# Science A Physics

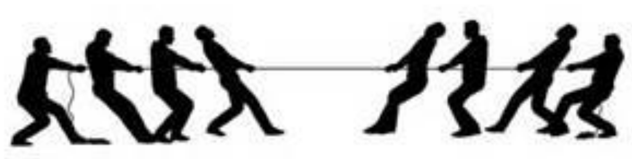
## Lecture 3:

## 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 3$^{rd}$ 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.

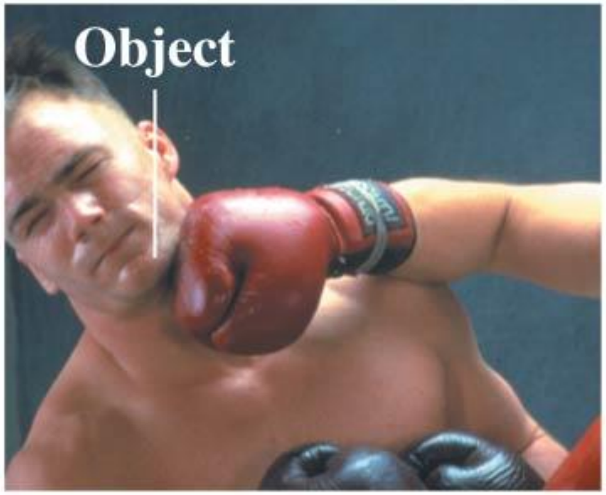
- In essence, **the idea of force** is what we use to explain the cause of motion.

- 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.

- 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?

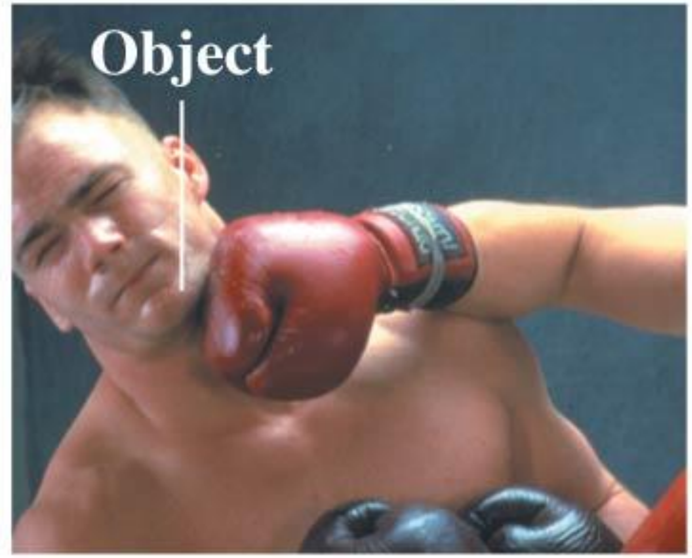
- **Contact forces** are interactions that result from objects directly touching one another.

**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?

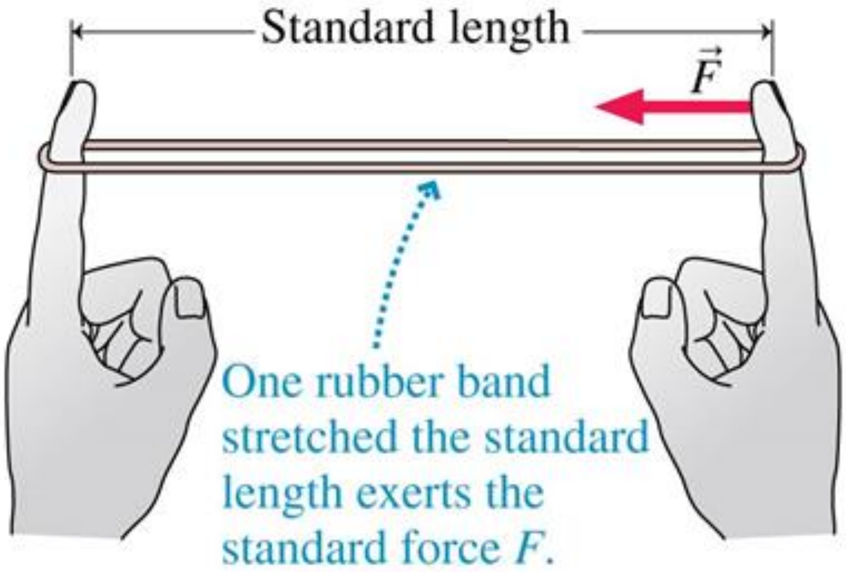




- If we quantify a push or a pull (force in other words) in terms of its magnitude, and then specify the force's direction, the **force becomes a vector**.

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

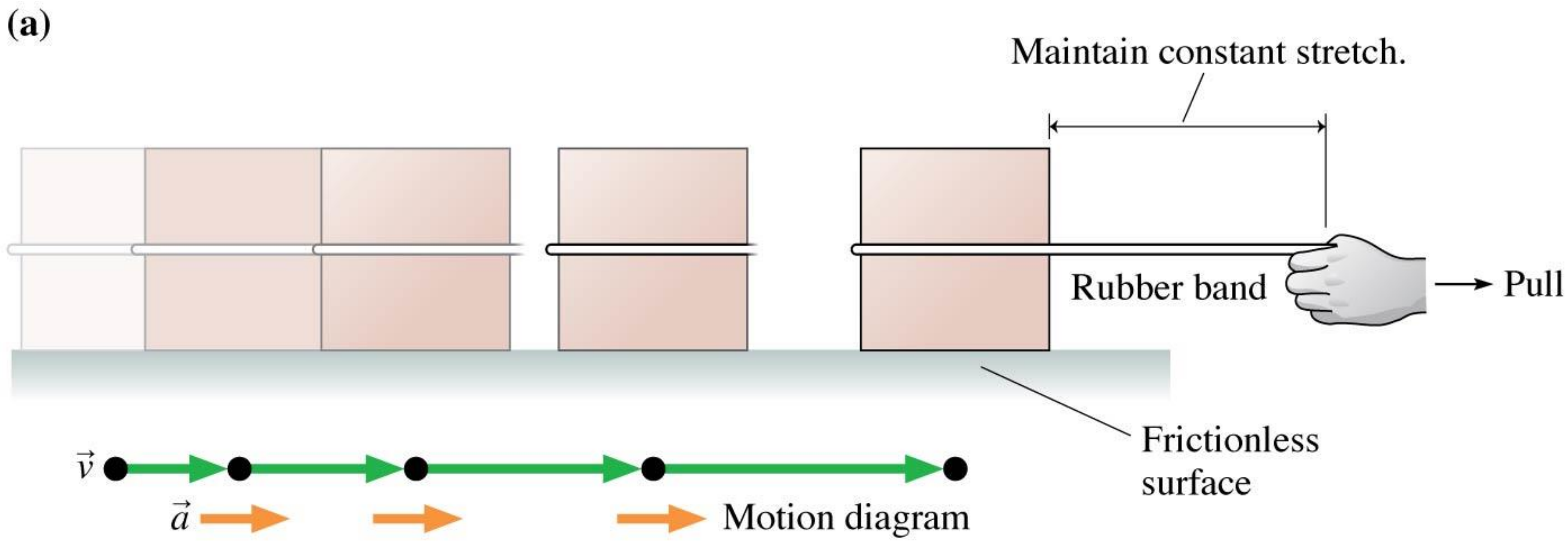
# 2. Quantifying Force

# Quantifying Force



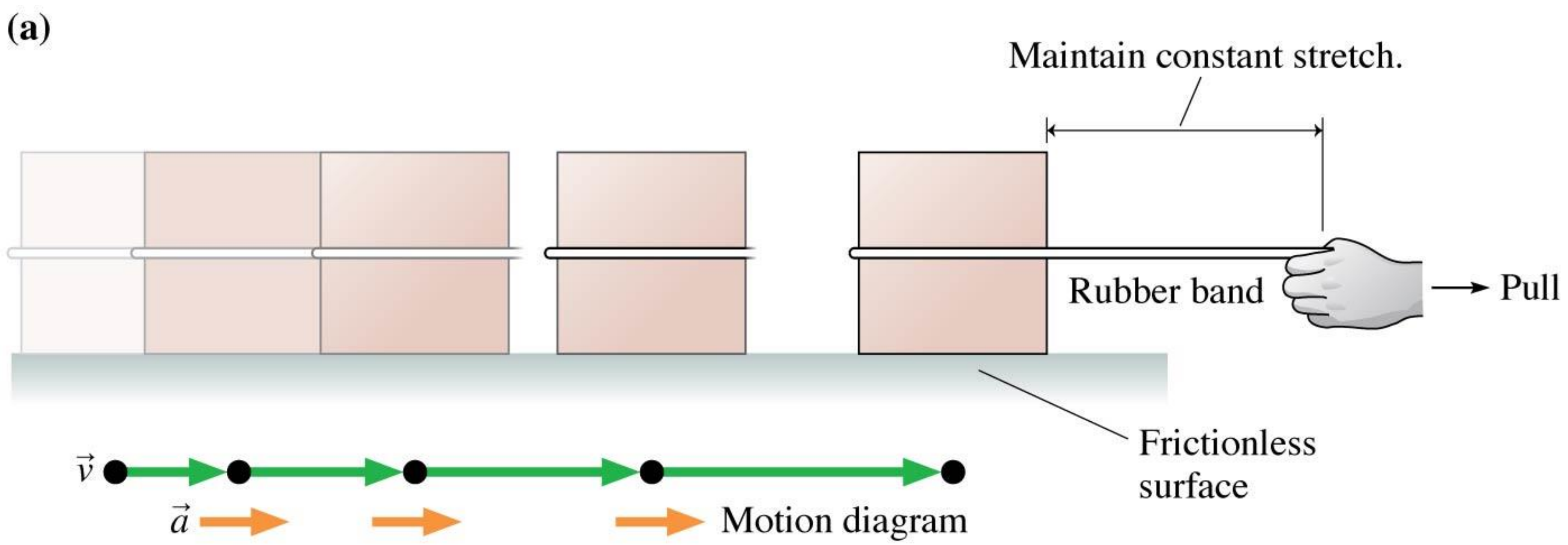

- We must first consider a standard rubber band stretched to some standard length.
- This will exert a reproducible force of magnitude $F$ on whatever it is attached to.
- $N$ side-by-side rubber bands exert $N$ times the standard force: $F_{net} = NF$.

