PC1221 Fundamentals of Physics I

Lectures 9 and 10
The Laws of Motion

A/Prof Tay Seng Chuan

Ground Rules

- Switch off your handphone and pager
- Switch off your laptop computer and keep it
- No talking while lecture is going on
- No gossiping while the lecture is going on
- Raise your hand if you have question to ask
- Be on time for lecture
- Be on time to come back from the recess break to continue the lecture
- Bring your lecturenotes to lecture

Force

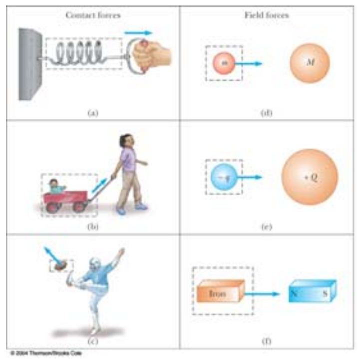
- Forces can cause a change in the velocity of an object
  - This is because a force can causes an acceleration
- The ***net force*** is the vector sum of all the forces acting on an object
  - A net force is also called the total force, resultant force, or unbalanced force

Zero Net Force

- When the net force is equal to zero:
  - The acceleration is equal to zero
  - The velocity is constant
- ***Equilibrium*** occurs when the net force is equal to zero
  - The object, if at rest, will remain at rest
  - If the object is moving, it will continue to move at a constant velocity

Classes of Forces

- Contact forces involve physical contact between two objects
- Field forces act through empty space
  - No physical contact is required



Fundamental Forces

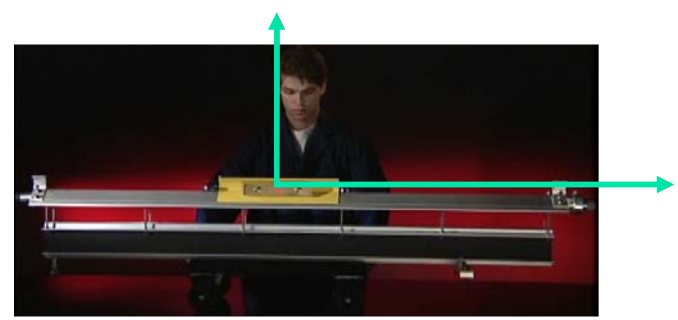
- Gravitational force
  - Between two objects
- Electromagnetic forces
  - Between two charges
- Nuclear force
  - Between subatomic particles
- Weak forces
  - Arise in certain radioactive decay processes

More About Forces

- A spring can be used to calibrate the magnitude of a force
- Forces are vectors, so you must use the rules for vector addition to find the net force acting on an object

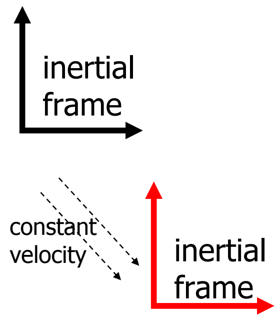
Newton's First Law

- If an object does not interact with other objects, it is possible to identify a reference frame in which the object has zero acceleration
  - This is also called the *law of inertia*
  - It defines a special set of reference frames called *inertial frames*,
    - We call this an ***inertial frame of reference***



Inertial Frames

- Any reference frame that moves with constant velocity relative to an inertial frame is itself also an inertial frame
- A reference frame that moves with constant velocity relative to the distant stars is the best approximation of an inertial frame
  - We can consider the Earth to be such an inertial frame



Newton's First Law – Alternative Statement

- In the absence of external forces, when viewed from an inertial reference frame, an object at rest remains at rest and an object in motion continues in motion with a constant velocity
  - Newton's First Law describes what happens in the absence of external forces, i.e., the resultant force is zero
  - It tells us that when the net force acts on an object is zero, the acceleration of the object is zero

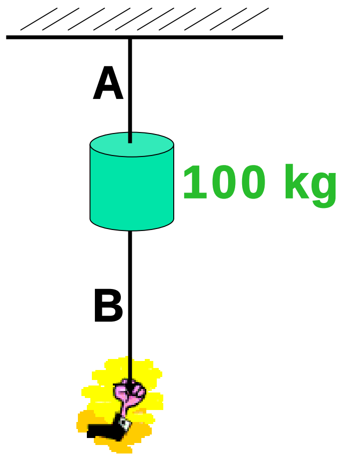
Why can the table cloth be pulled away without messing up the plates and glasses?

Answer: This is due to the inertia property of the objects above the table cloth. These objects have mass and they resist to change its original velocity (0 velocity).

Inertia and Mass

- The tendency of an object to resist any attempt to change its velocity is called ***inertia***
- ***Mass*** is that property of an object that specifies how much resistance an object exhibits to changes in its velocity

Which string will be broken?



If we pull string B downward slowly, which string will be broken or both will be broken? Why?

What if we pull string B downward at very fast speed, which string will be broken or both? Why?

