Essential University Physics

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4 Force and Motion

PowerPoint® Lecture prepared by Richard Wolfson

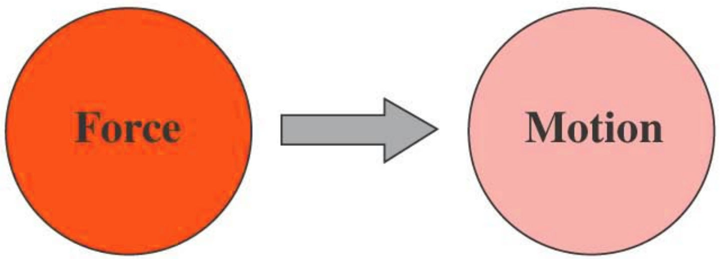
In this lecture you'll learn

- The concept of force and its role in causing *changes* in motion
- The fundamental forces of physics
- Newton's three laws of motion
- About the force of gravity
  - Including the distinction between mass and weight
- How to apply Newton's laws in one-dimensional motion

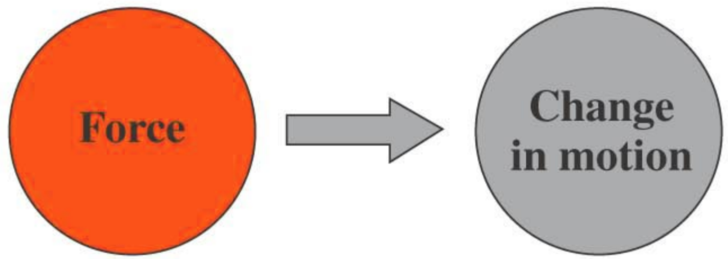
What causes motion?

- That's the wrong question!
  - The ancient Greek philosopher Aristotle believed that forces—pushes and pulls—caused motion.
    - The Aristotelian view prevailed for some 2000 years.
  - Galileo and Newton discovered the correct relation between force and motion.
    - Force causes not motion itself but *change* in motion.

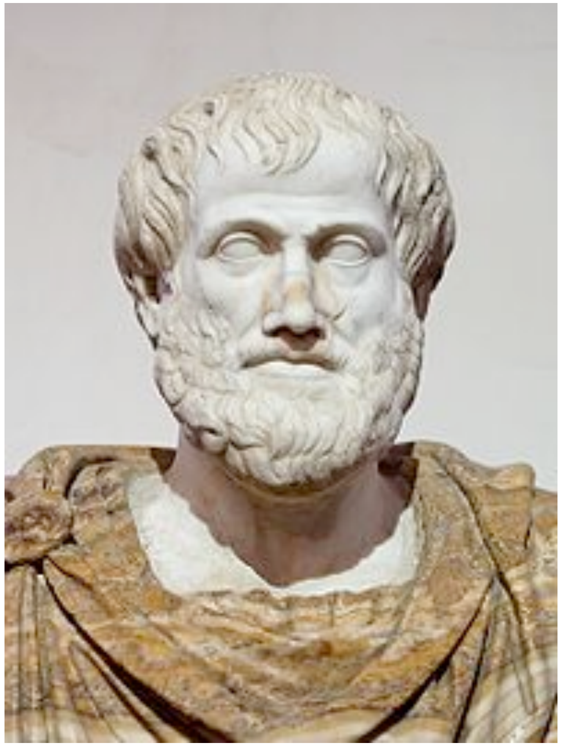
The Aristotelian view



The Newtonian view

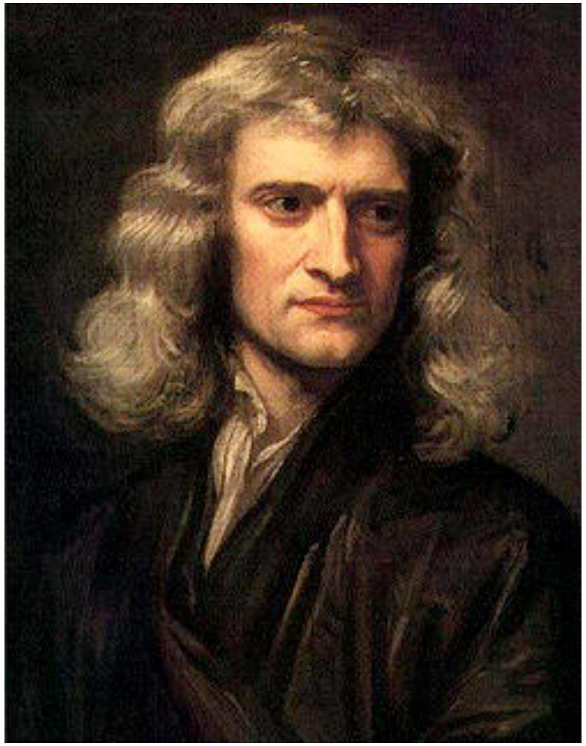


What causes *change* in motion?