# Quantifying Force



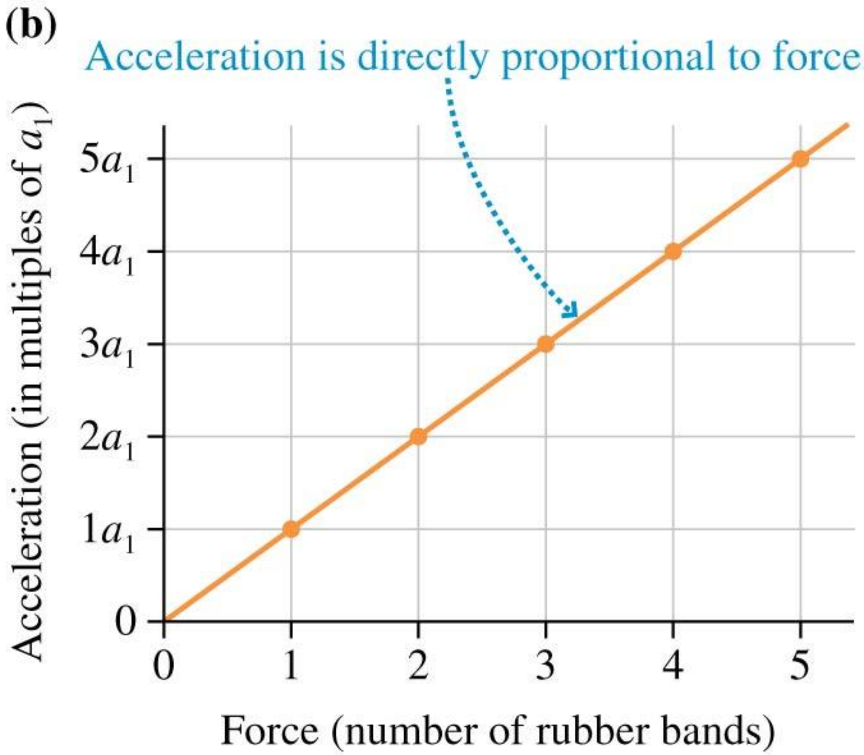

- Let's consider a block with a mass of 1 kg.
- Imagine attaching the stretched rubber band to this 1 kg block.
- Then imagine using the rubber band to pull the block across a horizontal, frictionless table.

# Quantifying Force



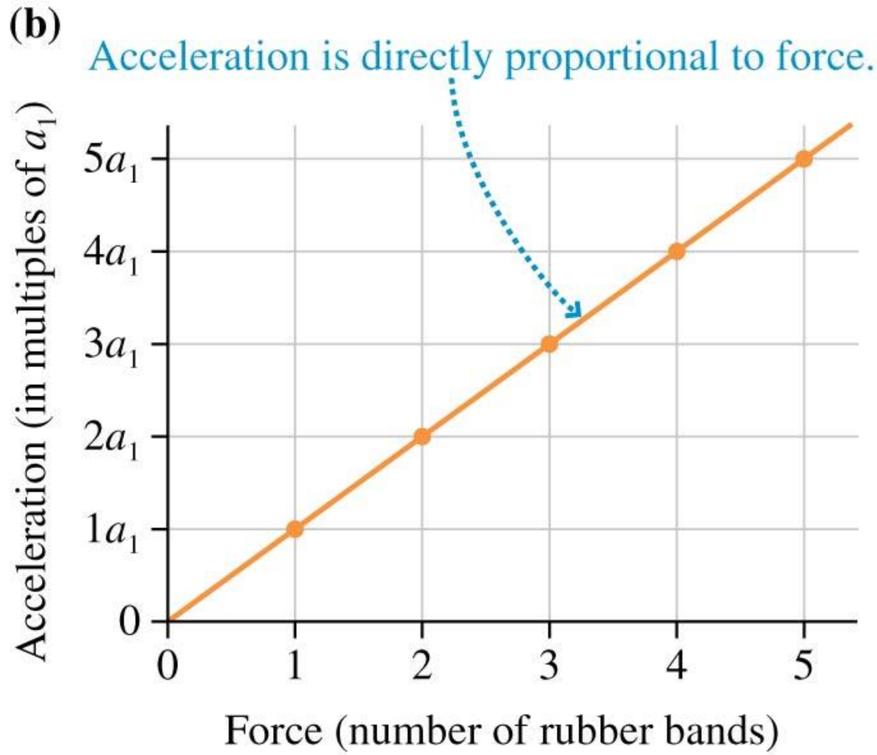

- We must also imagine keeping the rubber band stretched by a fixed amount.
- We thus find that the block moves with a **constant acceleration**.

# Quantifying Force




- 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**.

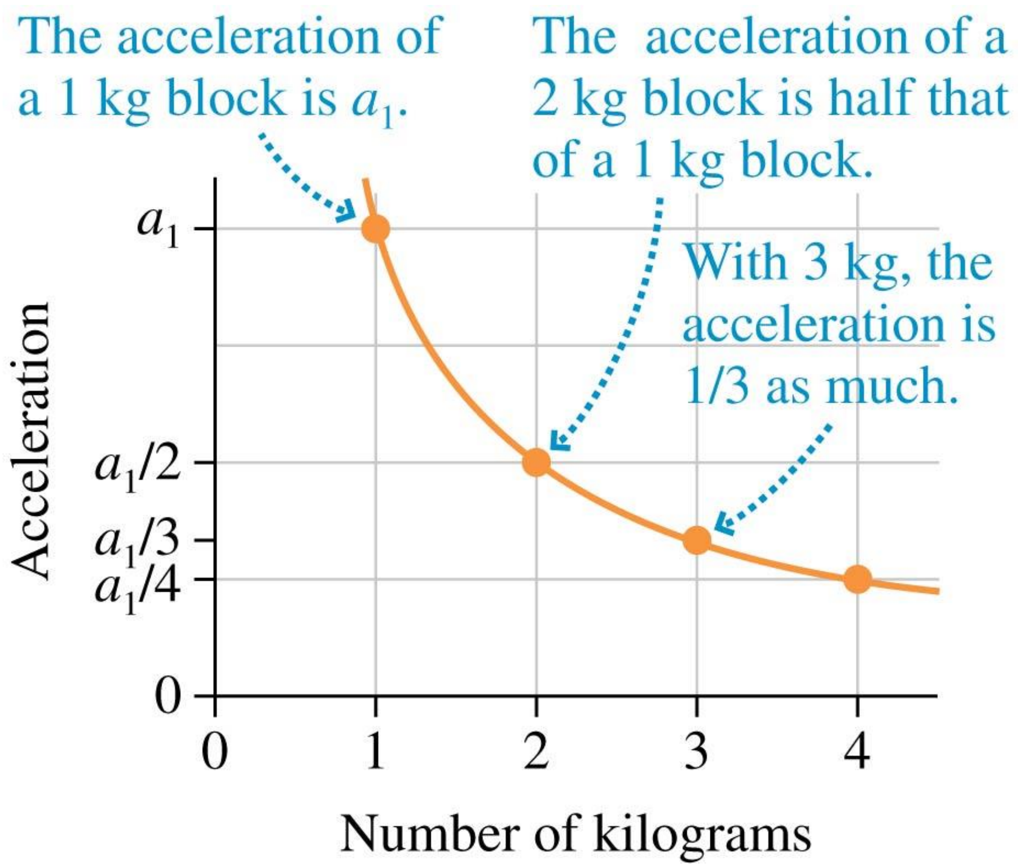
# Quantifying Force




- 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**.

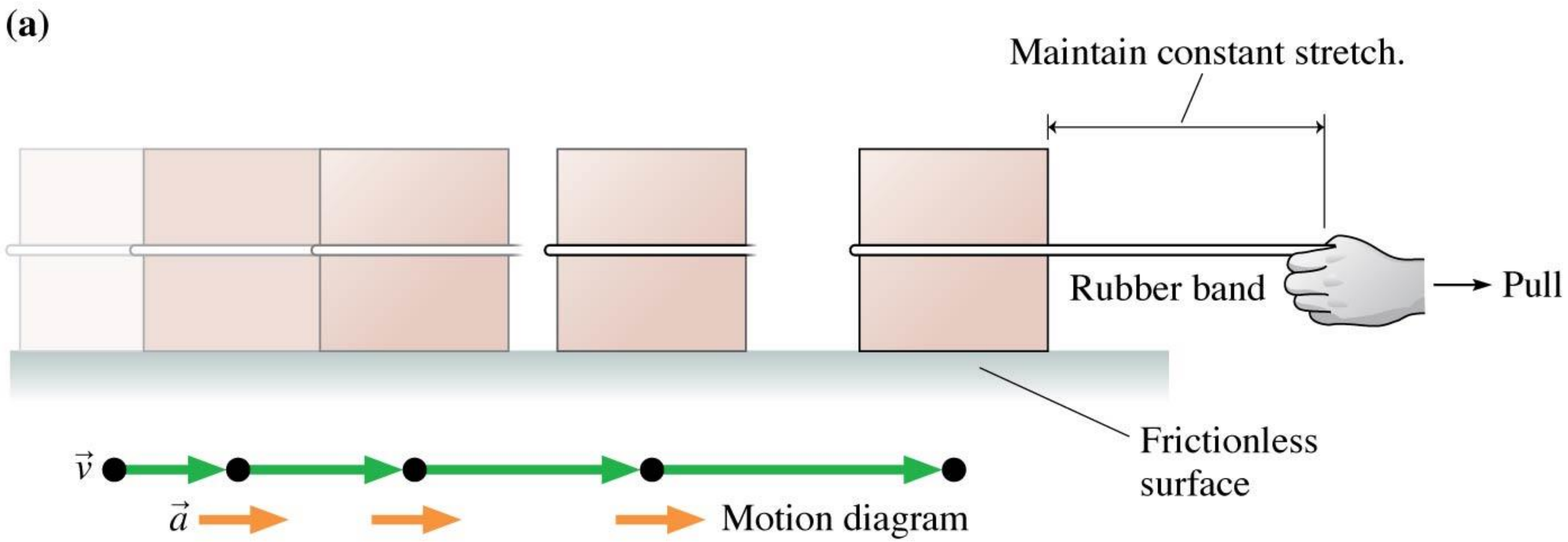
**Q.** What will happen to the acceleration of the object if we double, treble, or quadruple the mass, for example, while applying the same force?