More About Mass

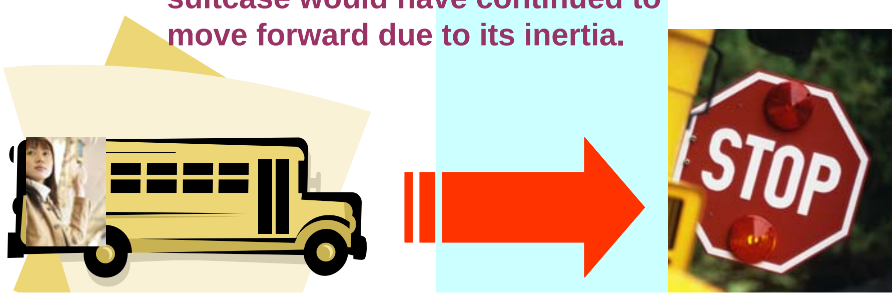
- Mass is an inherent property of an object
- Mass is independent of the object's surroundings
- Mass is also independent of the method used to measure it
- Mass is a scalar quantity
- The SI unit of mass is kg

Court Case:

A passenger sitting in the rear of a bus claimed that she was injured as the driver slammed on the brakes, causing a suitcase to come flying toward her from the front of the bus. Armed with the knowledge of Physics, you were invited to assist the judge in this case. What advice would you give to the judge? Why?

Answer:

The claim is not possible as the suitcase would have continued to move forward due to its inertia.



Mass vs. Weight

- Mass and weight are two different quantities
- Weight is equal to the magnitude of the gravitational force exerted on the object
  - Weight will vary with location.

Newton's Second Law

- When viewed from an inertial frame, the acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass
  - Force is the cause of the change in motion. The change in motion is measured by the acceleration
- Algebraically, $\Sigma \mathbf{F} = m\,\mathbf{a}$

More About Newton's Second Law

- $\Sigma \mathbf{F}$ is the net force
  - This is the vector sum of all the forces acting on the object
- Newton's Second Law can be expressed in terms of 3 components:
  - $\Sigma F_x = m\,a_x$
  - $\Sigma F_y = m\,a_y$
  - $\Sigma F_z = m\,a_z$

Units of Force

Table 5.1

Units of Mass, Acceleration, and Force[a]

System of Units	Mass	Acceleration	Force
SI	kg	m/s^2	$N = kg \cdot m/s^2$
U.S. customary	slug	ft/s^2	$lb = slug \cdot ft/s^2$

[a] 1 N = 0.225 lb.

Gravitational Force

- The gravitational force, $\mathbf{F_g}$, is the force that the earth exerts on an object
- This force is directed toward the center of the earth
- Its magnitude is called the weight of the object
- Weight = $|\mathbf{F_g}| = mg$

More About Weight

- Because weight is dependent on g, the weight varies with location
  - g, and therefore the weight, is smaller at higher altitudes
- Weight is not an inherent property of the object

Gravitational Mass vs. Inertial Mass

- In Newton's Laws, the mass is the inertial mass and measures the resistance to a change in the object's motion
- In the gravitational force, the mass is determining the gravitational attraction between the object and the Earth
- Experiments show that gravitational mass and inertial mass have the same value

Newton's Third Law

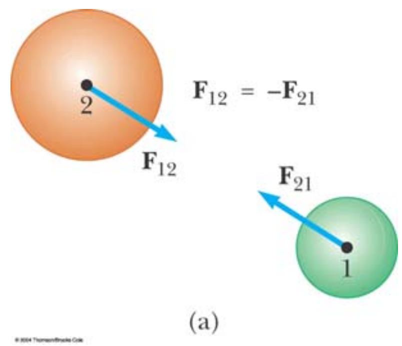
- If two objects interact, the force $\mathbf{F}_{12}$ exerted by object 1 on object 2 is equal in magnitude, and opposite in direction, to the force $\mathbf{F}_{21}$ exerted by object 2 on object 1
- $\mathbf{F}_{12} = -\mathbf{F}_{21}$
  - Note on notation: $\mathbf{F}_{AB}$ is the force exerted by A on B

Newton's Third Law, Alternative Statements

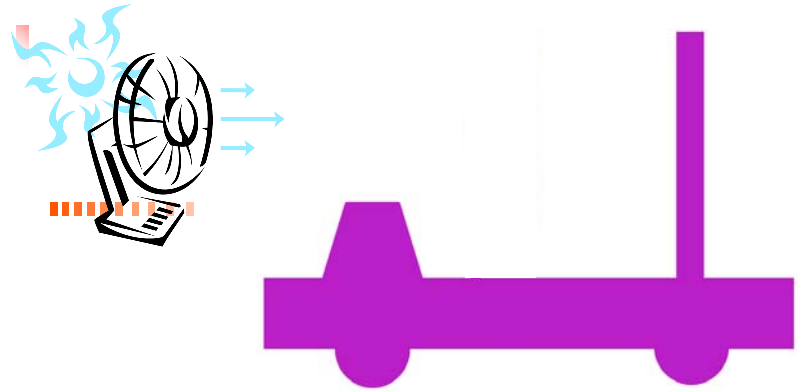
- Forces always occur in pairs
- A single isolated force cannot exist
- The action force is equal in magnitude to the reaction force and opposite in direction
  - One of the forces is the action force, the other is the reaction force
  - It doesn't matter which is considered the action and which the reaction
  - The action and reaction forces must act on different objects and be of the same type

