Physics 1

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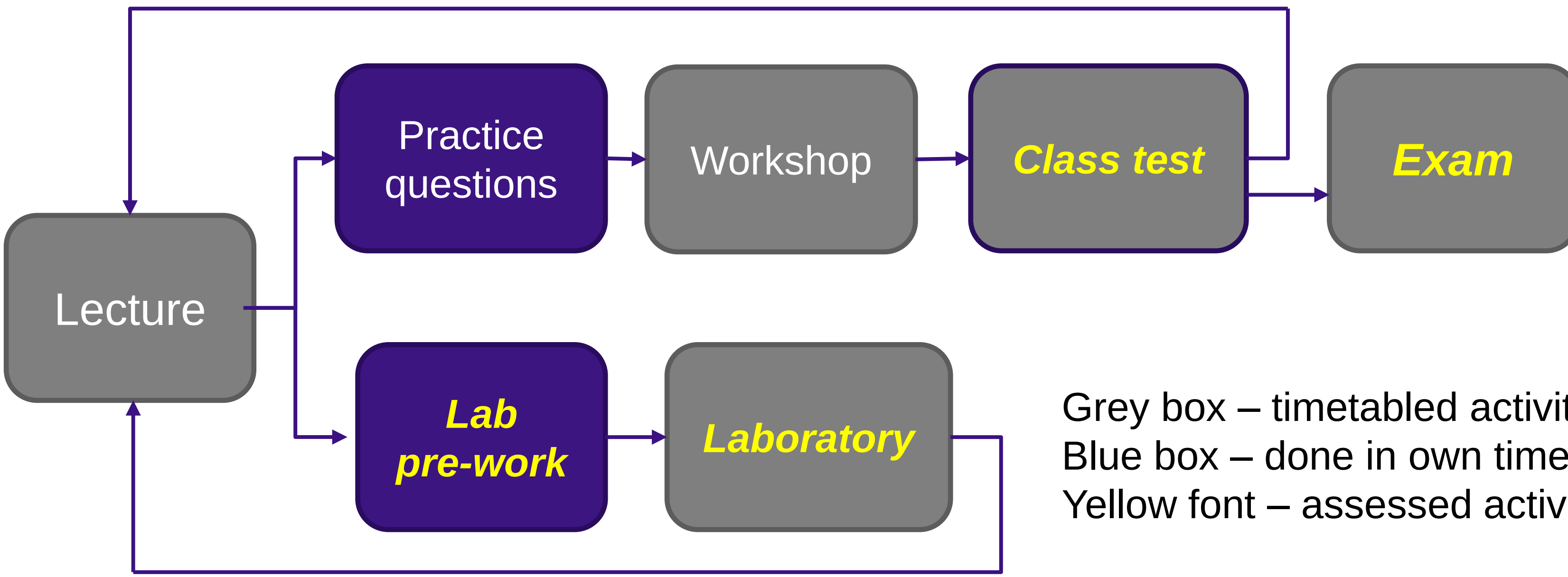
Lecture 1: Kinematics in One Dimension

How you'll learn in this subject

- You'll be introduced to new concepts and principles with worked examples in lectures
- You'll practise applying these concepts and models in workshops
- You'll test the validity of some models in laboratory