# Quantifying Force




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

# Quantifying Force

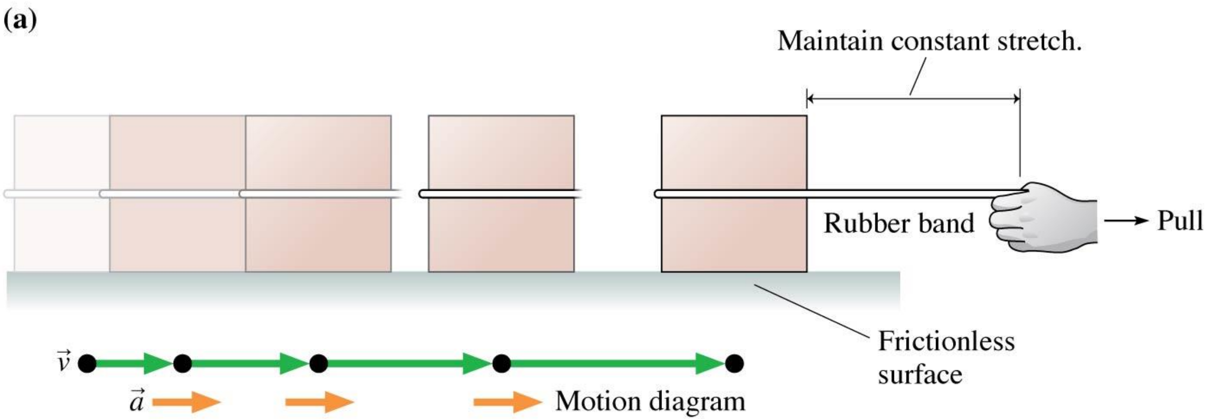


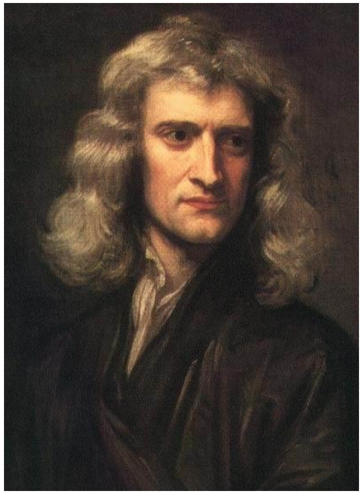

Thus,

- 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



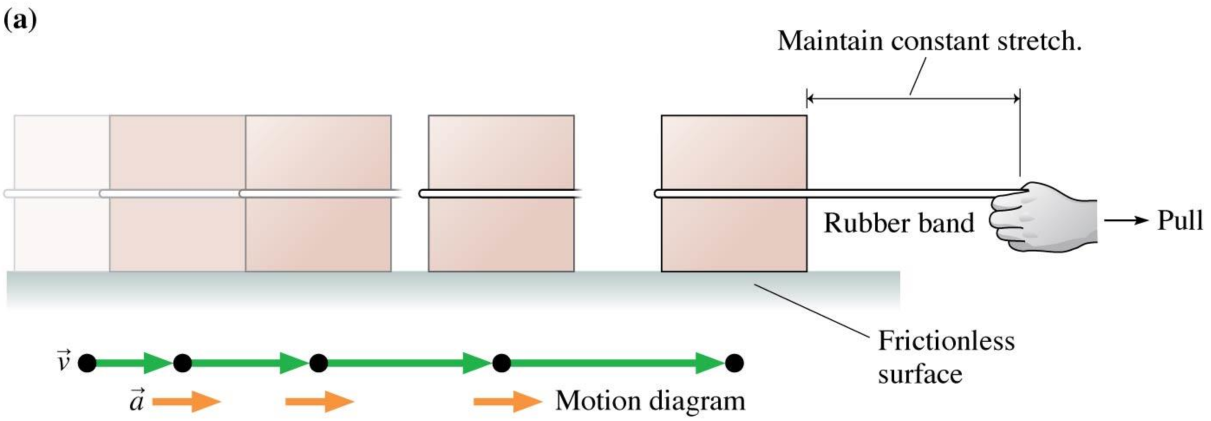



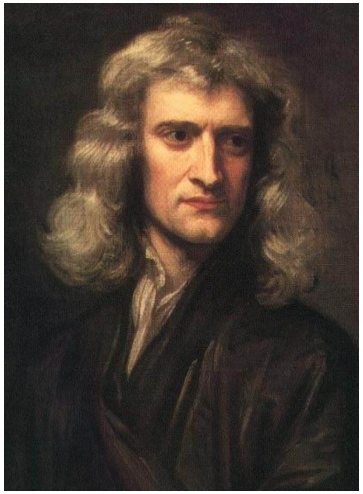
Sir Isaac Newton (1643-1727)

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

- 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.
- The unit for force is called the **Newton** $(\mathrm{N})$, named after Sir Isaac Newton.
- $1\ \mathrm{N} = 1\ \mathrm{kg\ ms^{-2}}$ , or in words, $1\ \mathrm{N}$ is a force that will accelerate an object of mass $1\ \mathrm{kg}$ by $1\ \mathrm{ms^{-2}}$.

# Newton's 2nd Law of Motion



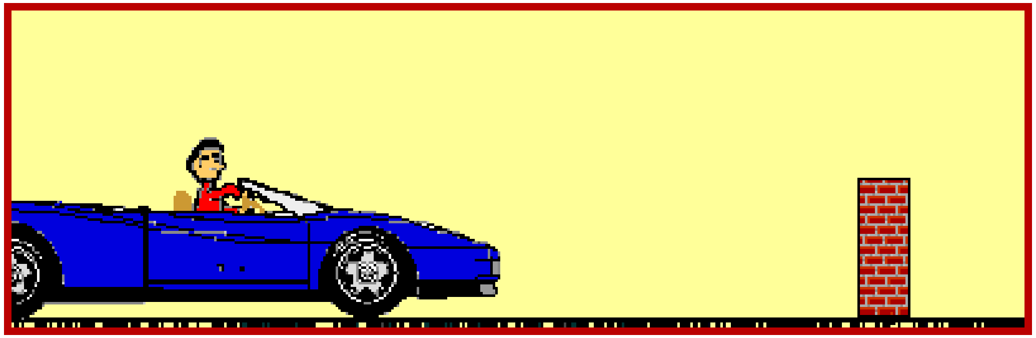
Sir Isaac Newton (1643-1727)

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

$$\vec{a} = \frac{\vec{F}_{net}}{m} \tag{5.5}$$

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

# Newton's 1st Law of Motion

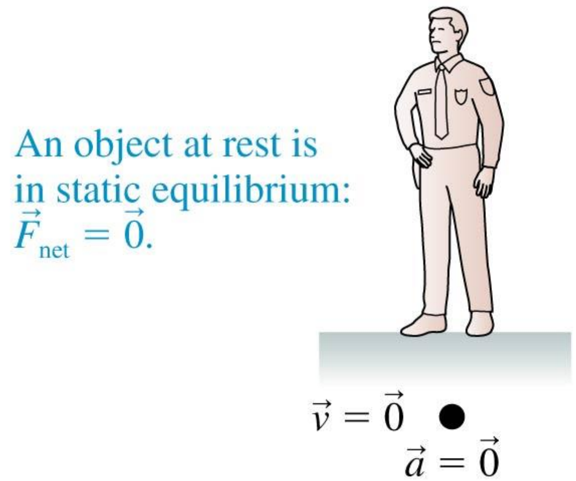


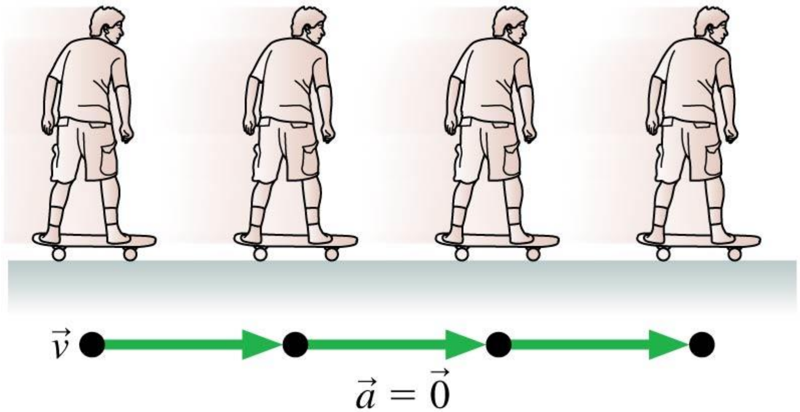
**Newton's first law** An object that is at rest will remain at rest, or an object that is moving will continue to move in a straight line with constant velocity, if and only if the net force acting on the object is zero.

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

# Newton's 1st Law of Motion

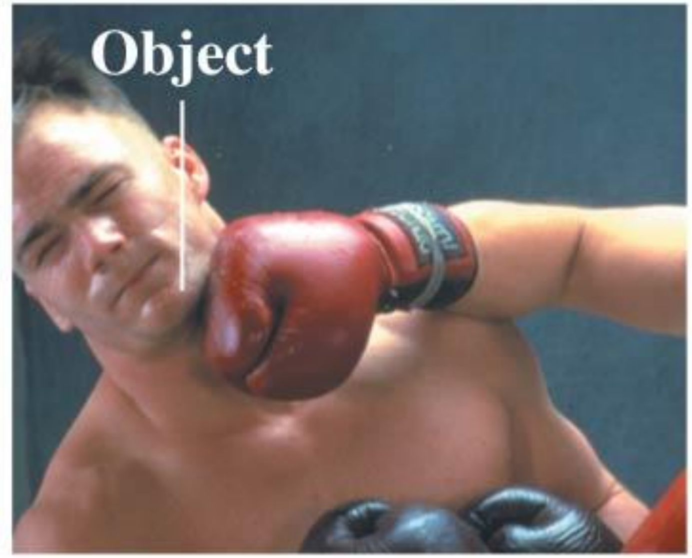
- An object on which the net force is zero is said to be in **mechanical equilibrium**.
- There are two forms of mechanical equilibrium:
  - If the object is at rest, then it is in **static equilibrium**.
  - If the object is moving with constant velocity, it is in **dynamic equilibrium**.




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**.

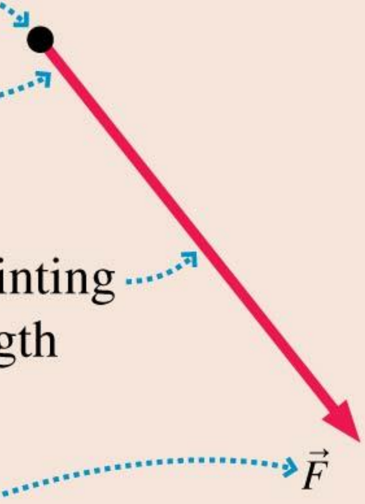
- We’ve now seen how we quantify force as well as looking at the first two laws of motion in the process; let’s now see how we draw force vectors and combine them.

