PHYC10003 Physics 1

Lecture 5: Force

Newton's First and Second Laws

Last Lecture

- Vector product (scalar and vector)
- Basic calculus of vectors
- Projectile motion
- Circular motion

4.6 Relative motion

- Measures of position and velocity depend on the **reference frame** of the measurer
  - How is the observer moving?
  - Our usual reference frame is that of the ground

- Read subscripts “PA”, “PB”, and “BA” as “P as measured by A”, “P as measured by B”, and “B as measured by A"

- Frames A and B are each watching the movement of object P

Frame *B* moves past frame *A* while both observe *P*.

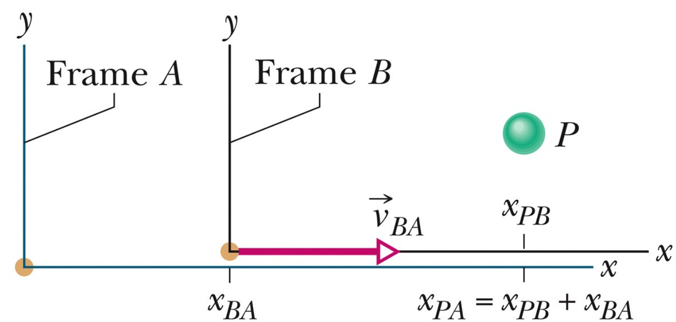


Figure 4-18

4.6 Relative motion

- Positions in different frames are related by:

$$x_{PA} = x_{PB} + x_{BA}. \qquad \text{Eq. (4-40)}$$

- Taking the derivative, we see velocities are related by:

$$\frac{d}{dt}(x_{PA}) = \frac{d}{dt}(x_{PB}) + \frac{d}{dt}(x_{BA}).$$

$$v_{PA} = v_{PB} + v_{BA}. \qquad \text{Eq. (4-41)}$$

- But accelerations (for non-accelerating reference frames, $a_{BA} = 0$) are related by

$$\frac{d}{dt}(v_{PA}) = \frac{d}{dt}(v_{PB}) + \frac{d}{dt}(v_{BA}).$$

$$a_{PA} = a_{PB}. \qquad \text{Eq. (4-42)}$$

4.6 Relative motion

Observers on different frames of reference that move at constant velocity relative to each other will measure the same acceleration for a moving particle.

Example

Frame A: $x = 2$ m, $v = 4$ m/s

Frame B: $x = 3$ m, $v = -2$ m/s

P as measured by A: $x_{PA} = 5$ m, $v_{PA} = 2$ m/s, $a = 1$ m/s^2

So P as measured by B:

- $x_{PB} = x_{PA} + x_{AB} = 5\text{ m} + (2\text{m} – 3\text{m}) = 4\text{ m}$
- $v_{PB} = v_{PA} + v_{AB} = 2\text{ m/s} + (4\text{ m/s} – -2\text{m/s}) = 8\text{ m/s}$
- $a = 1$ m/s^2