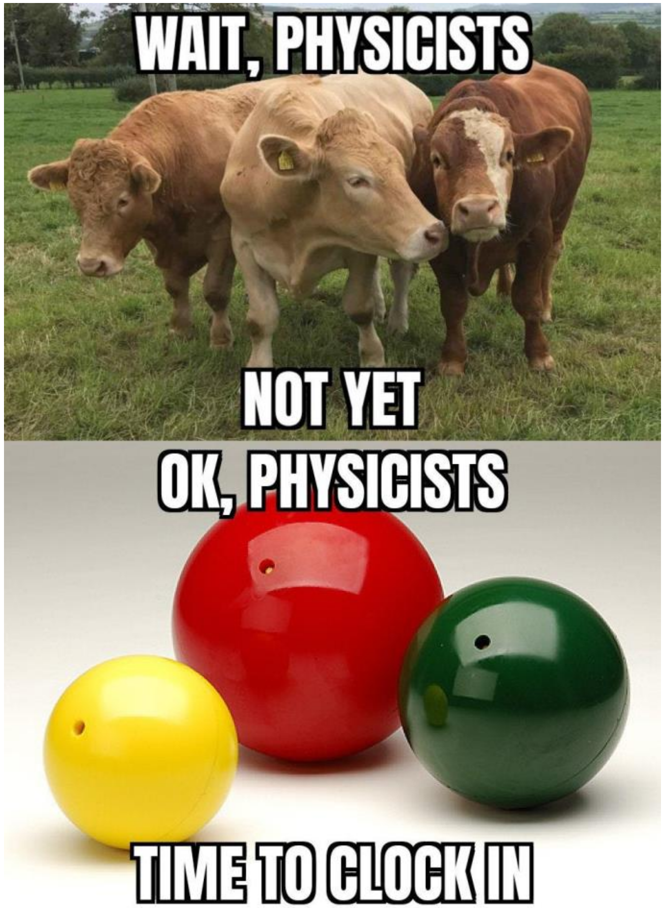


Grey box – timetabled activity
Blue box – done in own time
Yellow font – assessed activity

Physical Models

- Can be a bit too simple…
- But seriously, they are effective!

- We start simple, then add complexity only as needed



In this lecture

- Kinematics is the study of motion. Important physical quantities are displacement, velocity and acceleration;
- How these quantities help us describe straight-line motion;
- Equations of motion;
- Acceleration due to gravity;
- Newton's Laws;
- Forces and free body diagram.

Why study mechanics?

A quantitative understanding of motion and mechanics of solids/liquids underpins many scientific disciplines:

1. Strength of materials
2. Figuring out the size of a beam for a selected material
3. Design of static structures like bridges, dams, houses
4. Design of water systems, canals, chemical plants, jet engines
5. Aerodynamics and space travel

See, for example,
https://www.youtube.com/watch?v=9pillaOxGCo
https://www.youtube.com/watch?v=c0FoZOwhqIM