# 3. Drawing Force Vectors

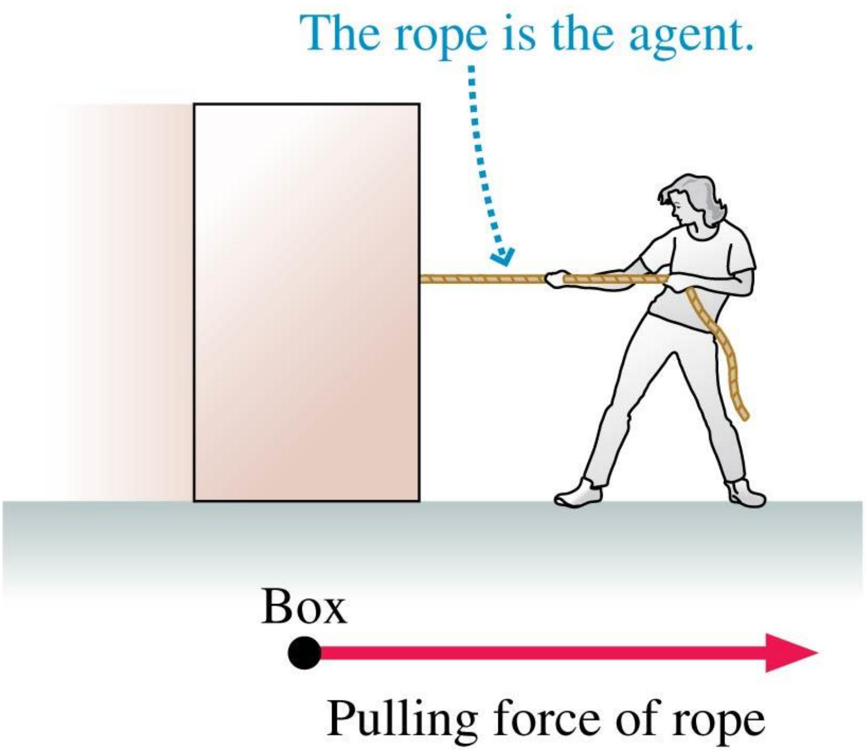
# Drawing Force Vectors

**TACTICS BOX 5.1** **Drawing force vectors**

1. Represent the object as a particle.
2. Place the *tail* of the force vector on the particle.
3. Draw the force vector as an arrow pointing in the proper direction and with a length proportional to the size of the force.
4. Give the vector an appropriate label.

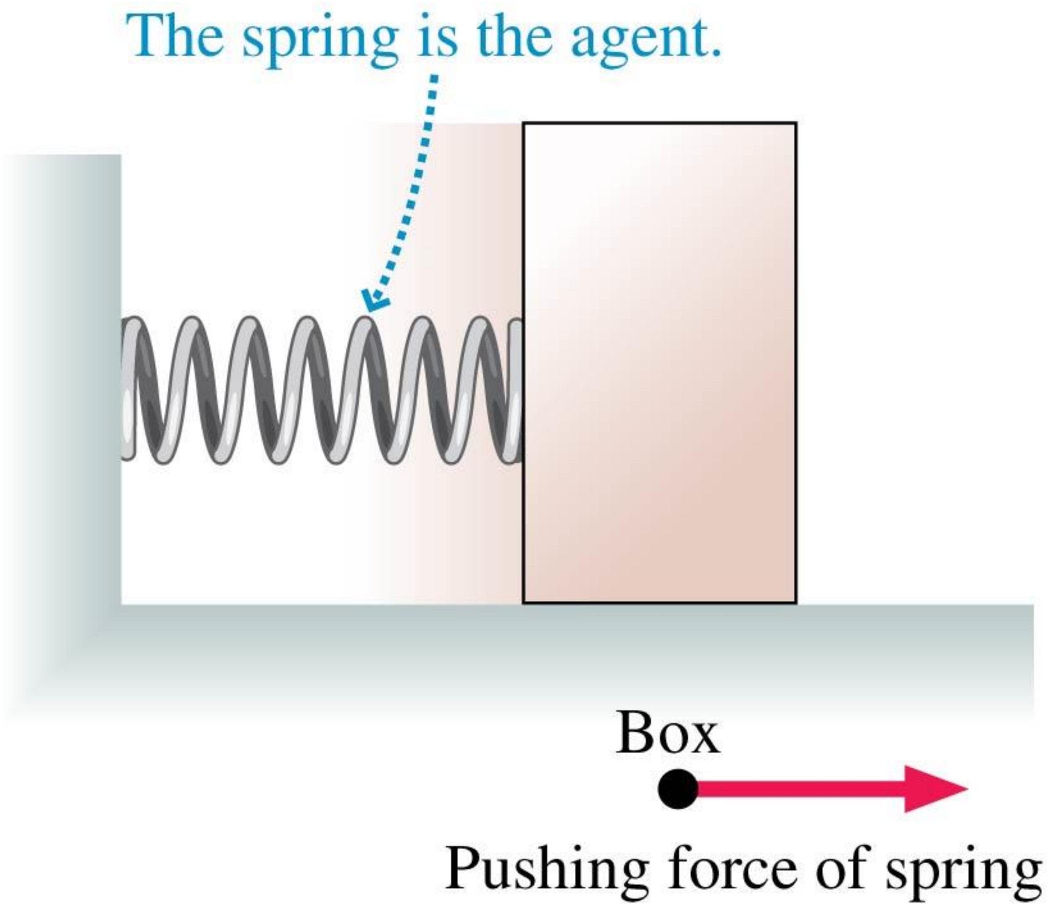


# Drawing Force Vectors



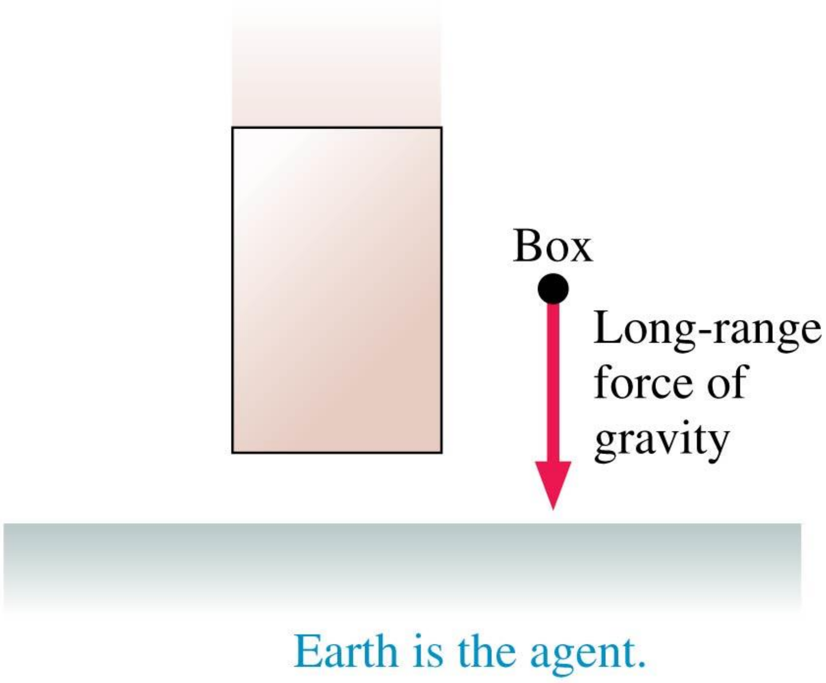

- In the above, a box is pulled to the right by a person.
- Because the rope used to do the pulling mediates the force applied by the person, we can say that the rope is the agent of the force in this situation.

# Drawing Force Vectors



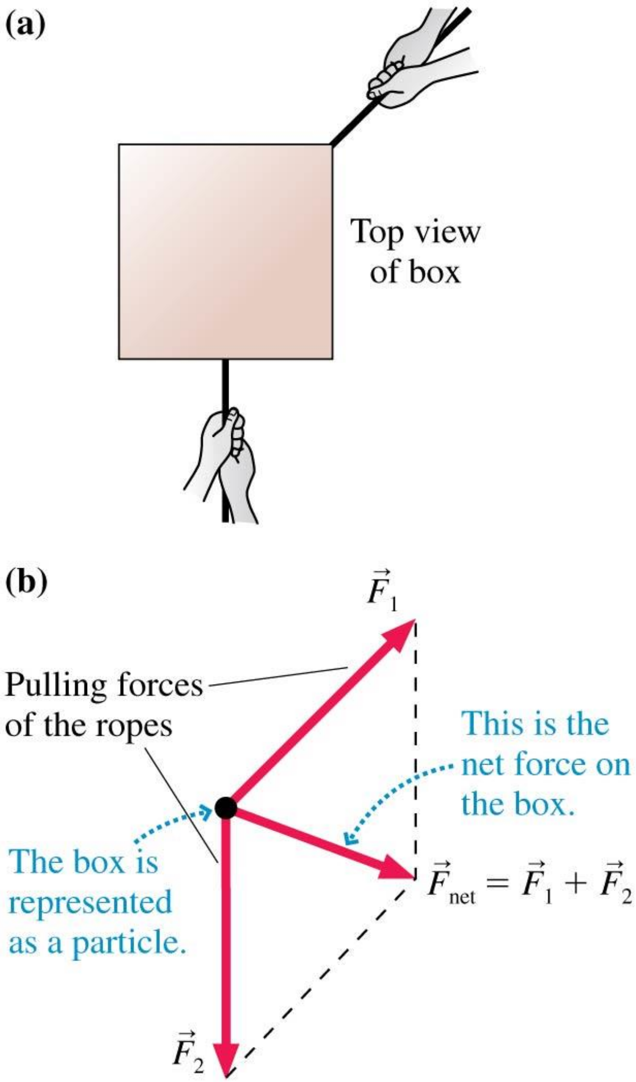

- Likewise for the above: a box is pushed to the right by a spring, and the spring can be called the agent of the force.

# Drawing Force Vectors




- 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

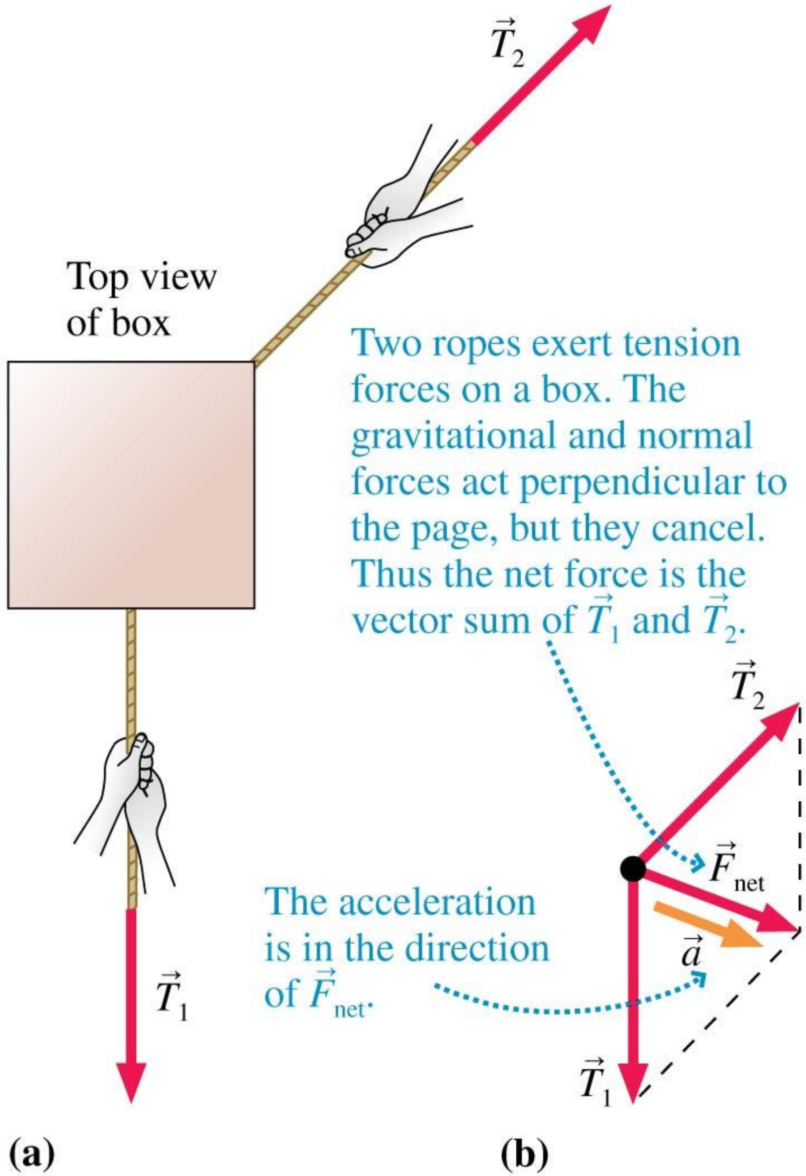



- When several forces are exerted on an object, they combine to form a **net force** given by the **vector sum** of **all** the forces:

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

- This is called a **superposition of forces**.
- Let's now look at the different manifestations of force.

