws of Motion

Initial Reference Frames

Newton's First and Second Laws only hold with reference frames moving with constant velocity. Because Newton's first law is about inertia, reference frames with constant velocity – that is, zero acceleration – are called **inertial reference frames**.



(a) Noninertial reference frame **(b)** Inertial reference frame

4.2 Newton's Laws of Motion

Newton's Third Law

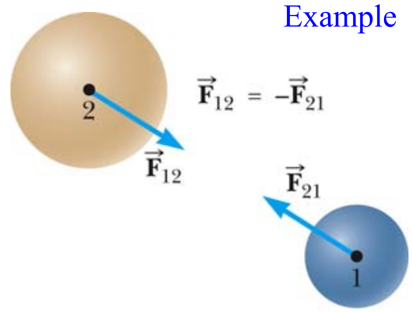
- Forces always come in pairs, acting on different objects:

- If object 1 exerts a force F on object 2, then object 2 exerts a force –F on object 1.

$$\vec{F}_{12} = -\vec{F}_{21}$$

- This is equivalent to saying a single isolated force cannot exist.
- They are called action-reaction pairs.

Example



(b)

- $\mathbf{F}_{12}$ may be called the *action* force and $\mathbf{F}_{21}$ the *reaction* force
  - Actually, either force can be the action or the reaction force
- The action and reaction forces act on **different** objects

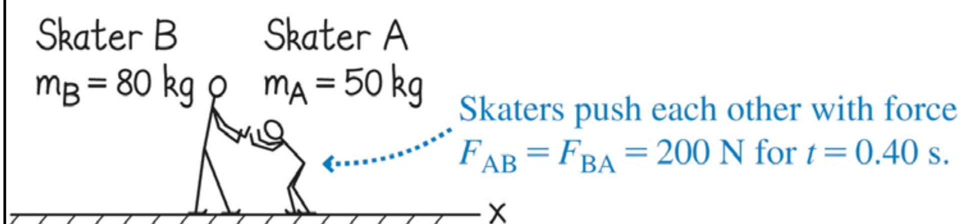
4.2 Newton's Laws of Motion

Solve Example 4.3 on page 72.

Two skaters, with masses m_A = 50 kg, and m_B = 80 kg, start from rest on frictionless ice and push off against each other with constant force. If they push with a constant 200-N force.

a) Find each skater's acceleration during the push.

b) If they push for 0.40 s, what are their velocities?



(a) Finding the accelerations

Solve at home: 40, 42

Question 4.5 Collision Course I

A small car collides with a large truck. Which experiences the greater impact force?

a) the car

b) the truck

c) both the same

d) it depends on the velocity of each

e) it depends on the mass of each

Question 4.3 Force and Two Masses

A force F acts on mass m_1 giving acceleration a_1. The same force acts on a different mass m_2 giving acceleration $a_2 = 2a_1$. If m_1 and m_2 are glued together and the same force F acts on this combination, what is the resulting acceleration?

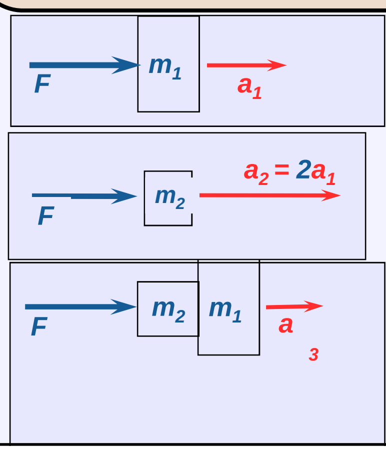
a) $\frac{3}{4}a_1$

b) $\frac{3}{2}a_1$

c) $\frac{1}{2}a_1$

d) $\frac{4}{3}a_1$

e) $\frac{2}{3}a_1$



Question 4.3 Force and Two Masses

A force F acts on mass m_1 giving acceleration a_1. The same force acts on a different mass m_2 giving acceleration $a_2 = 2a_1$. If m_1 and m_2 are glued together and the same force F acts on this combination, what is the resulting acceleration?

