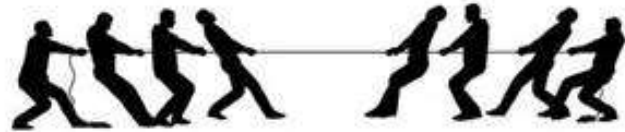# Foundation Physics

Lecture 3:
## Causing Motion

Aims of today's lecture

1. What is force?
2. Quantifying force
3. Drawing force vectors
4. Manifestations of force
5. Newton's 3rd law of Motion

Causing Motion

- As we have seen in our first two lectures, we can describe motion using terms such as 'displacement', 'velocity' and 'acceleration'.

- We can also describe motion in terms of equations (kinematics).

- In this lecture, we ask ourselves the question, **what causes an object to move?**

Causing Motion
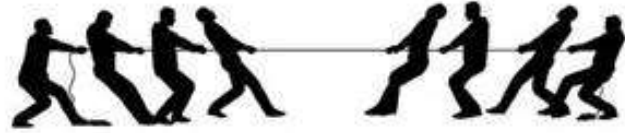
Q. What causes an object to move?

- The answer to this question has changed over the centuries.

- In essence, **the idea of force** is what we use to explain the cause of motion.

- When we combine this idea with kinematics, we are entering the science of **mechanics**.

- So let's look at what we mean by force. . .

1. What is Force?

What is Force?

- Simply put, a force is a **push** or a **pull** **'acting on'/ 'applied to'/ 'exerted on'** an object by another object.

Push   **Pull**
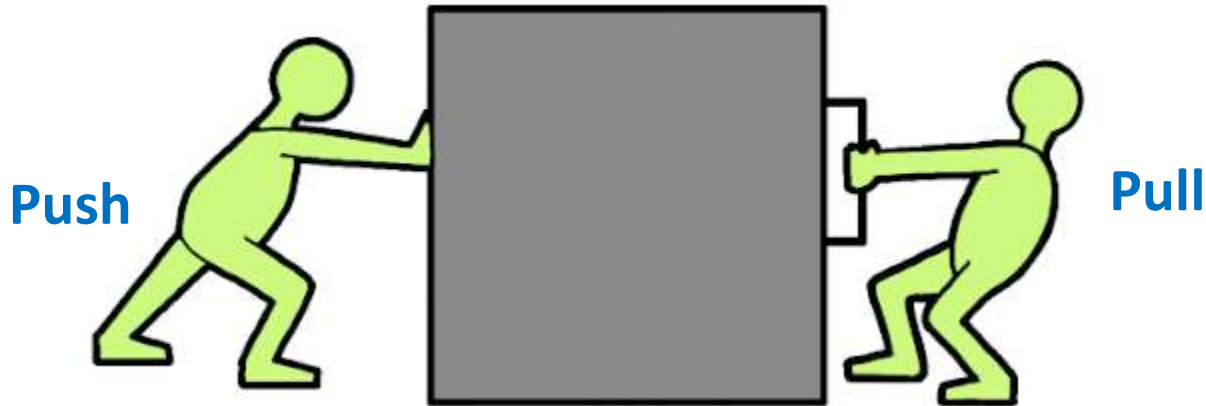
- Thus, a force is **an interaction between two or more objects**.

- What we will see later is that when two objects (**A** & **B**, for example) interact with one another, **A** exerts a force on **B**, and **B** exerts an equal and opposite force on **A**.

What is Force?

- **Contact forces** are interactions that result from objects directly touching one another.

**E.g.** the bat interacts with the ball, and the ball interacts with the bat.

- **Long-range forces** are again interactions, but in this case only one of the objects is visible to the naked eye.

E.g. a coffee cup released from your hand is pulled to the Earth by the long-range force of gravity.
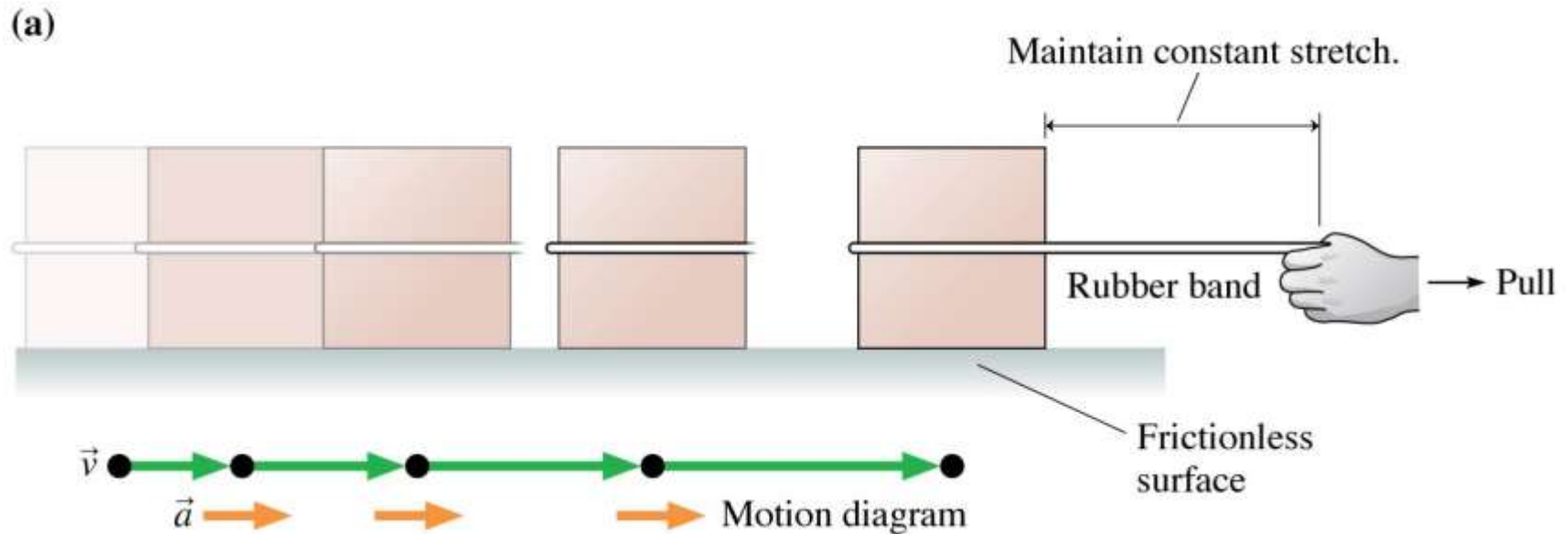
What is Force?

- If we quantify a **push or a pull** (force in other words) in terms of its magnitude, and then specify the force's direction, the **force becomes a vector**.

Push
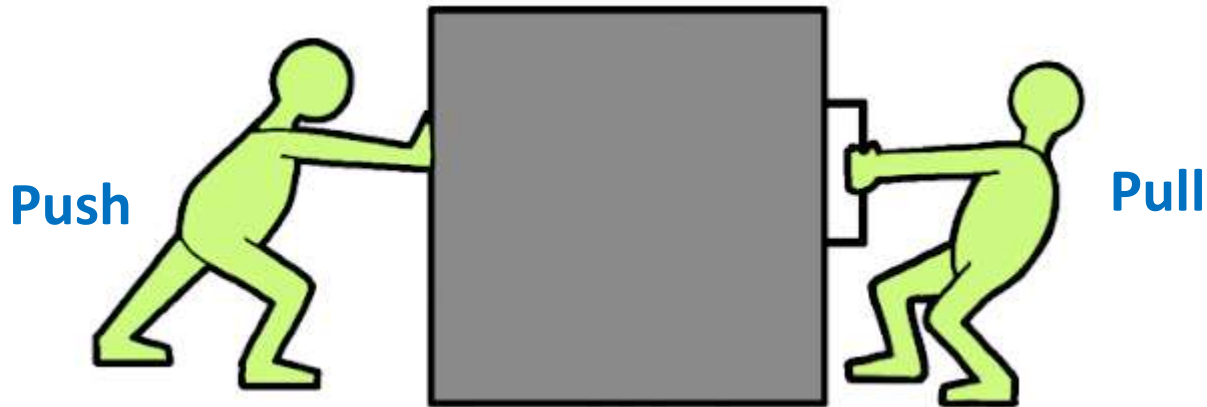
Pull

- So let's see how we quantify force.
  . .

2. Quantifying Force

Quantifying Force

(a)

Maintain constant stretch.

Rubber band → Pull

Frictionless surface

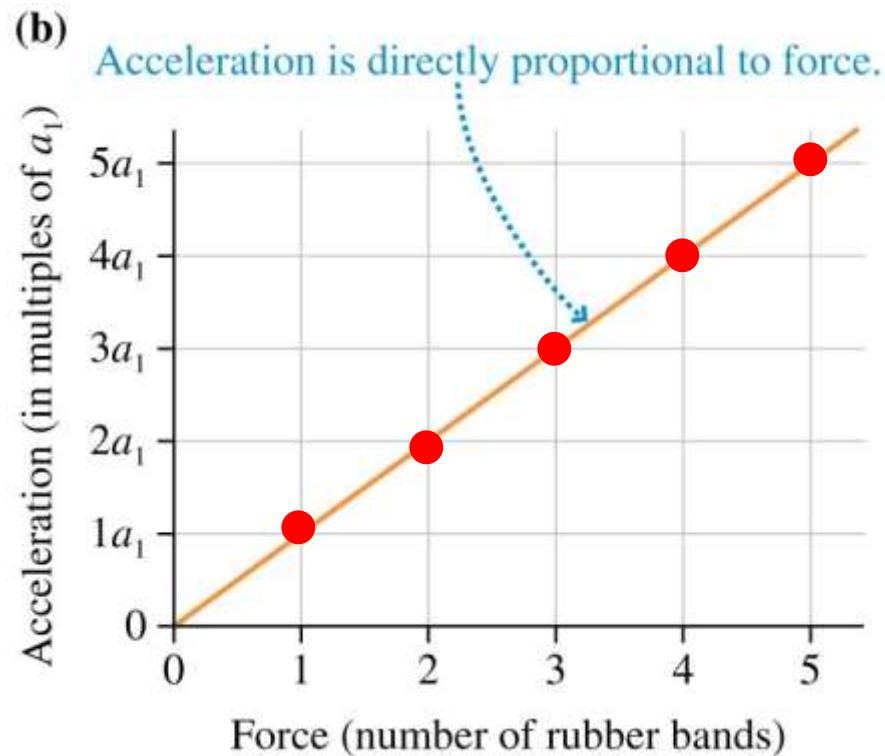$\vec{v}$

$\vec{a}$ → Motion diagram

- Let's consider a block with a mass of 1 kg.

- Imagine attaching the stretched rubber band to this 1 kg block.

- Then imagine using the rubber band to pull the block across a horizontal, frictionless table.

Quantifying Force

(a)

Maintain constant stretch.