Action-Reaction Examples, 1

- The force $\mathbf{F}_{12}$ exerted by object 1 on object 2 is equal in magnitude and opposite in direction to $\mathbf{F}_{21}$ exerted by object 2 on object 1
- $\mathbf{F}_{12} = - \mathbf{F}_{21}$

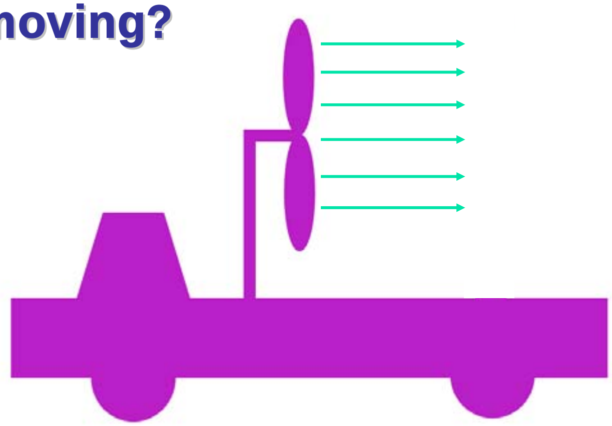


Which direction is this vehicle moving?



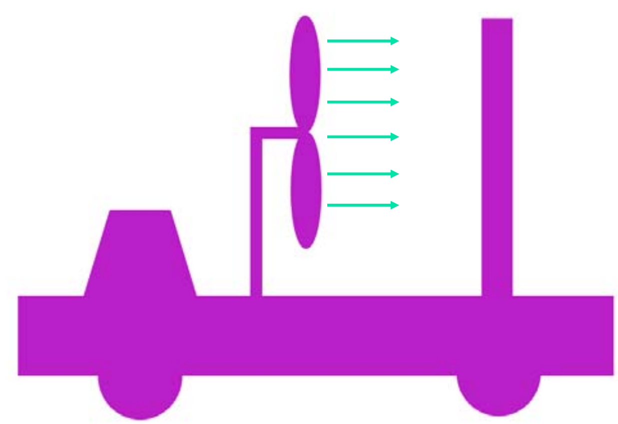
(i) The fan on vehicle is removed but a fan on the left of the vehicle is switched on.

Which direction is this vehicle moving?



(ii) The fan on vehicle is switched on, and the sail and the fan on the left is removed.

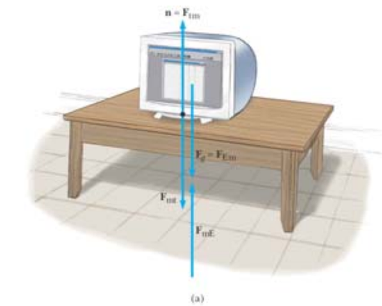
Which direction is this vehicle moving?



(iii) The fan on vehicle is switched on and the sail is attached, and the fan on the left is removed.

Action-Reaction Examples, 2

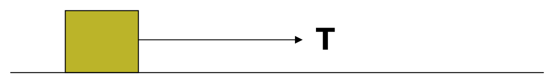
- The normal force (table on monitor) is the reaction of the force the monitor exerts on the table
  - Normal means perpendicular to the surface
  - The action (**F_g**, Earth on monitor) force, i.e. the weight of monitor, is equal in magnitude and opposite in direction to the reaction force



(a)

Applications of Newton's Law

- Assumptions
  - Objects can be modeled as particles
  - Masses of strings or ropes are negligible
    - When a rope attached to an object is pulling it, the magnitude of that force, **T**, is the **tension** in the rope



Objects in Equilibrium

- If the acceleration of an object that can be modeled as a particle is zero, the object is said to be in **equilibrium**
- Mathematically, the net force acting on the object is zero

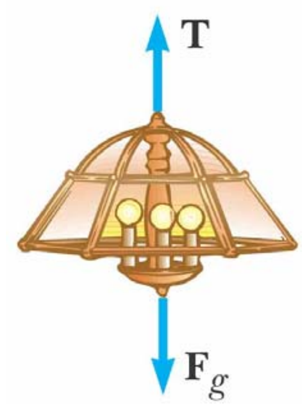
$$\sum F = 0$$

$$\sum F_x = 0 \text{ and } \sum F_y = 0$$

Equilibrium, Example 1a

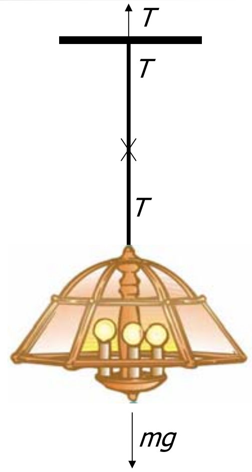
- A lamp is suspended from a chain of negligible mass
- The forces acting on the lamp are
  - the force of gravity (**F_g**)
  - the tension in the chain (**T**)
- Equilibrium gives

$$\sum F_y = 0 \rightarrow T - F_g = 0 \qquad T = F_g$$



Equilibrium, Example 1b

- If the chain is hooked on ceiling, the chain exerts a force of *T* on the ceiling
- On the ceiling the force acted on the chain is also *T*