Displacement

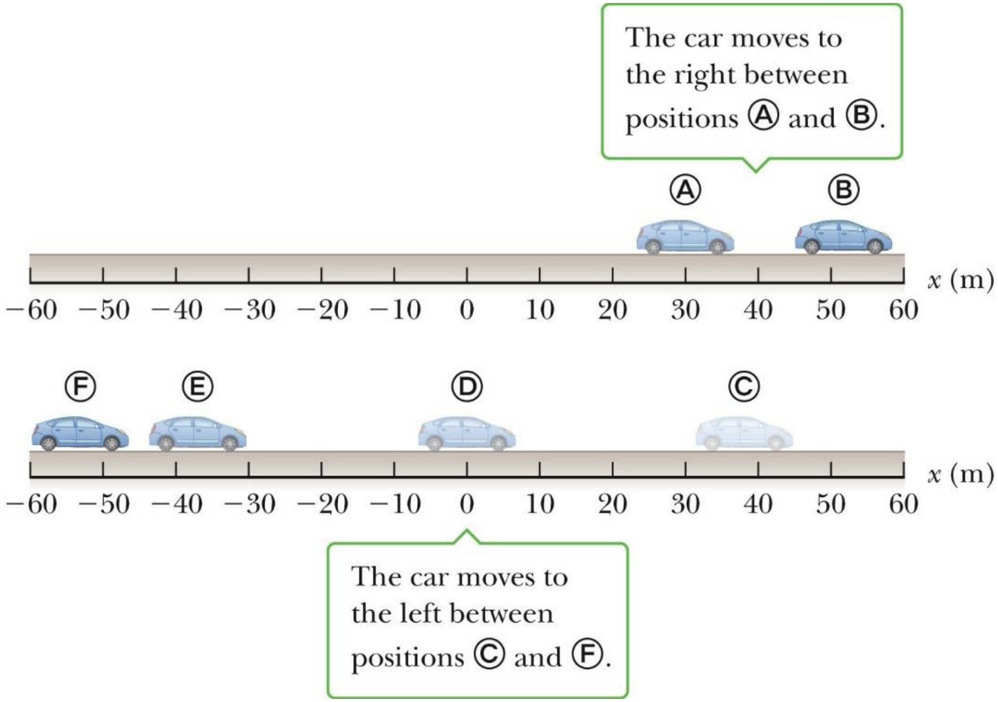
- Defined as the *change in position*

$$\Delta x \equiv x_f - x_i$$

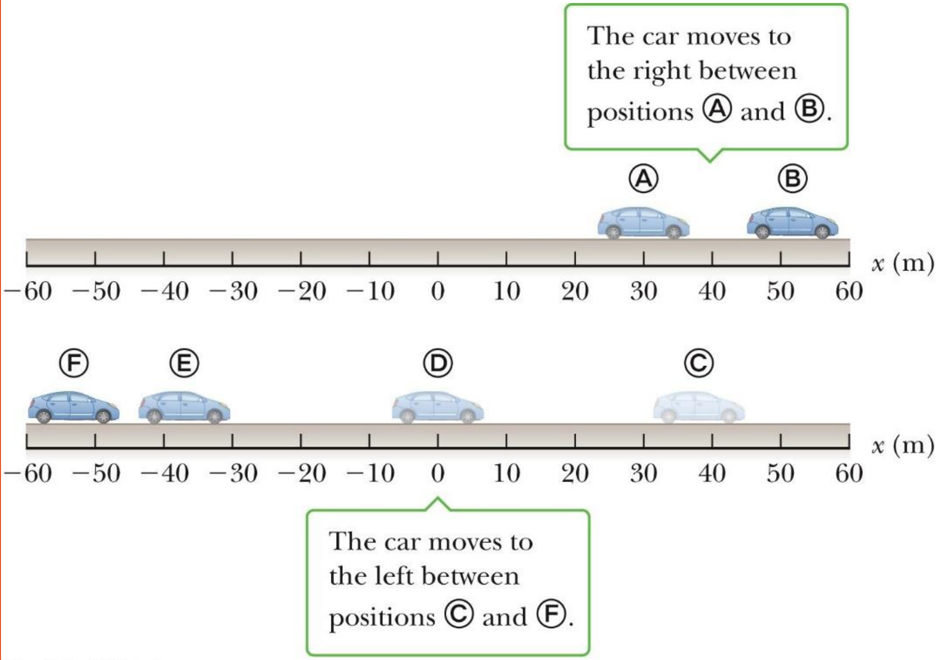
  - ***f*** stands for final and ***i*** stands for initial
  - Unit is meter (m) in SI