# An Implication of Combining Force Vectors

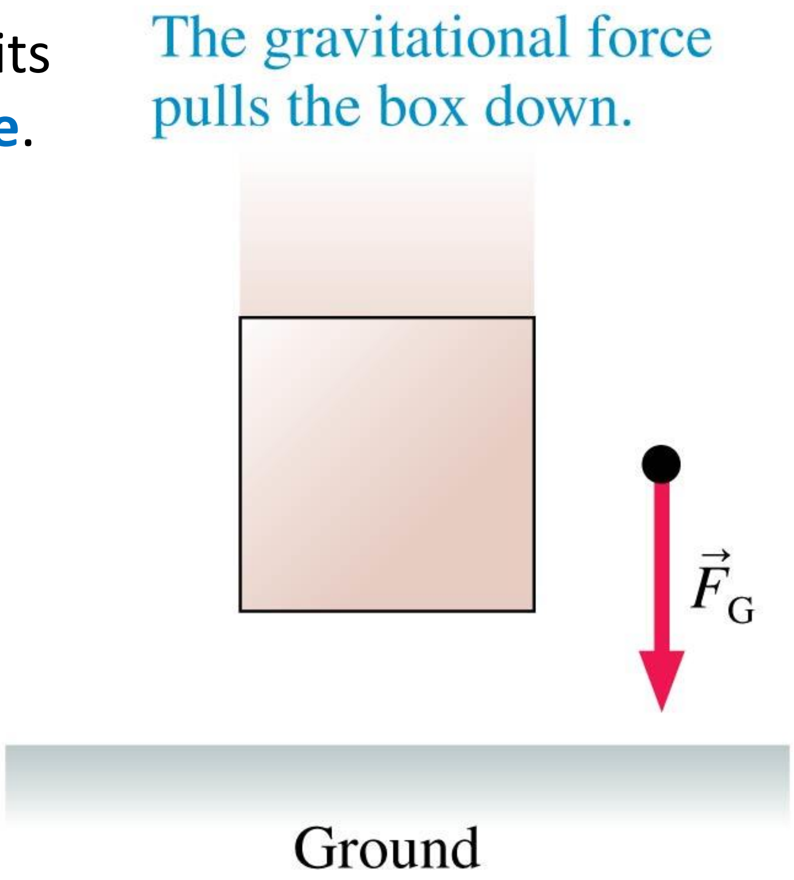



- When more than one force is acting on an object, the object accelerates in the direction of the net force vector $\vec{F}_{net}$ .

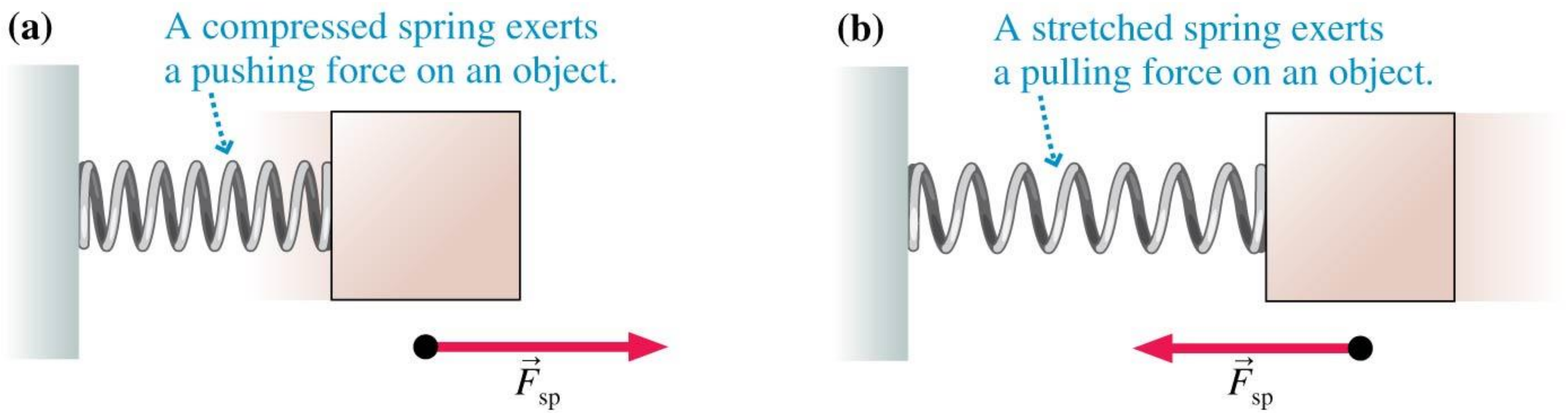
# 4. Manifestations of Force

# 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.

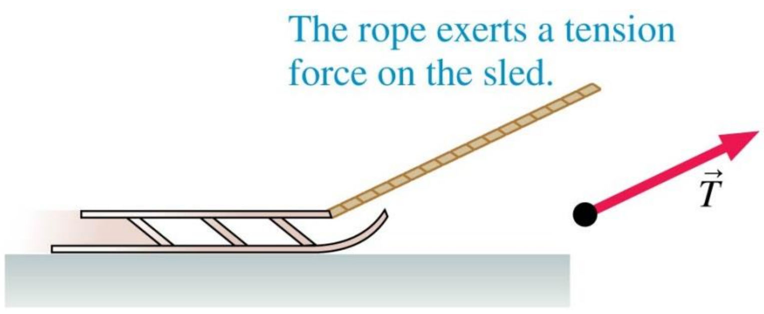


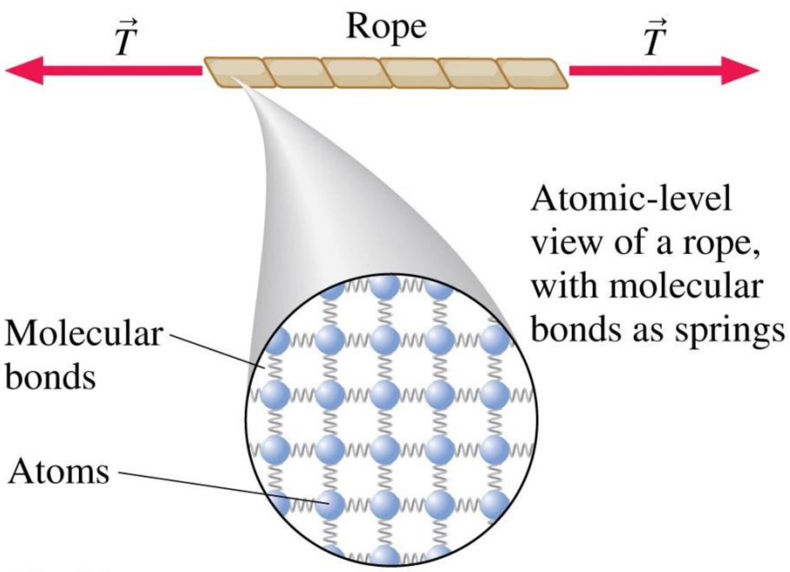
# The Spring Force




- A spring can either push (when compressed) or pull (when stretched).
- Not all springs are metal coils, though.
- Whenever an elastic object is flexed or deformed in some way, and then ‘springs’ back to its original shape when you let it go, we call this a **spring force**.

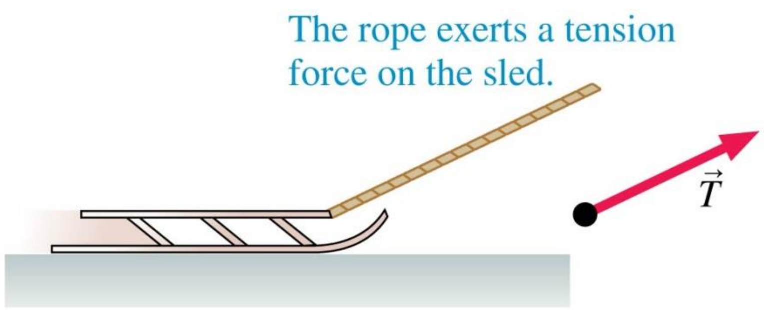
# The Tension Force

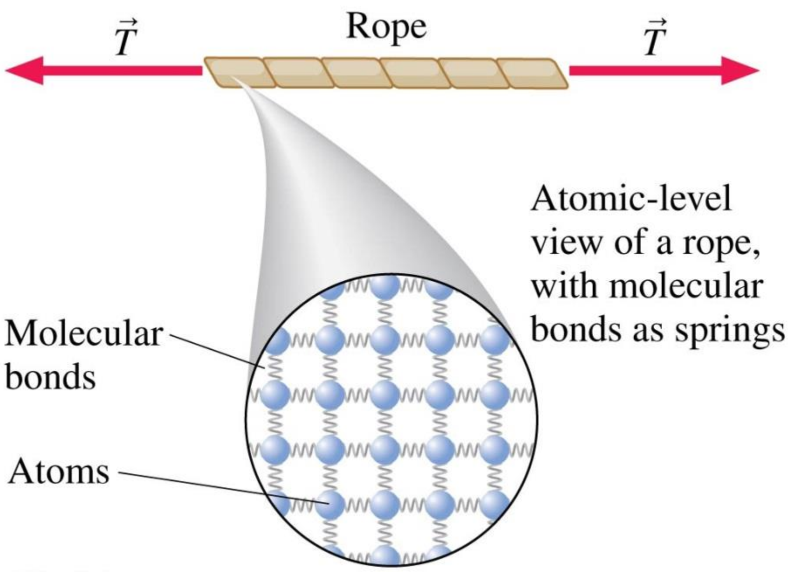



- When a string or rope or wire pulls on an object, it exerts a contact force that we call the **tension force**.
- We can model a rope as made of atoms joined together by molecular bonds.

