Physics 3A: Physics for the Life Sciences

Chapter 2: Forces

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What Causes Motion?

Everyday experience suggests motion stops without continuous pushing — but that's due to **friction**.

Galileo's insight: In the absence of friction, an object in motion continues moving forever in a straight line.

Experiments:

On smooth snow $\rightarrow$ sled stops quickly.
On slick ice $\rightarrow$ slides farther.
On frictionless surface $\rightarrow$ would never stop.

Newton's First Law (Law of Inertia):

An object at rest stays at rest, and an object in motion stays in motion unless acted upon by a

No force is required to *maintain* motion — only to *change* it.

Inertia: The resistance of an object to changes in its state of motion.

Force - Properties

Newton's key insight: No cause is needed to keep an object moving - only to **change** its motion.

Definition: A **force** is a **push or pull** that acts on an object and can change its motion.

Symbol: $\vec{F}$

Magnitude: $F = |\vec{F}|$

Essential properties:

- A force **acts on an object** - it cannot exist in isolation.
- Every force has an **agent** - something that causes it (hand, wall, Earth, etc.).
- A force is a **vector**: it has both magnitude and direction.

Two main types of forces:

- **Contact forces:** arise from physical touch
  e.g., friction, tension, normal force, applied push.
- **Long-range forces:** act without contact
  e.g., gravity, electric, magnetic forces.

In the **particle model**, an object is treated as a point, and each force is drawn as a **vector** acting on that point.

How to draw a force vector:

Represent the object by a small dot (the "particle").
Draw an arrow (**vector**) starting at the dot.
The arrow's **direction** shows which way the force acts.
The arrow's **length** shows the relative strength (magnitude) of the force.

Important: The **tail** of each force vector is placed on the particle (object). Moving a vector parallel to itself does **not change** the force.

Examples:

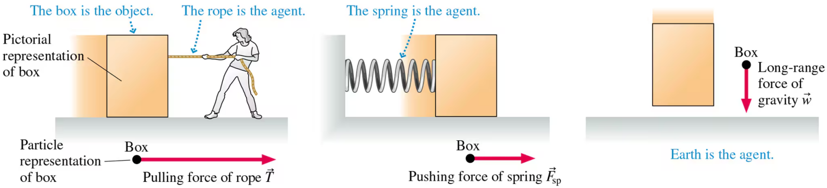


Figure: Forces can push or pull objects through contact or at a distance.

Vector Components and Vector Addition

A vector can be expressed as the sum of its **components** along the x- and y-axes:

$$\vec{A} = A_x \hat{i} + A_y \hat{j}$$

where

$$A_x = A\cos\theta, \qquad A_y = A\sin\theta$$

The **magnitude** and **direction** of the vector can be found from its components:

$$A = \sqrt{A_x^2 + A_y^2}, \qquad \tan\theta = \frac{A_y}{A_x}$$

To **add vectors**, add their components:

$$\vec{R} = \vec{A} + \vec{B} = (A_x, A_y) + (B_x, B_y) = (A_x + B_x, A_y + B_y)$$

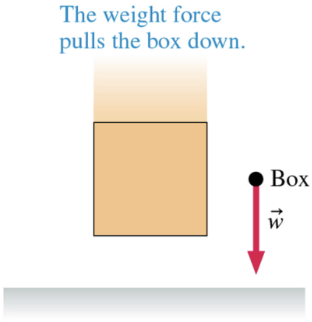
Then find the resultant's magnitude and direction:

$$R = \sqrt{R_x^2 + R_y^2}, \qquad \tan\theta_R = \frac{R_y}{R_x}$$

Weight Force ($\vec{w}$): Long-range gravitational pull of Earth on an object.

$$\boxed{\vec{F}_g = m\vec{g}}$$

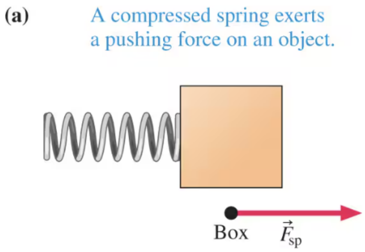
Direction: vertically downward.



Spring Force ($\vec{F}_s$): Pushes when compressed, pulls when stretched.

$$\boxed{\vec{F}_s = -k\,\Delta\vec{x}}$$

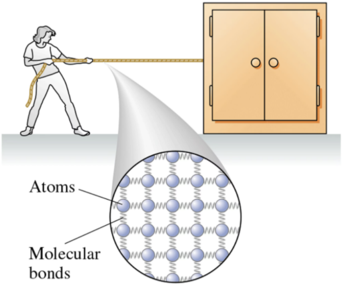
Acts along the spring's axis (Hooke's Law).



Tension Force ($\vec{T}$): Pulling force exerted by a rope or string.

$$\boxed{|\vec{T}| = \text{constant along the rope}}$$

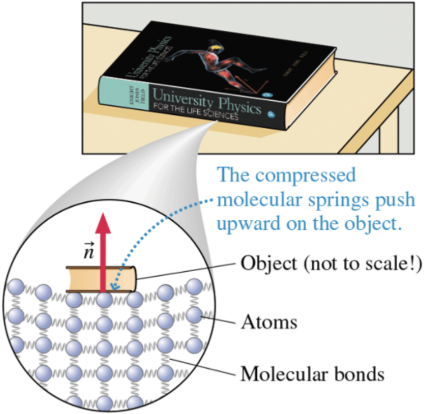
Direction: along the rope, away from the object.