Rubber band → Pull

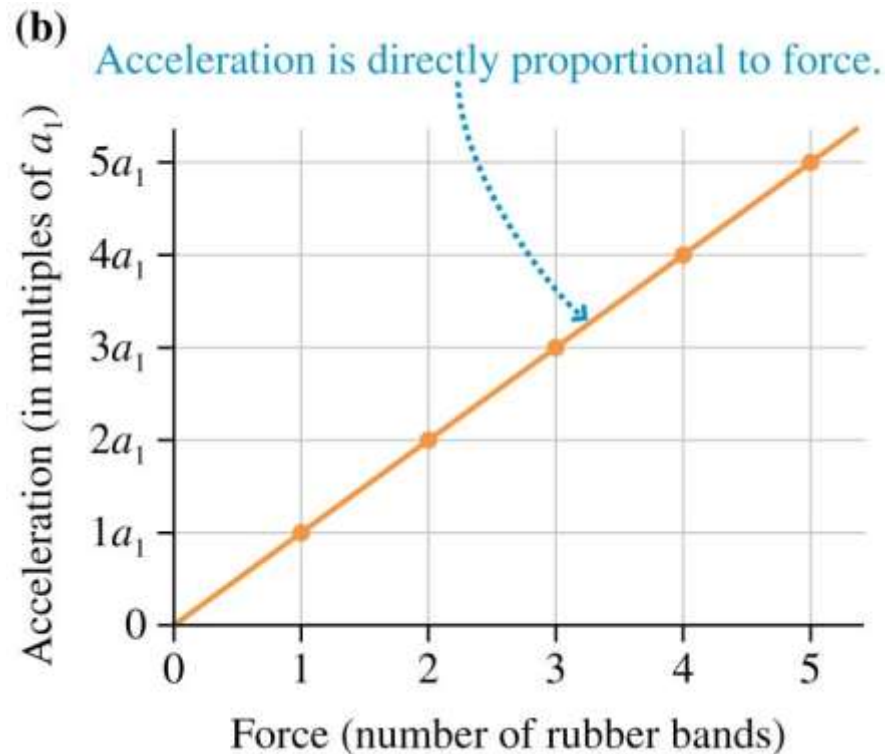Frictionless surface

$\vec{v}$ → → → → Motion diagram
$\vec{a}$ →
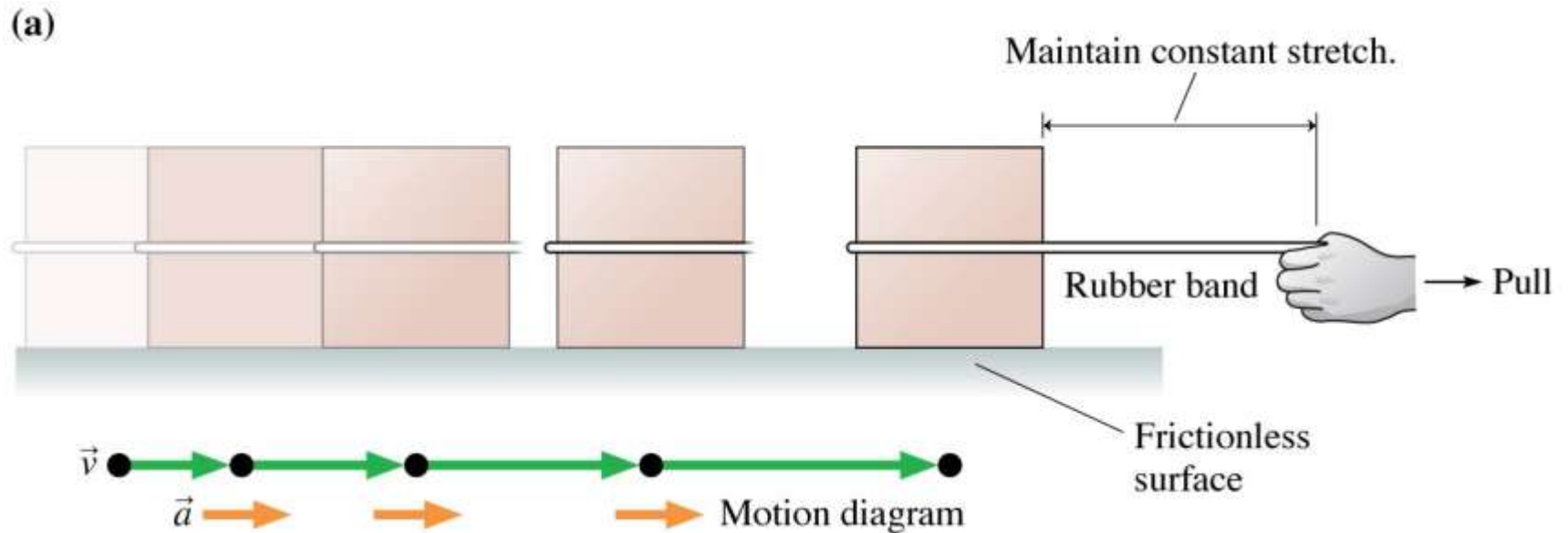
- We must also imagine keeping the rubber band **stretched by a fixed amount**.
- We find that the block moves with a **constant acceleration**.

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Quantifying Force

(b) Acceleration is directly proportional to force.

Graph: Acceleration (in multiples of a_1) vs. Force (number of rubber bands). Data points at $(1, 1a_1)$, $(2, 2a_1)$, $(3, 3a_1)$, $(4, 4a_1)$, $(5, 5a_1)$.

- When a 1 kg block is pulled on a frictionless surface by a single elastic band stretched to the standard length, it accelerates with **constant acceleration, a_1**.

- We can repeat the experiment with 2, 3, 4, and 5 rubber bands attached side-by-side, and when we do so, we find that the **acceleration of the object is directly proportional to the force applied to it**.

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Quantifying Force

(b) Acceleration is directly proportional to force.

Acceleration (in multiples of a_1)

$5a_1$

$4a_1$

$3a_1$

$2a_1$

$1a_1$

0

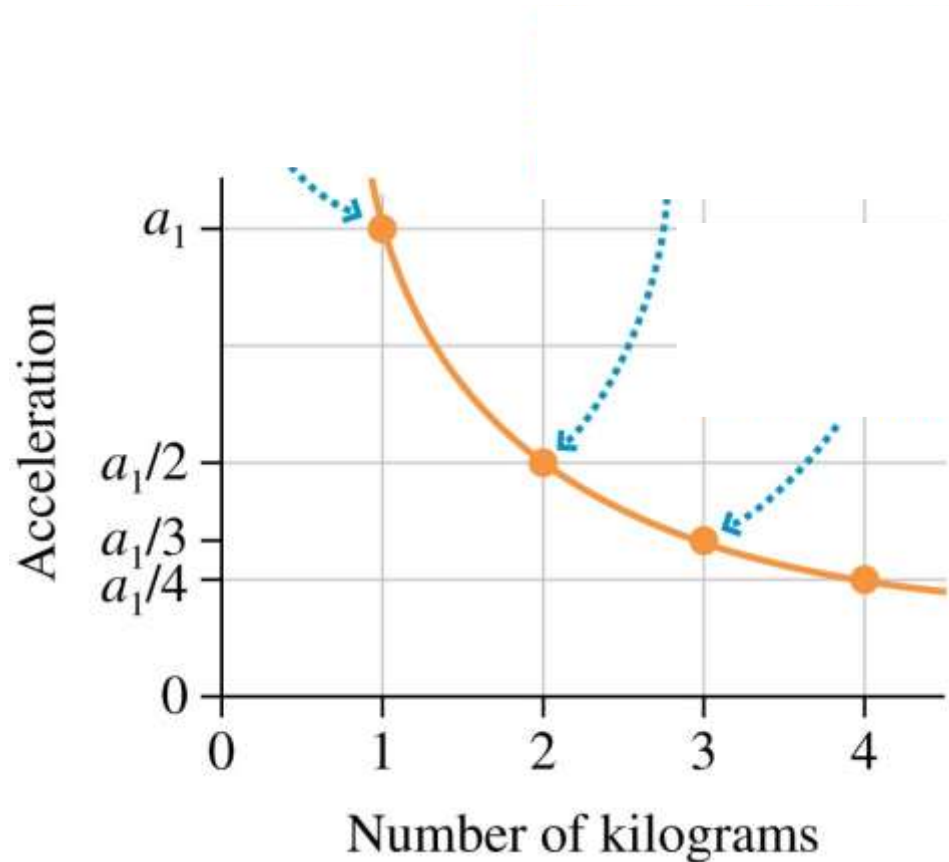0   1   2   3   4   5

Force (number of rubber bands)

- As it has been established that **acceleration of the object is directly proportional to the force applied to it**.

$$a \propto F$$

Q. What will happen to the acceleration of the object if we double, treble, or quadruple the mass, for example, while applying the same force?
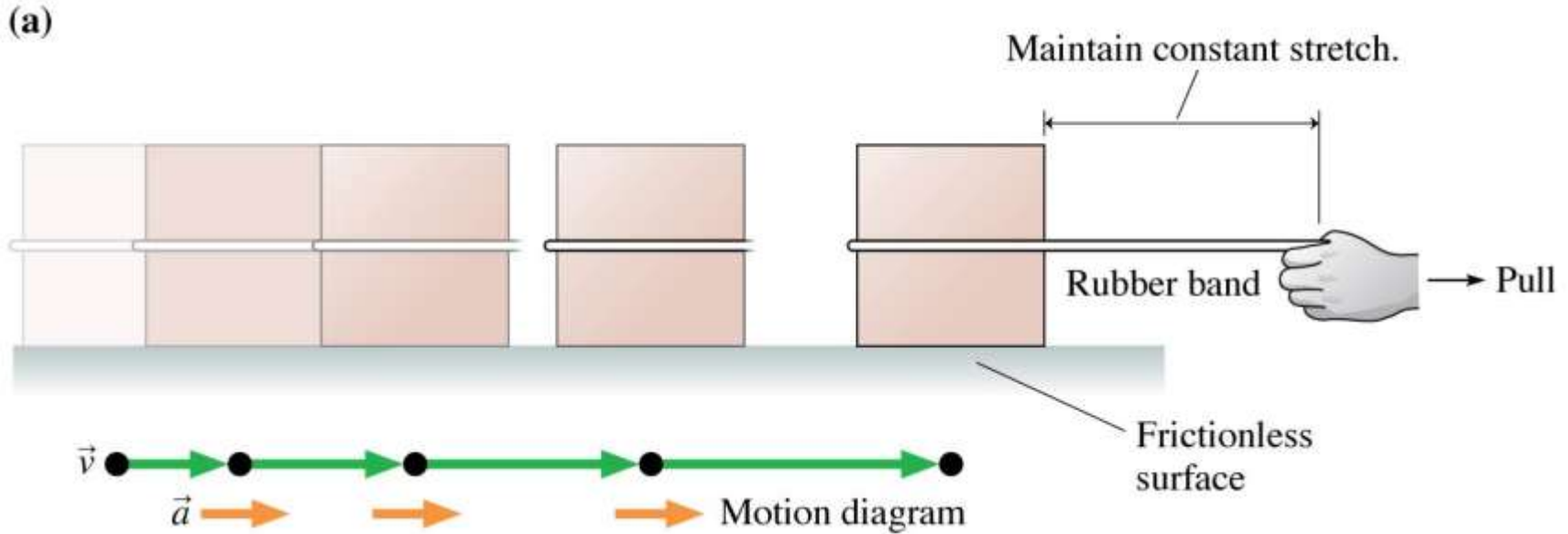
14