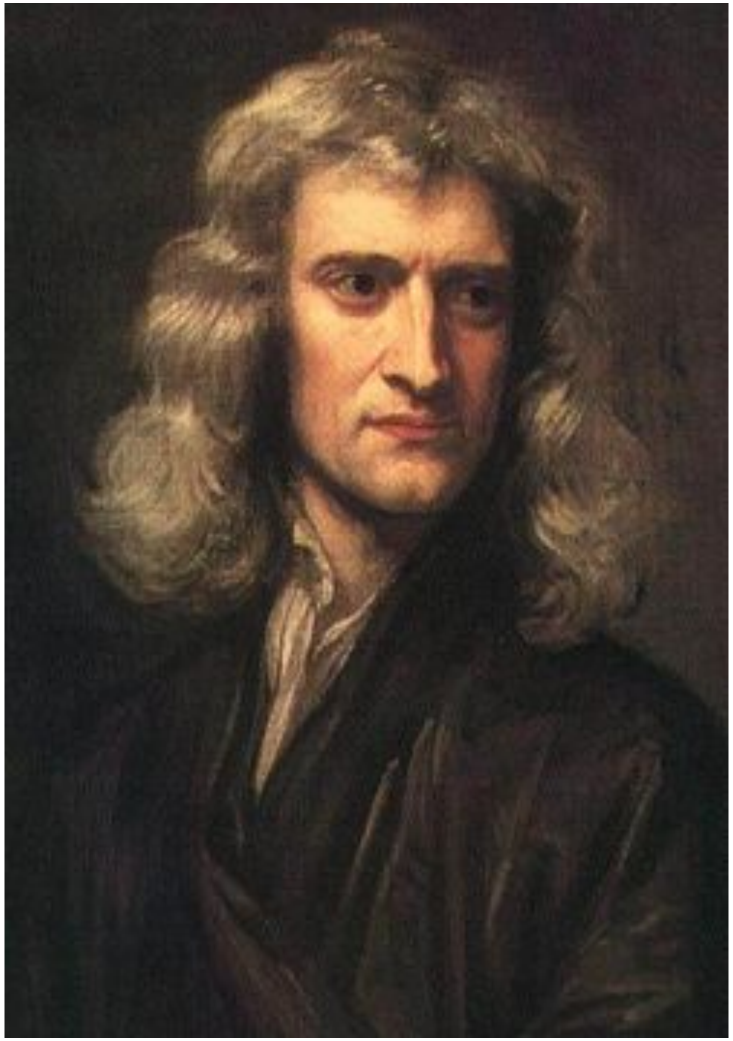
Aristotle (Greek: Ἀριστοτέλης) (384 BC – 322 BC) was a Greek philosopher, a student of Plato and teacher of Alexander the Great

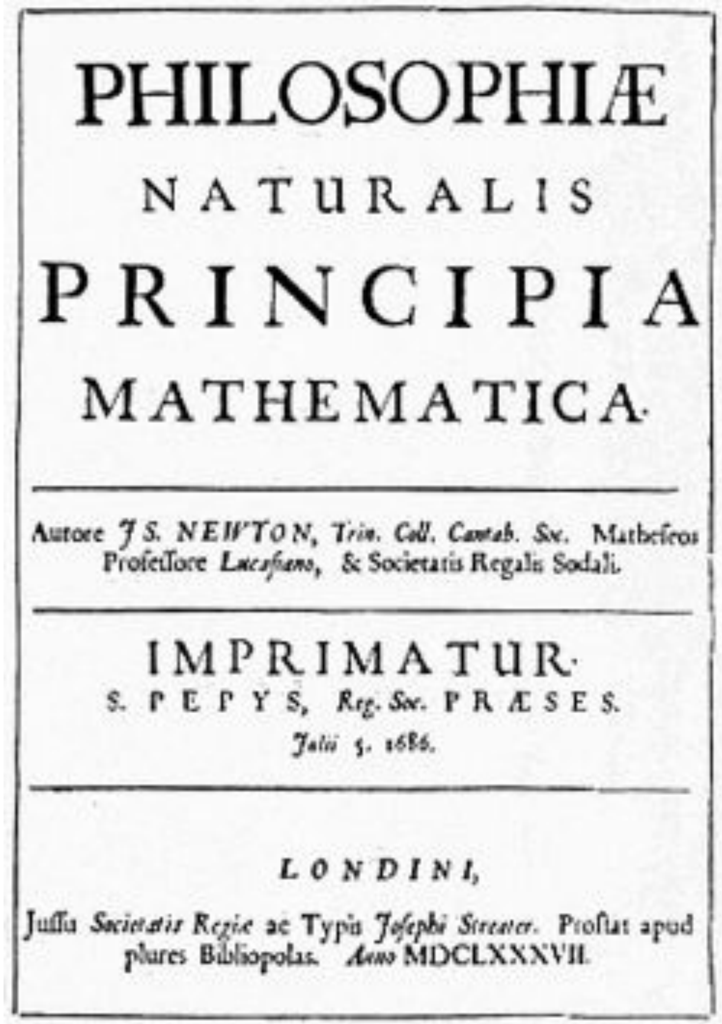
Galileo Galilei (1564-1642) was een Italiaans natuurkundige, astronoom, wiskundige en filosoof.