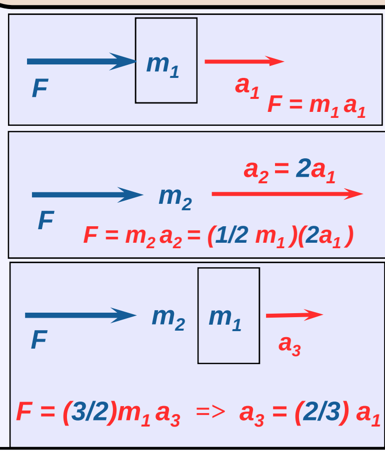
a) $\frac{3}{4}a_1$

b) $\frac{3}{2}a_1$

c) $\frac{1}{2}a_1$

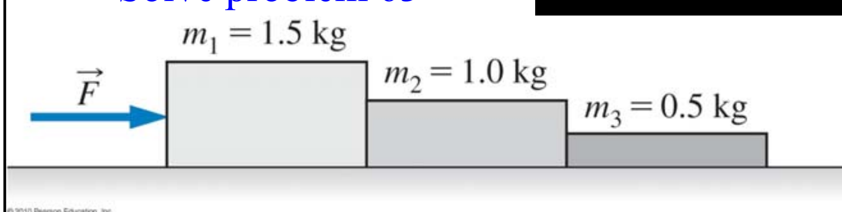
d) $\frac{4}{3}a_1$

e) $\frac{2}{3}a_1$



Mass m_2 must be ($\frac{1}{2}$ m_1) because its acceleration was $2a_1$ with the same force. Adding the two masses together gives $(3/2)m_1$, leading to an acceleration of $(2/3)a_1$ for the same applied force.

Solve problem 63



4.3 Applications of Newton's Laws

Assumptions:

- Objects behave as particles
  - Can ignore rotational motion (for now)
- Masses of strings or ropes are negligible
- Interested only in the forces acting on the object
  - Can neglect reaction forces

- Ignore any frictional effects of the rope
- Ignore the mass of the rope
- The magnitude of the force exerted along the rope is called the **tension**
- The tension is the same at all points in the rope

4.3 Applications of Newton's Laws

Newton's Second Law in Component Form

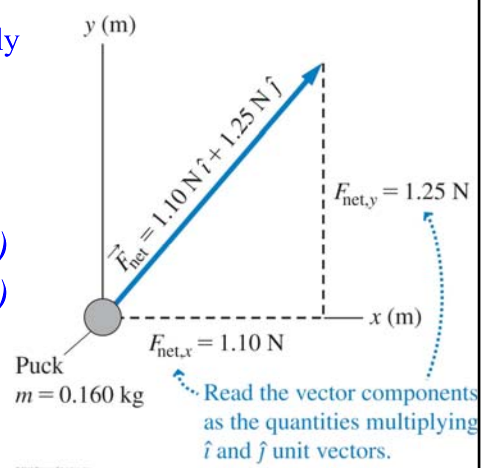
Solving problems in dynamics usually involves Newton's second law:

$\mathbf{F_{net}} = m \times \mathbf{a};$

If two vectors are equal, so are their respective components:

$F_{net,x} = m \times a_x$; *(x-component)*

$F_{net,y} = m \times a_y$; *(y-component)*

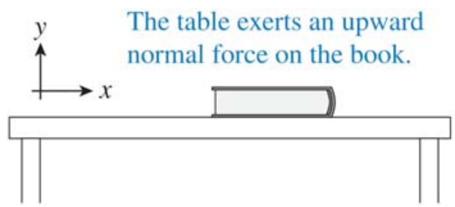


and as for any vector:

$\mathbf{F_{net}} = F_{net,x}\,\mathbf{i} + F_{net,y}\,\mathbf{j}$

4.3 Applications of Newton's Laws

The Normal Force
Is always normal (perpendicular) to the surface, whether the surface is horizontal or inclined. So it is **NOT necessary vertical**.