Normal Force ($\vec{N}$): Exerted by a surface, perpendicular to it.

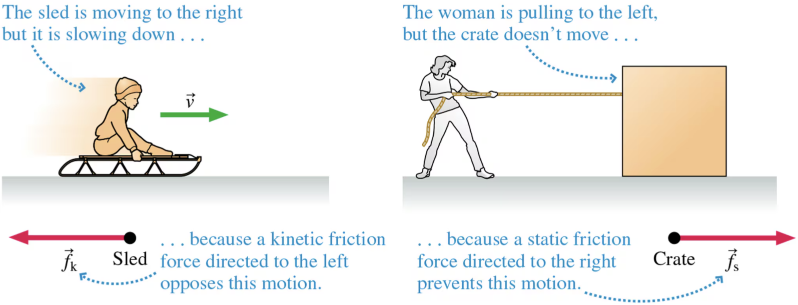
$$\boxed{|\vec{N}| = mg\cos\theta}$$

Balances the perpendicular component of weight.



Friction Force ($\vec{f}$): Opposes sliding or intended motion along a surface.

$$\boxed{\begin{array}{ll} f_s \leq \mu_s N & \text{(static)} \\ f_k = \mu_k N & \text{(kinetic)} \end{array}}$$



Why $\mu_s > \mu_k$? The Static Advantage

The analogy: climbing vs. sliding

The difference arises from how surfaces interact at the microscopic level.

Static Friction ($f_{s,max}$):

- **Micro-Interlocking:** Tiny peaks (asperities) on both surfaces have time to fully settle into each other's valleys.
- **Molecular Adhesion:** High contact pressure allows momentary **molecular bonds** (sometimes called "cold welding") to form.
- **Challenge:** A greater force is needed to **break** these settled-in physical and chemical connections.

Kinetic Friction (f_k):

- **Constant Motion:** Surfaces are continuously sliding past each other.
- **Reduced Contact:** Peaks only momentarily graze or skip over each other. There is insufficient time for deep interlocking or strong molecular bonds to form.
- **Result:** The resistance to motion drops once the initial bonds are broken.

Static and Kinetic Friction: Force and Acceleration

When an object is at rest, the **static friction** force balances the applied force up to a limit:

$$F_{\text{friction}} = F_{\text{pull}}, \quad \text{as long as } F_{\text{pull}} < F_{\text{static,max}}$$

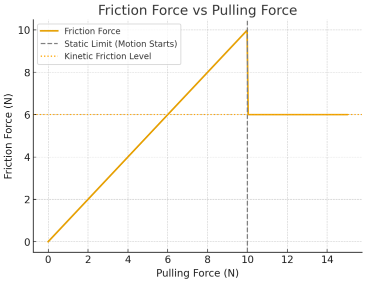
Once motion starts, the friction drops to the smaller, constant **kinetic friction**:

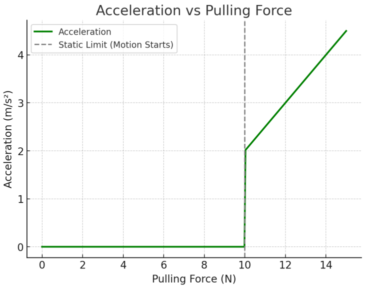
$$F_{\text{friction}} = F_{\text{kinetic}}$$

The acceleration is then determined by Newton's Second Law:

$$a = \frac{F_{\text{pull}} - F_{\text{friction}}}{m}$$

As a result: Acceleration is **zero** until motion begins. After motion starts, acceleration **increases linearly** with pulling force, starting with an offset.





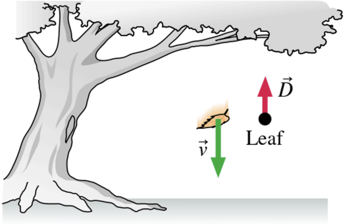
Friction and acceleration vs pulling force.

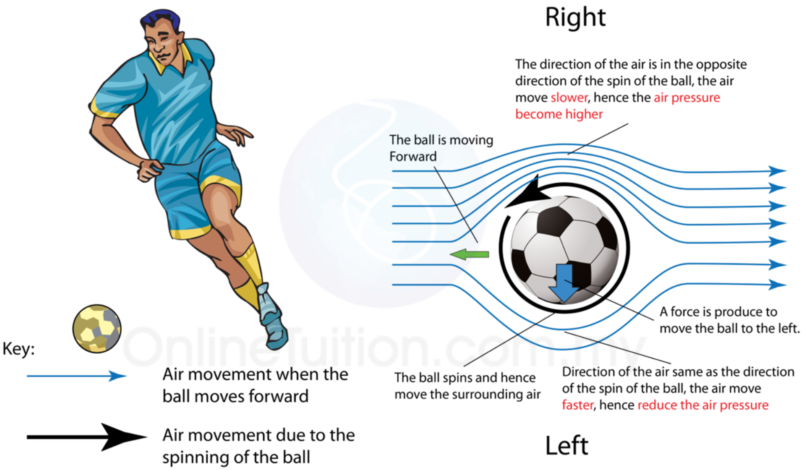
Drag Force ($\vec{D}$): Resistive force from a fluid (air or water).

$$\boxed{\vec{D} = -\frac{1}{2} C_d \, \rho A v^2 \, \hat{v}}$$

Opposes motion, increases rapidly with speed.

