Newton's Laws of Motion

Topic 2a

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Learning Outcomes for Topic 2a

- The concept of force and why forces are vectors, and the significance of the net force on an object.
- Result of zero net force on an object is zero, and the significance of inertial frames of reference.
- How the acceleration of an object is determined by the net force on the object and the object's mass.
- Characteristics and the difference between the mass of an object and its weight.
- Effect of forces that two objects exert on each other and how they are related.
- Free-body diagrams.
- The nature of the different types of friction forces and how to solve problems that involve these forces.

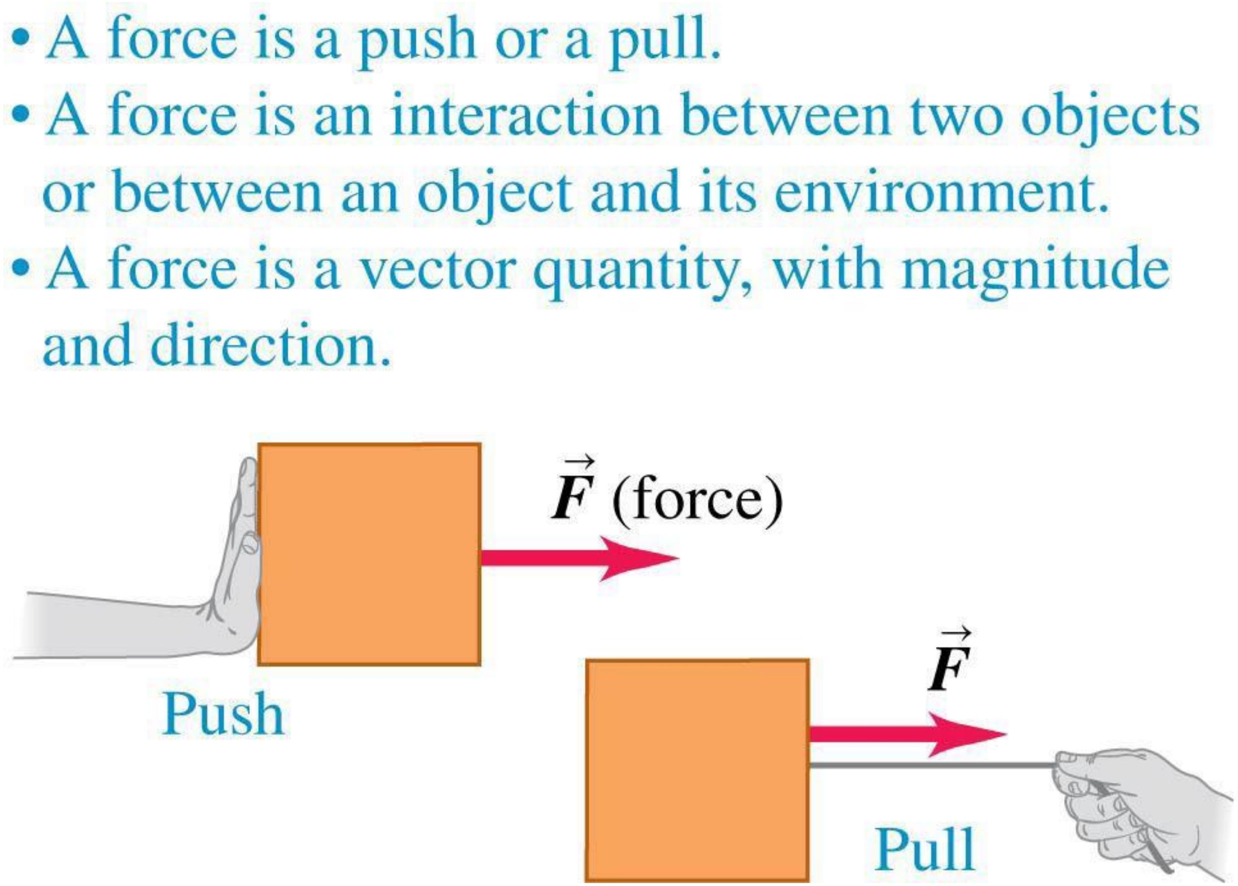
Overview of Topic 2a

- Force and its properties
- Types and representation of Forces
- Superposition of forces
- Decomposing a force into its components
- Newton’s first law
- Force and acceleration
- Mass and acceleration
- Newton’s second law
- Mass and weight
- Newton’s third law
- Free-body diagrams
- Frictional forces

Introduction

- We understand how to use ***kinematics*** to describe motion in one, two, or three dimensions.
- But what ***causes*** bodies to move the way that they do?
- The subject of ***dynamics*** relates motion to the forces that cause it.
- The principles of dynamics were clearly stated for the first time by ***Sir Isaac Newton***; today we call them Newton’s laws of motion.
- Newton did not *derive* these laws, but rather deduced them from a multitude of experiments performed by other scientists.

Force and its properties

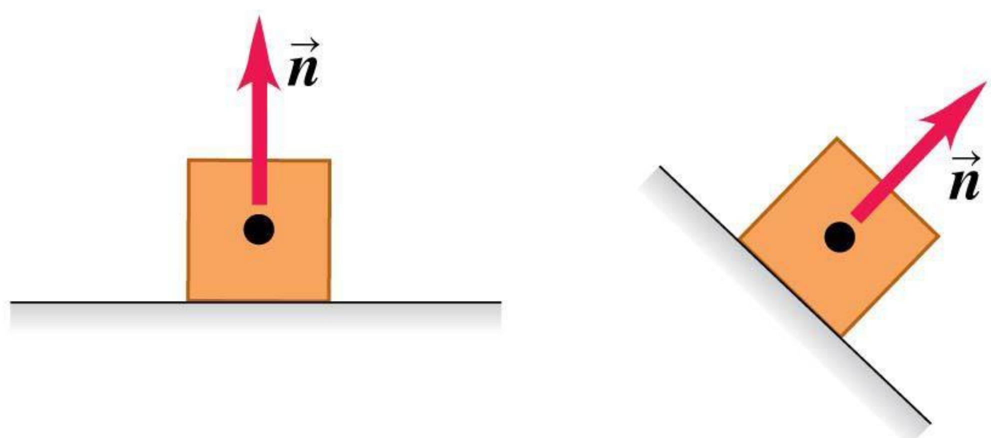


Types of Forces

- ***Contact force***: this force involves direct contact between 2 bodies
- Three types of contact forces:

  (a) Normal force

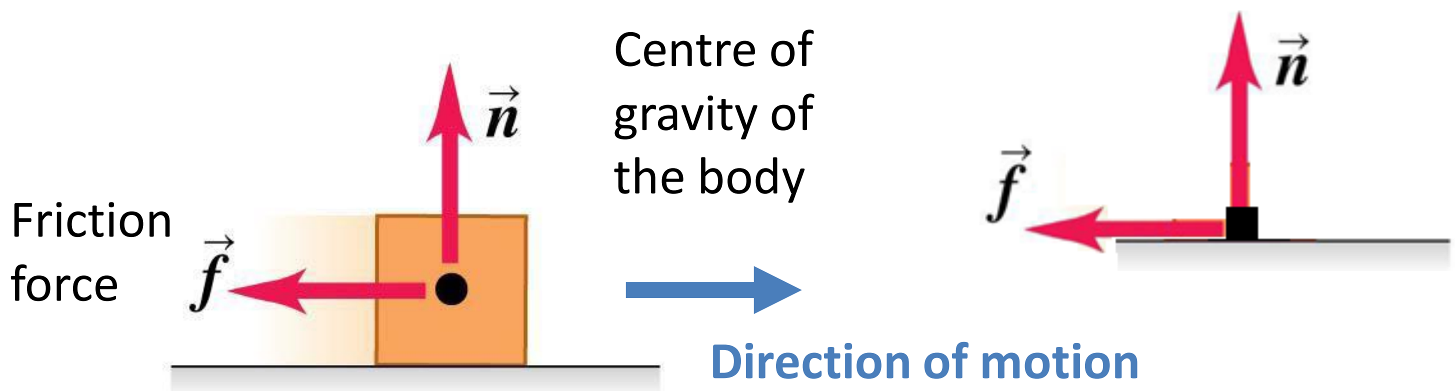
Normal force $\vec{n}$: When an object rests or pushes on a surface, the surface exerts a push on it that is directed perpendicular to the surface.



Types of Forces

(b) Frictional force

Friction force $\vec{f}$: In addition to the normal force, a surface may exert a friction force on an object, directed parallel to the surface.

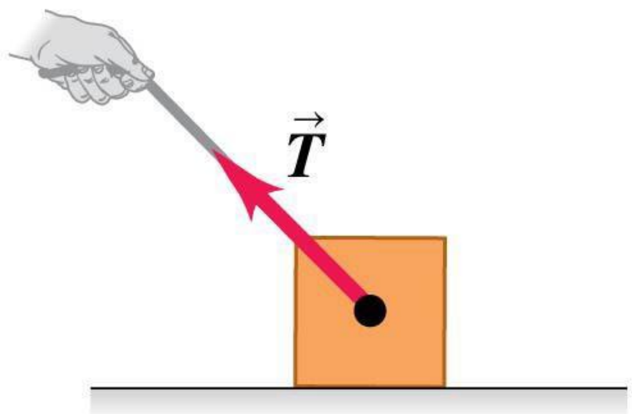


– Direction of Friction force is opposite to direction of movement.

Types of Forces

(c) Tension force

Tension force $\vec{T}$: A pulling force exerted on an object by a rope, cord, etc.

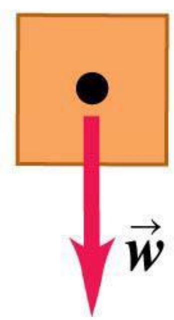


Types of Forces

– In addition to contact forces, we have other kinds of forces

- ***Long range forces***

Weight $\vec{w}$: The pull of gravity on an object is a long-range force (a force that acts over a distance).