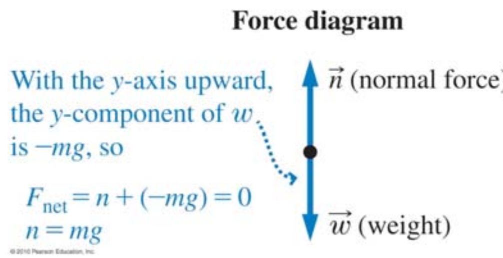


In this example, your equation is:

$\mathbf{F_{net}} = \mathbf{w} + \mathbf{n} = \mathbf{0}$

(Book at rest, a = 0, thus $\mathbf{F_{net}}$ = m**a** = 0)

Here: $F_{net,x} = 0$
Projecting on the y-axis: $F_{net,y} = 0$
$-w + n = 0$; (with $w = mg$)
$\Rightarrow (-mg) + n = 0$
$\Rightarrow$ **$n = mg$.**

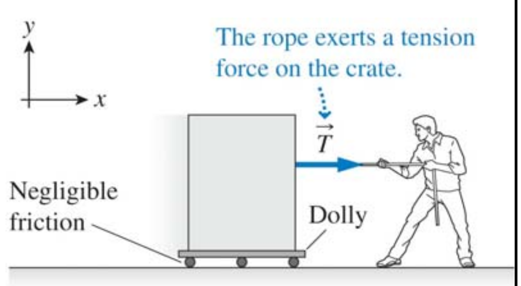


4.3 Applications of Newton's Laws

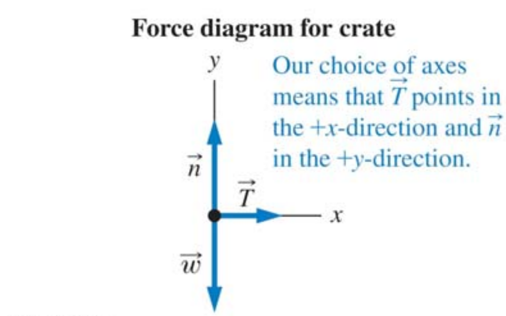
Tension

3 forces acting on the crate:
w, n and **T**.
Any motion along the y-axis?

NO =>
y-component :
n = mg.



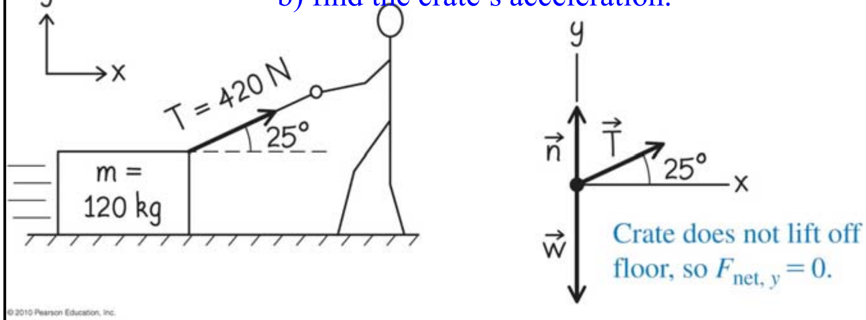
x-component:
$F_{net,x} = T = m\,a_x$.
=> $a_x = T/m$.



4.3 Applications of Newton's Laws

Solve Example 4.6: a) find the normal force between floor and crate

b) find the crate's acceleration.