Sir Isaac Newton (1643–1727) (was een Engelse natuurkundige,wiskundige, astronoom, natuurfilosoof, alchemist en theoloog.

Newton's laws





PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *J S. NEWTON*, *Trin. Coll. Cantab. Soc.* Matheseos Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,

Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtat apud plures Bibliopolas. *Anno* MDCLXXXVII.

Newton's laws of motion

- **Newton's first law of motion:** A body in uniform motion remains in uniform motion, and a body at rest remains at rest, unless acted on by a nonzero net force.
- **Newton's second law of motion:** The rate at which a body's momentum changes is equal to the net force acting on the body:

$$\vec{F}_{net} = \frac{d\vec{p}}{dt} \quad \text{(Newton's 2}^{\text{nd}}\text{ Law)}$$

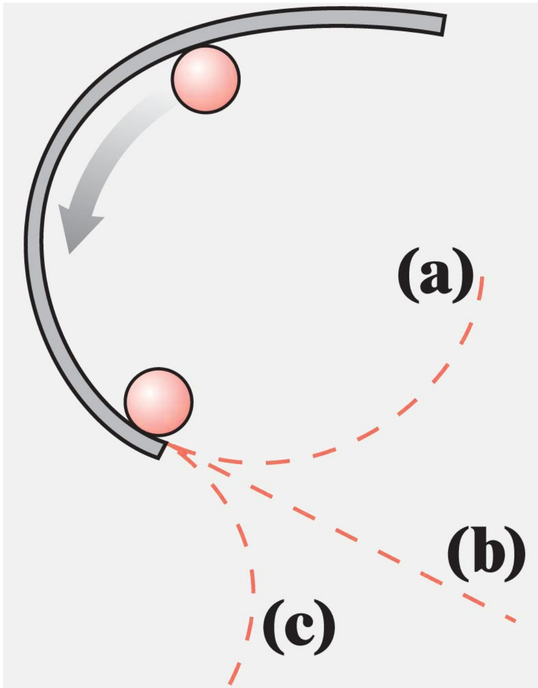
- **Newton's third law of motion:** If object A exerts a force on object B, then object B exerts an oppositely directed force of equal magnitude on A.

The first law

- The first law is a special case of the second law, when there's no net force acting on an object.
  - In that case the object's motion doesn't change.
  - If at rest it remains at rest.
  - If in motion, it remains in uniform motion.
    - Uniform motion is motion at constant speed in a straight line.
    - Thus the first law shows that uniform motion is a natural state, requiring no explanation.

Clicker question

- On a horizontal tabletop is a curved barrier that exerts a force on a ball, guiding its motion in a circular path as shown. After the ball leaves the barrier, which of the dashed paths shown does it follow?



The second law

- The second law tells quantitatively how force causes changes in an object's "quantity of motion."
  - Newton defined "quantity of motion," now called **momentum**, as the product of an object's mass and velocity:

$$\vec{p} = m\vec{v}$$

  - Newton's second law equates the rate of change of momentum to the net force on an object:

$$\vec{F} = \frac{d\vec{p}}{dt}$$

  - When mass is constant, Newton's second law becomes

$$\vec{F} = \frac{d\left(m\vec{v}\right)}{dt} = m\frac{d\vec{v}}{dt} = m\vec{a}$$

Clicker question

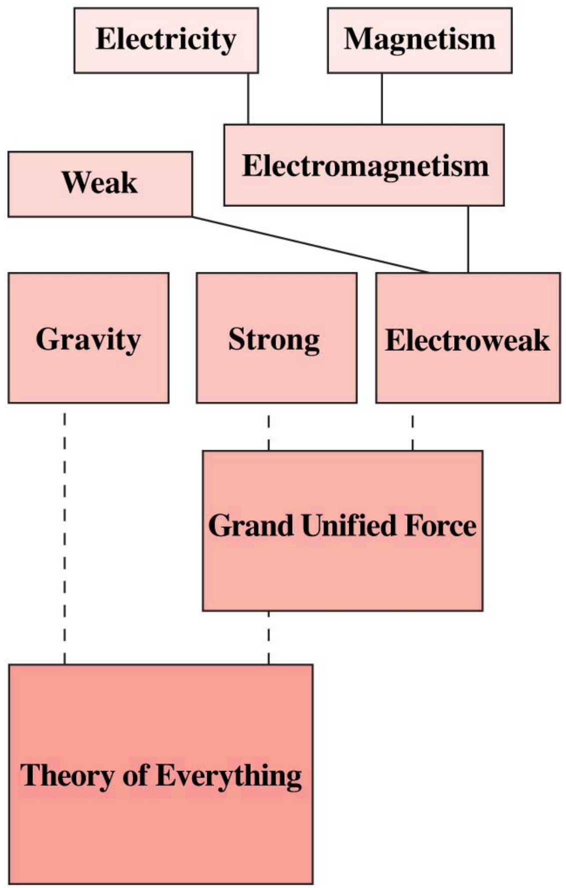
- A nonzero net force acts on an object. Does that mean the object necessarily moves in the same direction as the net force?