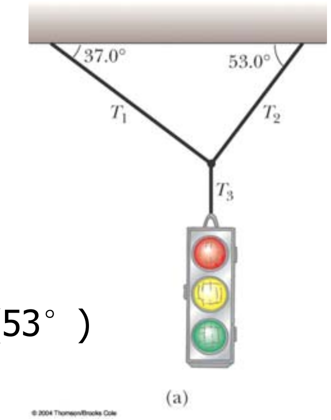


Equilibrium, Example 2

Let the mass of the traffic light be *m*.

We have $mg = T_3$

$T_3 = T_1 \sin(37^\circ) + T_2 \sin(53^\circ)$



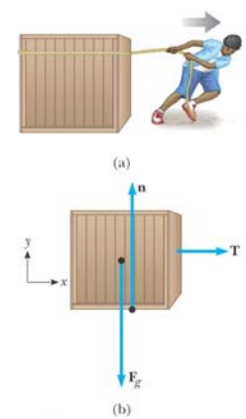
Objects Experiencing a Net Force

- If an object that can be modeled as a particle experiences an acceleration, there must be a nonzero net force acting on it.

Newton's Second Law, Example 1a

- Three Forces acting on the crate:
  - A tension, the magnitude of force **T**
  - The gravitational force, $\mathbf{F_g}$
  - The normal force, **n**, exerted by the floor

Ignore friction at the moment.



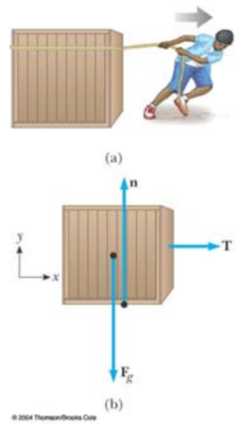
Newton's Second Law, Example 1b

- Apply Newton's Second Law in component form:

$$\sum F_x = T = ma_x$$

$$\sum F_y = n - F_g = 0 \rightarrow n = F_g$$

- Solve for the unknown(s)
- If **T** is constant, then *a* is constant and the kinematic equations can be used to describe the motion of the crate



Note About the Normal Force

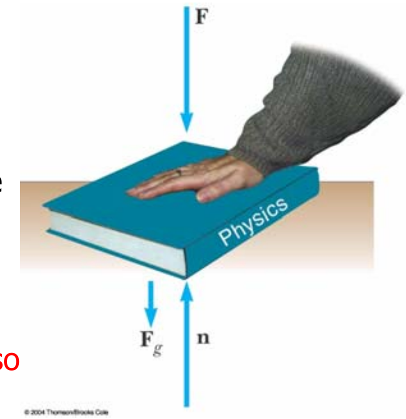
- The normal force is **not** always equal to the gravitational force of the object
- For example, in this case

$$\sum F_y = n - F_g - F = 0$$

$$\text{and } n = F_g + F$$

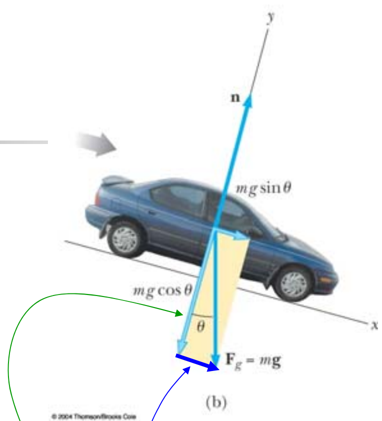
- Normal force (n) may also be less than the weight (F_g). How?

Use air cushion! Tie a string on the book and pull it up! Etc.



Inclined Planes

- Forces acting on the object:
  - The normal force, **n**, acts perpendicular to the plane
  - The gravitational force, $\mathbf{F_g}$, acts straight down
- Choose the coordinate system with *x* along the incline and *y* perpendicular to the incline
- Replace the force of gravity with its components

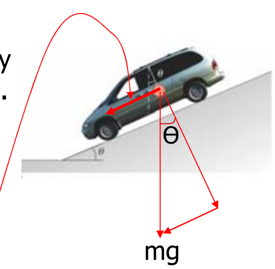


mg sinΘ = *ma*

mg cosΘ = *n*

What if Θ =0° ?

Example. A van accelerates down a hill, going from rest to 30.0 m/s in 6.00 s. During the acceleration, a toy (*m* = 0.100 kg) hangs by a string from the van's ceiling. The acceleration is such that the string remains perpendicular to the ceiling. Determine (a) the angle and (b) the tension in the string.