4.3 Applications of Newton's Laws

Motion on an incline

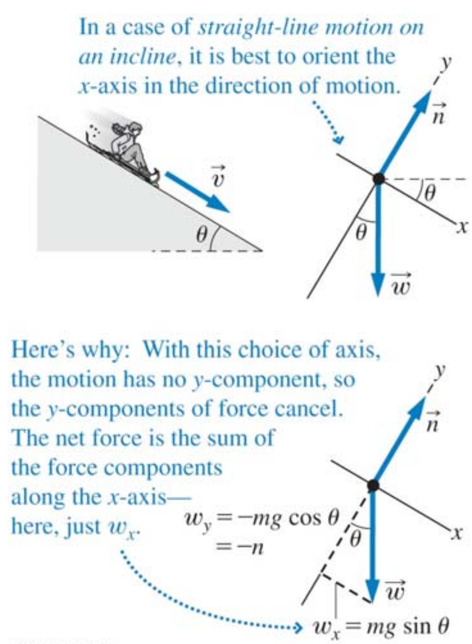
1- take x-axis along the incline
2- take y-axis normal to the incline

Notice:

3- the normal force **n** has a component only in the y-direction.

4 – the weight **w** has components in x and y.

5 – the angle between **w** and y-axis is also equal to θ of the incline.



4.3 Applications of Newton's Laws

Motion on an incline

Now we can find the acceleration:

x-component: $a_x \neq 0$

$F_{net,x} = mg \sin\theta = ma_x$

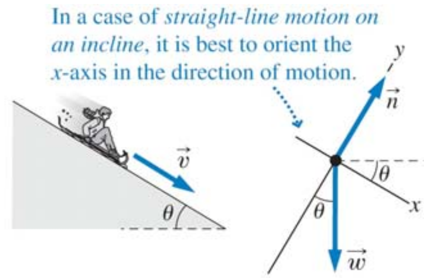
y-component: $a_y = 0$

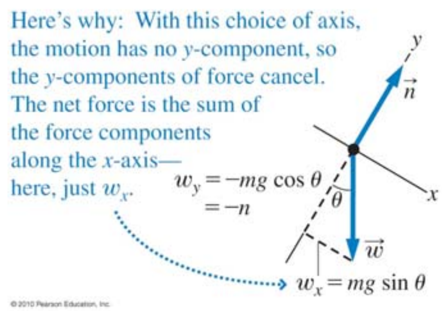
$F_{net,y} = n - m g \cos\theta$

$= ma_y = 0$

$\Rightarrow n = m g \cos\theta$

So for an object on a frictionless incline, subject only to gravity and the normal force; the normal force has a Lower value than in its value n = mg on a horizontal surface.





4.4 Friction and Drag

Frictional forces result from an interaction between the object and a surface it contacts. **Drag forces** affect objects moving through fluids. Friction results ultimately from electric forces on atoms in two contacting surfaces.

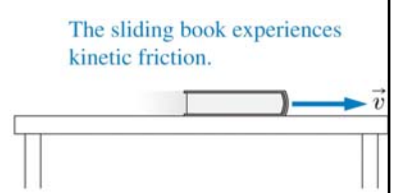
Kinetic Friction

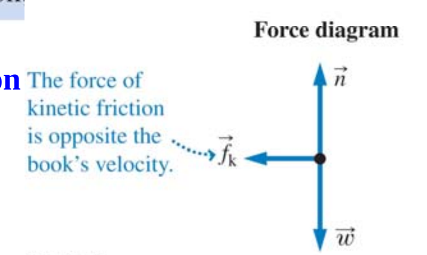
The magnitude of the frictional force f_k is proportional to the magnitude of the normal force n:

$f_k = \mu_k n$ (Force of kinetic friction

μ_k is the **coefficient of kinetic friction**

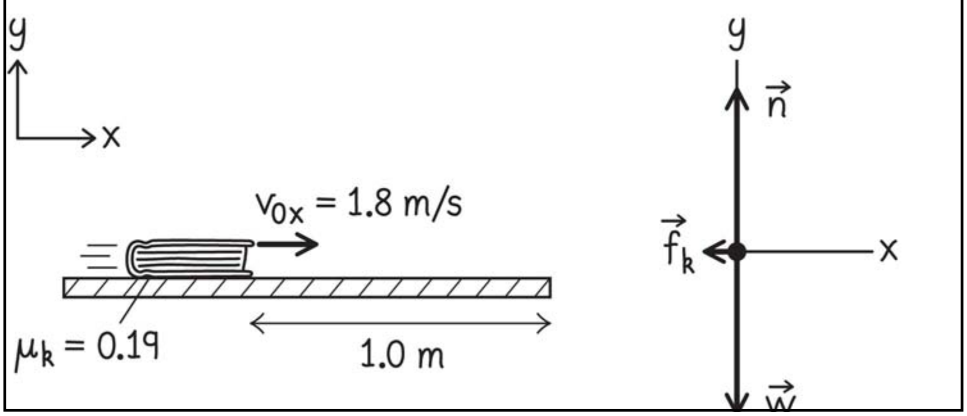
Smooth, slippery surfaces have low values of μ_k (< 0.2). Rough or sticky surfaces may have μ_k = 1 or more.





4.4 Friction and Drag
Kinetic Friction

Solve example 4.8 **– Sliding Away?**
You slide your textbook across a lab bench, starting at 1.8 m/s in the +x-direction. μ_k between the book and the bench is 0.19.
a)What's the book acceleration?
b)Will the book reach the edge of the bench, 1.0 m away?



4.4 Friction and Drag
Kinetic Friction

Solve example 4.9.

4.4 Friction and Drag

Rolling Friction

It involves a round object rolling on a surface. Quantitatively, rolling friction is similar to kinetic friction. The frictional force $\mathbf{f_r}$ is directed opposite the rolling body's velocity, with magnitude f_r proportional to the normal force:

$$f_r = \mu_r n \quad \text{(Force of rolling friction: SI unit: N)} \tag{4.7}$$

μ_r is the **coefficient of rolling friction**

Quantitatively, μ_r is about 40 times smaller than μ_k.
That's one reason why wheels are a great invention.

4.4 Friction and Drag

Static Friction

It results from attractive forces between atoms in the contacting surfaces. It is a force ($\mathbf{f_s}$) that adjusts to keep the sum of all forces (acting on an object at rest and including the static friction) equal to zero.

$$f_s \leq \mu_s n \quad \text{(Force of static friction; SI unit: N)} \tag{4.8}$$

μ_s is the **coefficient of static friction**
The equation above gives the magnitude of $\mathbf{f_s}$; its direction is whatever makes the net force on the object zero.
In general, μ_s is larger than μ_k because the forces between atoms in contacting surfaces are stronger than those for moving surfaces.
See table 4.1 in the book for a list of coefficients.

Solve example 4.10 on your own.

4.4 Friction and Drag

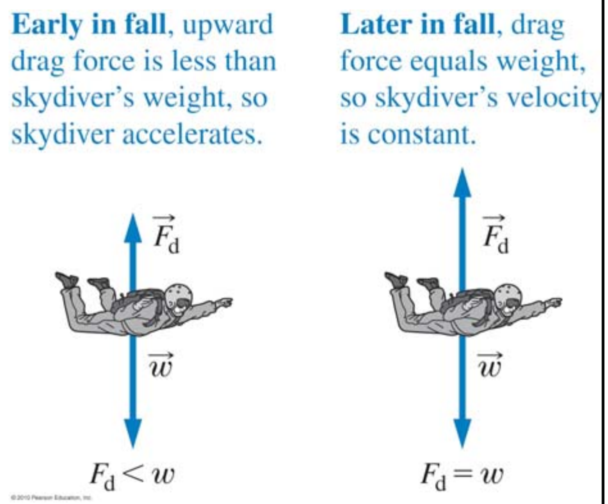
Moving with Friction

Read in the book.

Drag Force

Drag forces depend on the object's speed (they are not constant). F_{drag} can be proportional to v or to v^2.

From the figure on the right, is F_{drag} greater or smaller when v increases?