4.7 Relative motion – 3D frames of reference

- Frames A and B are both observing the motion of P

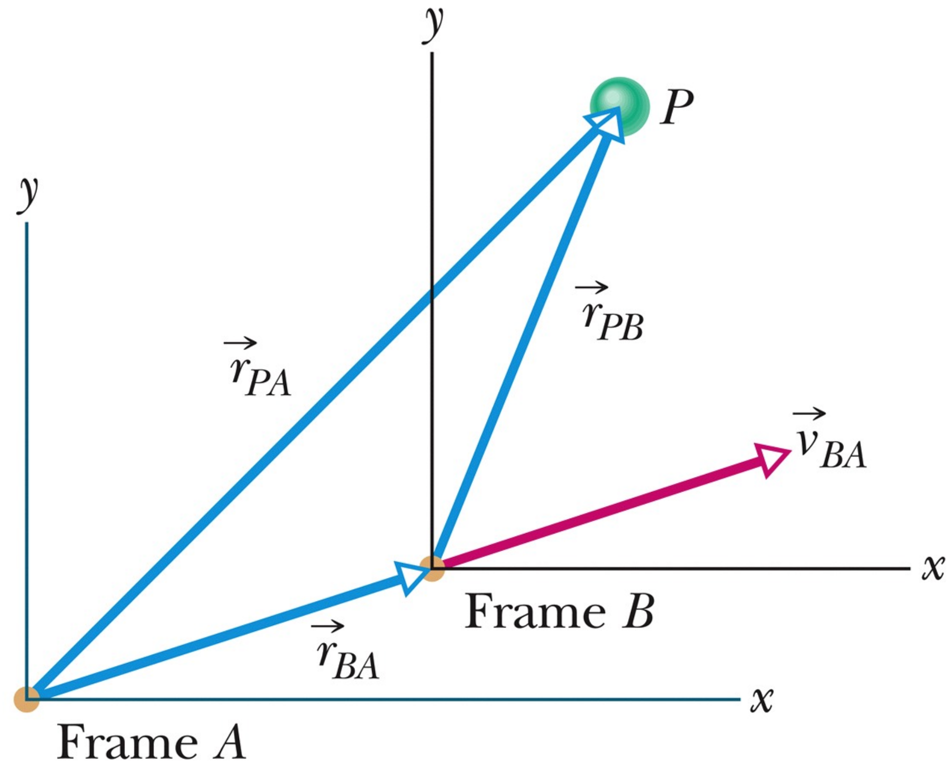


Figure 4-19

4.7 Relative motion – 3D frames of reference

- The same as in one dimension, but now with vectors:
- Positions in different frames are related by:

$$\vec{r}_{PA} = \vec{r}_{PB} + \vec{r}_{BA}.$$

Eq. (4-43)

- Velocities:

$$\vec{v}_{PA} = \vec{v}_{PB} + \vec{v}_{BA}.$$

Eq. (4-44)

- Accelerations (for non-accelerating reference frames):

$$\vec{a}_{PA} = \vec{a}_{PB}.$$

Eq. (4-45)

- Again, observers in different frames will see the same acceleration

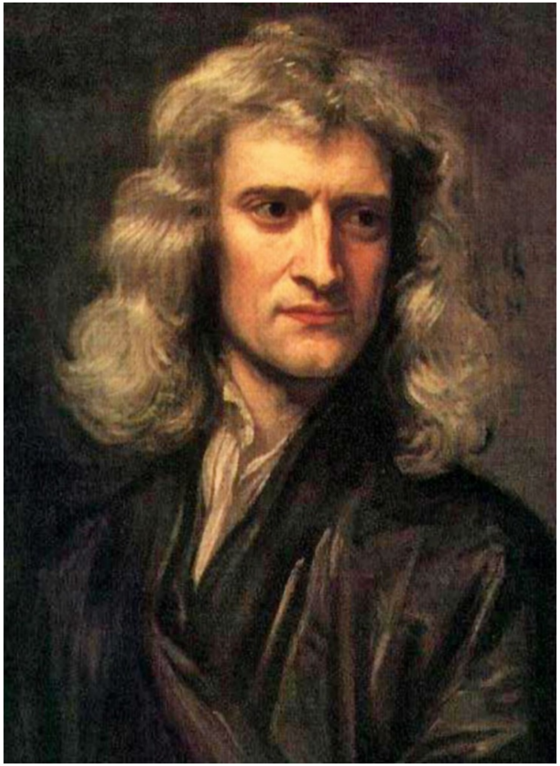
5-1 Force

- A **force**:
  - Is a "push or pull" acting on an object
  - Causes acceleration
- We will focus on Newton's three laws of motion:
  - **Newtonian mechanics** is valid for everyday situations
  - It is *not* valid for speeds which are an appreciable fraction of the speed of light (Special Relativity)
  - It is *not* valid for objects on the scale of atomic structure
  - May be viewed as an approximation to general relativity

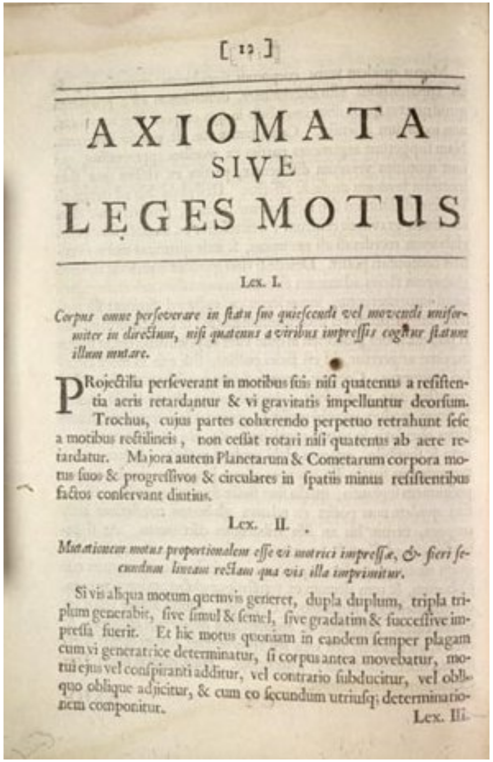
5-1 Newton's First Law of Motion

- Before Newtonian mechanics:
  - Some influence (force) was thought necessary to keep a body moving
  - The "natural state" of objects was at rest
- This seems intuitively reasonable (due to friction)
- But envision a **frictionless surface**
  - Does not slow an object
  - The object would keep moving forever at a constant speed
  - Friction is a force!