– Acts when bodies are not in contact but separated in space

- Example: Earth’s pull on Moon

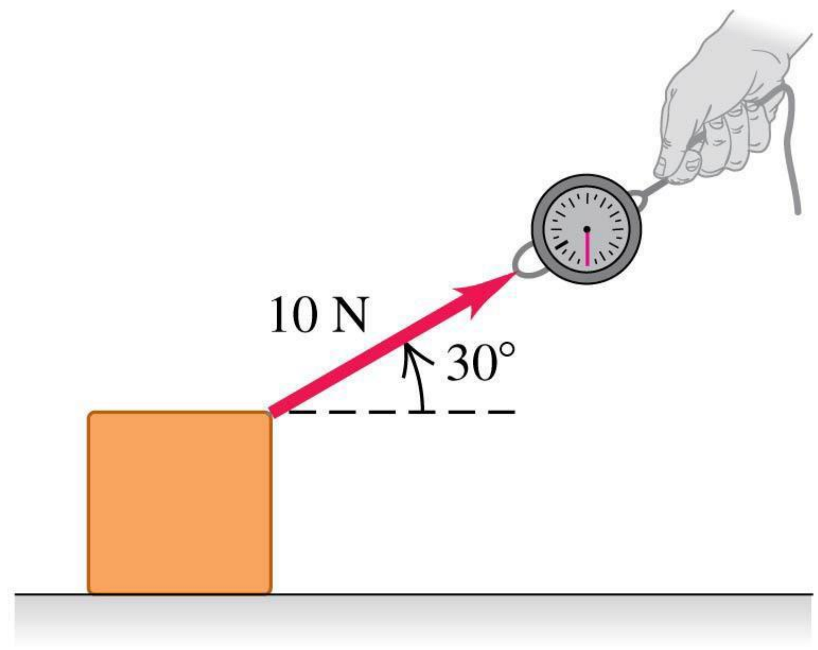
Representing force Vectors

- Force is a vector and hence described by both magnitude and direction
- SI unit for force is ***Newton (N)***
- Examples of force magnitudes
  - Weight of a large blue whale: 1.9×10^6 N
  - Maximum pulling force of a locomotive: 8.9×10^5 N
  - Weight of a medium size apple: 1 N
  - Electric attraction between the proton and the electron in a hydrogen atom: 8.2×10^{-8} N
  - Gravitational attraction between the proton and the electron in a hydrogen atom: 3.6×10^{-47} N

Representing force vectors

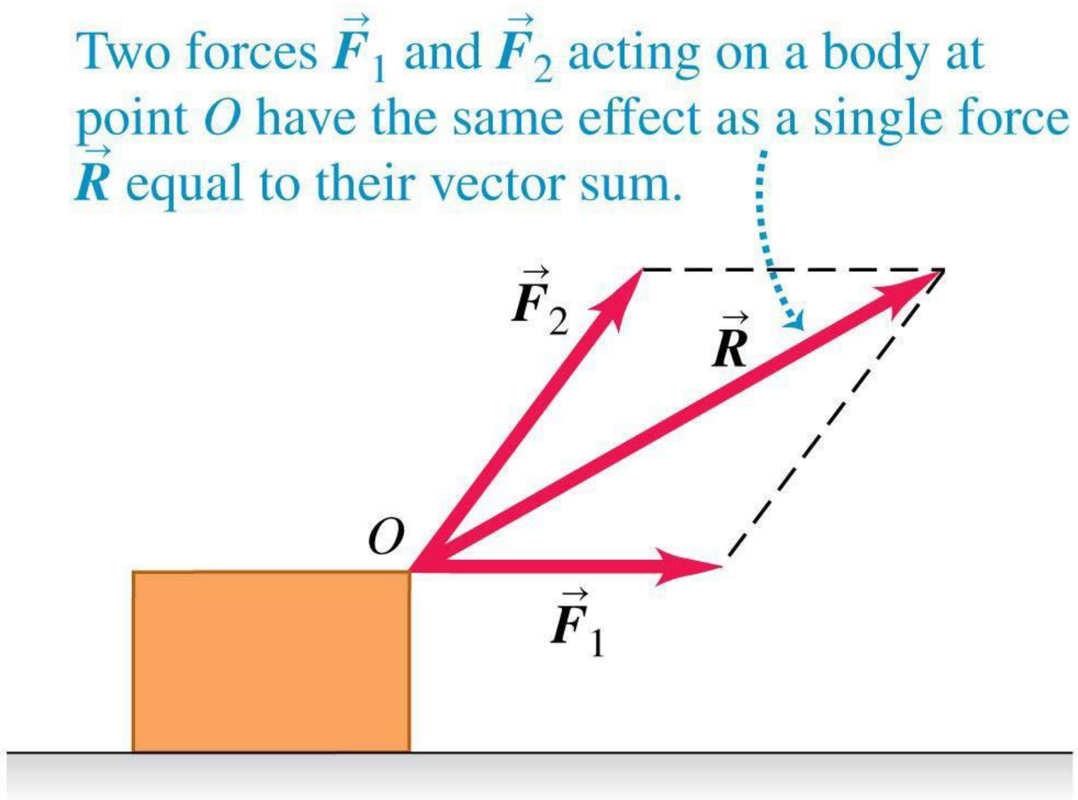
- A *spring balance* is used to measure force
- The figure shows a spring balance being used to measure a pull that we apply to a box.
- A ***vector*** is used to represent the ***applied force***.

- Length of the vector shows the magnitude
- The longer the vector, the greater the force magnitude

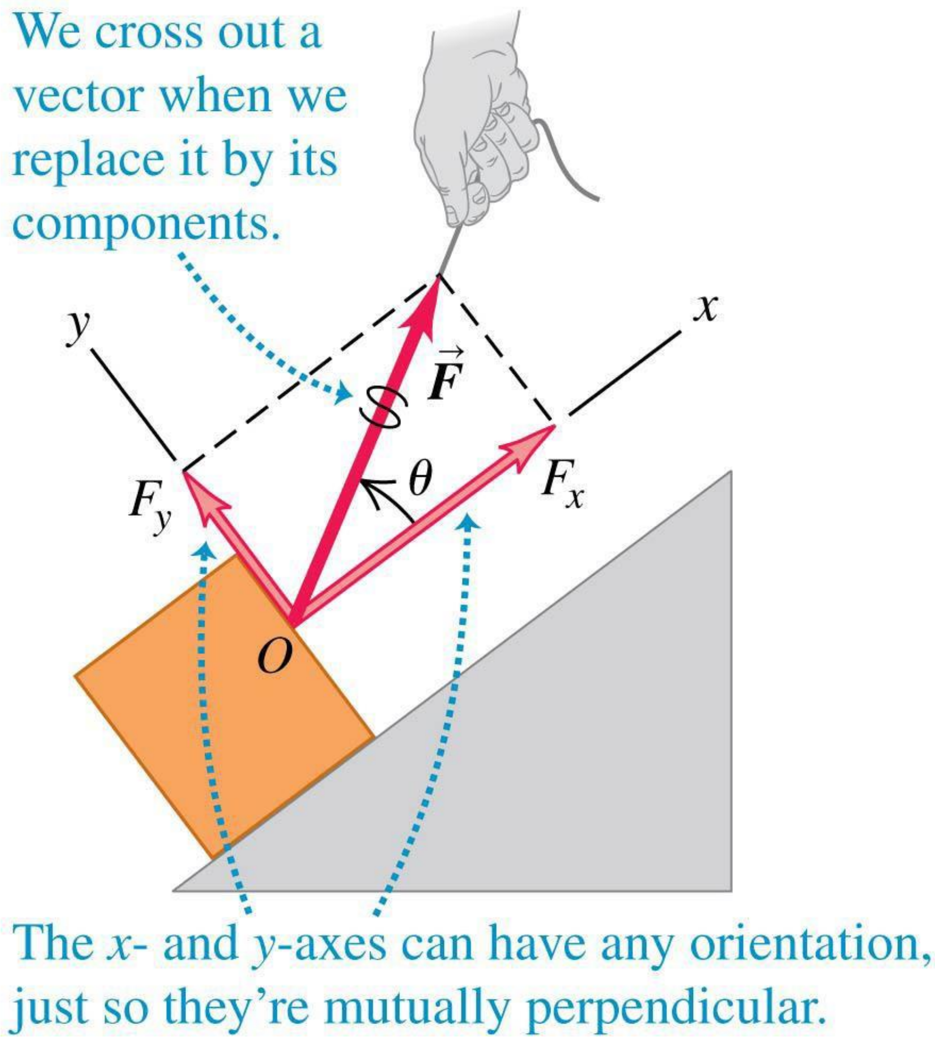


Superposition of forces

- Several forces acting on a body at a point have the same effect as a single force that is equal to the vector sum of individual forces

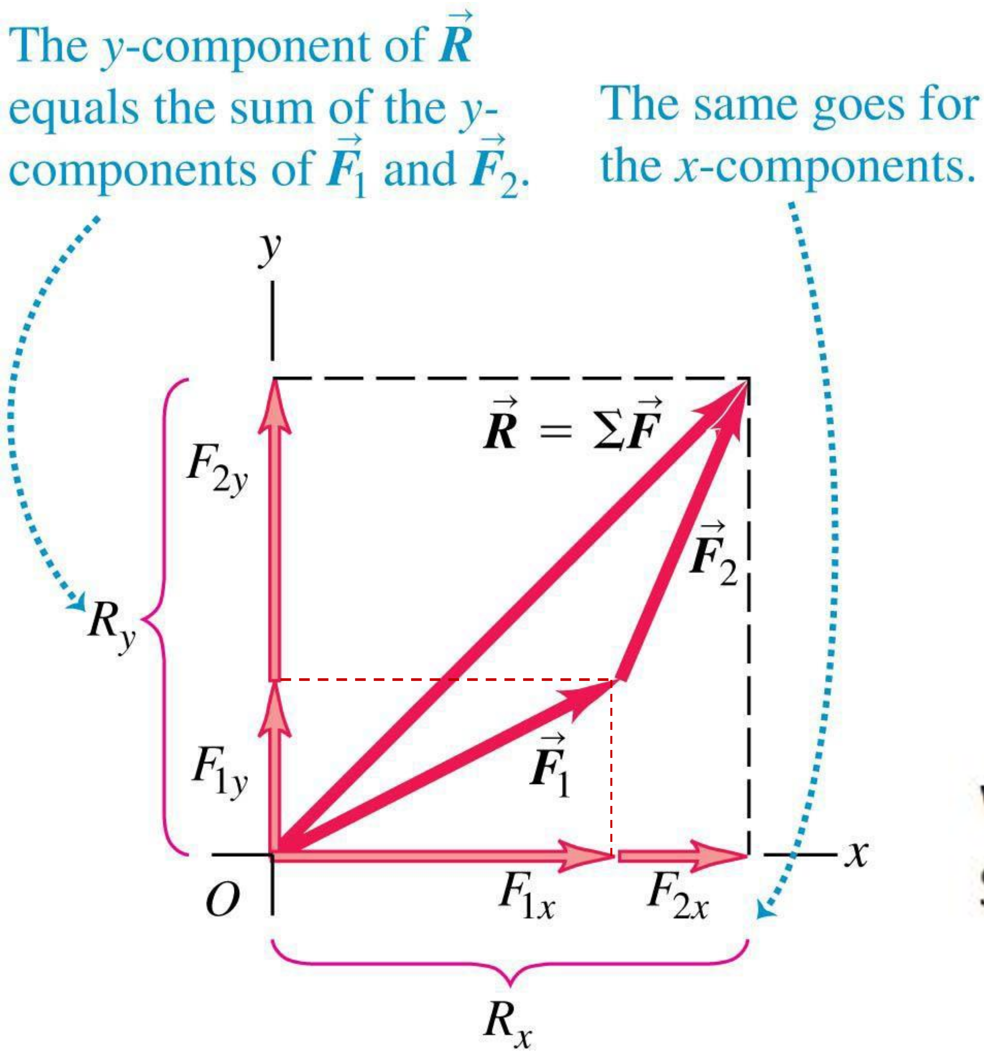


Decomposing a force into its component vectors



- Choose perpendicular *x*- and *y*-axes.
- ***F_x*** and ***F_y*** **:** components of a force along these axes.
- Use trigonometry to find these force components.