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



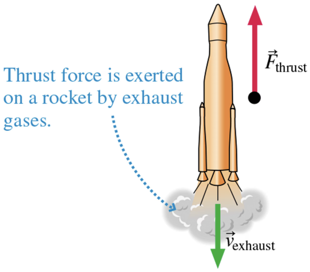


Friction and acceleration vs pulling force.

Thrust Force ($\vec{F}_{\text{thrust}}$): Generated by expelling gas or fluid backward.

$$\boxed{\vec{F}_{\text{thrust}} = \dot{m}\,\vec{v}_{\text{exhaust}}}$$

Pushes the engine forward.

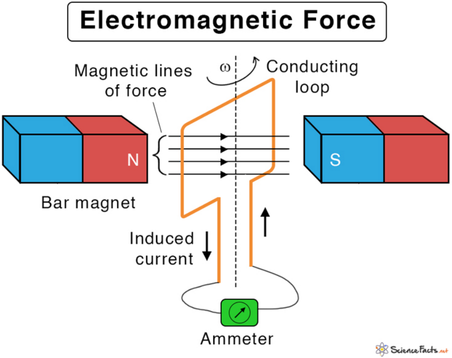


Electric and Magnetic Forces: Long-range forces acting on charged particles.

$$\boxed{\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})}$$

Govern all atomic and molecular interactions.

Long-range forces act through fields rather than contact.



The Unit of Force

From Newton's second law:

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

The unit of force is the product of mass and acceleration:

$$[F] = \text{kg} \cdot \frac{\text{m}}{\text{s}^2}$$

This unit is called the **newton (N)**:

$$1\ \text{N} = 1\ \frac{\text{kg} \cdot \text{m}}{\text{s}^2}$$

Typical magnitudes of forces in everyday life:

Force	**Magnitude (N)**
Weight of a U.S. nickel	0.05
Weight of $\frac{1}{4}$ cup of sugar	0.5
Weight of a 1 lb object	5
Weight of a house cat	50
Weight of a 110 lb person	500
Propulsion force of a car	5,000
Thrust of a small jet engine	50,000
Pulling force of a locomotive	500,000

Newton's Second Law (Concept)

A **force causes an object to accelerate**. The acceleration $\vec{a}$ is:

- **Directly proportional** to the net force $\vec{F}_{\text{net}}$.
- **Inversely proportional** to the inertial mass m.

$(m = F_g/g)$

For a single force:

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

The acceleration points in the **same direction** as the force.

Note: much after Newton's time it was shown experimentally that the inertial mass $(m = F/a)$ is equal to the gravitating mass to a very high precision.

The Principle of Superposition

For multiple forces acting together:

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

where

$$\vec{F}_{\text{net}} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 + \ldots$$

The net force is the vector sum of all forces on the object. Also called: principle of superposition.

The acceleration vector $\vec{a}$ points in the same direction as $\vec{F}_{net}$.

Figure 4.20 Forces on a bungee jumper.

Artist's version

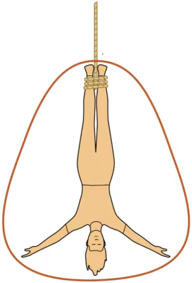


Figure 4.20 Forces on a bungee jumper.

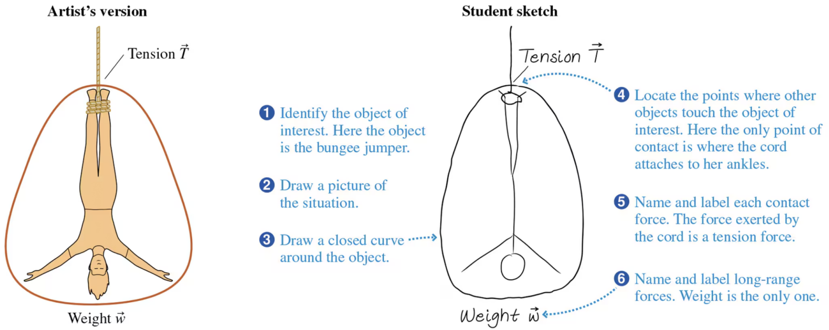
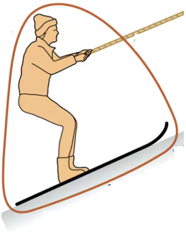


Figure 4.21 **Forces on a skier.**



Free Body Diagrams

Figure 4.21 Forces on a skier.