5-1 Newton's First Law of Motion



Isaac Newton by Godfrey Kneller (1646) : (Images-WikiCommons)



[12]

AXIOMATA
SIVE
LEGES MOTUS

Lex. I.

Corpus omne perſeverare in ſtatu ſuo quieſcendi vel movendi uniformiter in directum, niſi quatenus a viribus impreſſis cogitur ſtatum illum mutare.

PRojectilia perſeverant in motibus ſuis niſi quatenus a reſiſtentia aeris retardantur & vi gravitatis impelluntur deorſum. Trochus, cujus partes cohærendo perpetuo retrahunt ſeſe a motibus rectilineis, non ceſſat rotari niſi quatenus ab aere retardatur. Majora autem Planetarum & Cometarum corpora motus ſuos & progreſſivos & circulares in ſpatiis minus reſiſtentibus factos conſervant diutius.

Lex. II.

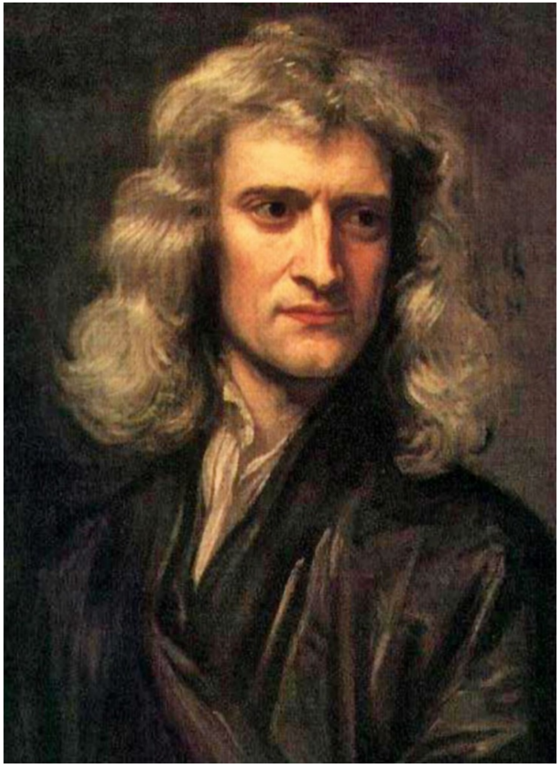
Mutationem motus proportionalem eſſe vi motrici impreſſæ, & fieri ſecundum lineam rectam qua vis illa imprimitur.

Si vis aliqua motum quemvis generet, dupla duplum, tripla triplum generabit, ſive ſimul & ſemel, ſive gradatim & ſucceſſive impreſſa fuerit. Et hic motus quoniam in eandem ſemper plagam cum vi generatrice determinatur, ſi corpus antea movebatur, motui ejus vel conſpiranti additur, vel contrario ſubducitur, vel obliquo oblique adjicitur, & cum eo ſecundum utriuſq; determinationem componitur.

Lex. III.

The Laws of Motion,
Principia Mathematica, 1687

5-1 Newton's First Law of Motion



"If no force acts on a body, the body's velocity cannot change; that is, the body cannot accelerate"…or

"In an inertial frame, a body will remain at rest or continue in uniform straight-line motion unless acted upon by an external force"

Isaac Newton by Godfrey Kneller (1646) : (Image-WikiCommons)

5-1 Force and superposition

- Characteristics of forces:
  - Unit: N, the newton; 1 N = 1 kg m/s^2
  - Acceleration of a mass is proportional to the exerted force
  - Forces are vectors
- **Net force** is the *vector sum* of all forces on an object
- **Principle of superposition for forces**:
  - A net force has the same impact as a single force with identical magnitude and direction
  - So we can restate more correctly:

Newton's First Law: If no *net* force acts on a body ($\vec{F}_{\text{net}} = 0$), the body's velocity cannot change; that is, the body cannot accelerate.

5-1 Newton's First Law; inertial frames

- Newton's first law is not true in all frames
- **Inertial frames**:

An inertial reference frame is one in which Newton's laws hold.