Quantifying Force

- What we find is that for the same applied force, the **acceleration is inversely proportional to the mass**.

$$a \propto \frac{1}{m}$$
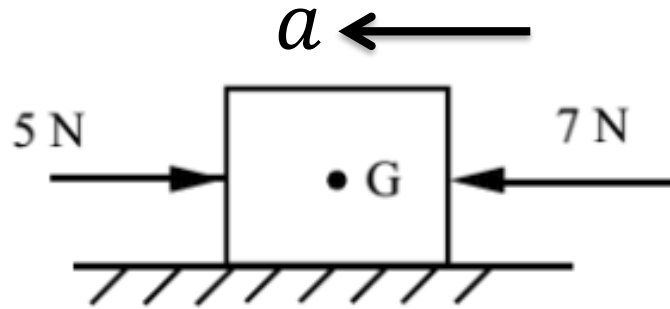
Quantifying Force

Thus,

- A force can cause an object to **accelerate**; this acceleration is what we observe when an **unbalanced force** is applied to an object. What we observe is the following:

$$a \propto \frac{F}{m}$$

Quantifying Force

Unbalanced force

Sir Isaac Newton (1643-1727)

- **So what we find is that** whatever the **unbalanced force** is acting on the object, it is equal to the **resultant acceleration** of the object multiplied by that object's mass.

$$F = ma$$

- The unit for force is called the **Newton** (N).

- $1 \text{ N} = 1 \text{ kg m/s}^2$, or in words, 1 N is a force that will accelerate an object of mass 1 kg by 1 m/s^2.

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Newton's 2ⁿᵈ Law of Motion
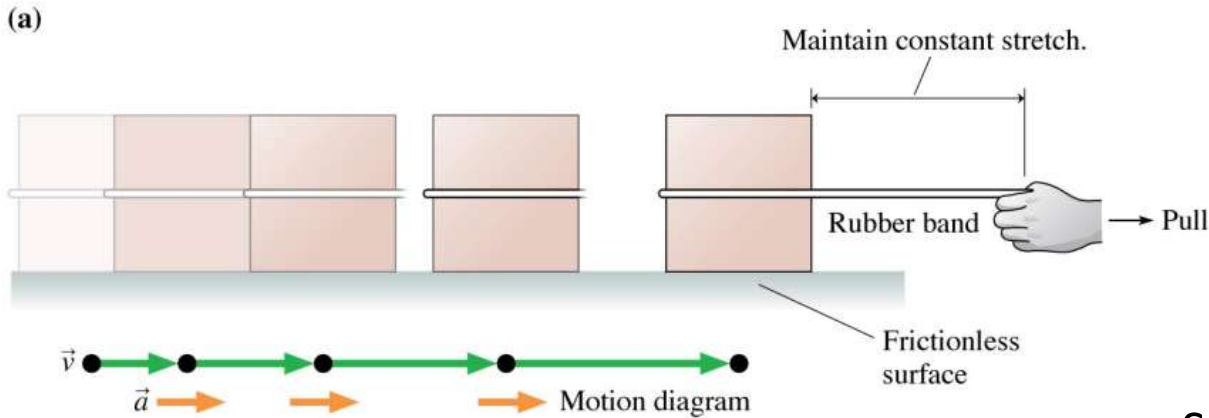
Sir Isaac Newton (1643-1727)

Newton's second law: An object of mass *m* is subjected to forces $\vec{F}_1, \vec{F}_2, \vec{F}_3, \ldots$ will undergo an acceleration $\vec{a}$ given by

$$\vec{a} = \frac{\vec{F}_{net}}{m}$$

Where the net force $\vec{F}_{net} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 + \cdots\cdots$
is the vector sum of all forces acting on the object. The acceleration vector $\vec{a}$ points in the direction of the force vector $\vec{F}_{net}$.

Newton's 1st Law of Motion

- **Newton's first law:** An object at rest tends to stay at rest and an object in motion tends to stay in motion in a straight line with constant velocity, **if and only if** the **net force ($\vec{F}_{net}$)** acting on the object is zero.

- Newton's 1st law of motion is also known as the **law of inertia.**

  Inertia: Is the tendency of an object to resist changes in its state of motion.

Newton's 1st Law of Motion

Why is the driver of a moving car thrown forward when the car hits a brick wall head on? Can you explain using Newton's first law


- When the car collides with the wall, the car stops suddenly, **but due to inertia**, the driver continues to move forward at the same speed that the car was traveling before the collision.

- This causes the **driver to be thrown forward** until they come into contact with the **seat belt**, **steering wheel**, or **dashboard**.

Newton's 1ˢᵗ Law of Motion

- An object on which the **net force is zero** is said to be in **mechanical equilibrium**.

- There are two forms of mechanical equilibrium: **static equilibrium and dynamic equilibrium**

o If the object is at rest, then it is in **static equilibrium**.

o If the object is moving with constant velocity, it is in **dynamic equilibrium**.

An object at rest is in static equilibrium:
$\vec{F}_{net} = \vec{0}.$

$\vec{v} = \vec{0}$ ●
$\vec{a} = \vec{0}$

$\vec{v}$ ●→●→●→●

$\vec{a} = \vec{0}$
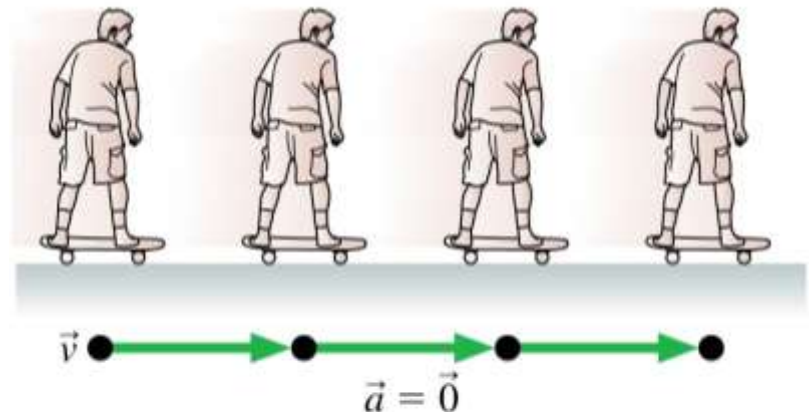
An object moving in a straight line at constant velocity is in dynamic equilibrium: $\vec{F}_{net} = \vec{0}.$

What is Force?

- If we quantify a push or a pull (force in other words) in terms of its **magnitude**, and then specify the **force's direction**, the **force becomes a vector**.
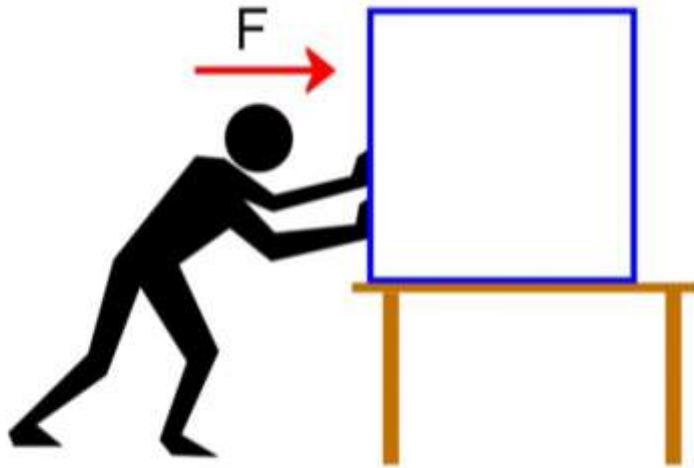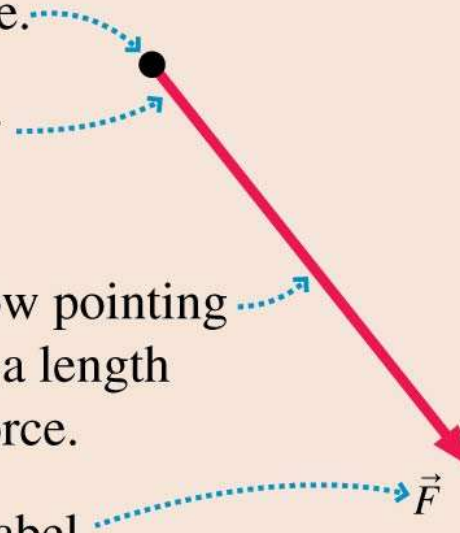

- We've now seen how we quantify force as well as looking at the first two laws of motion in the process;

- **let's now see how we draw force vectors and combine them**.
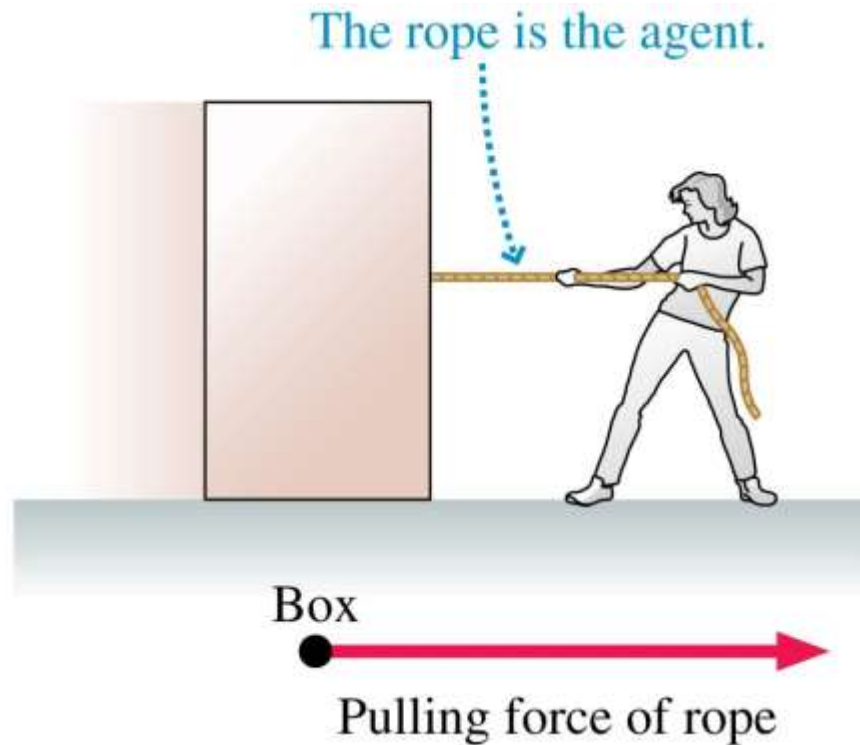
3. Drawing Force Vectors

Drawing Force Vectors

TACTICS BOX 5.1   **Drawing force vectors**

❶ Represent the object as a particle.