  A. Yes

  B. No

The fundamental forces

- Physicists now recognize three fundamental forces:
  - Gravity
  - The strong force
  - The electroweak force
- All common forces fall under these three categories.
  - Nearly all everyday forces, except gravity, are electromagnetic forces—one aspect of the electroweak force.
- Historically, more forces were once regarded as fundamental, but were later understood to be related.
- A goal of physics is to unify all forces in a "Theory of Everything."

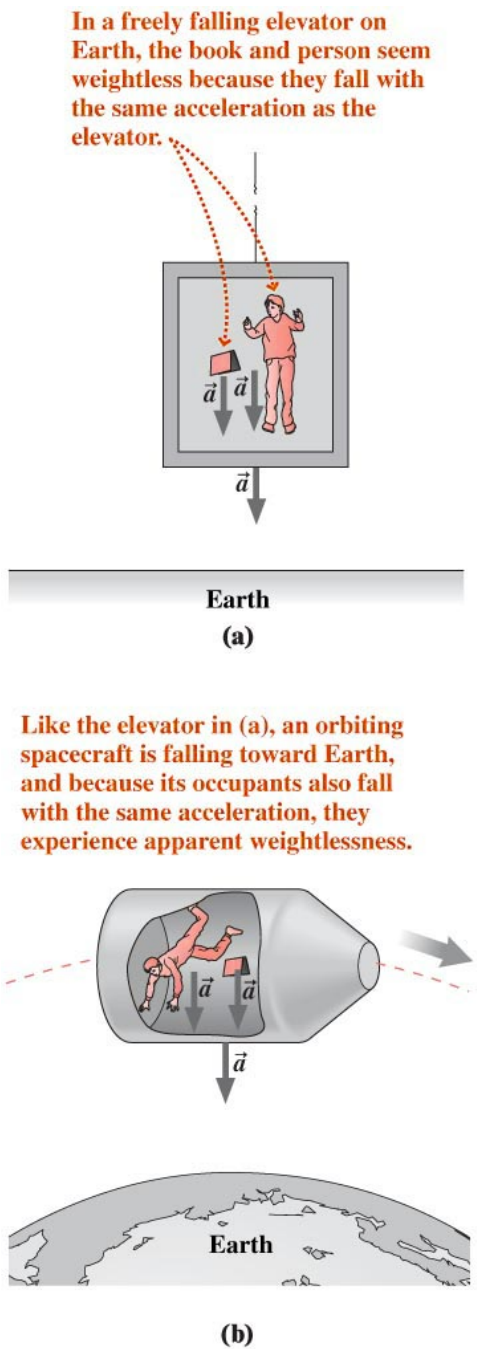


Mass, weight, and gravity

- **Weight** is the force of gravity on an object:

$$\vec{w} = m\vec{g}$$

  - Mass doesn't depend on the presence or strength of gravity.
  - Weight depends on gravity, so varies with location:
    - Weight is different on different planets.
    - Near Earth's surface, $\vec{g}$ has magnitude 9.8 m/s^2 or 9.8 N/kg, and is directed downward.
- All objects experience the same gravitational acceleration, regardless of mass.
  - Therefore objects in **free fall**—under the influence of gravity alone—appear "weightless" because they share a common accelerated motion.
  - This effect is noticeable in orbiting spacecraft
    - because the absence of air resistance means gravity is the only force acting.
    - because the apparent weightlessness continues indefinitely, as the orbit never intersects Earth.



Solving problems with Newton's second law

PROBLEM SOLVING STRATEGY 4.1 **Newton's Second Law**

INTERPRET Interpret the problem to be sure that you know what it's asking and that Newton's second law is the relevant concept. Identify the object of interest and all the individual interaction forces acting on it.

DEVELOP Draw a free-body diagram as described in Tactics 4.1. Develop your solution plan by writing Newton's second law, $\vec{F}_{net} = m\vec{a}$, with $\vec{F}_{net}$ expressed as the sum of the forces you've identified. Then choose a coordinate system so you can express Newton's law in components.

EVALUATE At this point the physics is done, and you're ready to execute your plan by solving Newton's second law and evaluating the numerical answer(s), if called for. Even in the one-dimensional problems of this chapter, remember that Newton's law is a vector equation; that will help you get the signs right. You need to write the components of Newton's law in the coordinate system you chose, and then solve the resulting equation(s) for the quantity(ies) of interest.

ASSESS Assess your solution to see that it makes sense. Are the numbers reasonable? Do the units work out correctly? What happens in special cases—for example, when a mass, a force, an acceleration, or an angle gets very small or very large?