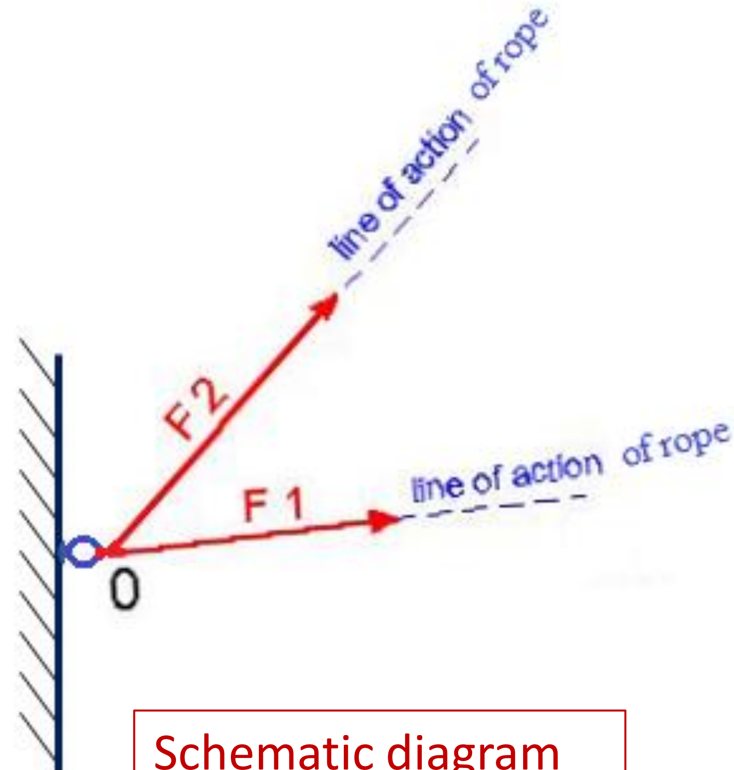
Vector Sum



Vector diagram

- The vector sum of all the forces on an object is called the ***resultant*** of the forces or the ***net force.***

Wall with a Screw eye hook



Schematic diagram

Newton's First Law

Every object will remain at rest or in uniform motion in a straight line unless compelled to change its state by the action of an external force.

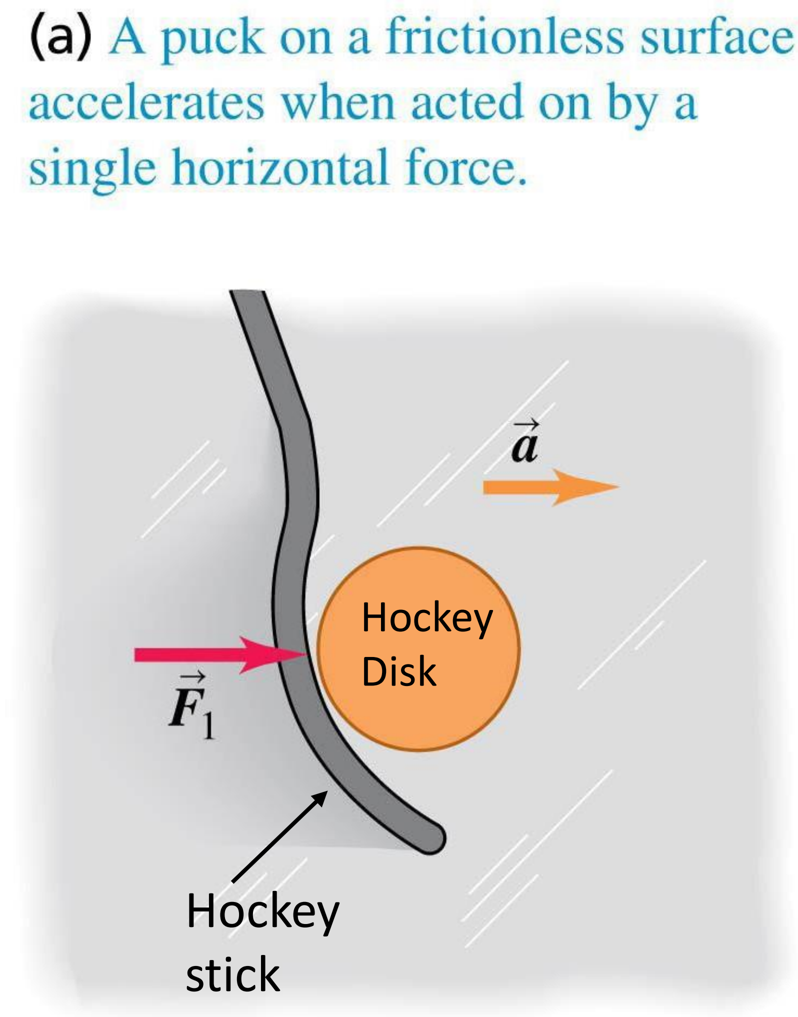
- This tendency to resist changes once set in motion or once it is at rest is called inertia.

- When a body is either at ***rest*** or ***moving with constant velocity*** (in a straight line with constant speed), we say that the body is in ***equilibrium***.
- For a body to be in equilibrium, it must be acted on by ***no*** forces, or by several forces such that their vector sum—that is, the ***net force—is zero***:

Newton's first law: Net force on a body ... $\sum \vec{F} = \mathbf{0}$ ... must be zero if body is in **equilibrium**.

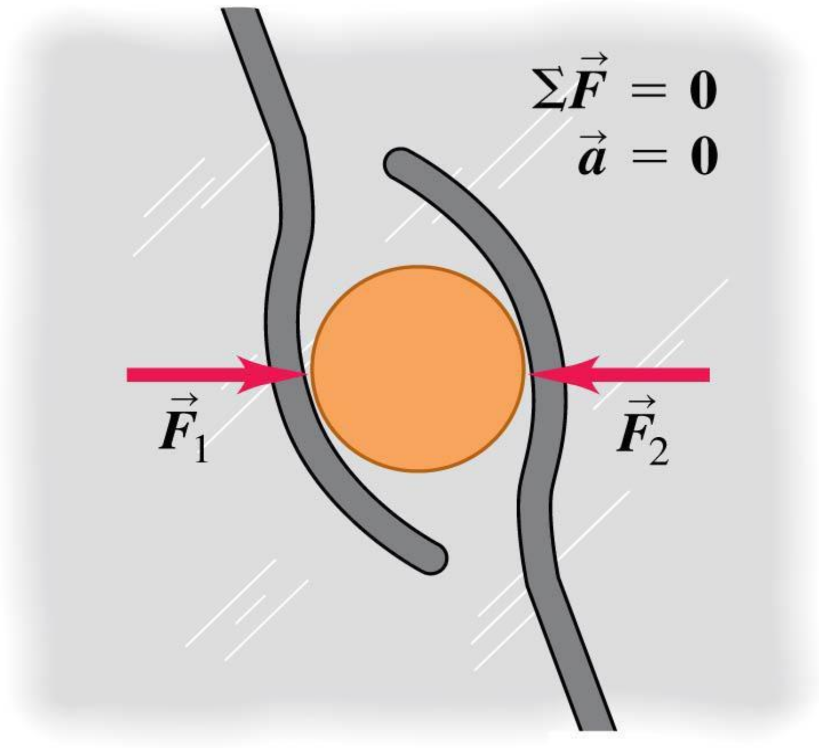
Net forces causes acceleration

- A hockey disk accelerates in the direction of a net applied force.



Newton’s First Law

This disk acted on by two horizontal forces whose vector sum is zero. The disk behaves as though no forces act on it.



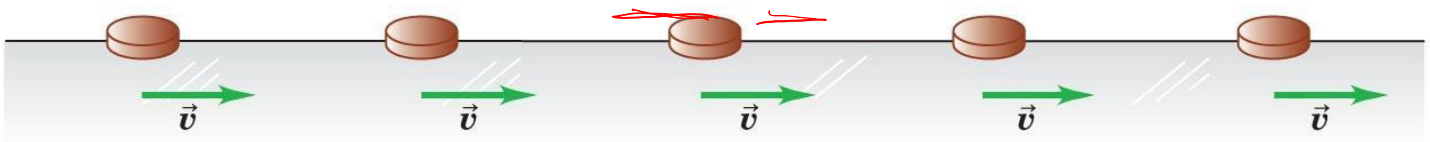
- When the net force is zero, the acceleration is zero, and the disk is in equilibrium.

Reference frames for Newton’s Ist Law

- Suppose that you are in a bus that is traveling on a straight road and speeding up.
- If you could stand in the aisle on roller skates, you would start moving *backward relative to the bus* as the bus gains speed.
- It looks as though *Newton’s first law is not obeyed*; there is *no net force* acting on you, yet *your velocity changes*.
- The bus is accelerating with respect to the earth and *is not a suitable frame* of reference for Newton’s first law.
- A frame of reference in which Newton’s first law is valid is called an *inertial frame of reference*.