❷ Place the *tail* of the force vector on the particle.

❸ Draw the force vector as an arrow pointing in the proper direction and with a length proportional to the size of the force.

❹ Give the vector an appropriate label. $\vec{F}$

Drawing Force Vectors


The rope is the agent.

Box

Pulling force of rope

- In the above image, a box is pulled to the right by a person.

- Because the rope used to do the pulling mediates the force applied by the person, we can say that the rope is the **agent of the force** in this situation.

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Drawing Force Vectors

The spring is the agent.

Box

Pushing force of spring
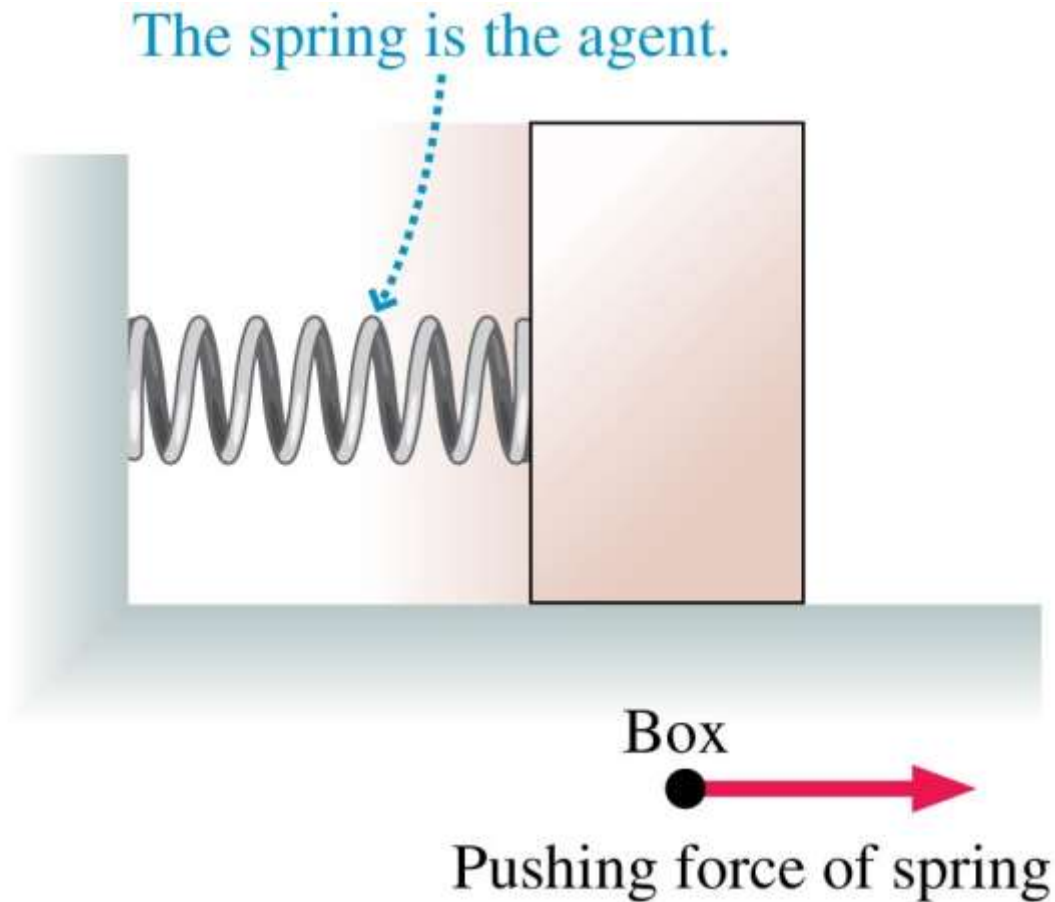
- Likewise for the above image: a box is pushed to the right by a spring, and the spring can be called the **agent of the force**.
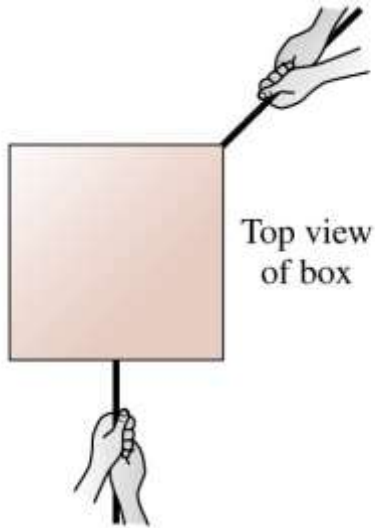
Drawing Force Vectors
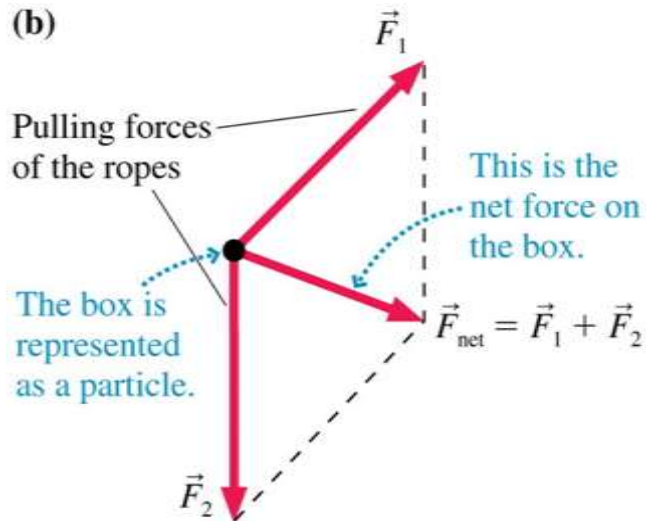

Box

Long-range force of gravity
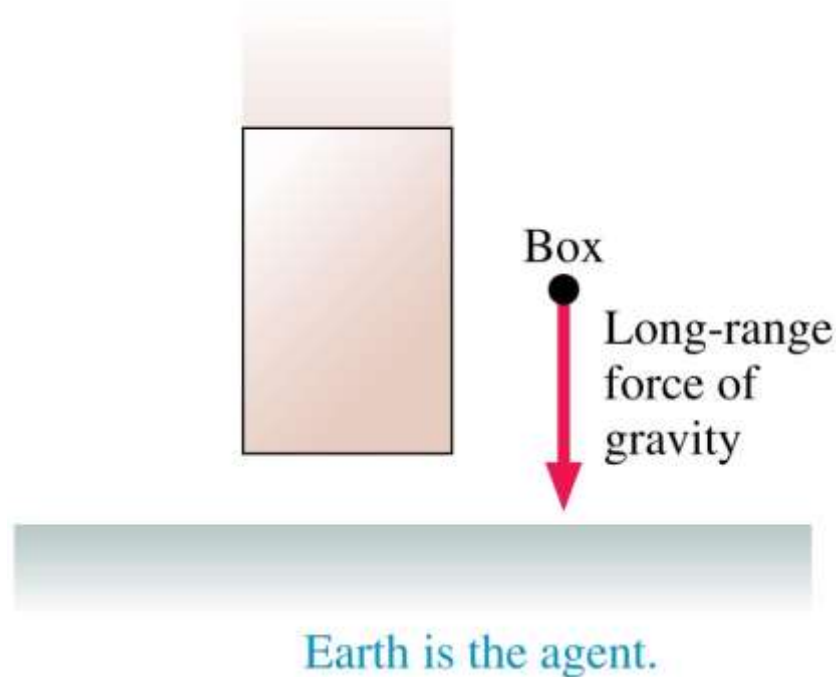
Earth is the agent.

- When the box is acted on by gravity, the cause of this gravity is the Earth, so you can say the Earth is the **agent of the force**, or vice-versa.

- Let's now see how we **combine force vectors when an object is acted on by different forces**.

Combining Force Vectors

(a)

Top view of box

(b)

$\vec{F}_1$

Pulling forces of the ropes

This is the net force on the box.

The box is represented as a particle.

$\vec{F}_{net} = \vec{F}_1 + \vec{F}_2$

$\vec{F}_2$
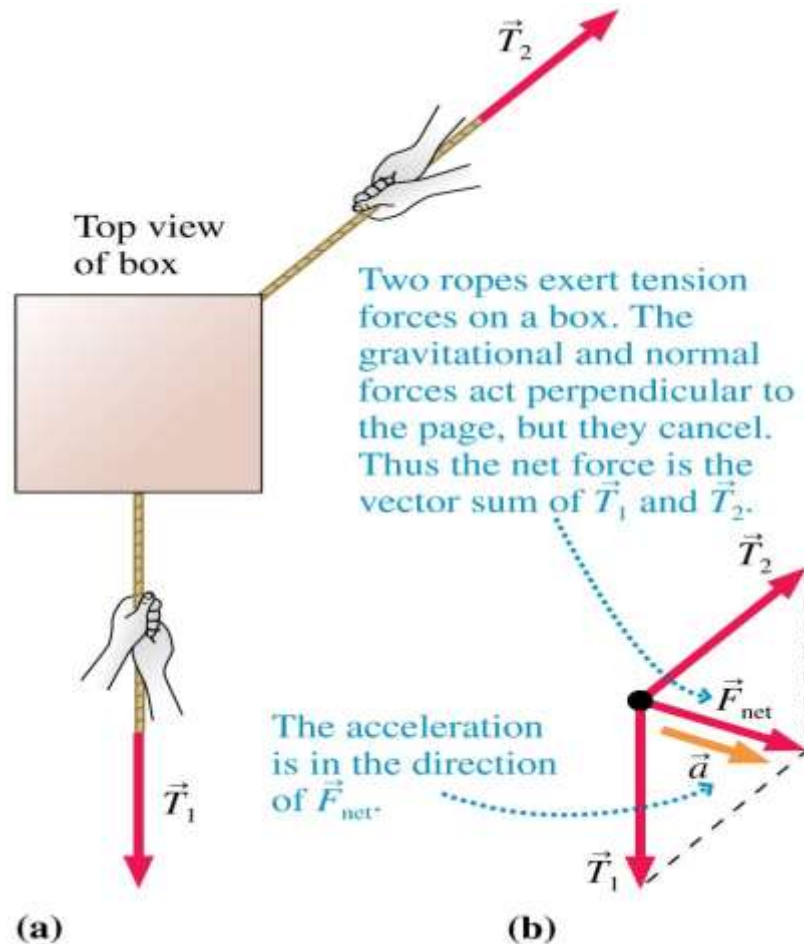
- When several forces are exerted on an object, they combine to form a **net force** given by the **vector sum** of **all** the forces:

$$\vec{F}_{net} = \sum_{i=1}^{N} \vec{F}_i = \vec{F}_1 + \vec{F}_2 + \cdots + \vec{F}_N$$

- This is called a **superposition of forces**.