- (a): a frictionless puck, pushed from the north pole, viewed from space
- (b): the same situation, viewed from the ground
- Over *long* distances, the ground is a **noninertial frame**
- In (b), a fictitious force would be needed to explain deflection

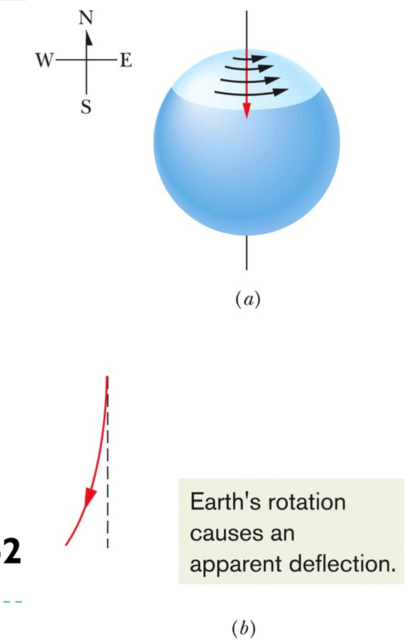


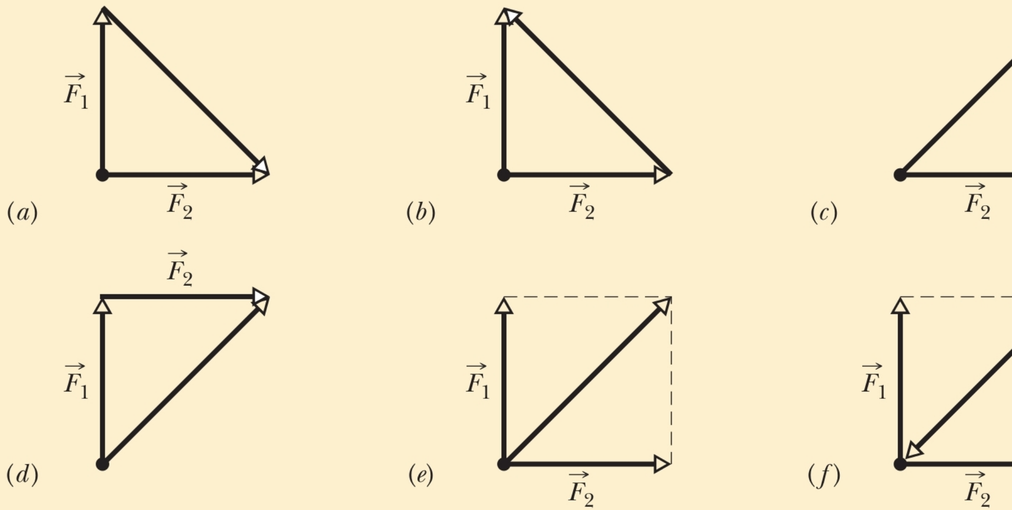
Figure 5-2

5-1 Inertial frames

- Generally, assume the ground is an inertial frame

Checkpoint 1

Which of the figure's six arrangements correctly show the vector addition of forces $\vec{F}_1$ and $\vec{F}_2$ to yield the third vector, which is meant to represent their net force $\vec{F}_{net}$?



Answer: (c), (d), (e)

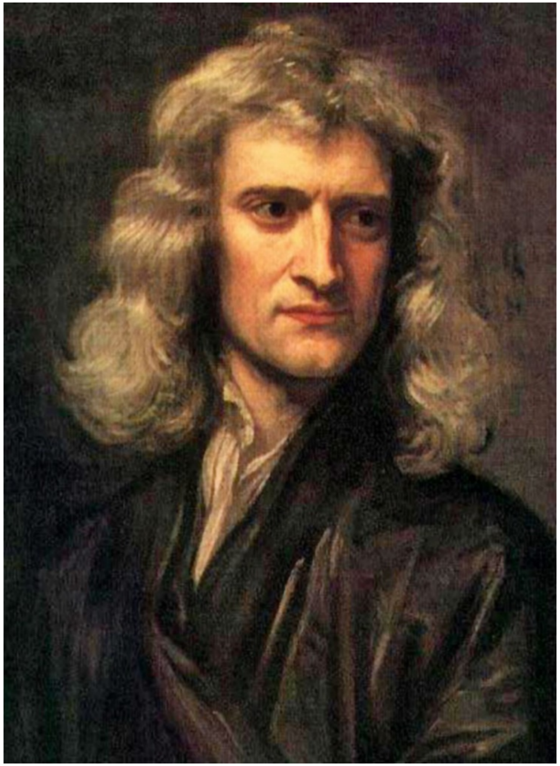
5-1 Mass and motion

- What is mass?
  - *"the mass of a body is the characteristic that relates a force on the body to the resulting acceleration"*
  - Mass is a measure of a body's resistance to a change in motion (change in velocity)
  - It is *not* the same as weight, density, size etc.
  - Mass is inversely proportional to acceleration