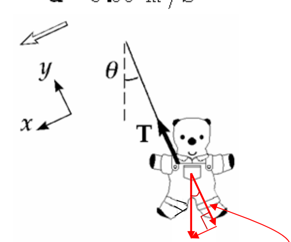
Answer:

Choose the x-axis pointing down the slope.

$$v_f = v_i + at: \quad 30.0 \text{ m/s} = 0 + a(6.00 \text{ s})$$

$$a = 5.00 \text{ m/s}^2 .$$

$$\mathbf{a} = 5.00 \text{ m/s}^2$$



Consider forces on the toy.

$$\sum F_x = ma_x: \quad mg\sin\theta = m(5.00 \text{ m/s}^2)$$

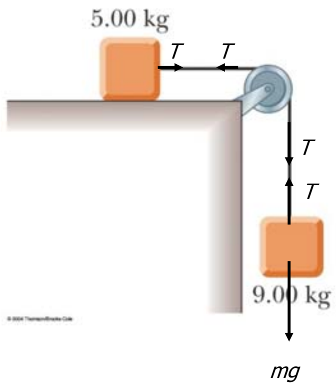
$$\theta = \boxed{30.7°}$$

$$\sum F_y = ma_y: \quad -mg\cos\theta + T = 0$$

$$T = mg\cos\theta = (0.100)(9.80)\cos 30.7°$$

$$T = \boxed{0.843 \text{ N}}$$

Example. A 5.00-kg object placed on a frictionless, horizontal table is connected to a cable that passes over a pulley and then is fastened to a hanging 9.00-kg object, as in Figure. Find the acceleration of the two objects and the tension in the string.



Answer:

$mg - T = 9\,a$

$9 \times 9.8 - T = 9\,a$

$88.2 - T = 9\,a$ --- (1)

$T = 5\,a$ --- (2)

Substitute (2) in (1)

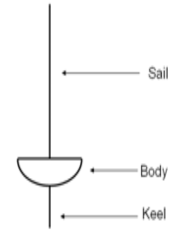
$88.2 - 5\,a = 9\,a$

$14\,a = 88.2$

$a = 6.3\ \text{m/s}^2$

$T = 5\,a = 5 \times 6.3 = 31.5\ \text{N}$

Example. A simplified model of a sail boat consists of 3 parts: (i) Sail - completely above water, (ii) Body – very small and only slightly immerged in water, and (iii) Keel – fully immerged in water. Both the sail and keel are steerable.

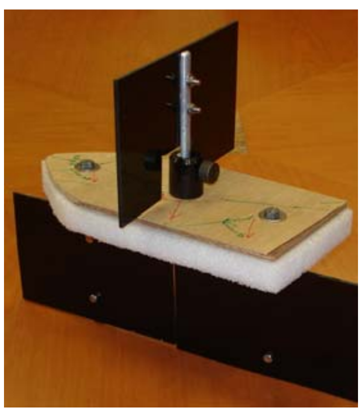


Front View of Model

Front View of Sail Boat

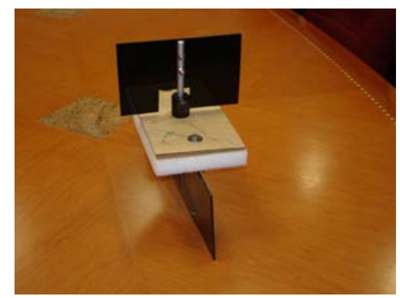
With the angles of the sail and keel properly set, the boat is able to sail upwind (against the wind) at an angle.

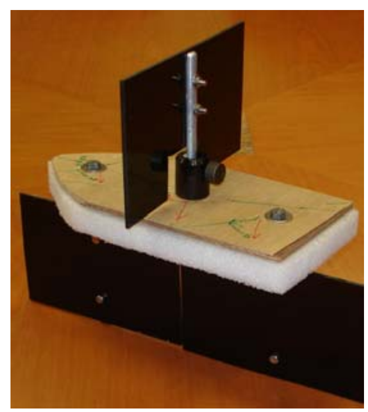
With the help of a plane-view diagram, explain how the boat can sail against the wind to reach a destination on the opposite side of a river bank. Assume that the wind has negligible effect on the surface water current, and under-water current does not exist.



Both the sail and keel are steerable.

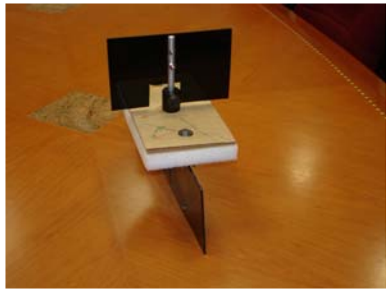
Which direction are these boats heading?

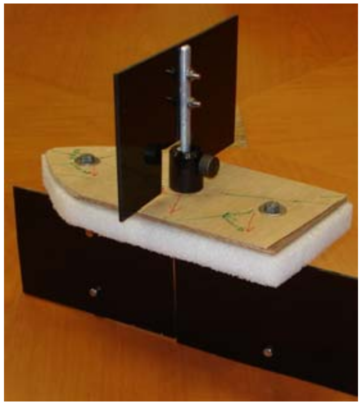




Wind Direction

Which direction are these boats heading?