  - Let's now look at the different manifestations of force.

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An Implication of Combining Force Vectors

- When **more than one force** is acting on an object, **the object accelerates in the direction of the net force vector** $\vec{F}_{net}$.

Top view of box

Two ropes exert tension forces on a box. The gravitational and normal forces act perpendicular to the page, but they cancel. Thus the net force is the vector sum of $\vec{T}_1$ and $\vec{T}_2$.

The acceleration is in the direction of $\vec{F}_{net}$.
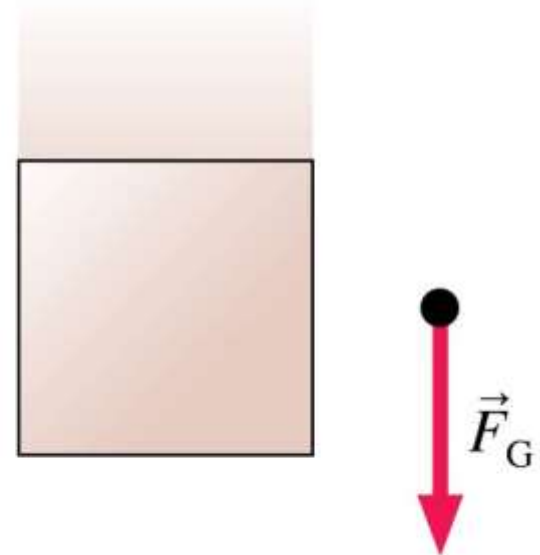
(a)

(b)

4. Manifestations of Force

The Gravitational Force

- The pull of a planet on an object near its surface is called the **gravitational force**.

- The agent for the gravitational force is the **entire planet**.

- Gravity acts on all objects, whether moving or at rest.

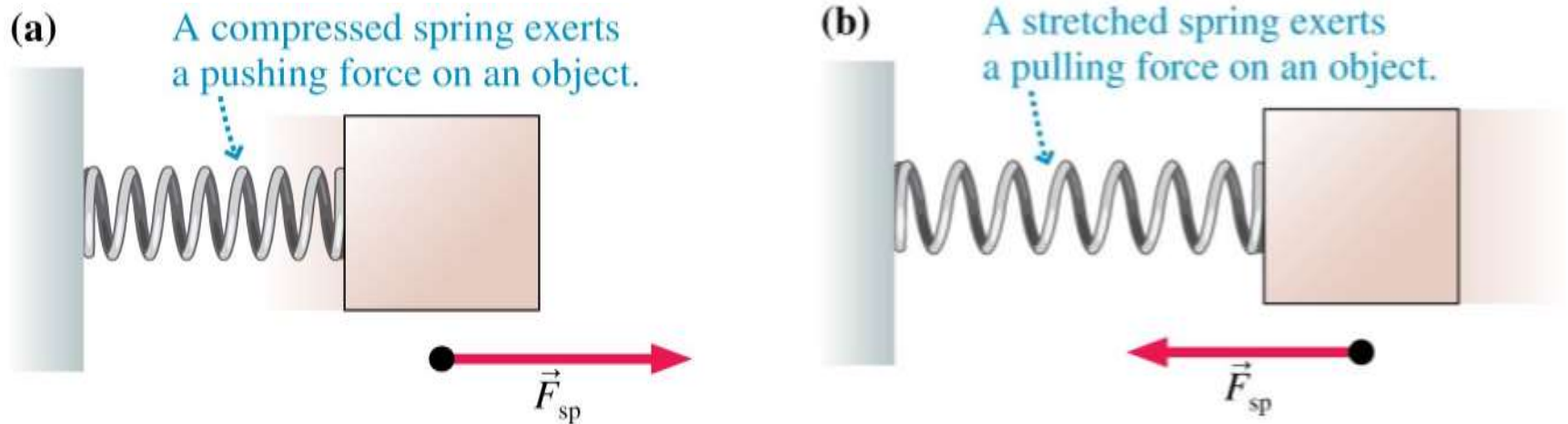- The gravitational force vector always points **vertically downward**.
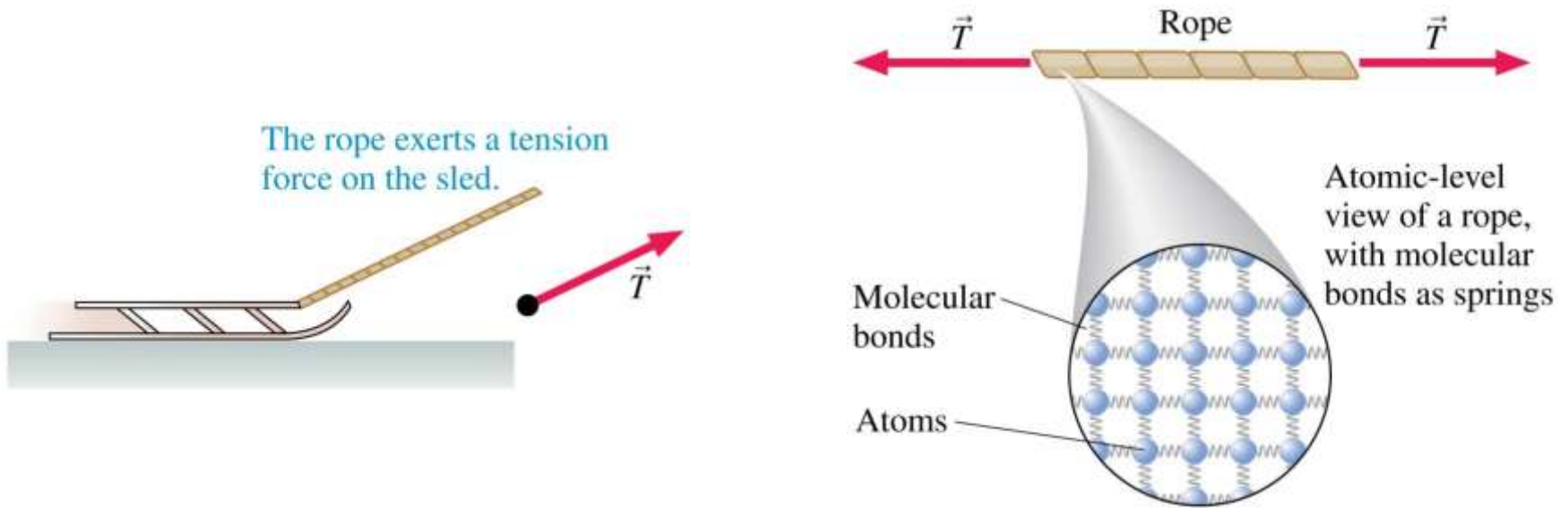
The gravitational force pulls the box down.

$\vec{F}_G$

Ground

$\vec{F}_G$

The Spring Force

(a) A compressed spring exerts a pushing force on an object.

$\vec{F}_{sp}$

(b) A stretched spring exerts a pulling force on an object.
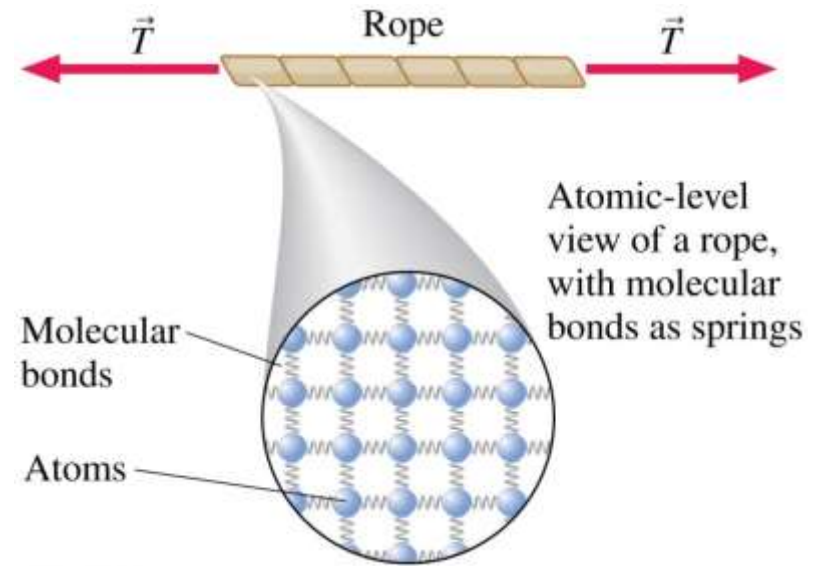
$\vec{F}_{sp}$

- A spring can either push (when compressed) or pull (when stretched).

- Not all springs are metal coils, though.

- Whenever an elastic object is deformed in some way, and then 'springs' back to its original shape when you let it go, we call this a **spring force**.

The Tension Force

The rope exerts a tension force on the sled.

$\vec{T}$

Rope

$\vec{T}$ $\vec{T}$

Atomic-level view of a rope, with molecular bonds as springs

Molecular bonds

Atoms

- When a string or rope or wire pulls on an object, it exerts a contact force that we call the **tension force**.

- We can model a rope as made of atoms joined together by molecular bonds.

The Tension Force

The rope exerts a tension force on the sled.

$\vec{T}$

$\vec{T}$ Rope $\vec{T}$

Molecular bonds

Atoms

Atomic-level view of a rope, with molecular bonds as springs

- Molecular bonds in the string or rope can be modeled as tiny springs holding the atoms together.

- Thus, tension is a result of many 'molecular springs' stretching ever so slightly.

The Normal Force

The compressed molecular springs push upward on the object.