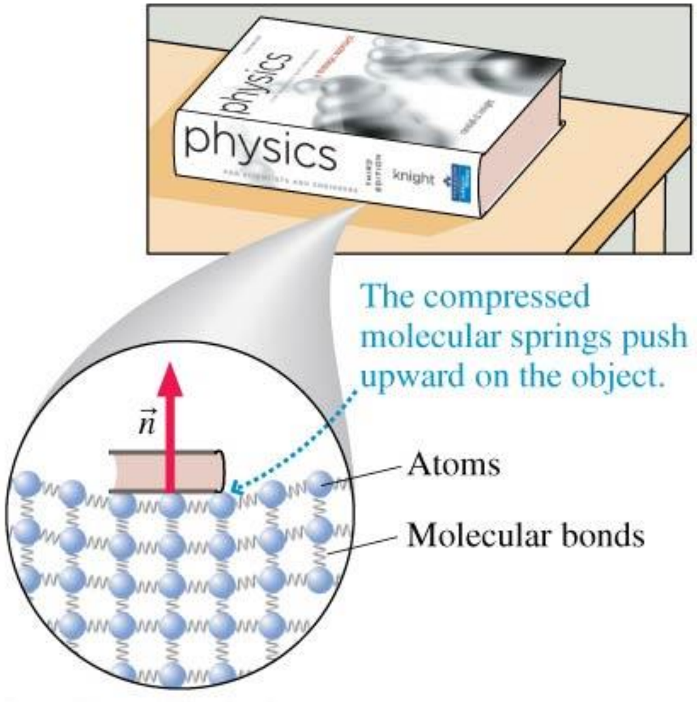
# The Tension Force



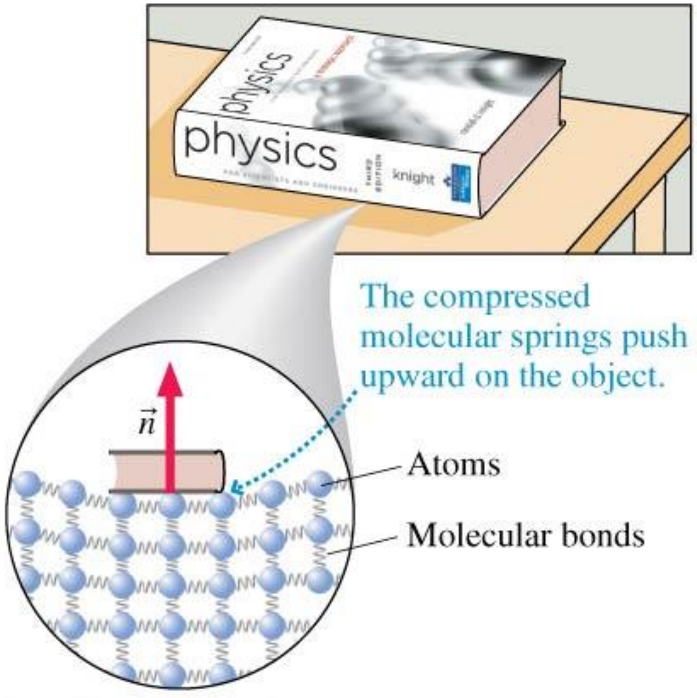

- Molecular bonds in the string or rope can be modeled as tiny springs holding the atoms together.
- Thus, tension is a result of many ‘molecular springs’ stretching ever so slightly.

# The Normal Force




- 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 thus called the **normal force**.

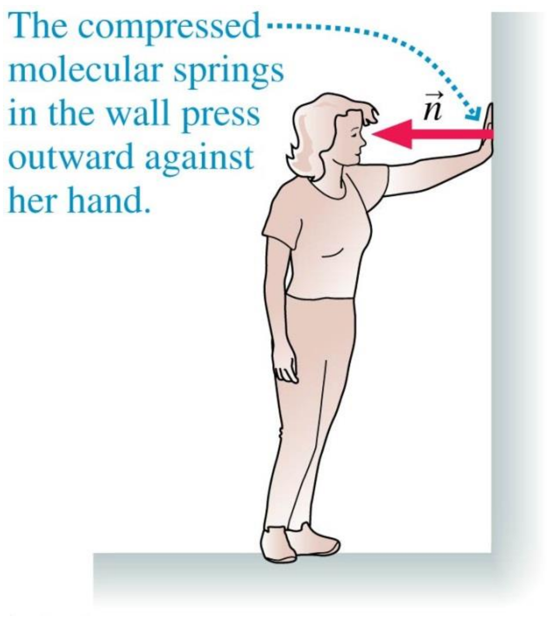
# The Normal Force



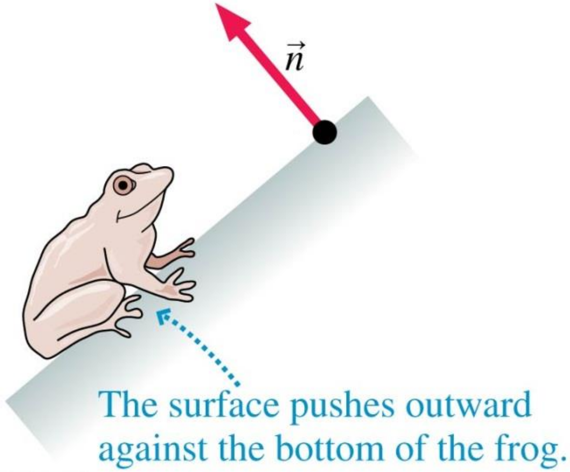

- A table is made of atoms joined together by molecular bonds which can be modelled as springs.
- The **normal force** is a result of many molecular springs being compressed ever so slightly.

# The Normal Force

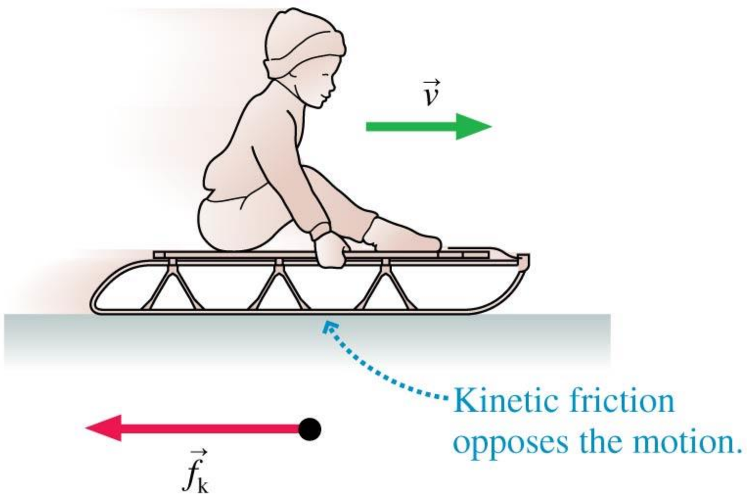
- Suppose you place your hand on a wall and lean against it.
- The wall exerts a horizontal **normal force** on your hand.




- Suppose a frog sits on an inclined surface.
- The surface exerts a tilted **normal force** on the frog.



# Kinetic Friction



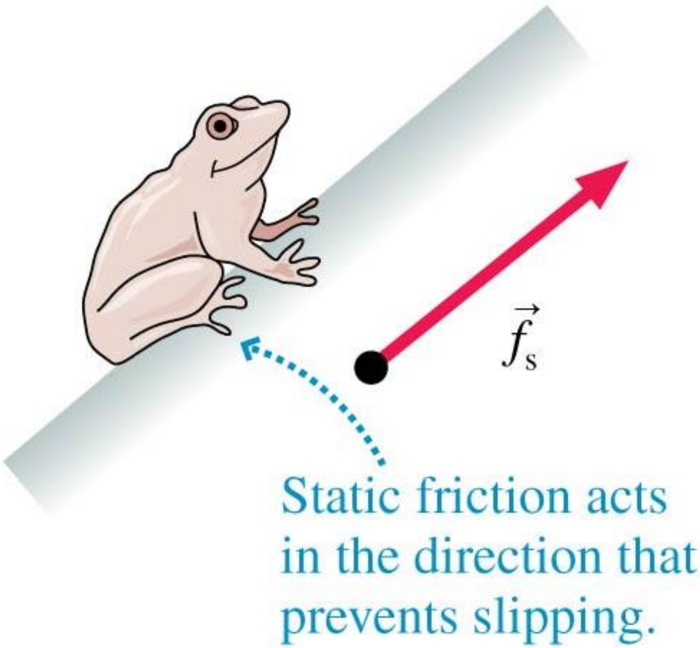

- When an object slides along a surface, the surface can exert a contact force which opposes the motion.
- This is called sliding friction or **kinetic friction**.
- The kinetic friction force is **directed at a tangent** to the surface, and opposite to the velocity of the object relative to the surface.
- Kinetic friction tends to slow down the sliding motion of an object in contact with a surface.

# Static Friction

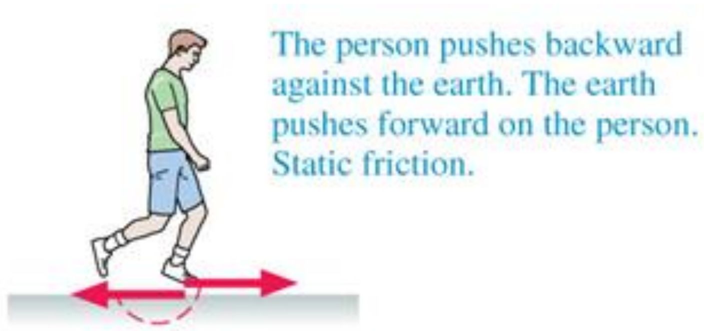
- **Static friction** is the contact force that keeps an object 'stuck' on a surface, and prevents relative motion.

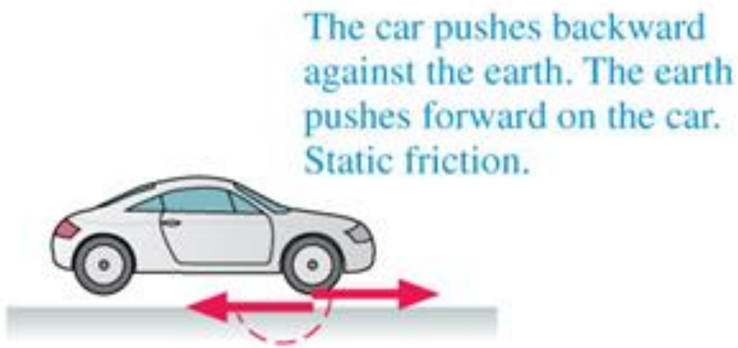
- The static friction force is directed at a tangent to the surface.