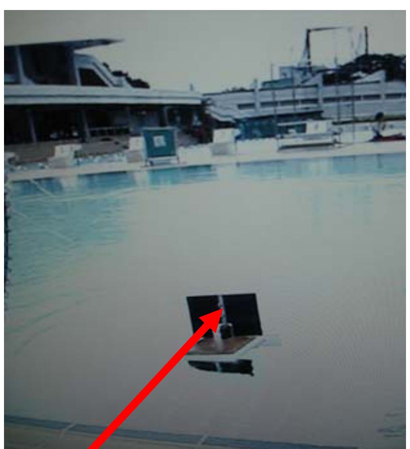
Your answer?

Wind Direction

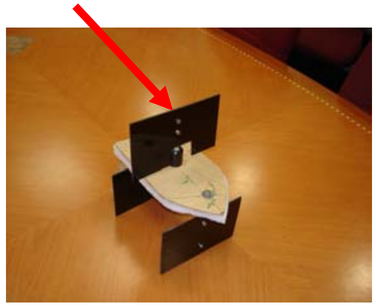
Wind Direction

Which direction is this boat heading?

Why was it so difficult for this boat to move forward in the same direction with the wind?

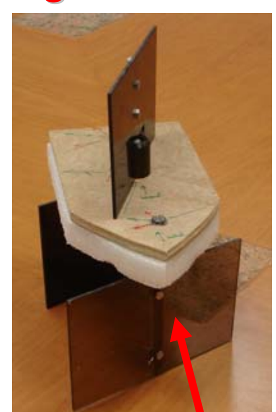


Wind Direction



Wind Direction

Which directions are these boats heading when the wind is against them?

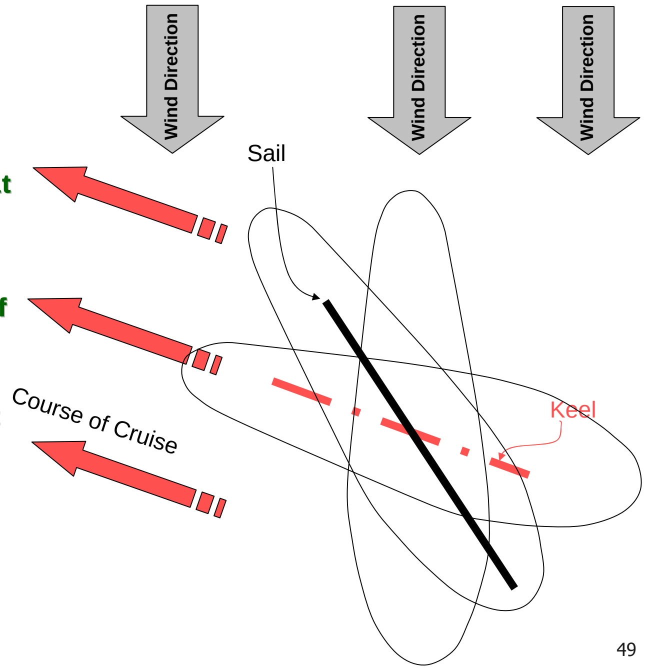


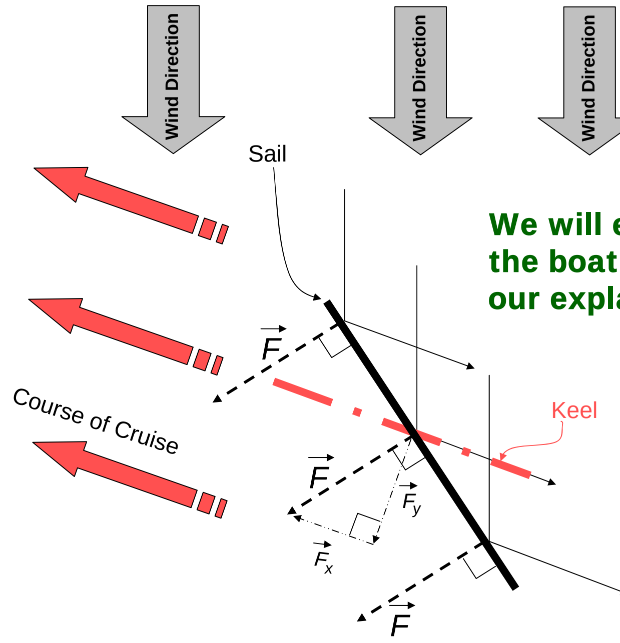
Wind Direction

Wind Direction

Three options (or more) for the boat body orientation but actually the Physics is the same if the size of the boat body is small.

However, the last orientation is the best because the mass of water body to be displaced is the least.