$\vec{n}$

Atoms

Molecular bonds
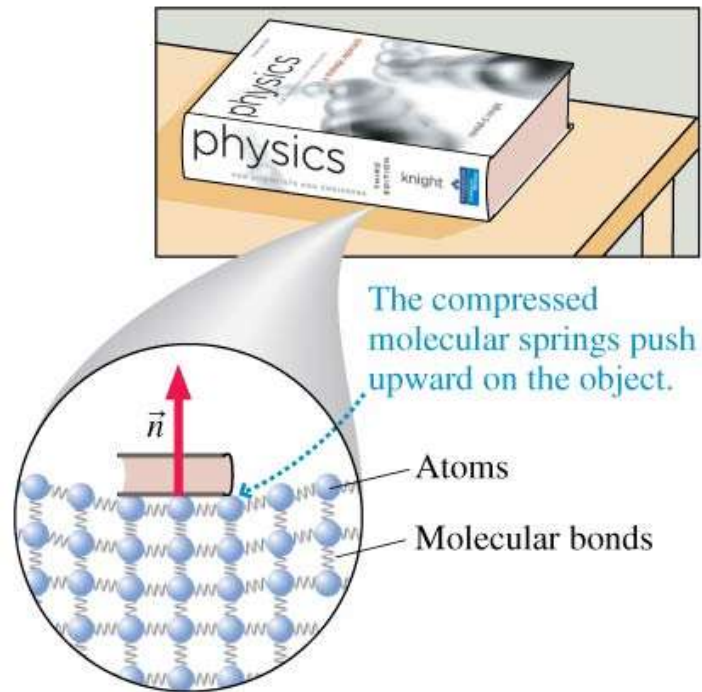
- When an object sits on a table, the table surface exerts an upward contact force on the object.

- This pushing force is directed perpendicular to the surface, and is called the **normal force**.

The Normal Force
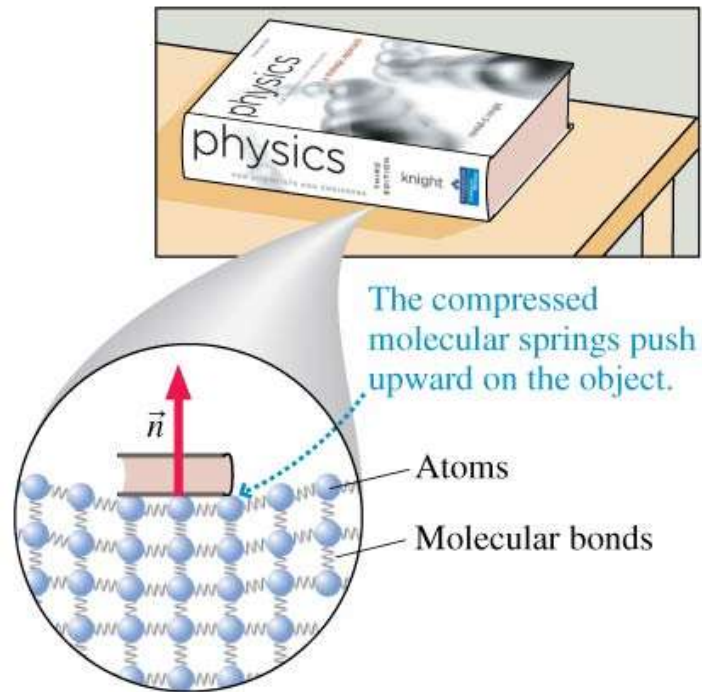
- A table is made of atoms joined together by molecular bonds which can be modelled as springs.

- The **normal force** is a result of many molecular springs being compressed ever so slightly.

The Normal Force

- Suppose you place your hand on a wall and lean against it.

- The wall exerts a horizontal **normal force** on your hand.

The compressed molecular springs in the wall press outward against her hand.

$\vec{n}$

- Suppose a frog sits on an inclined surface.

- The surface exerts a tilted **normal force** on the frog.

$\vec{n}$

The surface pushes outward against the bottom of the frog.
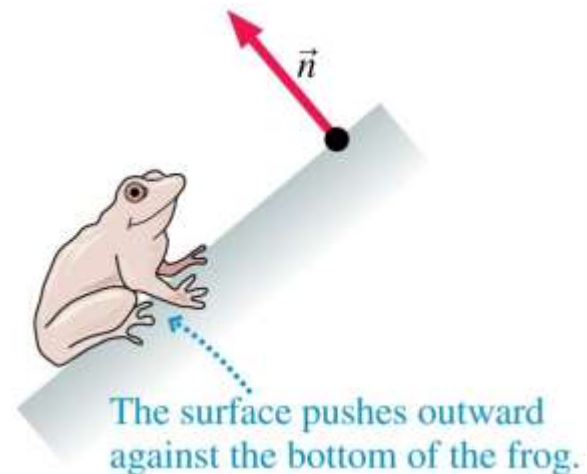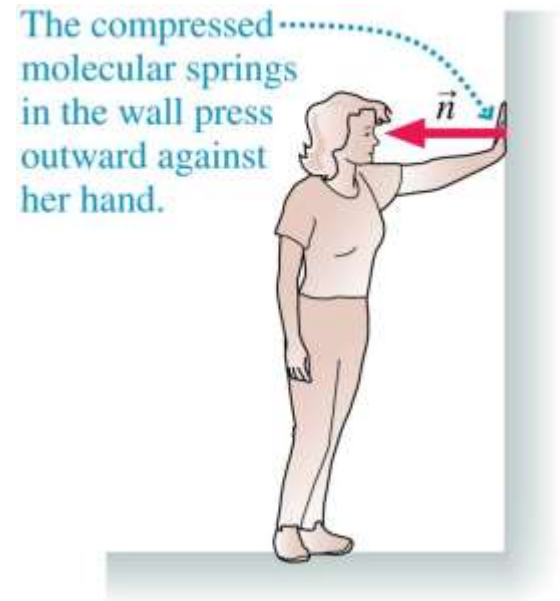
Kinetic Friction

- When an object slides along a surface, the surface can exert a contact force which opposes the motion.

Kinetic friction opposes the motion.
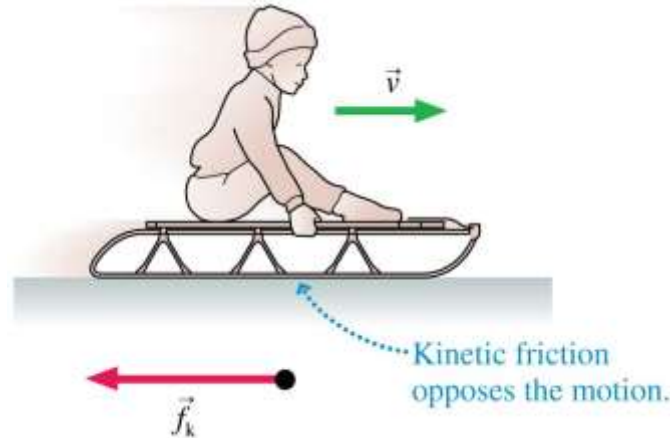
- This is called sliding friction or **kinetic friction**.

- The kinetic friction force is **directed at a tangent** to the surface, and opposite to the velocity of the object relative to the surface.

- Kinetic friction tends to slow down the sliding motion of an object in contact with a surface.

Static Friction

- **Static friction** is the contact force that keeps an object 'stuck' on a surface, and prevents relative motion.

Static friction acts in the direction that prevents slipping.
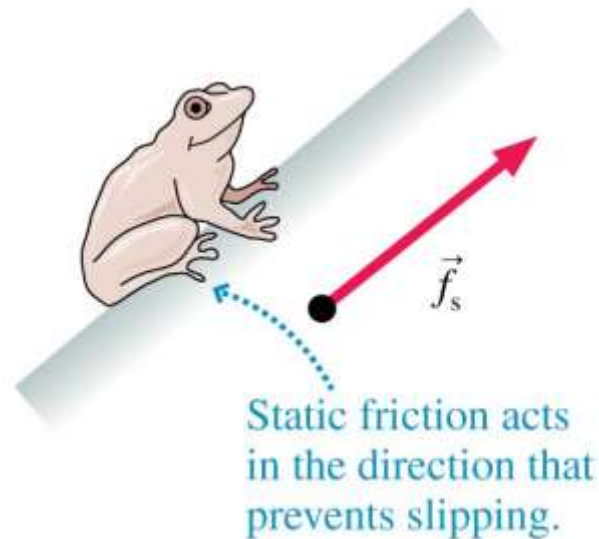
- The static friction force is directed at a tangent to the surface.

- Static friction points opposite the direction in which the object would move if there were no static friction.

Static Friction

- In order to walk, your foot must stick to the floor as you straighten your leg, moving your body forward.

The person pushes backward against the earth. The earth pushes forward on the person. Static friction.

- The force that prevents slipping is **static friction**.

- The static friction force points in the **forward direction**.

- It is static friction that propels/pushes object or you forward!

The car pushes backward against the earth. The earth pushes forward on the car. Static friction.
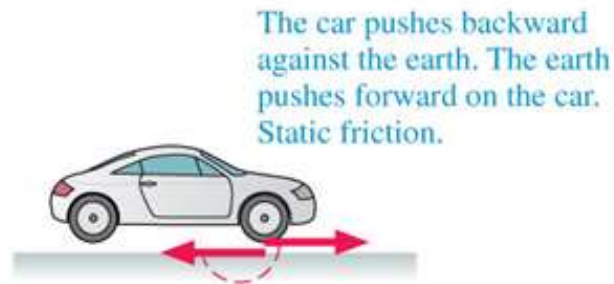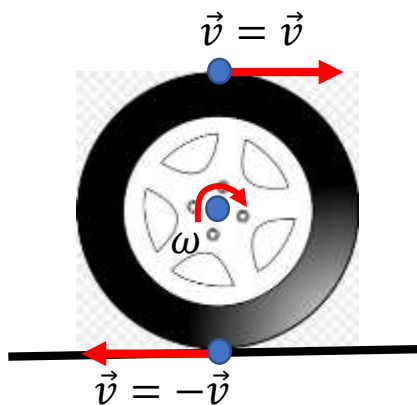
Static Friction

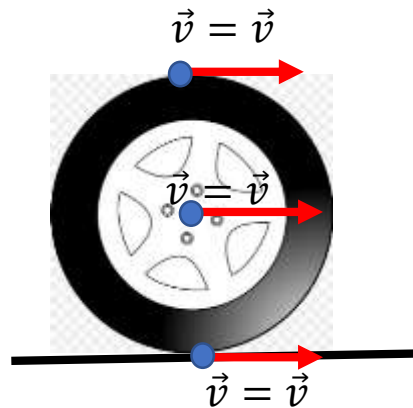
The person pushes backward against the earth. The earth pushes forward on the person. Static friction.