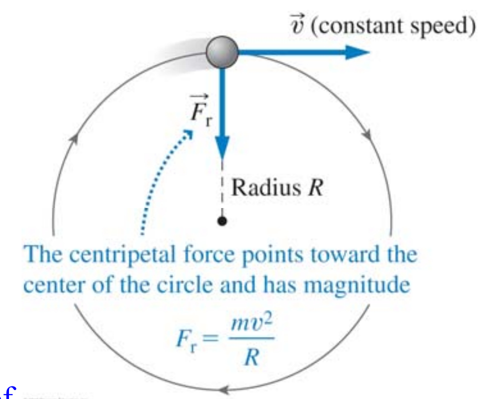


What motion do you have when F_{drag} is equal to w in magnitude?

That constant speed is called the terminal speed, and is ~ 50 – 80 m/s

4.5 Newton's Laws and Uniform Circular Motion

Recall an object in a uniform circular motion has a centripetal acceleration $a_r = v^2/R$(directed towards the center). Following Newton's second law $\mathbf{F_{net}} = m \times \mathbf{a}$, there must be a net force that is also directed towards the center. This is the centripetal force: $F_r = m \times v^2/R$ (SI units: N).

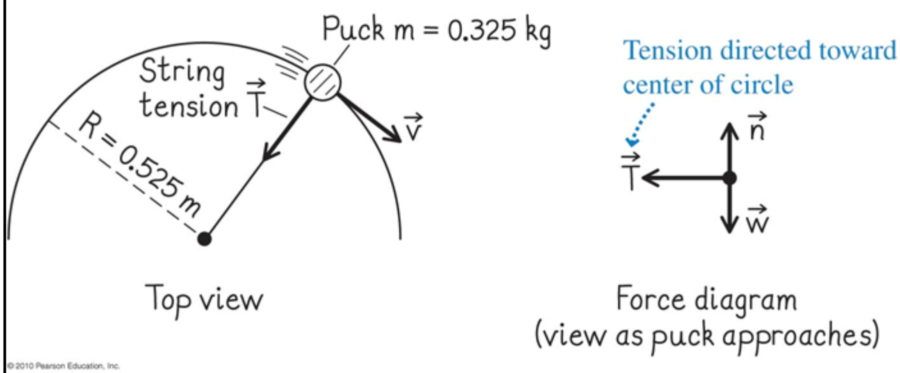


Note: F_r is not another category, of force like the normal force, tension or gravity. It is just the net force, i.e., the sum of all forces acting on the object.

Thus, when you draw a force diagram, do NOT include it on it.

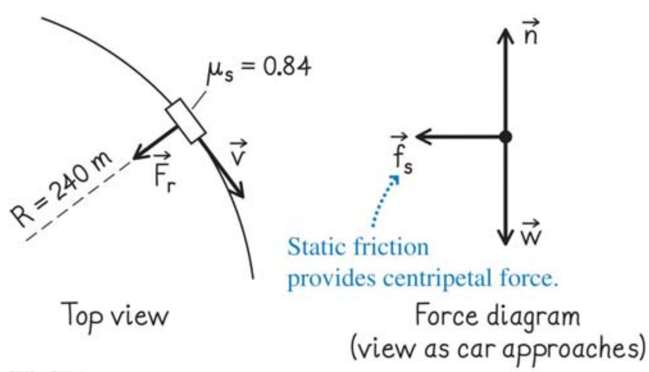
4.5 Newton's Laws and Uniform Circular Motion

Solve example 4.11 – **A Whirling Puck.**
A 0.525-m string connects a 0.325-kg puck to a peg at the center of a frictionless air table. If the string tension is 25.0 N, find the puck's *centripetal acceleration* and *its speed*.



4.5 Newton's Laws and Uniform Circular Motion

Exp 4.12: The coefficient of static friction between the car's tires and a flat road is 0.84. Find the maximum speed on a turn of radius 240 m.



Question 4.7 Around the Curve III

You drive your car too fast around a curve and the car starts to skid. What is the correct description of this situation?