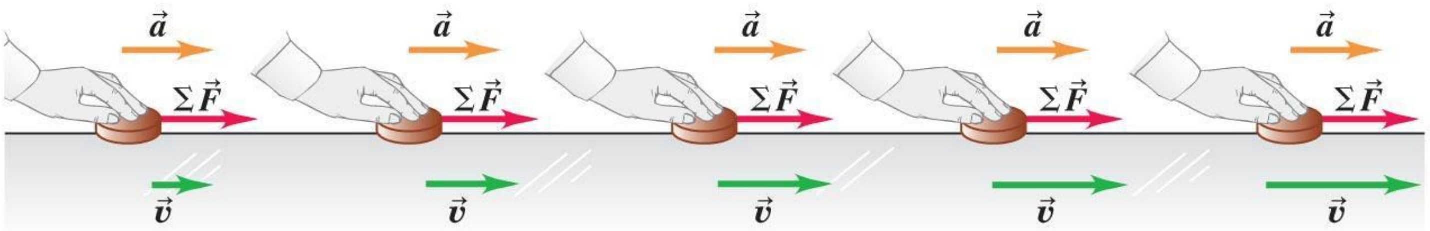
Force and acceleration direction

A puck moving with constant velocity: $\Sigma\vec{F} = 0$, $\vec{a} = 0$



(a)

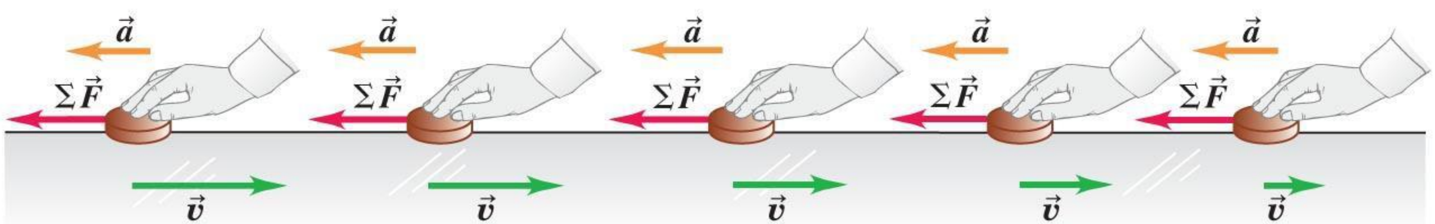
A constant force in the direction of motion causes a constant acceleration in the same direction as the force.



(b)

During the time ***F*** acts, velocity changes at *a* constant rate, and ***a*** is in the same direction as F

A constant force opposite to the direction of motion causes a constant acceleration in the same direction as the force.

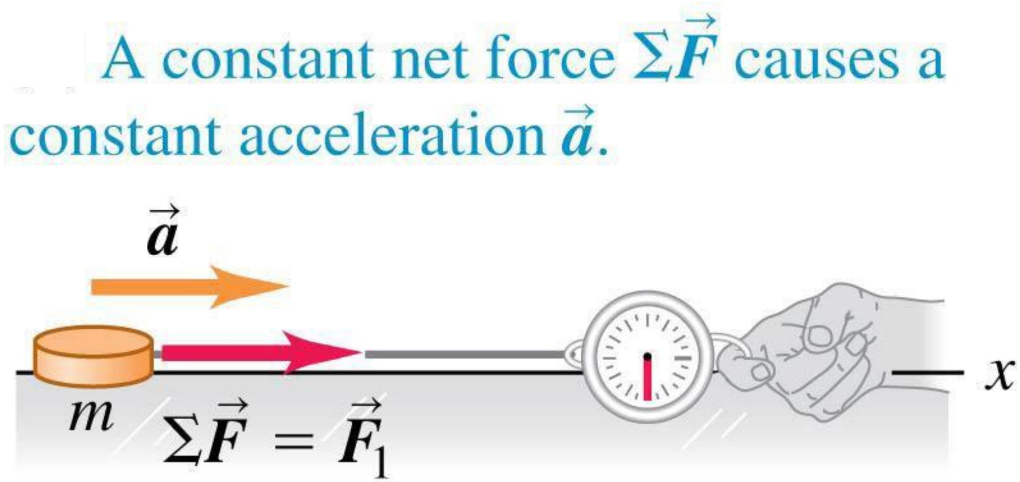


(c)

As ***F*** is reversed and the disk slows, ***a*** is in the same direction as F

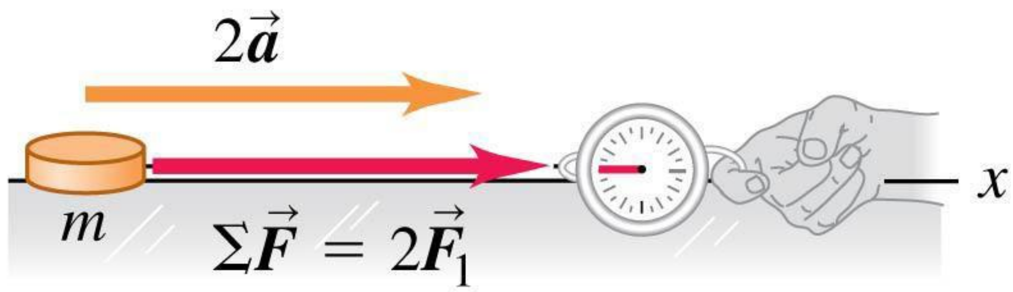
Force and acceleration

- The acceleration ***a*** of a particle is directly proportional to the net force ***F*** acting on it

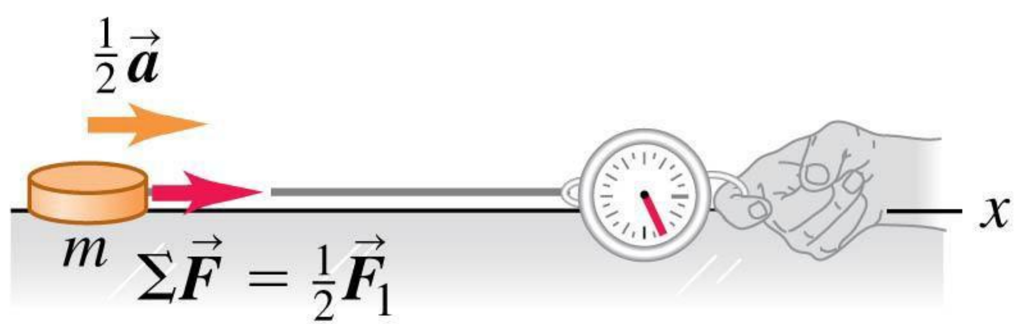


Force and acceleration

Doubling the net force doubles the acceleration.



Halving the force halves the acceleration.



Mass and acceleration

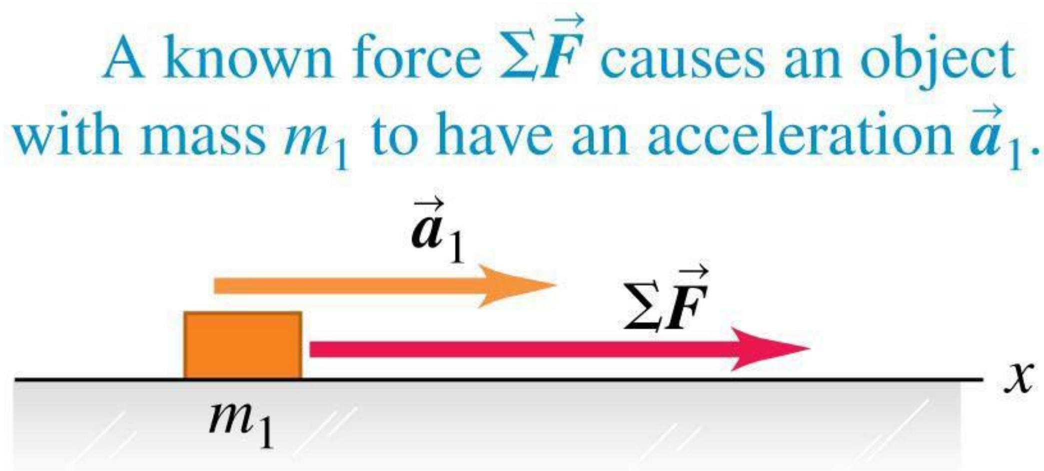
- The ratio of the magnitude of net force $|\sum \boldsymbol{F}|$ to the magnitude of acceleration $|\boldsymbol{a}|$ is a constant called ***inertial mass***

$$m_i = \frac{\left|\sum \vec{F}\right|}{|a|}$$

- The SI unit of mass is ***kilogram (kg)***

Mass and acceleration

- The acceleration of an object is inversely proportional to the object's mass if the net force remains fixed.



m_1 – known mass

Mass and acceleration

Applying the same force $\Sigma\vec{F}$ to a second object and noting the acceleration allow us to measure the mass.

Allows us to determine ***m_2***

$$\sum \vec{F} = m_1 a_1 = m_2 a_2$$

When the two objects are fastened together, the same method shows that their composite mass is the sum of their individual masses.

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 the mass of the object

Newton's second law:
If there is a net force on a body ... $\sum \vec{F} = m\vec{a}$ ... the body accelerates in same direction as the net force.
Mass of body

- The SI unit for force is the newton (N).

  1 N = 1 kg·m/s^2

- Caution: $m\vec{a}$ is ***not a force***, it is an acceleration that is the result of a nonzero net force and is not a force.

Example 1 : Force to accelerate a fast car.

Estimate the net force needed to accelerate (a) a 1,000-kg car at ½ g; (b) a 200-g apple at the same rate.

Apply eqn of motion, $v^2 = v_0^2 + 2as$

$$a = \frac{v^2 - v_0^2}{2s} = \frac{0 - \left(100 \times \frac{1000}{3600}\right)^2}{2(55)}$$

$$= -7.02 \ m/s^2$$

Example 2 : Force to stop a car.

What average net force is required to bring a 1,500-kg car to rest from a speed of 100 km/h within a distance of 55 m?