The car pushes backward against the earth. The earth pushes forward on the car. Static friction.
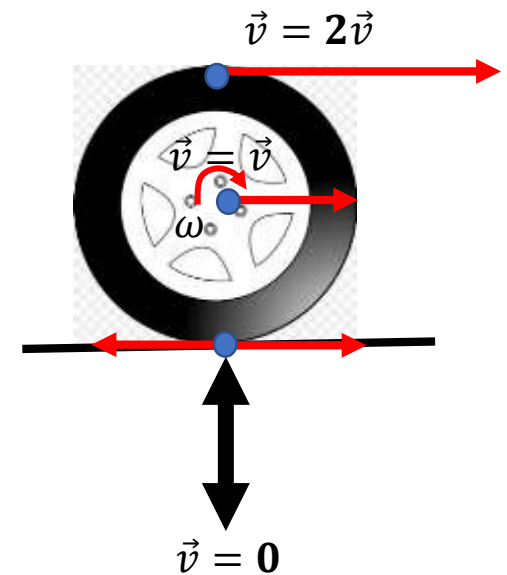
Rotational motion

$\vec{v} = \vec{v}$

ω

$\vec{v} = -\vec{v}$

+

Translational motion

$\vec{v} = \vec{v}$

$\vec{v} = \vec{v}$

$\vec{v} = \vec{v}$

=

Rolling motion

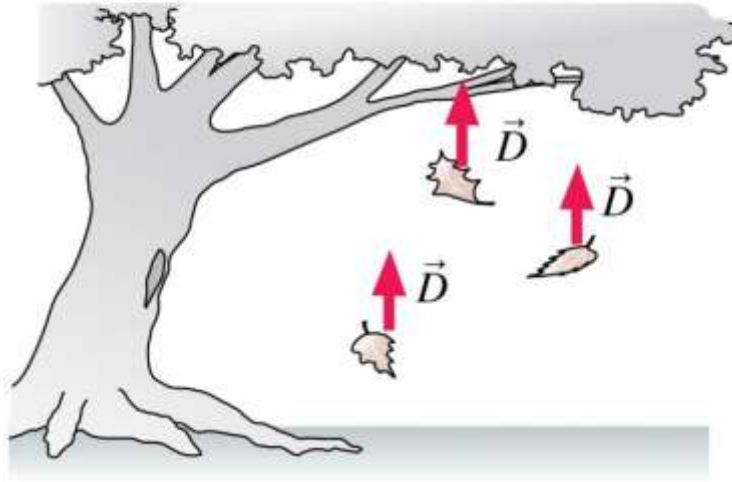$\vec{v} = 2\vec{v}$

$\vec{v} = \vec{v}$

ω

$\vec{v} = 0$

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Drag

Air resistance is a significant force on falling leaves. It points opposite the direction of motion.

- Kinetic friction is a **resistive force**, which opposes or resists motion.

- Resistive forces are also experienced by objects moving through fluids.

- This resistive force due to a fluid is called **drag**.

Drag

Air resistance is a significant force on falling leaves. It points opposite the direction of motion.
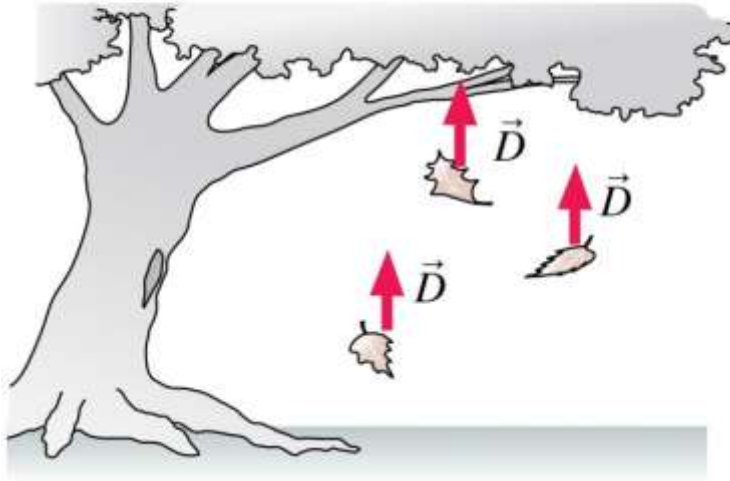
- Drag points opposite the direction of motion.
- For heavy and compact objects in air, the drag force is fairly small.

N.B. You can neglect air resistance (drag) in all problems unless a problem explicitly asks you to include it.

Thrust

Thrust force is exerted on a rocket by exhaust gases.
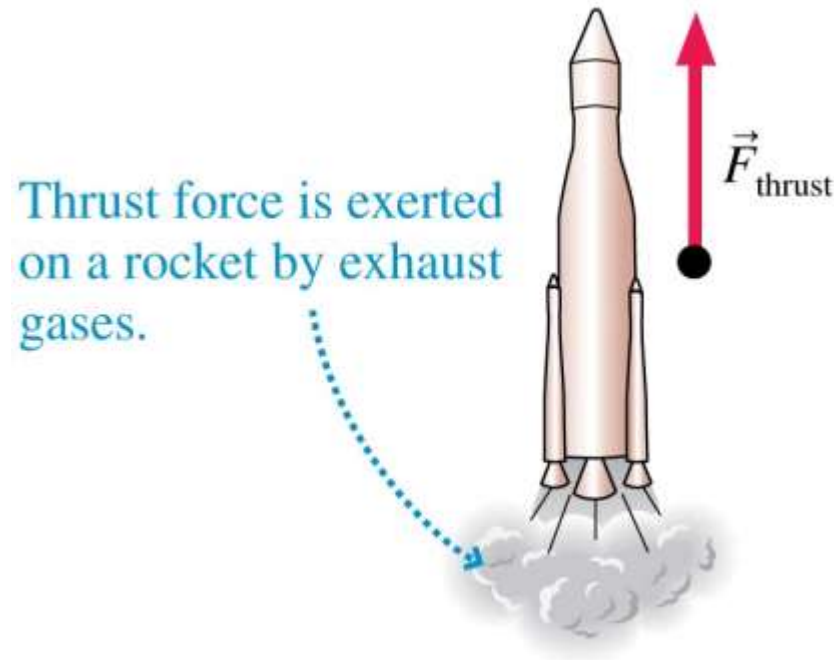
$\vec{F}_{\text{thrust}}$

- A jet airplane or a rocket has what we call a **thrust** force pushing it forward during takeoff.

- Thrust occurs when an engine expels gas molecules at high speed.

- These exhaust gas molecules exert a contact force on the engine.

- The direction of thrust is opposite the direction in which the exhaust gases are expelled.

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Electric and Magnetic Forces

- Electricity and magnetism, like gravity, exert **long-range forces**.

- As we will see in later lectures, and more so in Semester 2 **(Fdn Chemistry),** atoms and molecules are made of electrically charged particles, and molecular bonds are due to the electric force between these particles.

Symbols for the Different Manifestations of Force

Force	Notation
General force	$\vec{F}$
Gravitational force	$\vec{F}_G$
Spring force	$\vec{F}_{sp}$
Tension	$\vec{T}$
Normal force	$\vec{N}$
Thrust	$\vec{F}_{thrust}$
Static friction	$\vec{f}_s$
Kinetic friction	$\vec{f}_k$
Drag	$\vec{D}$

5. Newton's 3rd Law of Motion

Newton's 3rd Law of Motion

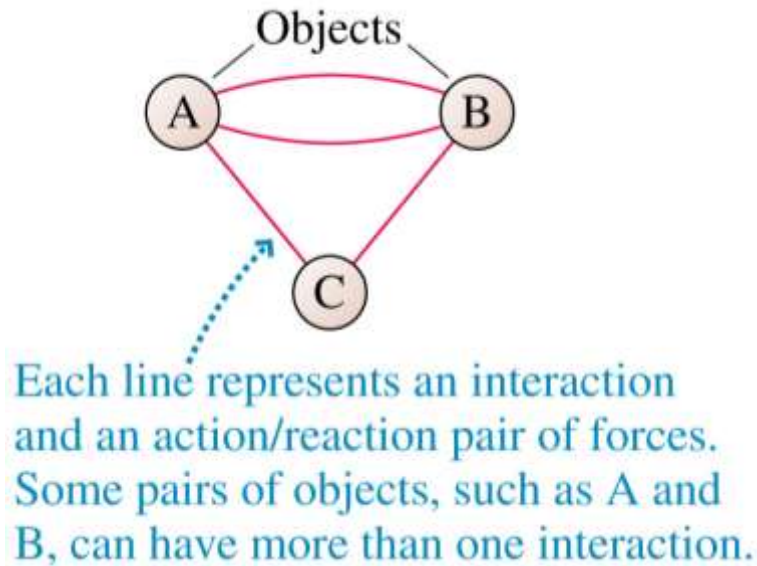The force of the nail on the hammer.

The force of the hammer on the nail
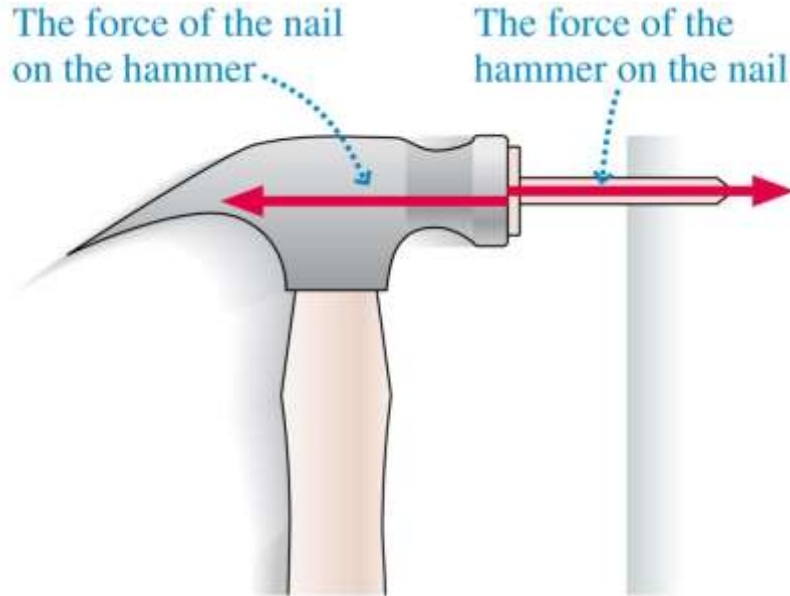
- When a hammer hits a nail, it exerts a forward force on the nail.

  - At the same time, the nail exerts a backward force on the hammer.