Example (I) (Newton's 2nd law)

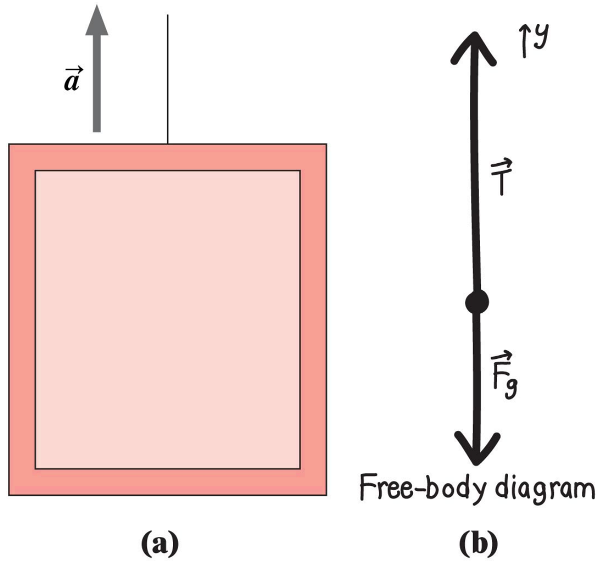
- A 740-kg elevator accelerates upward at 1.1 m/s^2, pulled by a cable of negligible mass. Find the tension force in the cable.
  - INTERPRET: The object of interest is the elevator; the forces are gravity and the cable tension.
  - DEVELOP: Newton's law reads

$$\vec{F}_{net} = \vec{T} + \vec{F}_g = m\vec{a}$$

  - EVALUATE: In a coordinate system with y axis upward, Newton's law reads $T_y + F_{gy} = m \cdot a_y$

    Solving gives

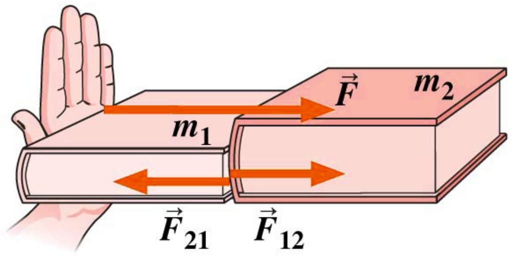
$$T = m\left(a_y + g\right) = 8.1 \text{ kN}$$



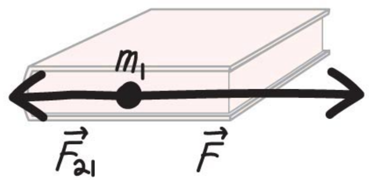
  - ASSESS: Makes sense; look at some special cases. When $a = 0$, $T = mg$ and the cable tension balances gravity. When $T = 0$, $a = -g$, and the elevator falls freely.

Newton's third law

- Forces come in pairs.
  - If object A exerts a force on object B, then object B exerts an oppositely directed force of equal magnitude on A.
  - Obsolete language: "For every action there is an equal but opposite reaction."
  - Important point: The two forces always act on *different* objects; therefore they can't cancel each other.
- Example:
  - Push on book of mass m_1 with force $\vec{F}$
  - Note third-law pair $\vec{F}_{12}$ and $\vec{F}_{21}$
  - Third law is necessary for a consistent description of motion in Newtonian physics.



(a)



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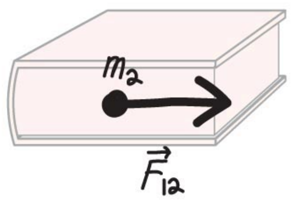
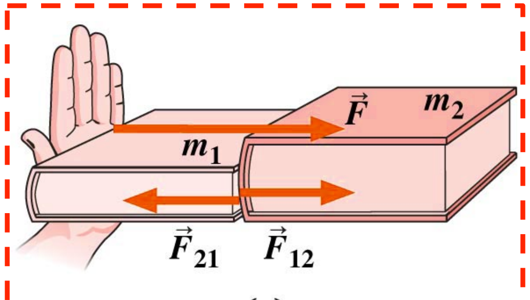


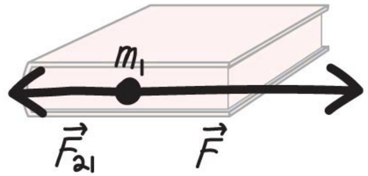
(c)

Example (II)

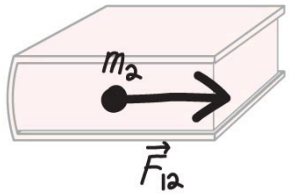
- On a frictionless horizontal surface, you push with force *F* on a book of mass m_1 that in turn pushes on a book of mass m_2. What force does the second book exert on the first?
  - INTERPRET: This problem is about interaction between 2 objects – so both books are objects of interest.
  - DEVELOP: Multiple body problems – always draw a separate free-body diagram for each object Figs.(b) and (c). How to find force F_{21}? Newton's 3rd law: $F_{12} = F_{21}$. Since only horizontal forces are acting on books we will apply Newton's 2nd law.