Apply eqn of motion, $v^2 = v_0^2 + 2as$

$$a = \frac{v^2 - v_0^2}{2s} = \frac{0 - \left(100 \times \frac{1000}{3600}\right)^2}{2(55)}$$

$$= -7.02\ m/s^2$$ (i.e. decelerating)

Apply Newton's 2nd Law, $\Sigma F = ma$

$= (1500)(-7.02) = -10.53\text{kN}$ (Force required is 10.53kN in the opposite direction)

System of Units

- In the British system, force is measured in ***pounds***, distance in ***feet***, and mass in ***slugs***.
- In the CGS system, mass is in ***grams***, distance in ***centimeters***, and force in ***dynes***

System of Units	Force	Mass	Acceleration
SI	newton (N)	kilogram (kg)	m/s^2
cgs	dyne (dyn)	gram (g)	cm/s^2
British	pound (lb)	slug	ft/s^2

Mass and weight

- The ***weight*** of an object (on the earth) is the gravitational force that the earth exerts on it.
- The weight ***w*** of an object of mass *m* is:

Magnitude of weight of a body

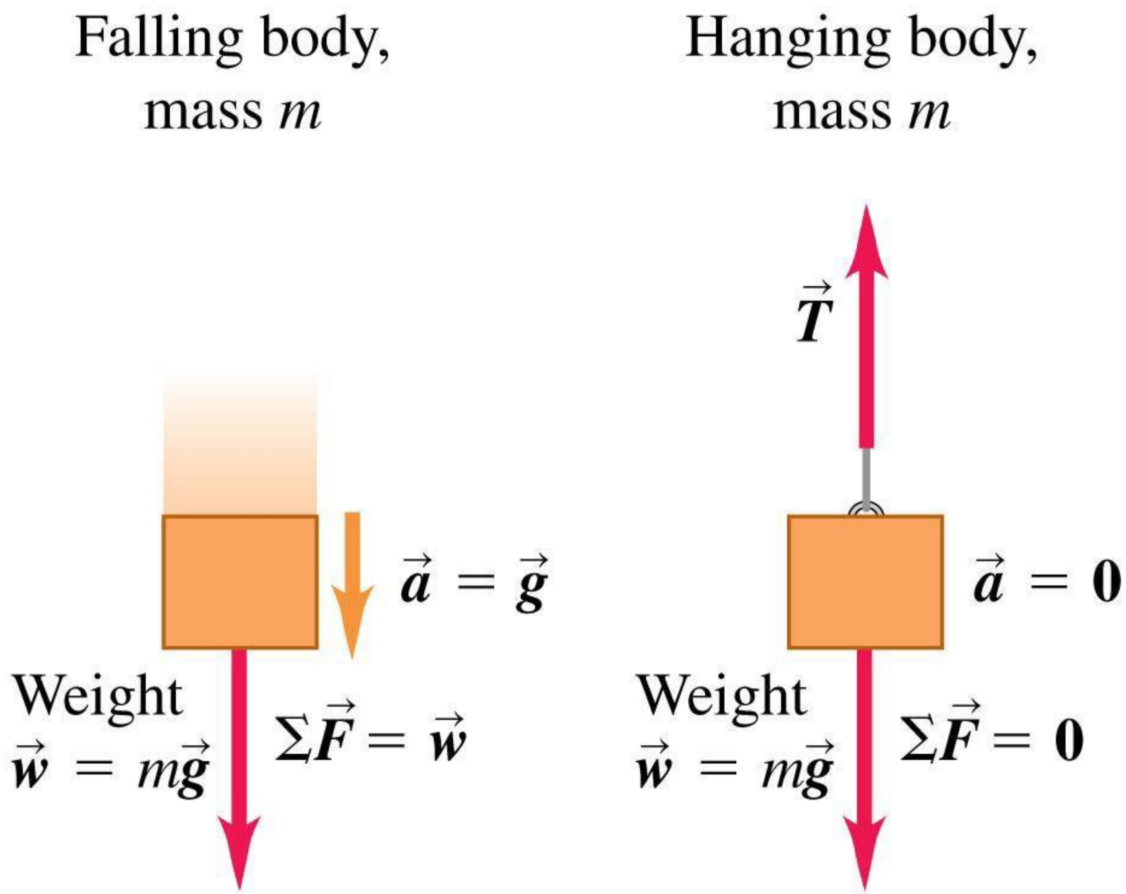
$$w = mg$$

Mass of body

Magnitude of acceleration due to gravity

- The value of ***g*** depends on the location (9.78 ~ 9.82 m/s^2)
- On other planets, ***g*** will have an entirely different value than on the earth.

Relating mass and weight of a body



- The relationship of mass to weight: $\vec{w} = m\vec{g}$.
- This relationship is the same whether a body is falling or stationary.

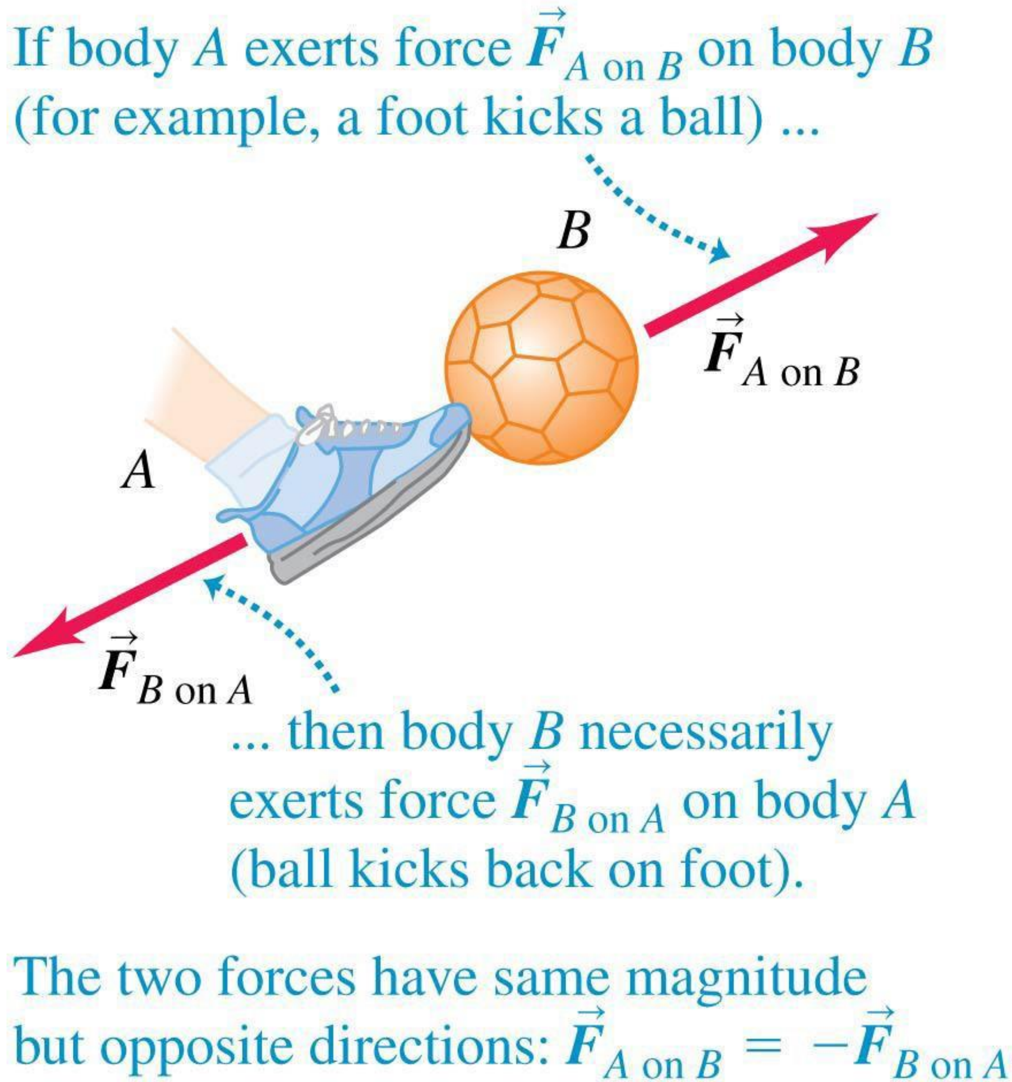
Apparent weight & weightlessness

- When a passenger with mass *m* rides in an elevator with *y*-acceleration a_y, a scale shows the passenger's apparent weight as $n = m(g + a_y)$ a_y =+ve upward

- The extreme case occurs when the elevator has a downward acceleration (**free fall**) $a_y = -g$
- Here ***n = 0*** and the passenger *seems* to be weightless.
- Similarly, an astronaut orbiting the earth in a spacecraft experiences ***apparent weightlessness***

Newton’s third law of motion

When two bodies interact, the two forces that they exert on each other are equal and opposite in direction



Example 3 : Weight, normal force, and a box

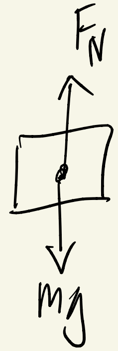
A friend has given you a special gift, a box of mass 10.0 kg with a mystery surprise inside. The box is resting on the smooth (frictionless) horizontal surface of a table.

(a) Determine the weight of the box and the normal force exerted on it by the table.

(b) Now your friend pushes down on the box with a force of 40.0 N. Again determine the normal force exerted on the box by the table.

(c) (c) If your friend pulls upward on the box with a force of 40.0 N, what now is the normal force exerted on the box by the table?

a) Weight, $W = mg = 10 \times 9.81 = 98.1\ N$



or use Newton's 2^{nd} Law

$$\Sigma F_y = F_N - mg = 0$$

$$\therefore F_N = mg = 98.1\ N$$

b)

Ans (138.1N)

c) Apply Newton's 2^{nd} Law,

$$\Sigma F_y = F_N + F_a - mg =$$

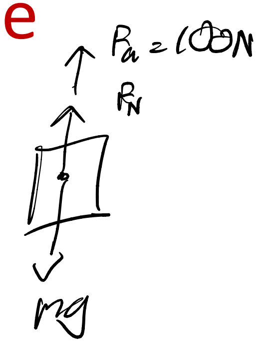
$$\therefore F_N = mg - F_a$$

$$= 98.1 - 40$$

$$= 58.1\ N$$

Example 4 : Accelerating the box

What happens when a person pulls upward on the box in the previous example with a force greater than the box's weight, say 100.0 N?



Net force on box is $\Sigma F_y = F_N + F_a - mg$

$= F_N + 100 - 98.1$

if we set $\Sigma F_y = 0$ (thinking the box is still at rest)

we get $F_N = -1.9N$ which means it acts downwards which is impossible. It lowest value is 0 at which the box starts to take off with an acceleration $\therefore \Sigma F_y = F_a - mg$

$= 100 - 98.1 = 1.9N$

Apply Newton's 2nd Law, $\Sigma F_y = m \cdot a_y$

$\therefore a_y = \frac{\Sigma F_y}{m} = \frac{1.9}{10} = 0.19 m/s^2$

Example 5 : Apparent weight loss

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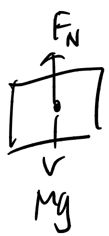
A 65-kg woman descends in an elevator that briefly accelerates at 0.20*g* downward. She stands on a scale that reads in kg.