Example Apply an 8.0 N force to various bodies:

- Mass: 1kg → acceleration: 8 m/s^2
- Mass: 0.5kg → acceleration: 16 m/s^2
- Acceleration: 2 m/s^2 → mass: 4 kg

5-1 Newton's Second Law of Motion



Isaac Newton by Godfrey Kneller (1646) :
(Image-WikiCommons)

"The net force on a body is equal to the product of its mass and acceleration"…or

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

5-1 Newton's Second Law of Motion

- Identify the body in question, and *only* include forces that act *on* that body!
- Separate the problem axes (they are independent):

$$\vec{F}_{\text{net}} = m\vec{a}$$ **Eq. (5-1)**

$$F_{\text{net},x} = ma_x, \quad F_{\text{net},y} = ma_y, \quad \text{and} \quad F_{\text{net},z} = ma_z.$$ **Eq. (5-2)**

The acceleration component along a given axis is caused *only by* the sum of the force components along that *same* axis, and not by force components along any other axis.

5-1 Force and equilibrium

- If the net force on a body is zero:
  - Its acceleration is zero
  - The forces and the body are in *equilibrium*
  - *But* there may still be forces!
- Units of force:

Table 5-1 Units in Newton's Second Law (Eqs. 5-1 and 5-2)

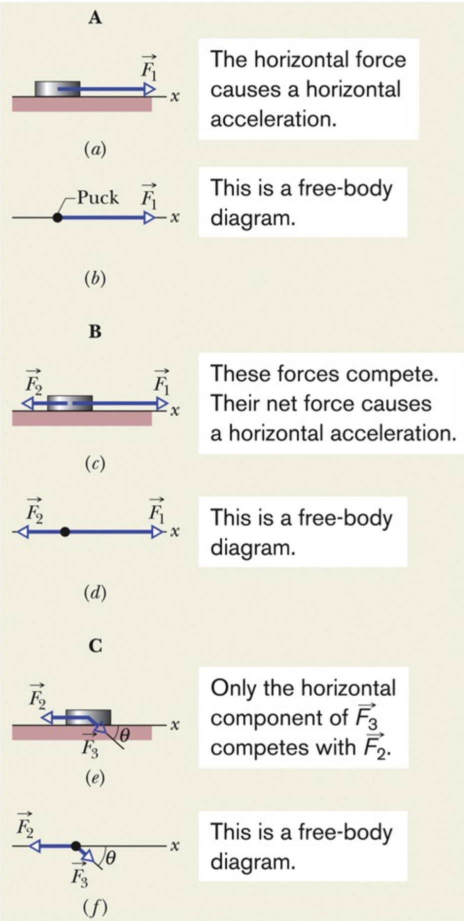
System	Force	Mass	Acceleration
SI	newton (N)	kilogram (kg)	m/s^2
CGS[a]	dyne	gram (g)	cm/s^2
British[b]	pound (lb)	slug	ft/s^2

[a] $1 \text{ dyne} = 1 \text{ g} \cdot \text{cm/s}^2$.

[b] $1 \text{ lb} = 1 \text{ slug} \cdot \text{ft/s}^2$.

Tab. (5-1)

5-1 Forces – free body diagrams

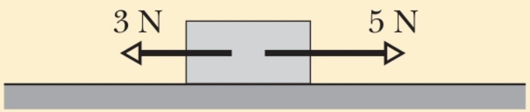


- To solve problems with forces, we often draw a **free body diagram**
- The only body shown is the one we are solving for
- Forces are drawn as vector arrows with their tails on the body
- Coordinate system shown
- Acceleration is NEVER part of a free body diagram – only forces on a body are present.

Figure 5-3

5-1 Forces

Checkpoint 2



The figure here shows two horizontal forces acting on a block on a frictionless floor. If a third horizontal force $\vec{F}_3$ also acts on the block, what are the magnitude and direction of $\vec{F}_3$ when the block is (a) stationary and (b) moving to the left with a constant speed of 5 m/s?