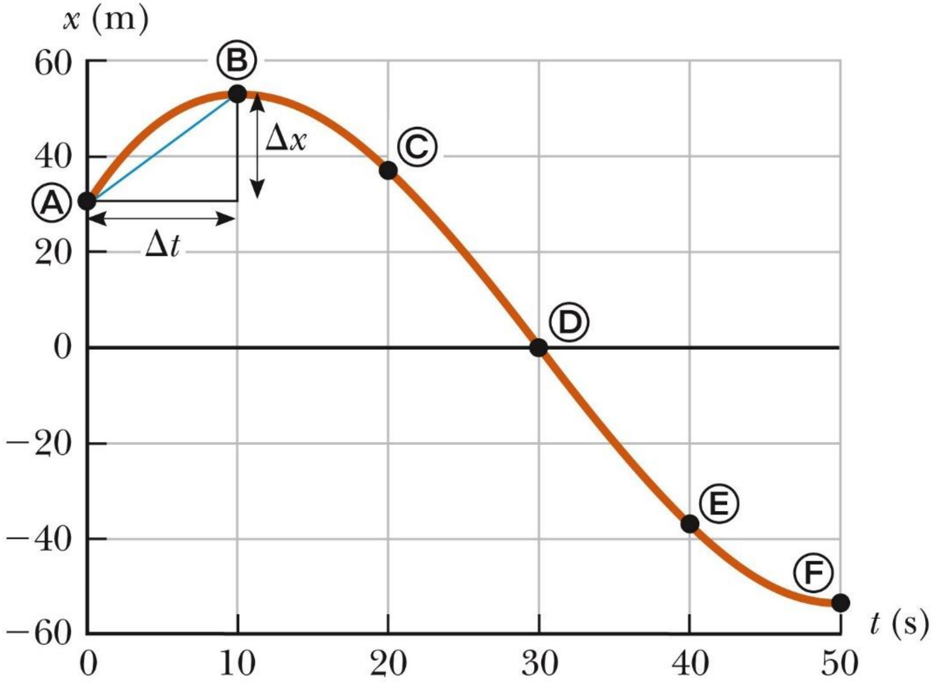
Displacement examples

- From A to B
  - x_i = 30 m
  - x_f = 52 m
  - Δx = 22 m
  - The displacement is positive, indicating the motion was in the positive x direction
- From C to F
  - x_i = 38 m
  - x_f = -53 m
  - Δx = -91 m
  - The displacement is negative, indicating the motion was in the negative x direction



Displacement, Graphical





Speed

- The **average speed** of an object is defined as the total distance traveled divided by the total time elapsed

$$\text{Average speed} = \frac{\text{distance } traveled}{\text{elapsed time}}$$

$$v = \frac{d}{t}$$

  - Speed is a scalar quantity
  - Suggest you use SI units: *d* in meter (m), *t* in second (s) and *v* in m/s

Velocity

- It takes time for an object to undergo a displacement
- The **average velocity** is rate at which the displacement occurs

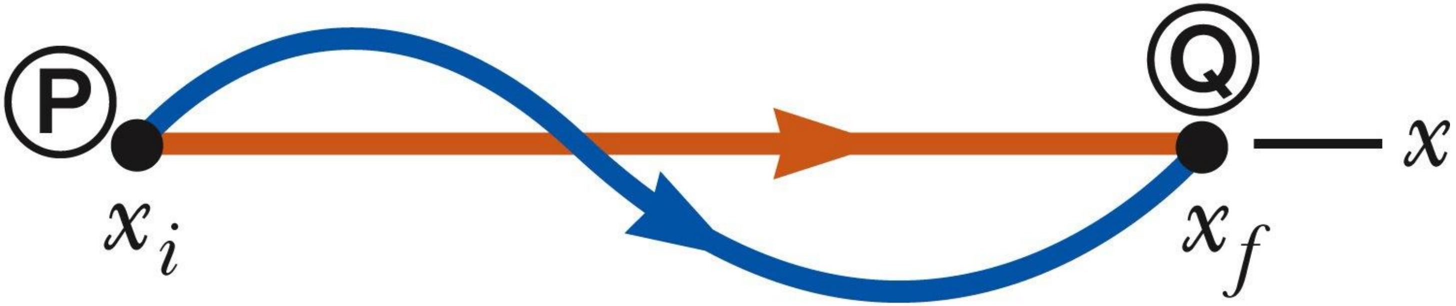
$$v_{average} = \frac{\Delta x}{\Delta t} = \frac{x_f - x_i}{t_f - t_i}$$

- Velocity can be positive or negative, but Δt is always positive
- Speed is not the same as velocity although they are usually used interchangeably.

Example: A ball is thrown vertically upwards at 20 m/s and caught again at the same height above the ground from which it was thrown. What is the displacement and average velocity of the ball?