(a) During this acceleration, what is her weight and what does the scale read?

(b) What does the scale read when the elevator descends at a constant speed of 2.0 m/s?

a)



Effective 'g' is $1g - 0.2g = 0.8g$

Her apparent weight is

$W_{app} = m(0.8g)$

$= 65(0.8 \times 9.81) = 510.1\,N$

Scale reads $\frac{510.1}{9.81} = 52\,kg$

b) $\Sigma F_y = F_N - W = 0$

Constant speed = 0 acc^n)

$\therefore F_N = W = mg$

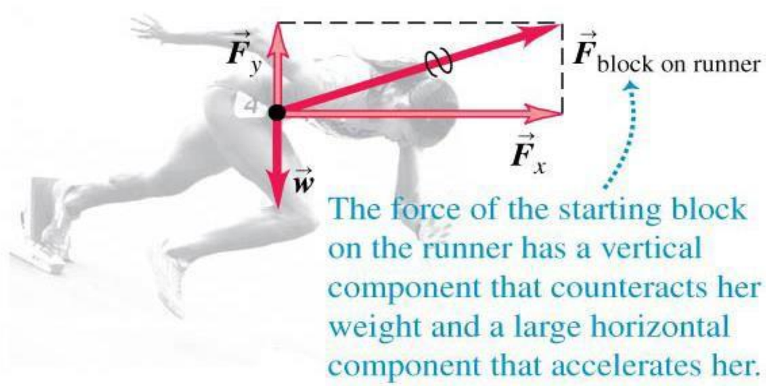
$= 65 \times 9.81 = 637.7\,N$

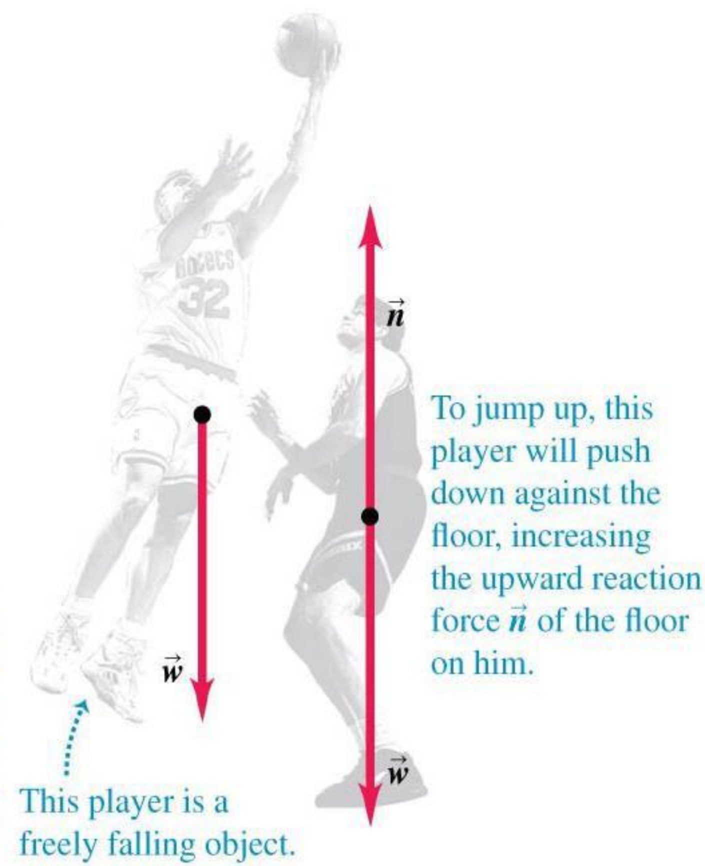
Scale reads $\frac{637.7}{9.81} = 65\,kg$

Free-body diagrams

- Free-body diagrams are necessary to identify relevant forces acting on a body.
- Vectors are drawn to show magnitude and direction of all forces acting on the body.
- Does not include the forces the body exerts on surroundings.
- Be careful not to include force that body exerts on any other body. Action reaction pair never appears in the diagram.
- When there is more than one body, separate diagrams are used for each body.

Free-body diagrams

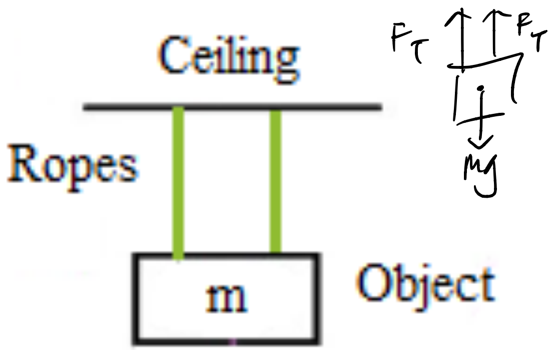




Examples on free-body diagrams

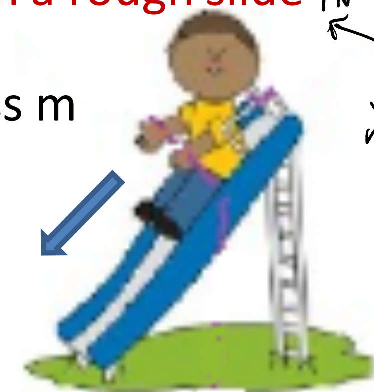
Draw free-body diagram for each of the following as specified.

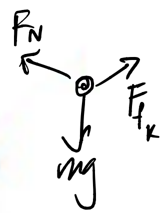
Draw FBD for object



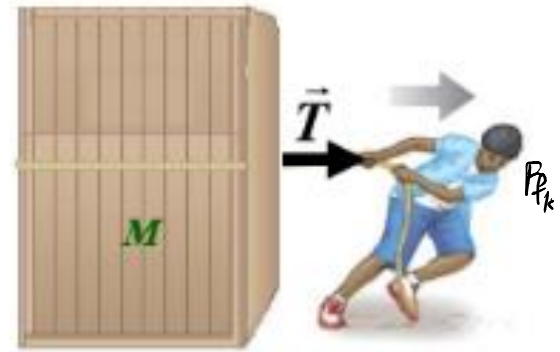
Draw FBD for child going down a rough slide

Mass m

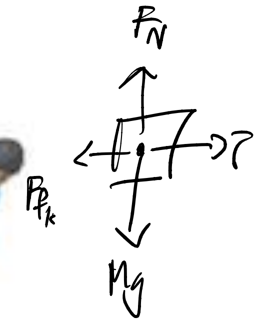




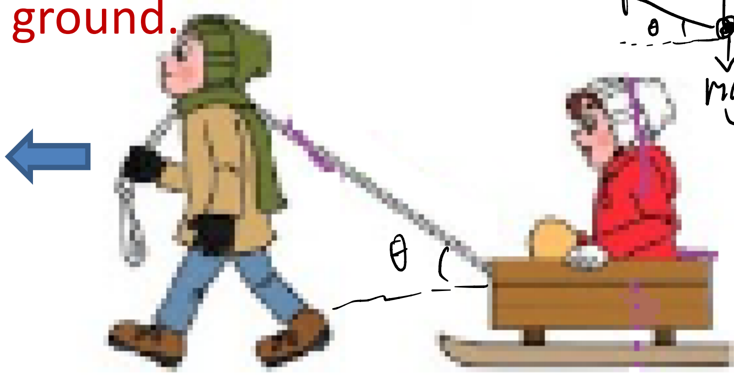
Draw FBD for moving crate being pulled.

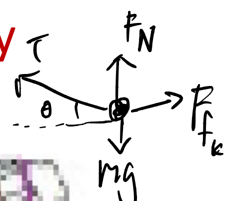


Rough ground



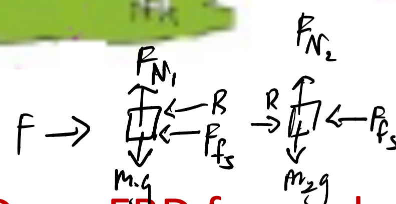
Draw FBD for moving sled (with rider) being pulled on snowy ground.



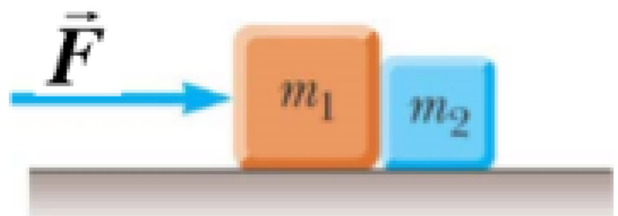


Rough ground

Total mass m

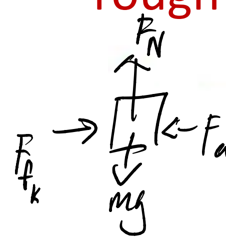


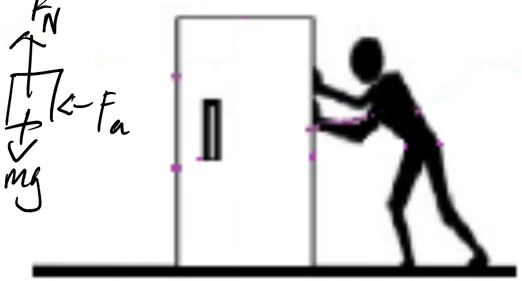
Draw FBD for each mass (stationary)



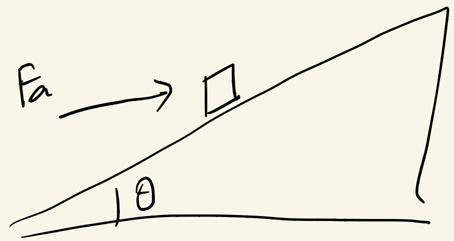
Rough ground

Draw FBD for stationary fridge being pushed on rough ground.