(a)



(b)



(c)

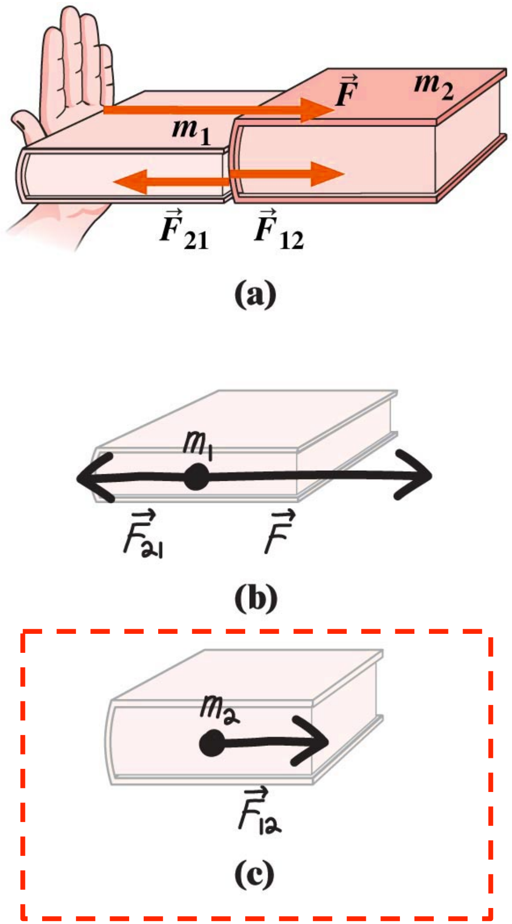
Example (II)

- EVALUATE: Total mass of the two books is m_1+m_2 and the net force applied to the combination is *F*. Newton's 2nd law:

$$\vec{a} = \frac{\vec{F}}{m} = \frac{\vec{F}}{m_1 + m_2}$$

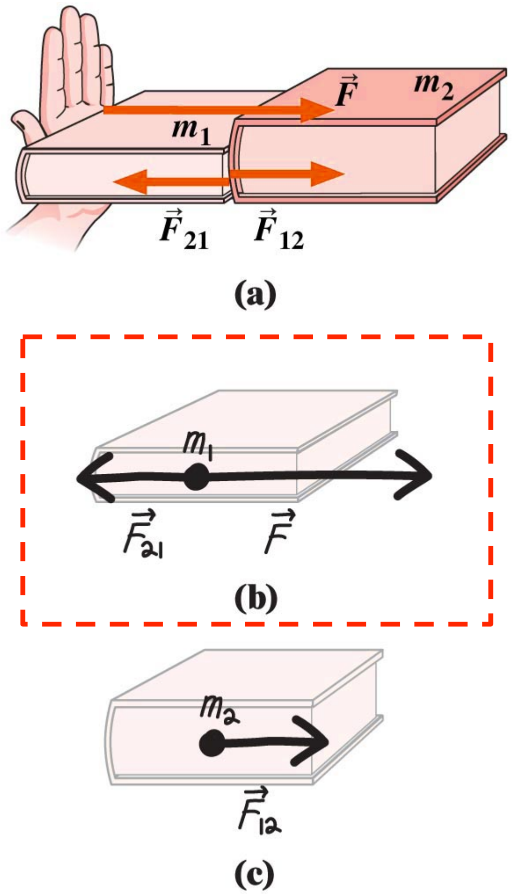
$$\vec{F}_{12} = m_2 \vec{a} = m_2 \frac{\vec{F}}{m_1 + m_2}$$