Answer: F_3 = 2 N to the left in *both* cases

5-1 Forces – internal and external

- A **system** consists of one or more bodies
- Any force on the bodies inside a system exerted by bodies outside the system is an **external force**
- Net force on a system = sum of external forces
- Forces between bodies in a system: **internal forces**
  - Not included in a FBD *of the system* since internal forces cannot accelerate the system

Note: do not confuse a free body diagram of an entire system with free body diagrams of individual bodies within a system.

5-2 Forces - gravity

- The **gravitational force**:
  - A pull that acts on a body, directed toward a second body
  - Generally we consider situations where the second body is Earth
- In free fall (y direction, with no drag from the air):

$$-F_g = m(-g)$$

$$\boxed{F_g = mg.} \qquad \textbf{Eq. (5-8)}$$

- This force still acts on a body at rest!
- We can write it as a vector:

$$\vec{F}_g = -F_g\hat{\mathrm{j}} = -mg\hat{\mathrm{j}} = m\vec{g}, \qquad \textbf{Eq. (5-9)}$$

5-2 Force - weight

Weight :

- The name given to the gravitational force that one body (like the Earth) exerts on an object
  - It is a force measured in newtons (N)
  - It is directed downward towards the centre

$$W = F_g \qquad \text{(weight, with ground as inertial frame).}$$

The weight W of a body is equal to the magnitude F_g of the gravitational force on the body.

Eq. (5-12)

5-2 Force – weight, mass and gravity

Example To relate weight to mass, consider an apple in free fall. The only force on the apple is the gravitational force which results in an acceleration of g.
Applying Newton's 2nd Law

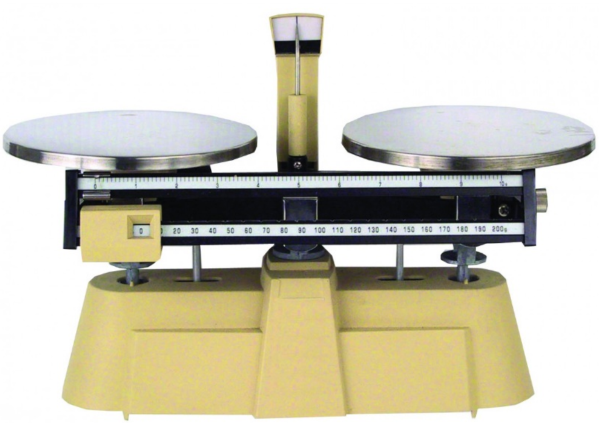
$$F_{net} = ma \quad \text{where } F_{net} = F_g = W \quad \text{and} \quad a = g$$

$$F_g = W = mg$$

Thus,

$$W = mg \quad \text{(mass – weight relationship)}$$

5-2 Force – measuring weight



- A pan balance (left) measures mass by comparing two known masses, independent of the local value of g.
- A spring balance (right) measures *weight*, because the deflection of the spring depends on both the mass and the local value of g.

5-2 Force – measuring weight

- Measuring weight:
  - Use a balance to compare a body to known masses, find its mass, and compute its weight
  - Use a spring scale that measures weight on a calibrated scale
  - Weight is not the same as mass: a pan balance will read the same for different values of g, a scale will read differently for different values of g
- Weight must be measured when the body is not accelerating vertically
  - E.g., in your bathroom, or on a train
  - But not in an lift or aerobatic aircraft

Summary

Newtonian Mechanics

- Forces are pushes or pulls
- Forces cause acceleration

Force

- Vector quantities
- $1\ \text{N} = 1\ \text{kg m/s}^2$
- Net force is the sum of all forces on a body

Newton's First Law

- If there is no net force on a body, the body remains at rest if it is initially at rest, or moves in a straight line at constant speed if it is in motion.

Inertial Reference Frames

- Frames in which Newtonian mechanics holds

Summary

Mass

- The characteristic that relates the body's acceleration to the net force
- Scalar quantity

Particular Forces

- Weight:

$$W = mg \quad \textbf{Eq. (5-12)}$$

Newton's Second Law

$$\vec{F}_{\text{net}} = m\vec{a} \quad \textbf{Eq. (5-1)}$$

- Free-body diagram represents the forces on one object

Preparation for the next lecture

1. Read 5.1-5.3 and 2.6 of the text
2. You will find short answers to the odd-numbered problems in each chapter at the back of the book and further resources on LMS. You should try a few of the simple odd numbered problems from each section (the simple questions have one or two dots next to the question number).