Answer: displacement = 0, velocity = 0 (but the speed is > 0)

Speed vs Velocity



- Cars traveling on two different paths have the same average velocity since they had the same displacement over the same time interval
- The car on the blue path will have a greater average speed since the path length it traveled is larger

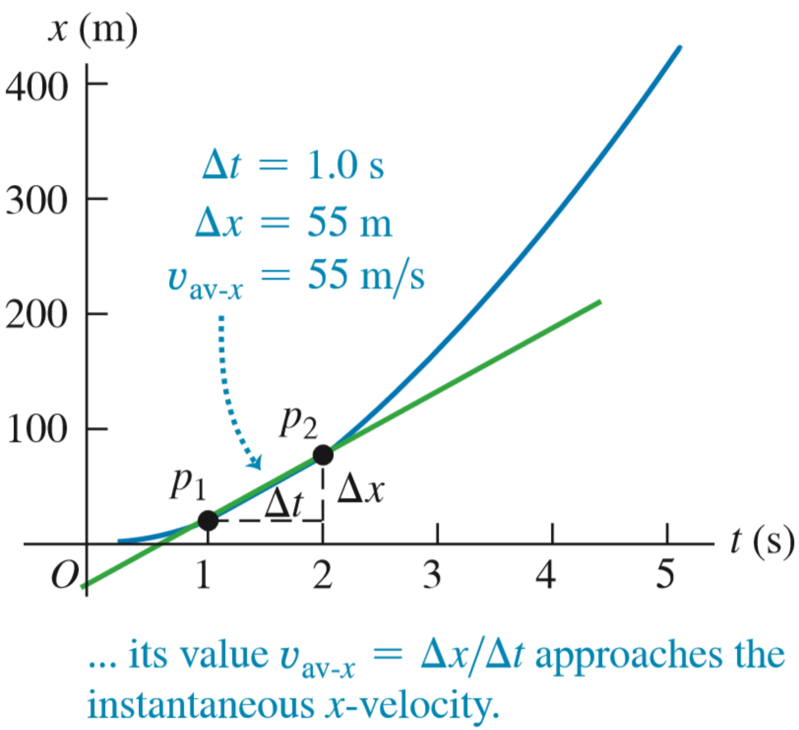
See also https://www.youtube.com/watch?v=-6lrr6-ADY0

Instantaneous Velocity

- **Instantaneous velocity** is the velocity at a specific instant of time or specific point along the path and is given by

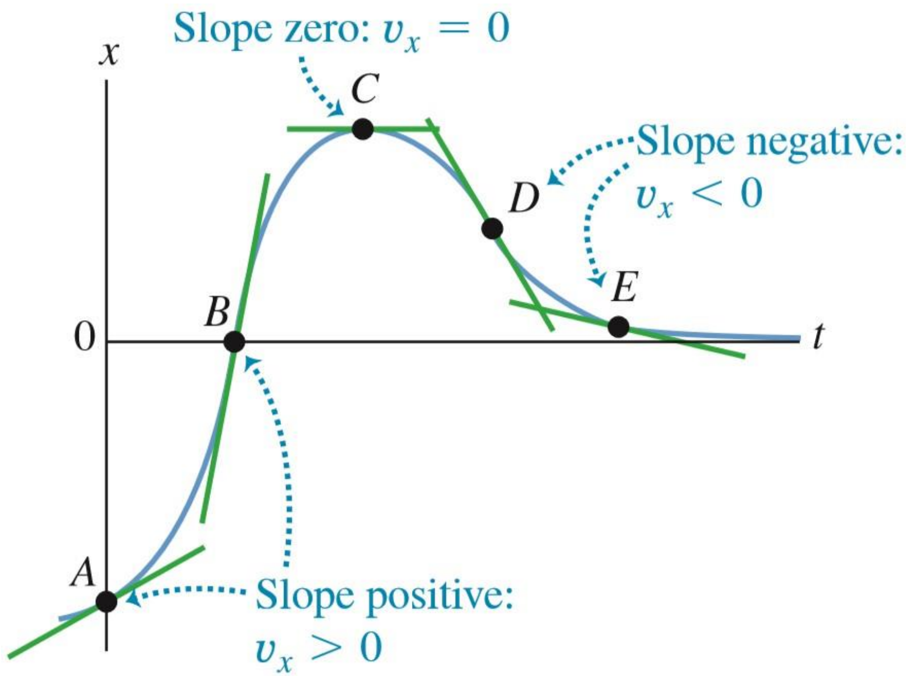
$$v_x = \frac{dx}{dt}.$$

- The instantaneous velocity equals to the limit of the object's average velocity as the time interval approaches zero.