$$\vec{F}_{21} = -\vec{F}_{12} = -m_2 \frac{\vec{F}}{m_1 + m_2}$$



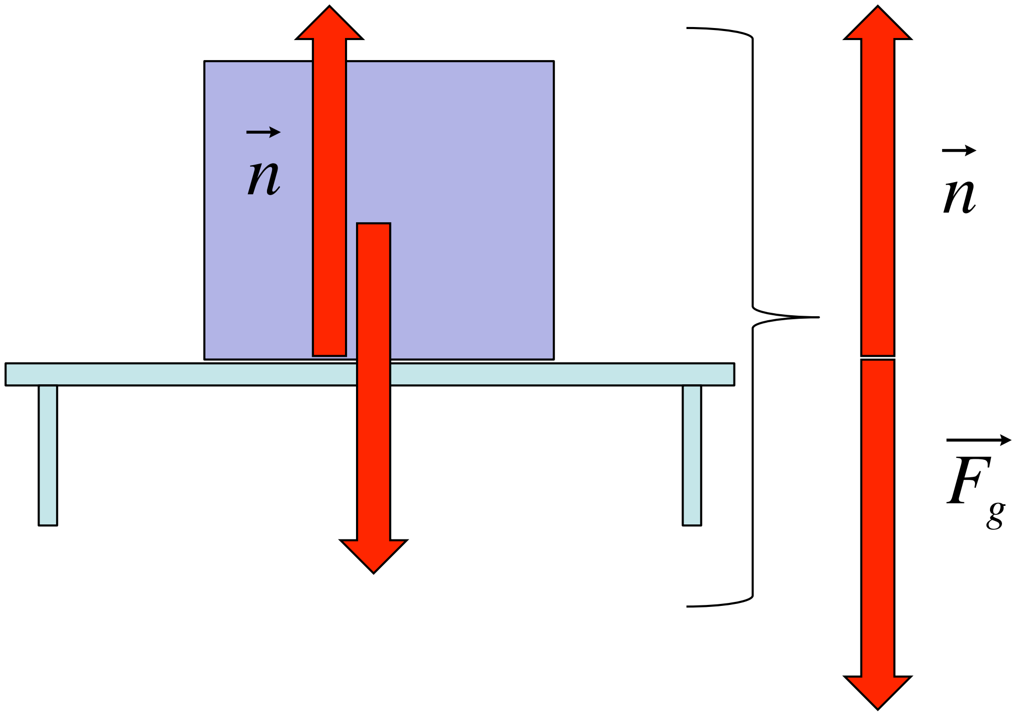
Example (II)

- ASSES: Let consider the first book. It too undergoes same acceleration but there are TWO FORCES acting on it: the applied F and the F_{21} from the second book. So the net force on the first book is:

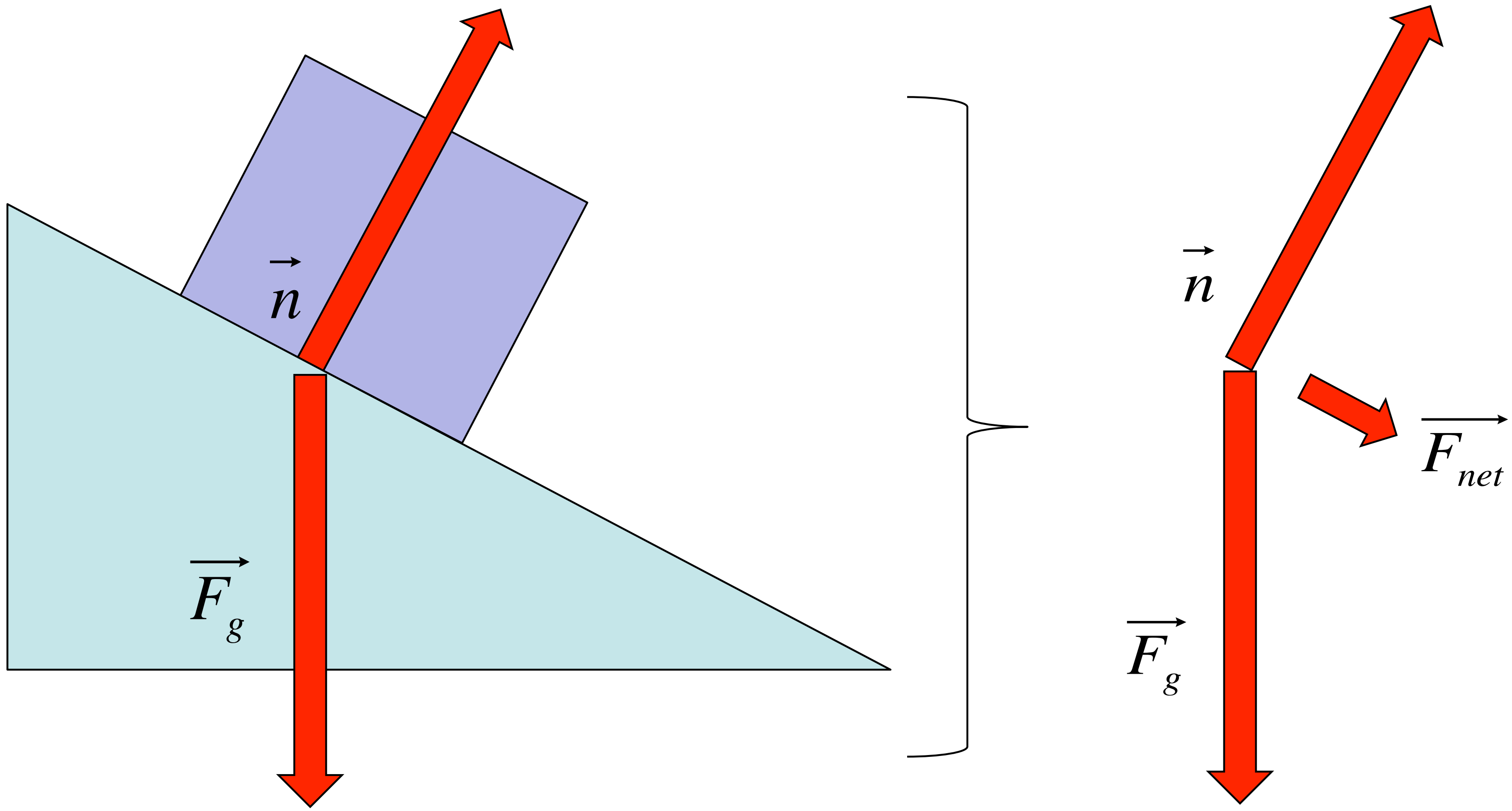


$$\vec{F} + \vec{F_{21}} = \vec{F} - \frac{m_2}{m_1 + m_2}\vec{F} = \frac{m_1}{m_1 + m_2}\vec{F}$$