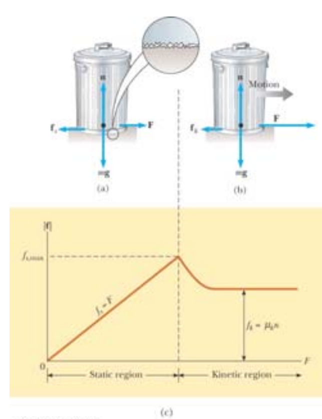




We will exclude the boat body in our explanation

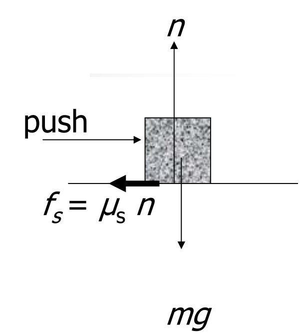
Forces of Friction

- When an object is in motion on a surface or through a viscous medium, there will be a resistance to the motion
  - This is due to the interactions between the object and its environment
- This resistance is called the *force of friction*



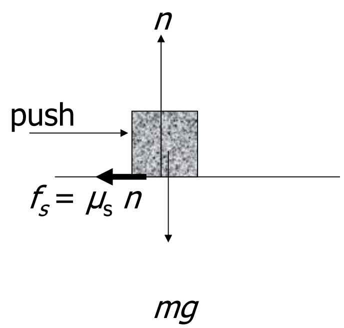
Forces of Friction, cont.

- Friction is proportional to the normal force
  - $f_s \le \mu_s n$ and $f_k = \mu_k n$
  - These equations relate the magnitudes of the forces, they are not vector equations
- The force of static friction is generally greater than the force of kinetic friction
- The coefficient of friction (μ) depends on the surfaces in contact
- μ is an empirical value. The common observation is that μ is less than 1. As such, many people have the idea that μ must be less than 1 **- this is wrong.**
- μ can be greater than 1, such as on a rubber coated surface.



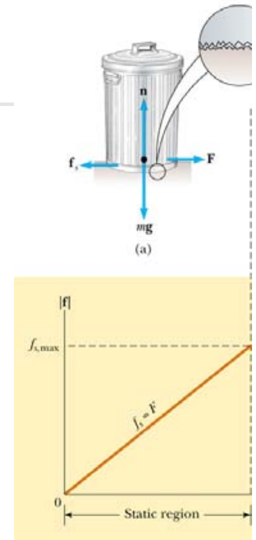
Forces of Friction, final

- The direction of the frictional force is opposite to the direction of motion and parallel to the surfaces in contact
- The coefficients of friction are independent of the area of contact



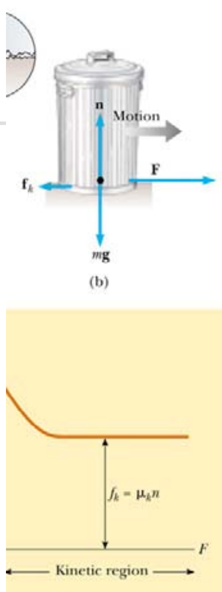
Static Friction

- Static friction acts to keep the object from moving
- If **F** increases, so does $\boldsymbol{f}_s$
- If **F** decreases, so does $\boldsymbol{f}_s$
- $\boldsymbol{f}_s \le \mu_s n$ where the equality holds when the surfaces are on the verge of slipping
  - Called impending motion

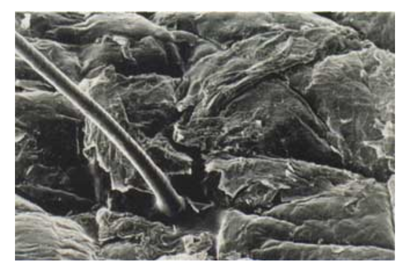


Kinetic Friction

- The force of kinetic friction acts when the object is in motion
- Although μ_k can vary with speed, we shall neglect any such variations
- $f_k = \mu_k n$

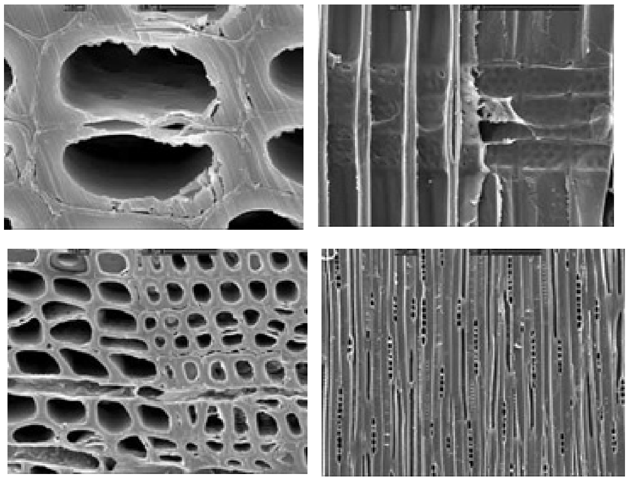


Microscopic View of Human Skin



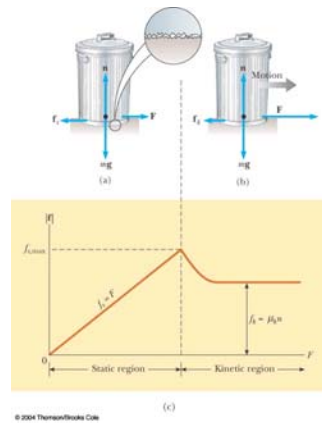
It is not smooth under such a magnification.