- If you don't believe it, imagine hitting the nail with a glass hammer.
- It's the force of the nail on the hammer that would cause the glass to shatter!
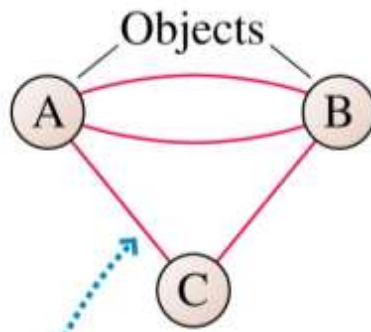
Interacting Objects
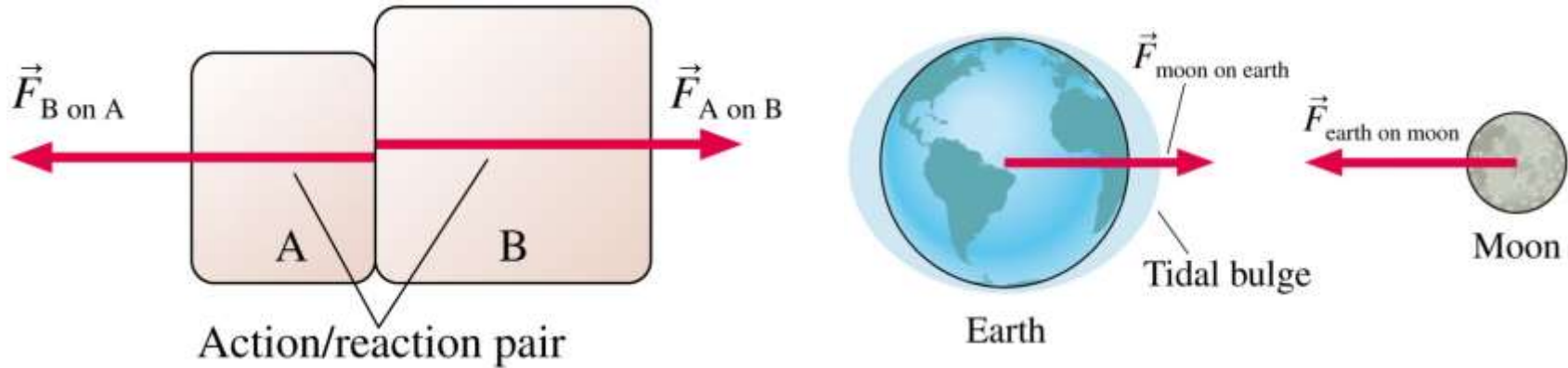
- If object A exerts a force on object B, then object B exerts an equal and opposite force on object A.

  - The pair of forces, as shown in each situation, is called an **action/reaction pair**.
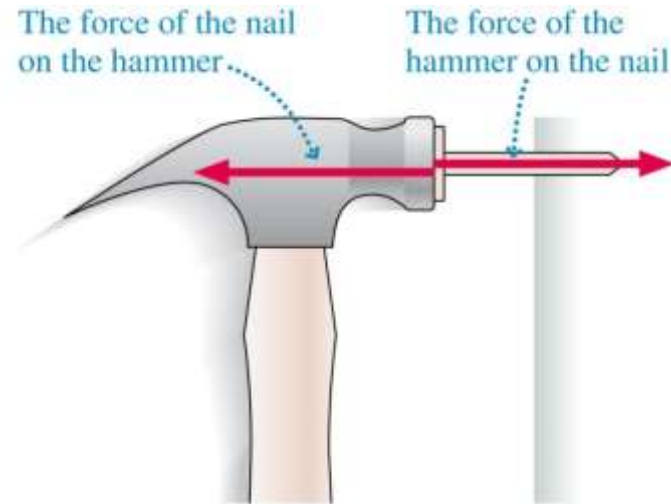
Objects, Systems, and the Environment

Objects

Each line represents an interaction and an action/reaction pair of forces. Some pairs of objects, such as A and B, can have more than one interaction.

- The figure shows three objects interacting via action/reaction pairs of forces.

- The forces can be given labels, such $\vec{F}_{A \, on \, B}$ and $\vec{F}_{B \, on \, A}$.

- We define the **system** as those objects whose motion we want to analyse, and we define the **environment** as objects external to the system.

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Objects, Systems, and the Environment
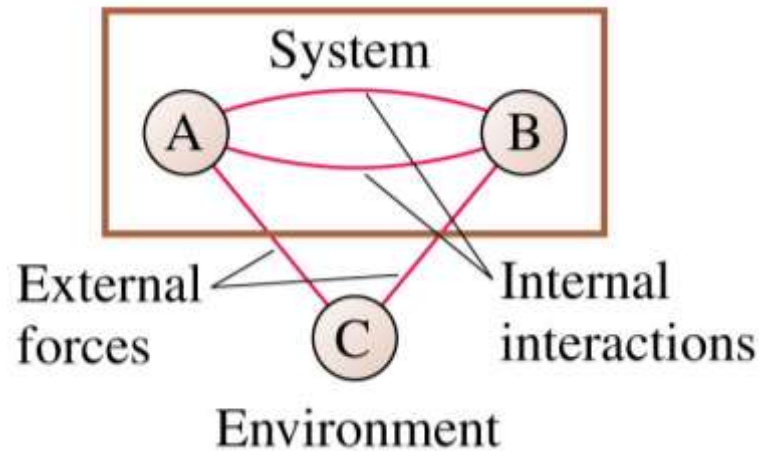
Objects

A ⟷ B

C

Each line represents an interaction and an action/reaction pair of forces. Some pairs of objects, such as A and B, can have more than one interaction.

The force of the nail on the hammer

The force of the hammer on the nail

• For example:
  • Object A = the hammer
  • Object B = the nail
  • Object C = the earth

• The Earth interacts with both the hammer and the nail via gravity.

• Practically, the Earth remains at rest while the hammer and the nail move.
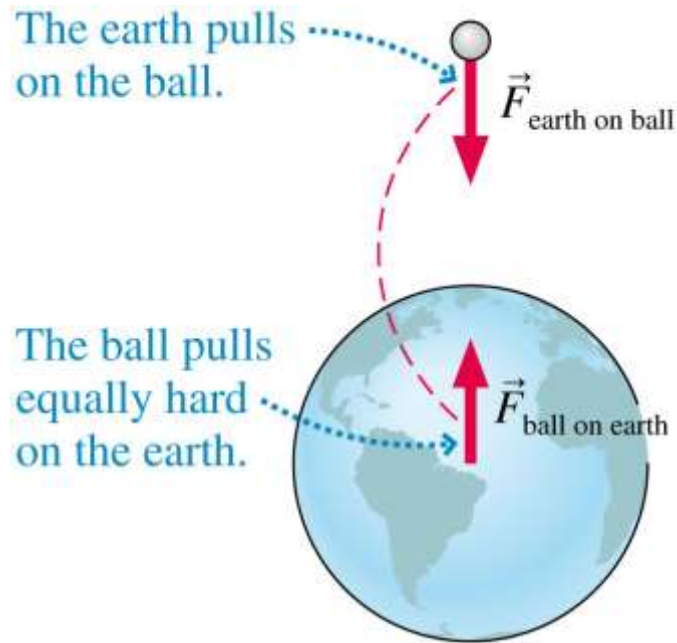
Objects, Systems, and the Environment

- The figure shows a new kind of diagram, an **interaction diagram**.

- The objects of the system are in a box.

- Interactions are represented by lines connecting the objects.

- Interactions with objects in the environment are called **external forces**.
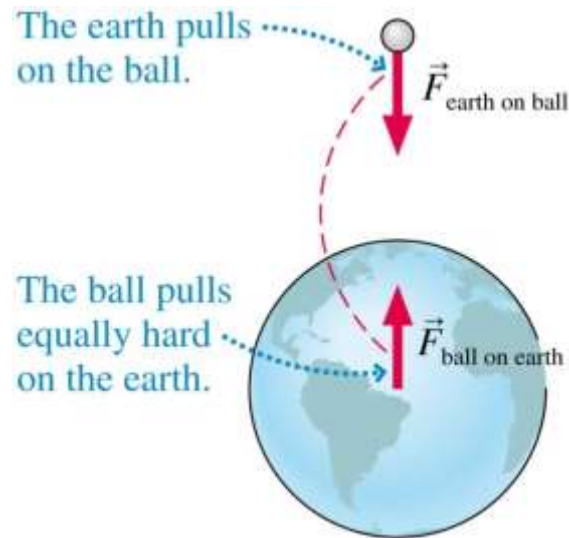
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Have a Think: Pushing a Crate
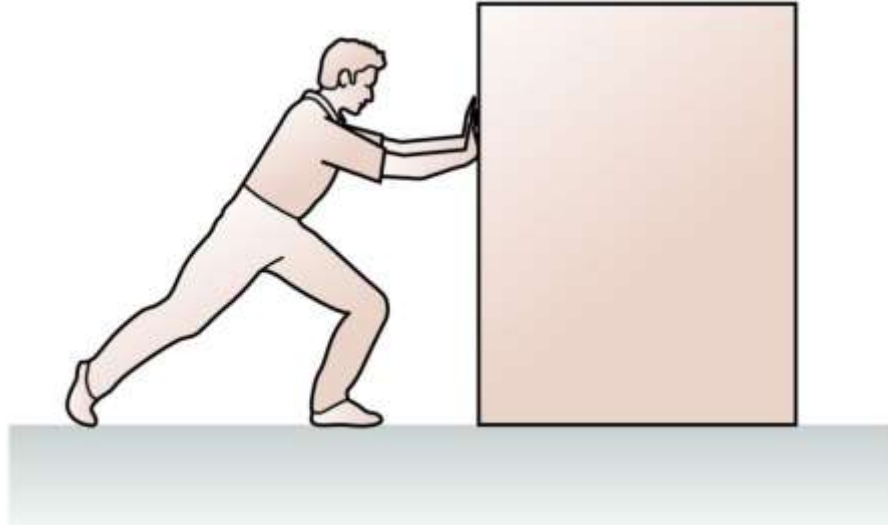
Q.1 The above figure shows a person pushing a large crate across a rough surface. Identify all interactions, showing them on an interaction diagram. Then draw free-body diagrams of the person and the crate.

Newton's 3rd Law

The earth pulls on the ball.

$\vec{F}_{earth\ on\ ball}$

The ball pulls equally hard on the earth.

$\vec{F}_{ball\ on\ earth}$

- When you release a ball, it falls down.

- The action/reaction forces of the ball and the earth are equal in magnitude.

- Thus, the acceleration of the ball due to the Earth is $g = \dfrac{\vec{F}_{earth\ on\ ball}}{m}$

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Newton's 3rd Law

The earth pulls on the ball.

$\vec{F}_{\text{earth on ball}}$

The ball pulls equally hard on the earth.

$\vec{F}_{\text{ball on earth}}$

• And the acceleration of the Earth due to the ball is

$$\vec{a}_E = \frac{\vec{F}_{ball\ on\ Earth}}{m_E} = \frac{m_B}{m_E} g$$

=> If the ball has a mass of 1 kg, the Earth accelerates upward at 2×10^{-24} m/s^2, which is something we don't notice.

Summary of today's Lecture

1. What is force?
2. Quantifying force
3. Drawing force vectors
4. Manifestations of force
5. Newton's 3rd law of Motion

Lecture 3: Recommended Readings

- **Ch. 4.1**, Force; p.139-140.

- **Ch. 4.2**, Newton's 1st law; p.141-143.

- **Ch. 4.3**, Mass and Newton's 2nd law ; p.143-148.

- **Ch. 4.4**, Mass and weight; p.148-151.

- **Ch. 4.5**, Newton's 3rd law; p.151-153.

Online weekly Quizzes

Do not forget to complete Quiz 2

The deadline for this assessment is Friday, 25th October 2024, 3pm.