Velocity

- Instantaneous velocity is the derivative of the position function so it can be positive, negative or zero.
- Slope of the tangent line at the object's position



Acceleration

- Changing velocity means an acceleration is present
- Average acceleration is the rate of change of the velocity

$$\bar{a} \equiv \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t_f - t_i}$$

- Units are m/s^2 (SI)
- Similarly, the **instantaneous** acceleration for an object travelling in *x* direction is

$$a_x = \frac{dv_x}{dt} = \frac{d^2x}{dt^2}$$

Equations of Motion

- You can use the below equations (which we will not prove) in situations where acceleration is constant
- If the acceleration, a, is constant these equations are very useful for calculating displacements and velocities

$$v = v_o + at$$

$$s = v_o t + \tfrac{1}{2}at^2$$

$$v^2 = v_o^2 + 2as$$

where: v_o is the initial velocity

v is the final velocity

t is the time interval for the motion

a is the acceleration

s is the displacement

Example 1

A body is moving with an initial velocity of 3.0 m/s. If it has an acceleration of 2.0 m/s^2 in the same direction as its velocity, calculate:

a) the distance travelled by the body in 10 s.

b) the velocity of the body after 10 s.

Example 2

A shot putter launches a shot straight upward with a velocity of 10.0 m/s. Given the point of release is 1.8 m above the ground, determine the time it takes for the shot to return to the ground. (You may assume that the shot putter avoids any collision with the shot)?

Free Fall

- A freely falling object is any object moving freely under the influence of gravity alone
  - Free fall does not depend on the object's original motion
- All objects falling near the Earth's surface fall with a constant acceleration (if air resistance is ignored)
- The acceleration is called the acceleration due to gravity, and indicated by $g = 9.81\ m/s^2$

$$v = v_o + at$$

Ball and feather falling in vacuum

https://www.youtube.com/watch?v=E43-CfukEgs

Acceleration due to Gravity

- Symbolized by g
- $g = 9.81\ m/s^2$
  - When estimating, use $g \approx 10\ m/s^2$
- g is always directed downward
  - Toward the center of the earth

- Ignoring air resistance and assuming g doesn't vary with altitude over short vertical distances, free fall is constantly accelerated motion.

Classical Mechanics

- Describes the relationship between the motion of objects in our everyday world and the forces acting on them
- Conditions when Classical Mechanics does not apply
  - Very tiny objects (< atomic sizes)
  - Objects moving near the speed of light