Microscopic View of a Smooth Pine Wood Surface



It is not smooth under such a magnification.

Static Friction Vs Kinetic Friction



To a certain degree, any surface is not smooth at microscopic level. Under such magnification we can see tooth-like jagged edges and some are of shape of micro hoops.

When two surfaces are in contact and do not slide, such jagged edges are interlocked due to the weight of the object on top thus the force required to separate them is larger.

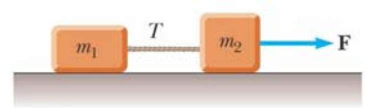
When two surfaces slide on each other, the jagged edges slide and separate without interlocking thus the force required to separate them is reduced.

Friction in Newton's Laws Problems

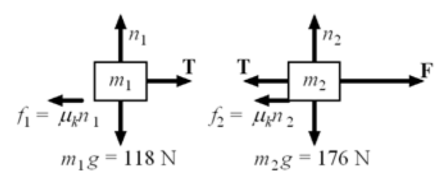
- Friction is a force, so it is included in the Σ**F** in Newton's Laws
- The rules of friction allow you to determine the direction and magnitude of the force of friction

Example . Two blocks connected by a rope of negligible mass are being dragged by a horizontal force **F**. Suppose that F = 68.0 N, m_1 = 12.0 kg, m_2 = 18.0 kg, and the coefficient of kinetic friction between each block and the surface is 0.100. (a) Draw a free-body diagram for each block. (b) Determine the tension T and the magnitude of the acceleration of the system.

Answer:



$$68.0 - T - \mu m_2 g = m_2 a \quad \text{(Block \#2)}$$
$$T - \mu m_1 g = m_1 a \quad \text{(Block \#1)}$$



Adding,

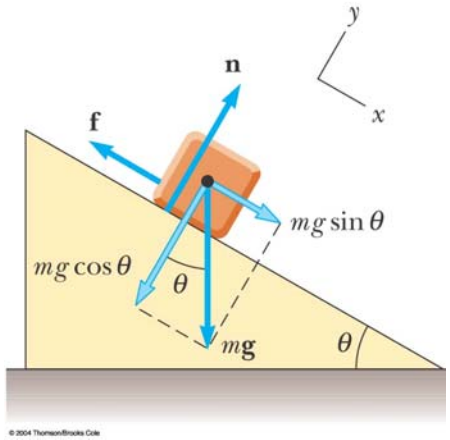
$$68.0 - \mu(m_1 + m_2) g = (m_1 + m_2) a$$

$$a = \frac{68.0}{(m_1 + m_2)} - \mu g = \boxed{1.29\ \text{m}/\text{s}^2}$$

$$T = m_1 a + \mu m_1 g = \boxed{27.2\ \text{N}}$$

Friction Example

- The block is sliding down the plane, so friction acts up the plane
- This setup can be used to experimentally determine the coefficient of friction
- $\mu = \tan\theta$
  - For μ_s, use the angle where the block just slips
  - For μ_k, use the angle where the block slides down at a constant speed



Example. The coefficient of static friction between a brick and a wooden board is 0.40 and the coefficient of kinetic friction between the brick and board is 0.30. We place the brick on the board and slowly lift one end of the board off the ground until the brick starts to slide down the board.

(i) What angle does the board make with the ground when the brick starts to slide?

Answer:

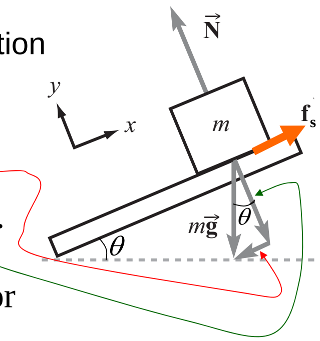
The brick must first overcome the static friction before it will start to slide.

$$mg\sin\theta = f_s \longrightarrow \sin\theta = \frac{f_s}{mg} = \frac{\mu_s N}{mg}$$

$$\sum F_y = N - mg\cos\theta = 0, \text{ so } N = mg\cos\theta.$$

$$\sin\theta = \frac{\mu_s N}{mg} = \frac{\mu_s mg\cos\theta}{mg}, \text{ so } \tan\theta = \mu_s \text{ or}$$

$$\theta = \tan^{-1}\mu_s = \tan^{-1}0.40 = \boxed{22^\circ \text{ with respect to the horizontal}}.$$



(ii) What is the acceleration of the brick as it slides down the board?

Answer:

After the brick starts to slide, the net force on it is the difference between the force of gravity and the kinetic friction. Use Newton's second law:

$$mg\sin\theta - f_k = ma$$

$$mg\sin\theta - \mu_k mg\cos\theta = ma$$

$$g\sin\theta - \mu_k g\cos\theta = a$$

$$a = g(\sin\theta - \mu_k\cos\theta)$$

$$= g(\sin 22^\circ - 0.3\times\cos 22^\circ)$$

$$\boxed{= 0.91\frac{m}{s^2}}$$