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



# Static Friction

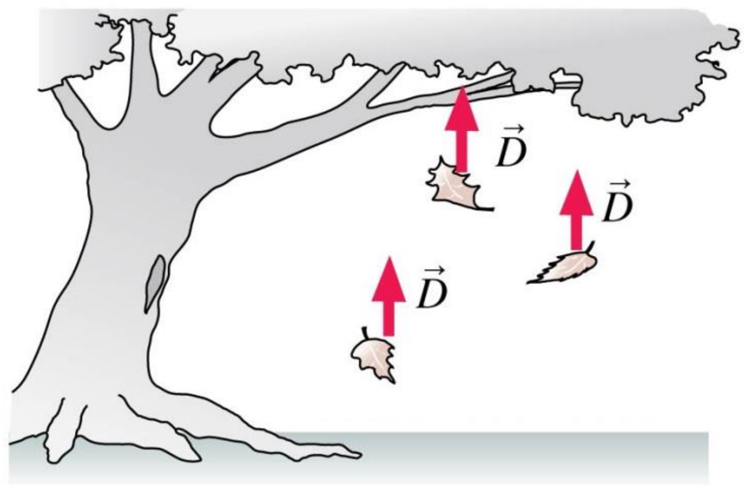



- If you try to walk across a frictionless floor, your foot slips and slides backward.
- In order to walk, your foot must stick to the floor as you straighten your leg, moving your body forward.
- The force that prevents slipping is **static friction**.
- The static friction force points in the forward direction.
- It is static friction that propels/pushes you forward!

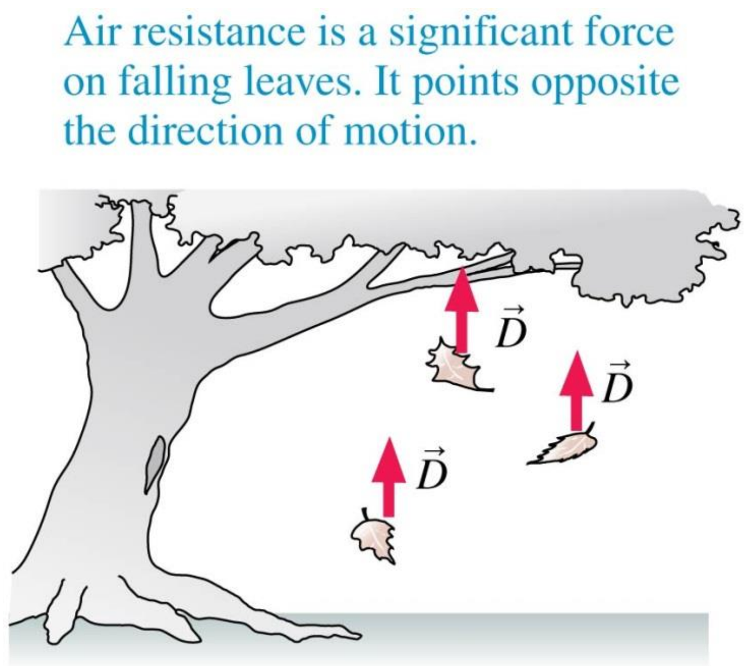
# Drag

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**.

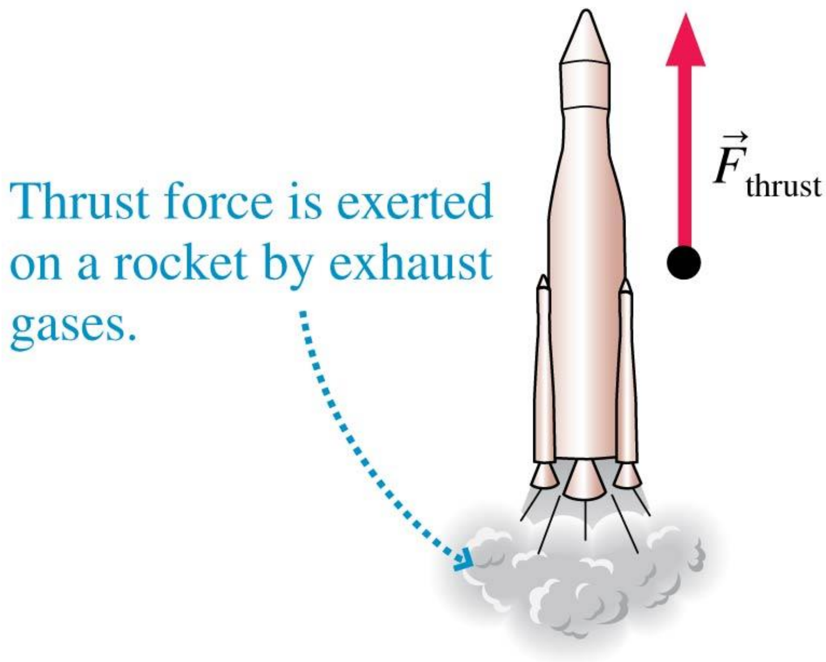
# Drag




- 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




- 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.

# Electric and Magnetic Forces

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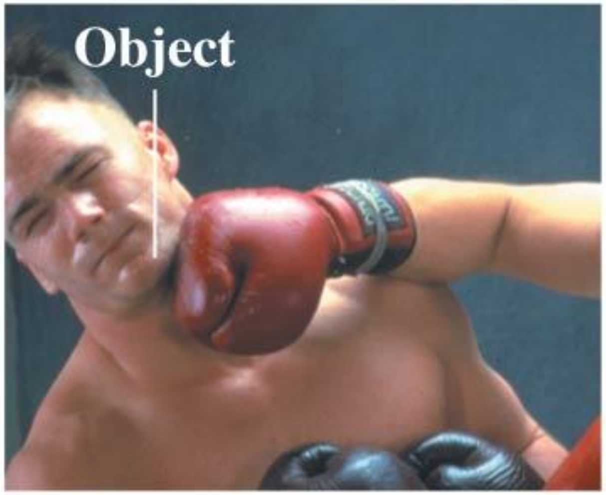
- Electricity and magnetism, like gravity, exert **long-range forces**.
- As we will see in later lectures, and more so in Semester 2 (if you study Foundation Science B), atoms and molecules are made of electrically charged particles, and molecular bonds are due to the electric force between these particles.

# Symbols for the Different Manifestations of Force

| Force | Notation |
|---|---|
| General force | $\vec{F}$ |
| Gravitational force | $\vec{F}_{\mathrm{G}}$ |
| Spring force | $\vec{F}_{\mathrm{sp}}$ |
| Tension | $\vec{T}$ |
| Normal force | $\vec{n}$ |
| Static friction | $\vec{f}_{\mathrm{s}}$ |
| Kinetic friction | $\vec{f}_{\mathrm{k}}$ |
| Drag | $\vec{D}$ |
| Thrust | $\vec{F}_{\mathrm{thrust}}$ |

# What is Force?

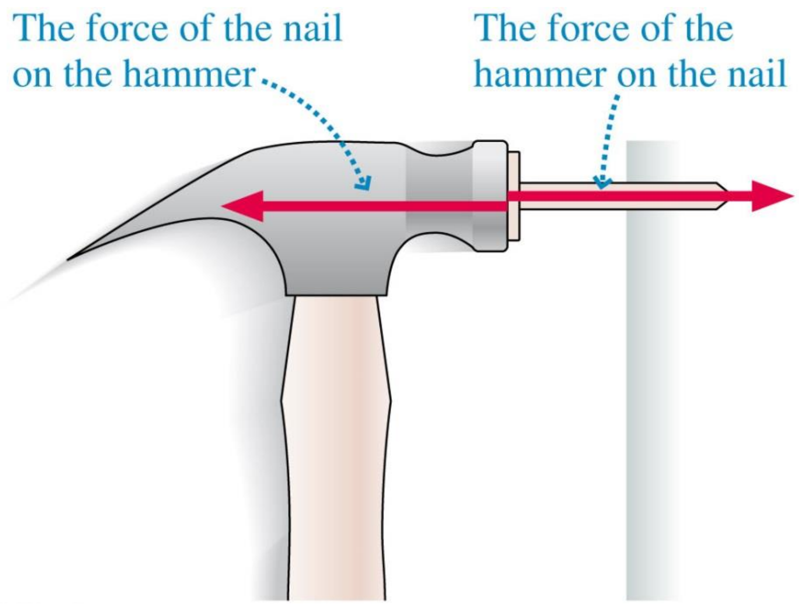

- Simply put, a force is a **push** or a **pull** **'acting on'/ 'applied to'/ 'exerted on'** an object by another object.

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

- 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; we call this **Newton's 3rd Law of Motion**

# 5. Newton’s 3rd Law of Motion

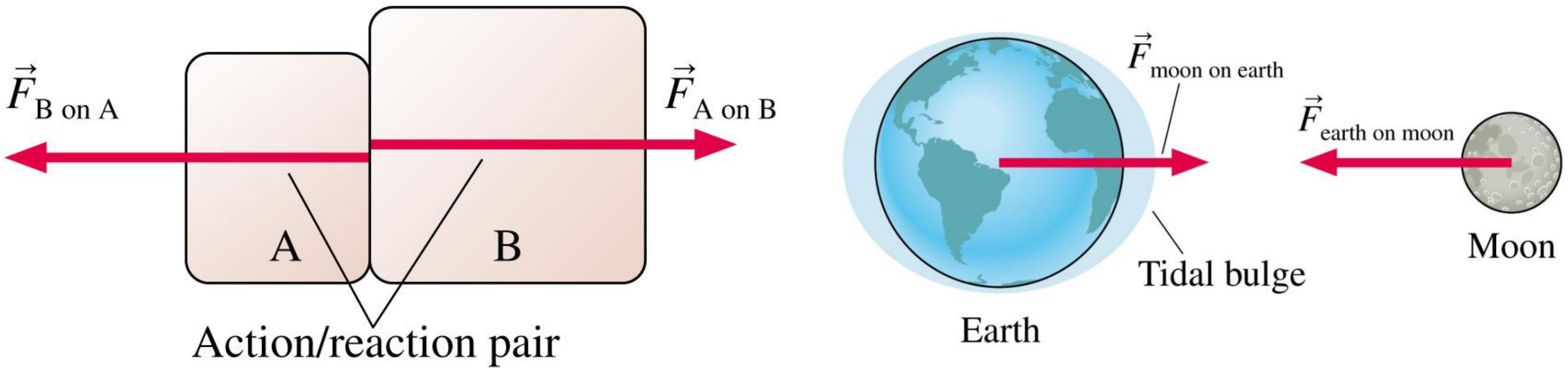
# Newton’s 3$^{rd}$ Law of Motion




- 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.