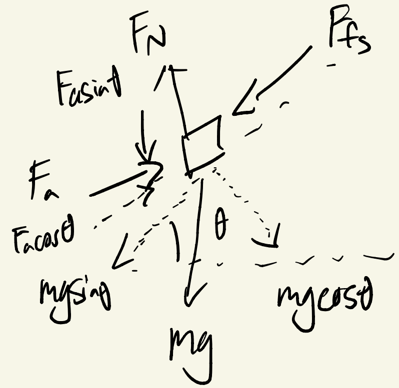




Box just about to move up (impending Motion)



Rough Incline

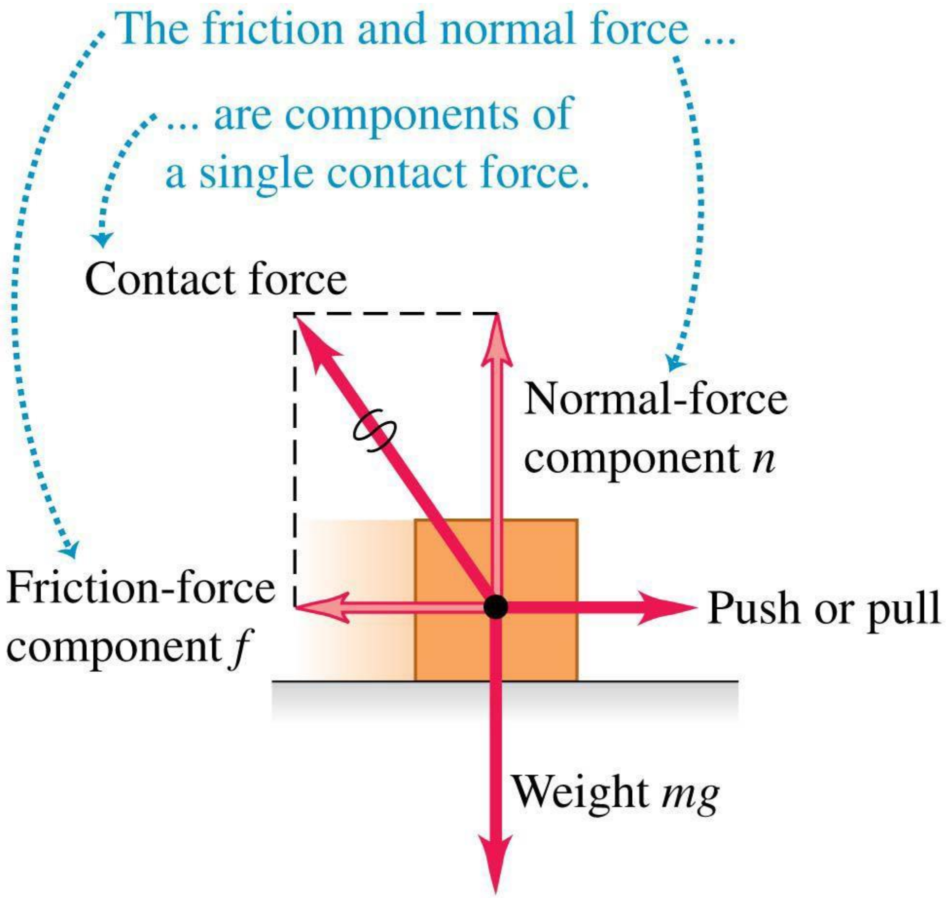


Frictional Forces

- We know that when a body is either resting or sliding on a surface, the surface exerts a force on the body
- That is, the interaction between the two can be described by a ***contact force***
  - Ex: Normal force
- Another type of contact force is ***friction***

Frictional Forces

- When a body rests or slides on a surface, *the friction* force is parallel to the surface and opposite in direction to the applied force.



We can think of the surface exerting a single contact force on the body, with components perpendicular and parallel to the surface

Kinetic and Static Friction

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- ***Kinetic friction force*** $\vec{f}_k$: occurs when a body slides over surface
  - Proportional to magnitude of the normal force ***N (=*** $\vec{F}_N$ ***)***

$$f_k = \mu_k \times N \rightarrow$$ Moving at constant velocity

Coefficient of kinetic friction – $\boldsymbol{\mu_k}$ is a constant

- ***Static friction*** acts when there is no relative motion between bodies.

at impending motion

$F_{fs} = \mu_s \times F_N$

  - The *static friction force* can vary between zero and its maximum value

In general,

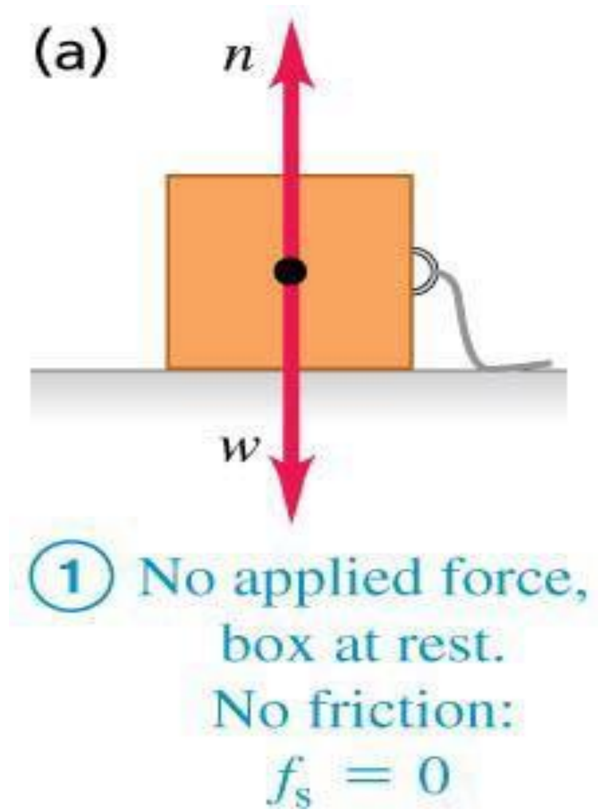
$$f_s \leq \mu_s \times N$$

$\mu_s > \mu_k$

  - Coefficient of static friction – $\boldsymbol{\mu_s}$ is a constant

Static friction followed by kinetic friction

- Before the box slides, static friction acts. The applied forces has to overcome static friction. But once it starts to slide, kinetic friction acts.



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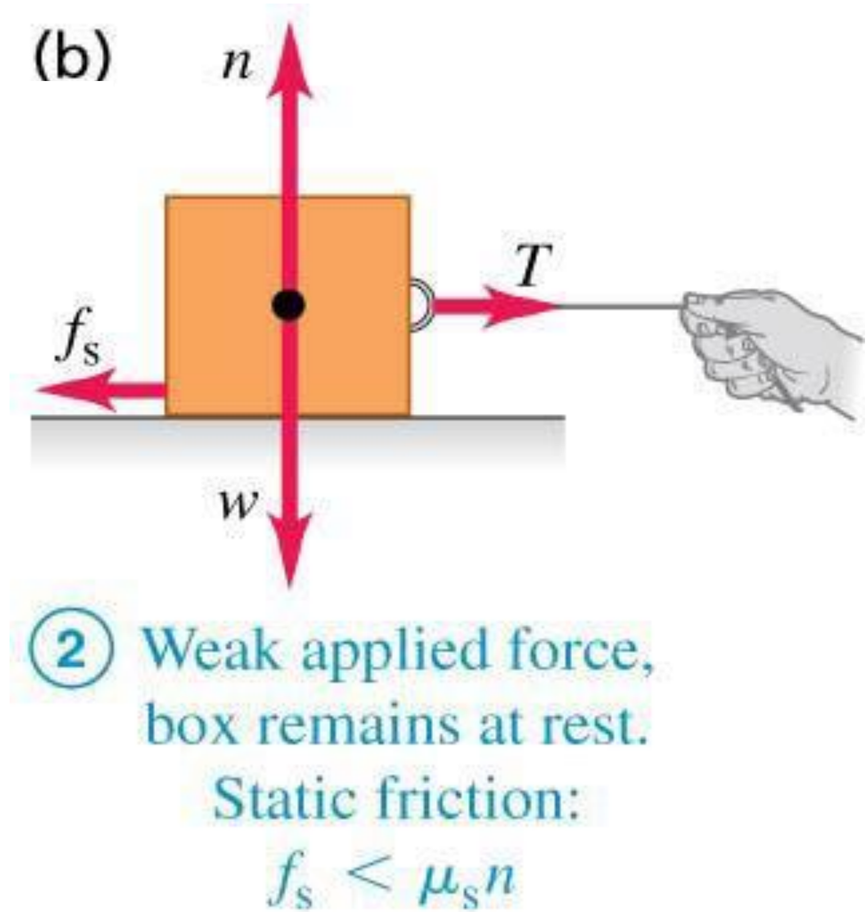

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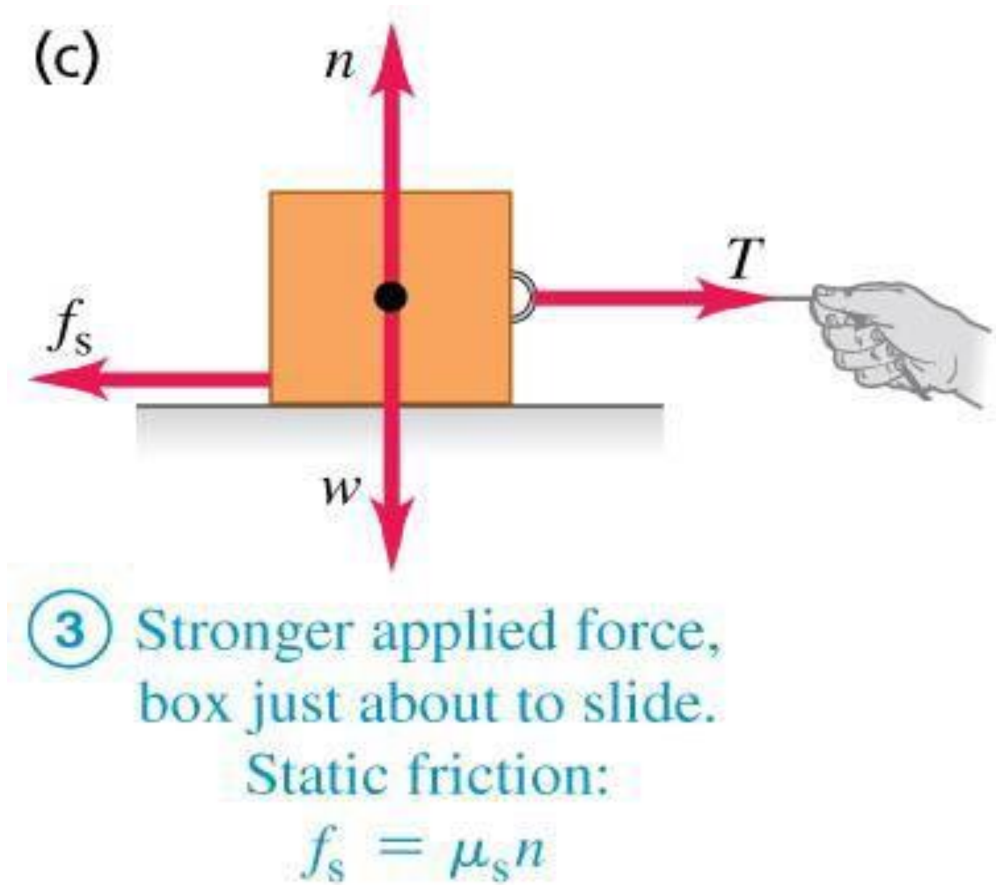