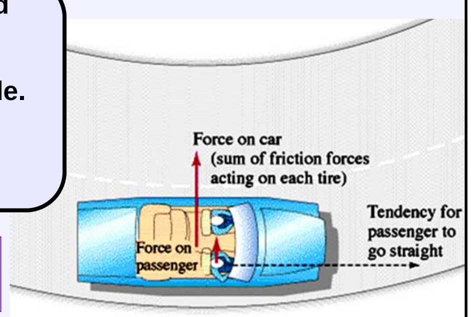
a) car's engine is not strong enough to keep the car from being pushed out
b) friction between tires and road is not strong enough to keep car in a circle
c) car is too heavy to make the turn
d) a deer caused you to skid
e) none of the above

Question 4.7 Around the Curve III

You drive your dad's car too fast around a curve and the car starts to skid. What is the correct description of this situation?

a) car's engine is not strong enough to keep the car from being pushed out
b) friction between tires and road is not strong enough to keep car in a circle
c) car is too heavy to make the turn
d) a deer caused you to skid
e) none of the above

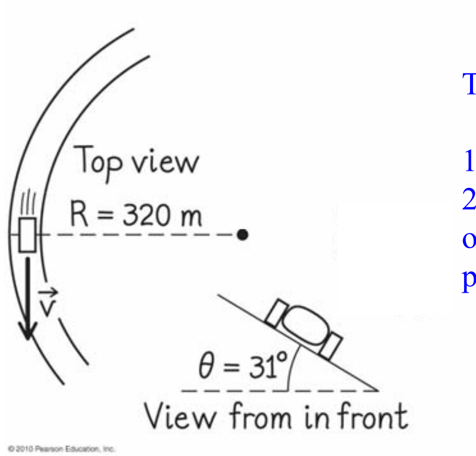
The friction force between tires and road provides the centripetal force that keeps the car moving in a circle. If this force is too small, the car continues in a straight line!



Follow-up: What could be done to the road or car to prevent skidding?

4.5 Newton's Laws and Uniform Circular Motion

Solve example 4.13 – **A Banked Curve.**
The Daytona International Speedway has one of the steepest banked curves, with maximum angle 31° on a curve of radius 320 m. What is the maximum speed for this curve, assuming no friction?



Think about the choice of your axis:

1- What is the direction of the $\mathbf{a}_r$?
2- Do I take the x-axis horizontal or in the direction of the inclined plane?

Question 4.8 Around the Curve I

You are a passenger in a car, not wearing a seat belt. The car makes a sharp left turn. From your perspective in the car, what do you feel is happening to you?

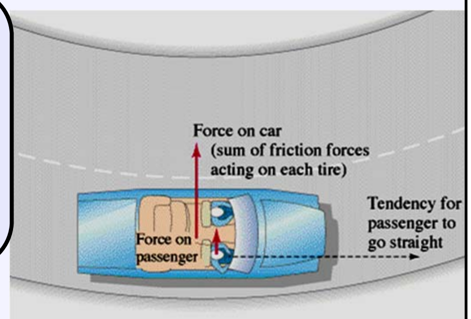
a) you are thrown to the right
b) you feel no particular change
c) you are thrown to the left
d) you are thrown to the ceiling
e) you are thrown to the floor

Question 4.8 Around the Curve I

You are a passenger in a car, not wearing a seat belt. The car makes a sharp left turn. From your perspective in the car, what do you feel is happening to you?

a) you are thrown to the right
b) you feel no particular change
c) you are thrown to the left
d) you are thrown to the ceiling
e) you are thrown to the floor

The passenger has the tendency to continue moving in a straight line. From your perspective in the car, it feels like you are being thrown to the right, hitting the passenger door.



Question 4.9 Around the Curve II

During that sharp left turn, you found yourself hitting the passenger door. What is the correct description of what is actually happening?

a) centrifugal force is pushing you into the door
b) the door is exerting a leftward force on you
c) both of the above
d) neither of the above

Question 4.9 Around the Curve II

During that sharp left turn, you found yourself hitting the passenger door. What is the correct description of what is actually happening?