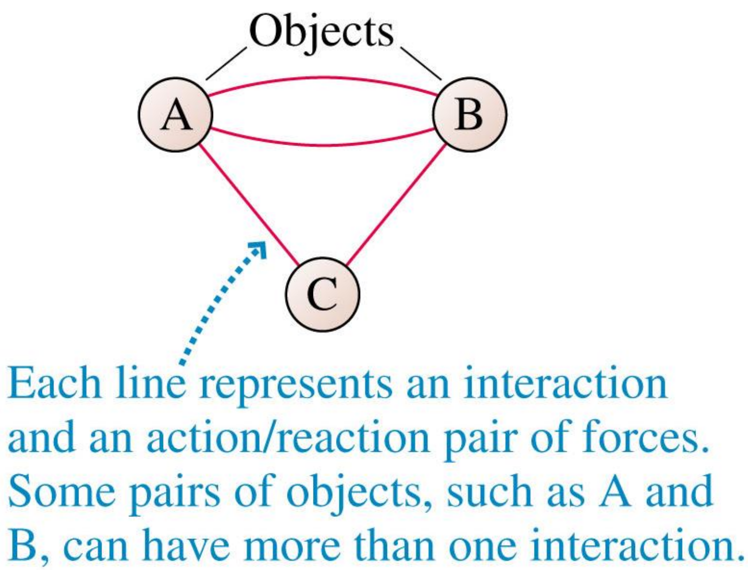
- If you don’t believe it, imagine hitting the nail with a glass hammer.
- It’s the force of the nail on the hammer that would cause the glass to shatter!

# Interacting Objects



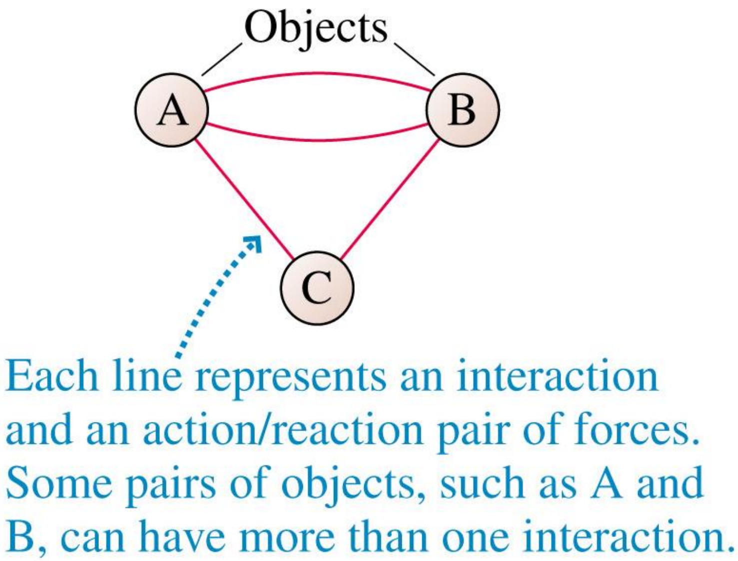

- If object A exerts a force on object B, then object B exerts an equal and opposite force on object A.
- The pair of forces, as shown in each situation, is called an **action/reaction pair**.

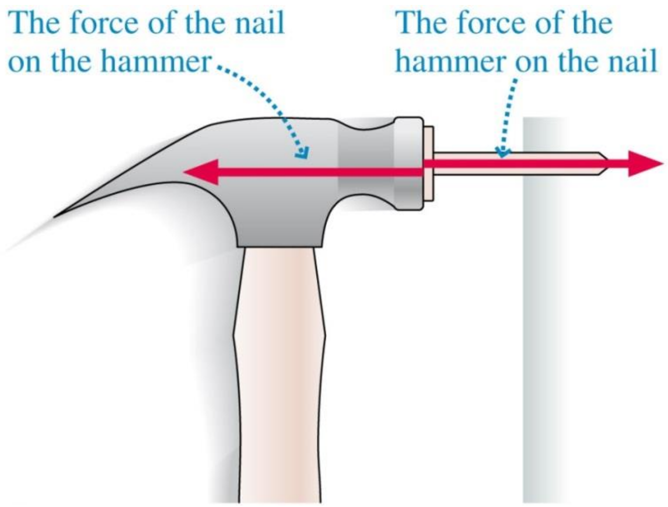
# Objects, Systems, and the Environment




- 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.

# Objects, Systems, and the Environment

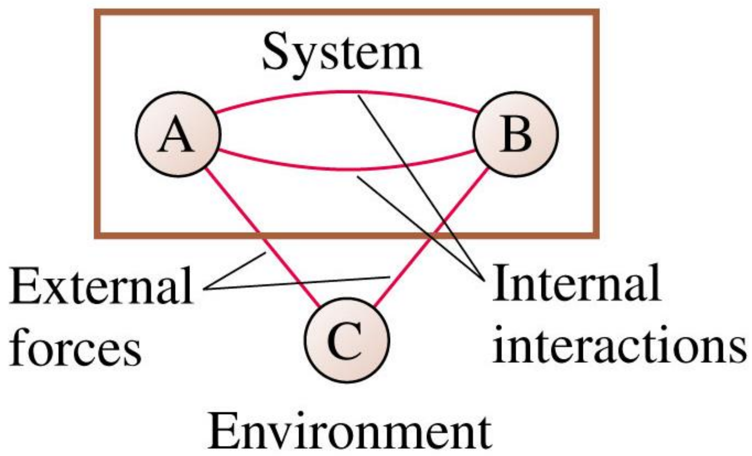



- For example:
  - Object A = the hammer
  - Object B = the nail
  - Object C = the earth

- 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.

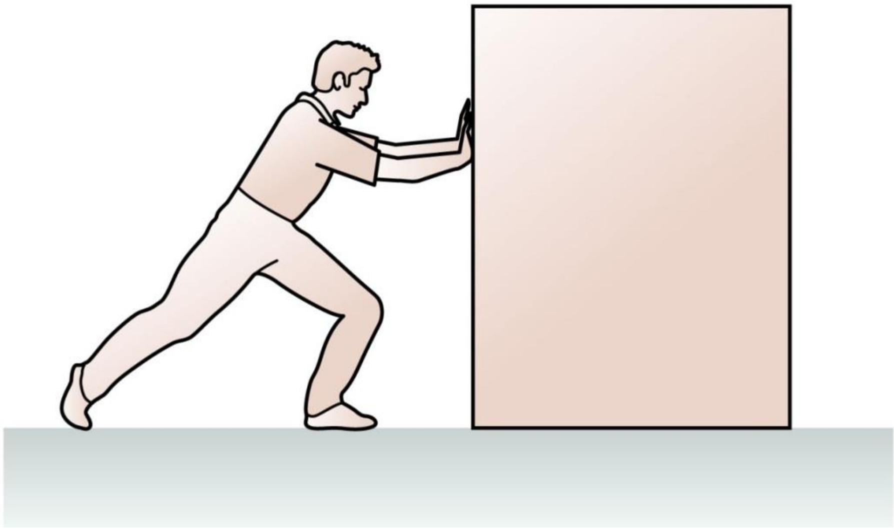
# Objects, Systems, and the Environment




This is an *interaction diagram.*

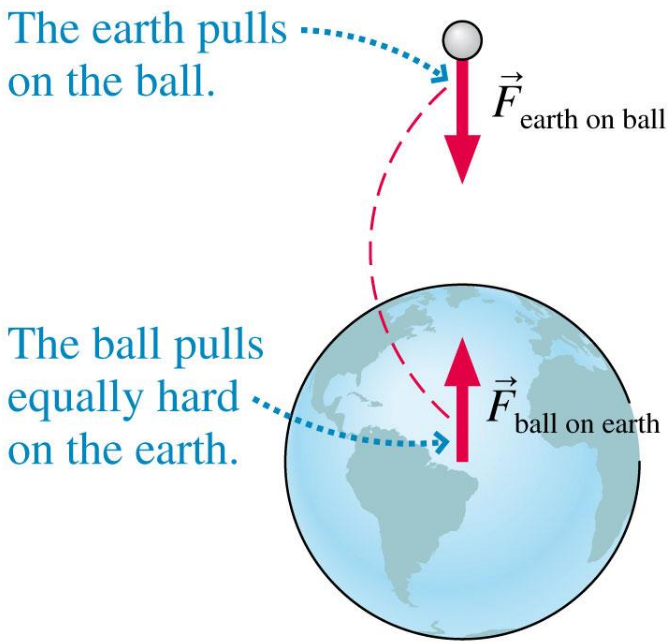
- The figure shows a new kind of diagram, an **interaction diagram**.
- The objects of the system are in a box.
- Interactions are represented by lines connecting the objects.
- Interactions with objects in the environment are called **external forces**.

# Have a Think: Pushing a Crate



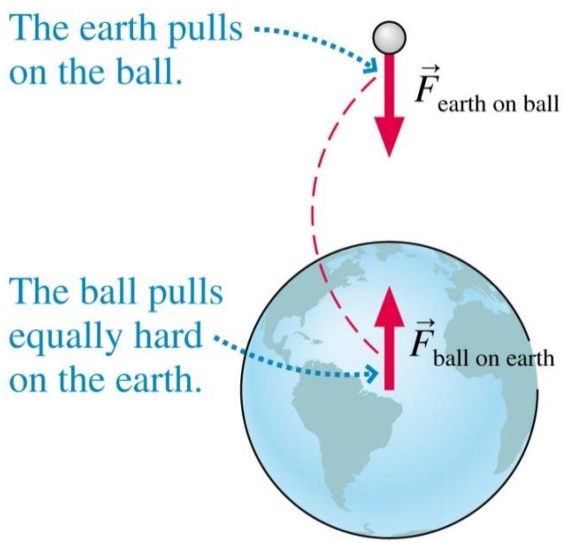
**Q.1** The above figure shows a person pushing a large crate across a rough surface. Identify all interactions, showing them on an interaction diagram. Then draw free-body diagrams of the person and the crate.

# Newton's 3rd Law




- 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 $g = \frac{\vec{F}_{earth\ on\ ball}}{m}$

# Newton's 3rd Law




- 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 $1\ \mathrm{kg}$, the Earth accelerates upward at $2 \times 10^{-24}\ \mathrm{ms}^{-2}$, 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 3$^{rd}$ law of Motion

# Lecture 3: Optional Reading

- **Ch. 4.1**, Force; p.102
- **Ch. 4.2**, Newton's $1^{st}$ law of motion; p.102-103
- **Ch. 4.3**, Mass; p.104
- **Ch. 4.4**, Newton's $2^{nd}$ law of motion; p.104-106
- **Ch. 4.5**, Newton's $3^{rd}$ law of motion; p.107-109

# Home Work

Do not forget you can attempt the **Additional Problems** for this lecture