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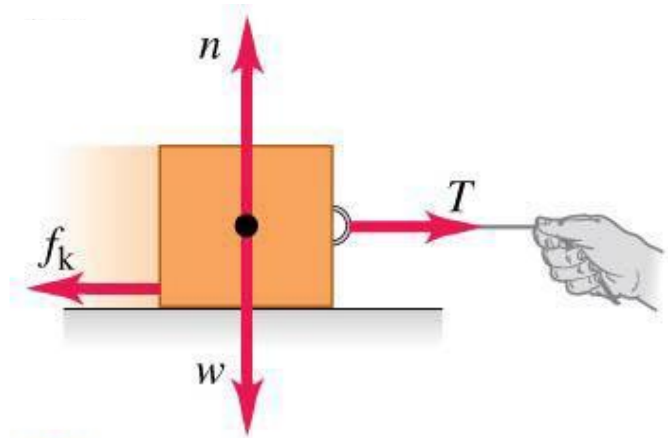
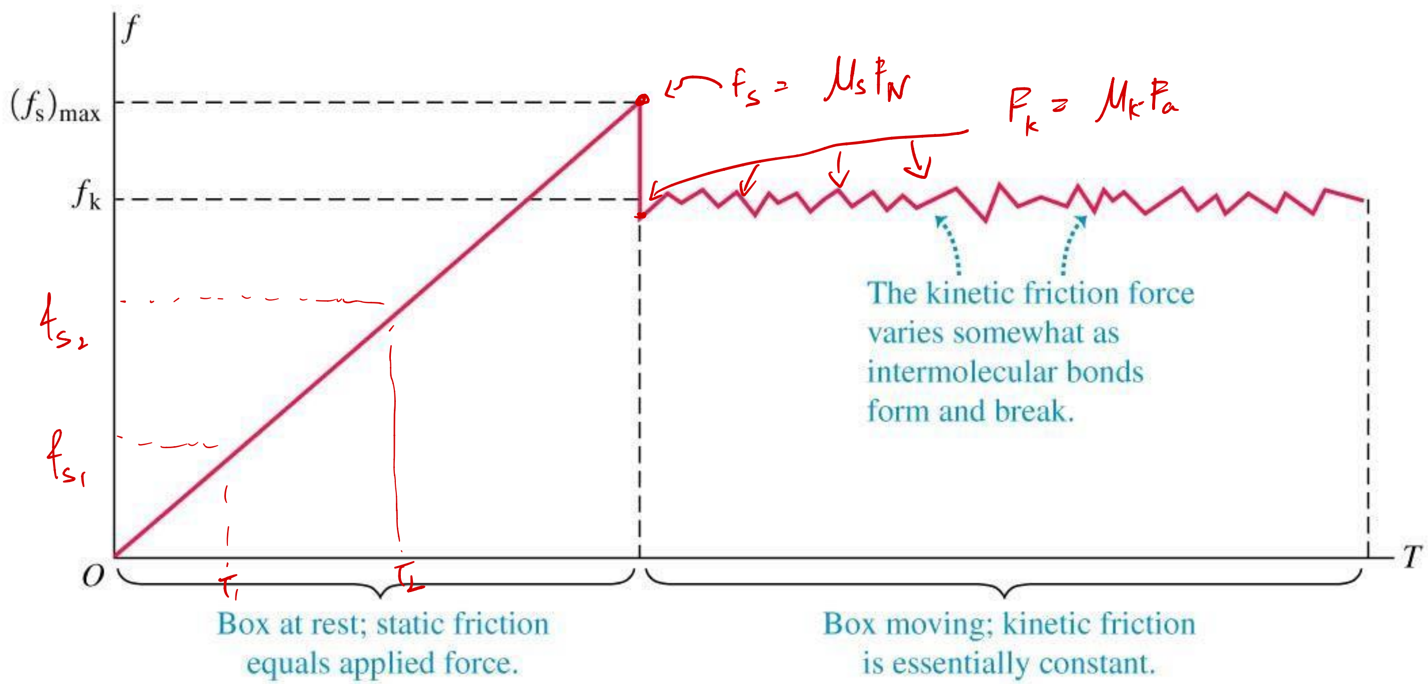


4 Box sliding at constant speed. Kinetic friction: $f_k = \mu_k n$

Kinetic and Static Friction

- Before the box slides, static friction acts. But once it starts to slide, kinetic friction acts. (remember, static friction is parallel to both contact surfaces).
- Force needed to overcome static friction is higher than that needed to overcome kinetic friction.

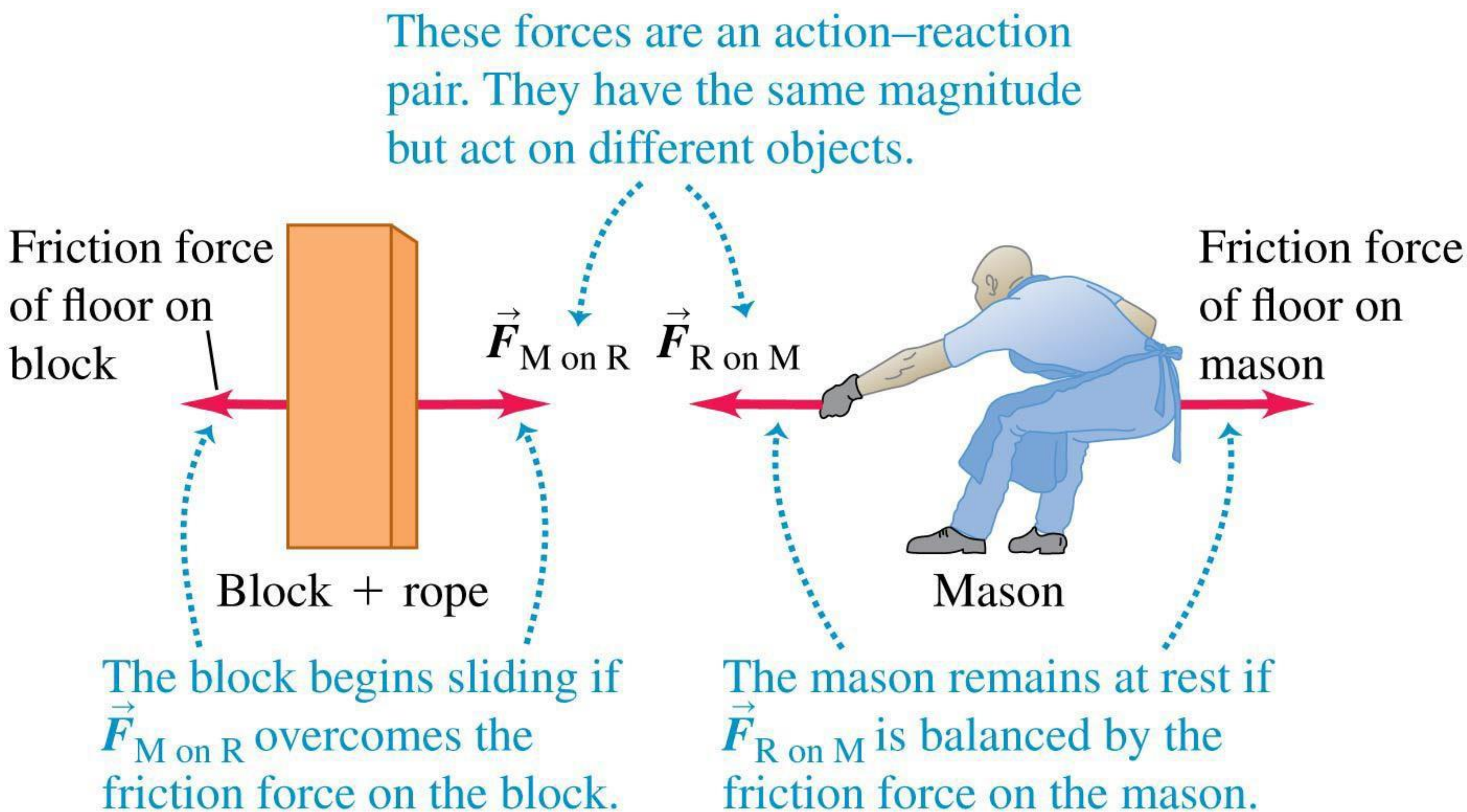


Some approximate coefficients of friction

Materials	Coefficient of Static Friction, μ_s	Coefficient of Kinetic Friction, μ_k
Steel on steel	0.74	0.57
Aluminum on steel	0.61	0.47
Copper on steel	0.53	0.36
Brass on steel	0.51	0.44
Zinc on cast iron	0.85	0.21
Copper on cast iron	1.05	0.29
Glass on glass	0.94	0.40
Copper on glass	0.68	0.53
Teflon on Teflon	0.04	0.04
Teflon on steel	0.04	0.04
Rubber on concrete (dry)	1.0	0.8
Rubber on concrete (wet)	0.30	0.25

A paradox

- If an object pulls back on you just as hard as you pull on it, how can it ever accelerate?



Summary

- Force as a vector
- Net force on a body and Newton's first law

Newton's first law:
Net force on a body ... $\sum \vec{F} = \mathbf{0}$ ... must be zero if body is in **equilibrium**.

- Mass, acceleration and Newton's second law

Newton's second law:
If there is a net force on a body ... $\sum \vec{F} = m\vec{a}$ ... the body accelerates in same direction as the net force.
Mass of body

- Weight

Magnitude of weight of a body $w = mg$
Mass of body
Magnitude of acceleration due to gravity

- Newton's third law

$$\vec{F}_{\text{A on B}} = \vec{F}_{\text{B on A}}$$

- Free-body diagram is drawn involving forces acting on a single-body, even in a multiple-body system.

- ***Kinetic friction force*** f_k: occurs when a body slides over a surface

$$f_k = \mu_k \times N$$

- ***Static friction*** acts when there is no relative motion between body and surface.

$$f_s \le \mu_s \times N$$

At impending motion of the body, $f_s = \mu_s \times N$

End