Normal forces (free-body diagrams)

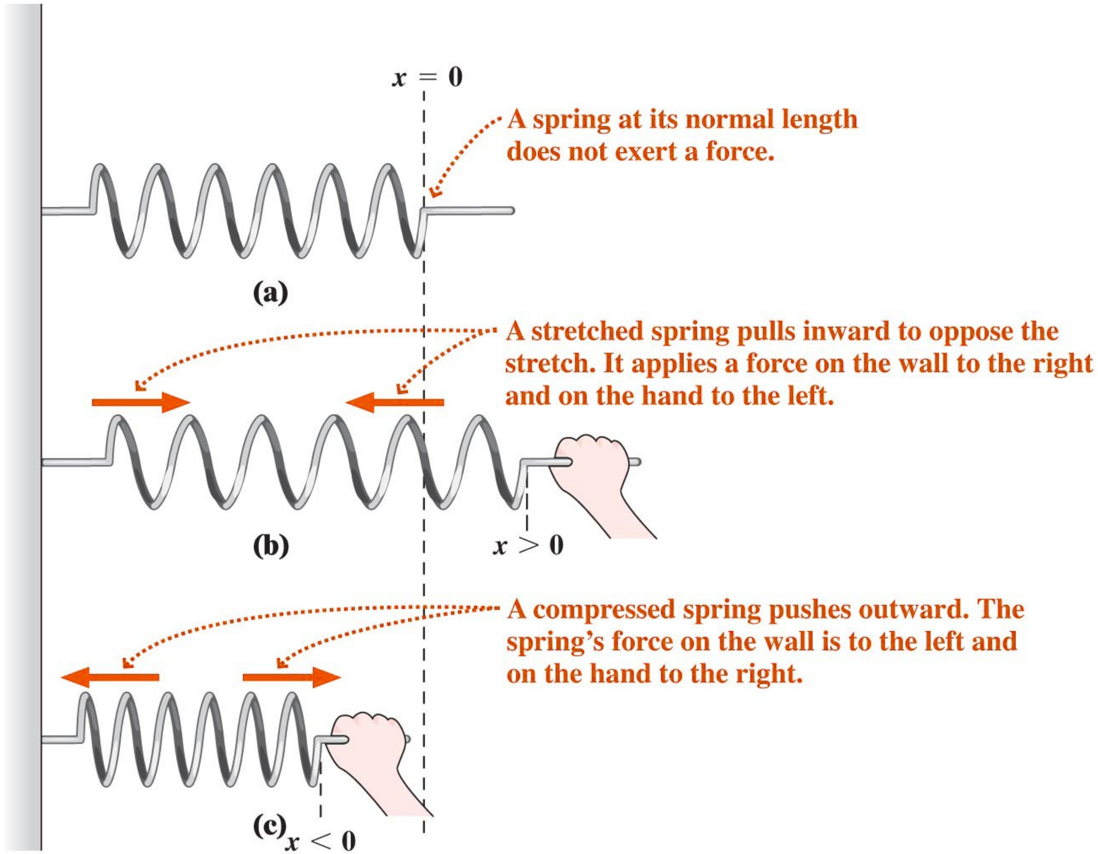


Normal forces (free-body diagrams)



Measuring Force (Spring forces)

- A stretched or compressed spring produces a force proportional to the stretch or compression from its equilibrium configuration: $F_{sp} = -kx$.
  - The spring force is a **restoring force** because its direction is opposite that of the stretch or compression.
  - Springs provide convenient devices for measuring force.



Summary

- In Newtonian physics, force—a push or pull—causes not motion itself but *change* in motion.
  - Newton's three laws are
    - **First law**: A body in motion remains in uniform motion, and a body at rest remains at rest, unless acted on by a nonzero net force.
    - **Second law**: The rate at which a body's momentum changes is equal to the net force acting on the body:

$$\vec{F} = \frac{d\vec{p}}{dt}; \quad \text{for} \quad \text{constant} \quad \text{mass}, \vec{F} = m\vec{a}$$

    - **Third law**: If object A exerts a force on object B, then object B exerts an oppositely directed force of equal magnitude on A.
- Physicists recognize three fundamental forces.
- An object's **weight** is the force that gravity exerts on it.

Clicker question

- The figure shows two blocks with two forces acting on the pair. Is the net force on the larger block (A) less than 2 N, (B) equal to 2 N, or (C) greater than 2 N?