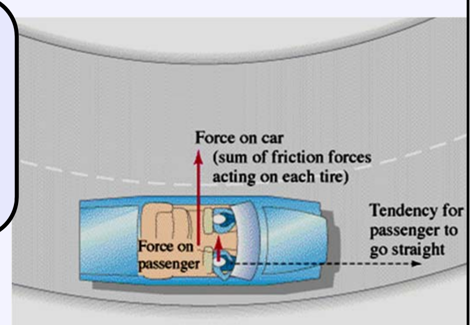
a) centrifugal force is pushing you into the door

b) the door is exerting a leftward force on you

c) both of the above

d) neither of the above

The passenger has the tendency to continue moving in a straight line. There is a centripetal force, provided by the door, that forces the passenger into a circular path.



Question 4.10 Going in Circles I

You're on a Ferris wheel moving in a vertical circle. When the Ferris wheel is at rest, the normal force n exerted by your seat is equal to your weight mg. How does n change at the top of the Ferris wheel when you are in motion?

a) n remains equal to mg

b) n is smaller than mg

c) n is larger than mg

d) none of the above

Question 4.10 Going in Circles I

You're on a Ferris wheel moving in a vertical circle. When the Ferris wheel is at rest, the normal force *n* exerted by your seat is equal to your weight *mg*. How does *n* change at the top of the Ferris wheel when you are in motion?

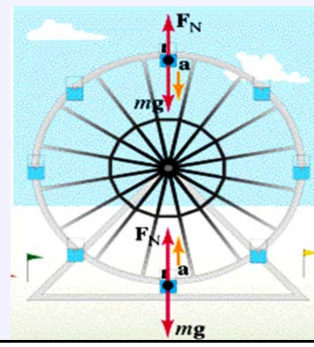
a) *n* remains equal to *mg*

b) *n* is smaller than *mg*

c) *n* is larger than *mg*

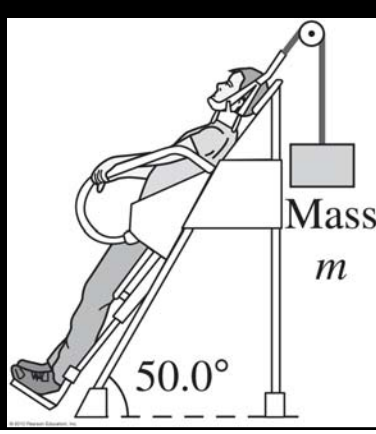
d) none of the above

You are in circular motion, so there has to be a centripetal force pointing *inward*. At the top, the only two forces are *mg* (down) and *N* (up), so *n* must be smaller than *mg*.



Follow-up: Where is *n* larger than *mg*?

Problem 82



Problem 56

Summary of Chapter 4

•Force: interaction between two objects, a push/pull or action at a distance
•Mass (inertia): resistance to change in motion
•Net Force: sum of all forces acting on an object; $\boldsymbol{F}_{net} = \boldsymbol{F}_1 + \boldsymbol{F}_2 + \boldsymbol{F}_3$
•**Newton's Laws of Motion:**
1st Law: Zero net force implies constant velocity
2nd Law: Net force is proportional to acceleration; $\mathbf{F}_{net} = m \times \mathbf{a}$.
3rd Law: Forces come in pairs – action-reaction pairs; $\mathbf{F}_{12} = -\mathbf{F}_{21}$.
•Given an object's mass and the force(s) acting on it, you can find its acceleration by **writing Newton's 2nd Law in components**: $\mathbf{F}_{net,x}$ & $\mathbf{F}_{net,y}$

•Frictional forces result from interactions between an object and the surfac it rests on or moves across.
•Drag forces retard a motion moving through a fluid.
Kinetic friction: $f_k = u_k n$; rolling friction : $f_r = u_r n$; static friction: $f_s = u_s n$

•Centripetal force, the net force on an object in uniform circular motion, is toward the center of the circle.
Centripetal force: $F_r = mv^2/R$.