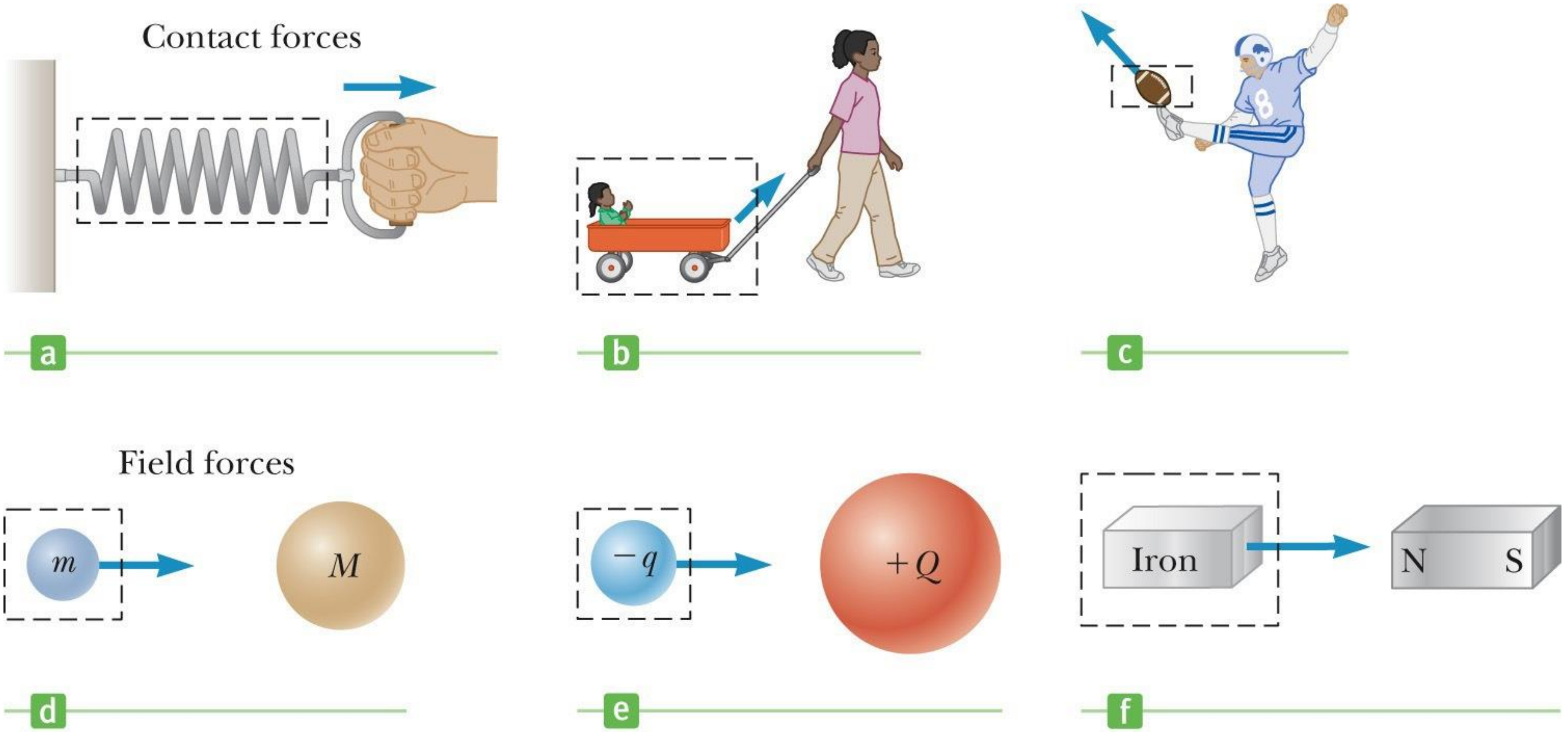
Newton’s Laws

- This section will look at an introduction to Newton’s three laws of motion and his law of gravity.
- These laws are considered among the greatest achievements of the human mind.

Forces in nature

- Commonly imagined as a push or pull on some object
- Forces can put an object into motion or change its direction
- Vector quantity
- May be a **contact force** or a **field force**
  - Contact forces result from physical contact between two objects
  - Field forces act between disconnected objects. An object experiences force without physical contact. Examples are gravitational, electric and magnetic forces.

Contact and Field Forces



Newton's First Law

- An object remains at rest or moves with a constant velocity unless acted on by a net force.
  - The net force is defined as the vector sum of all the external forces exerted on the object

- If forces are balanced on a body, there is no resultant force acting on a body.

Newton's Second Law

- The acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass:
- $F = m.a$
- Or, in vector form:

$$\vec{\mathbf{a}} = \frac{\sum \vec{\mathbf{F}}}{m} \quad or \quad \sum \vec{\mathbf{F}} = m\vec{\mathbf{a}}$$

- This is a simple but powerful relationship between force and acceleration. Essentially the harder we push, the greater is the acceleration.
- Can also be applied three-dimensionally

Example 3

Two forces act on a 3.0 kg body as shown in the diagram below.

i) What is the resultant force on the body?

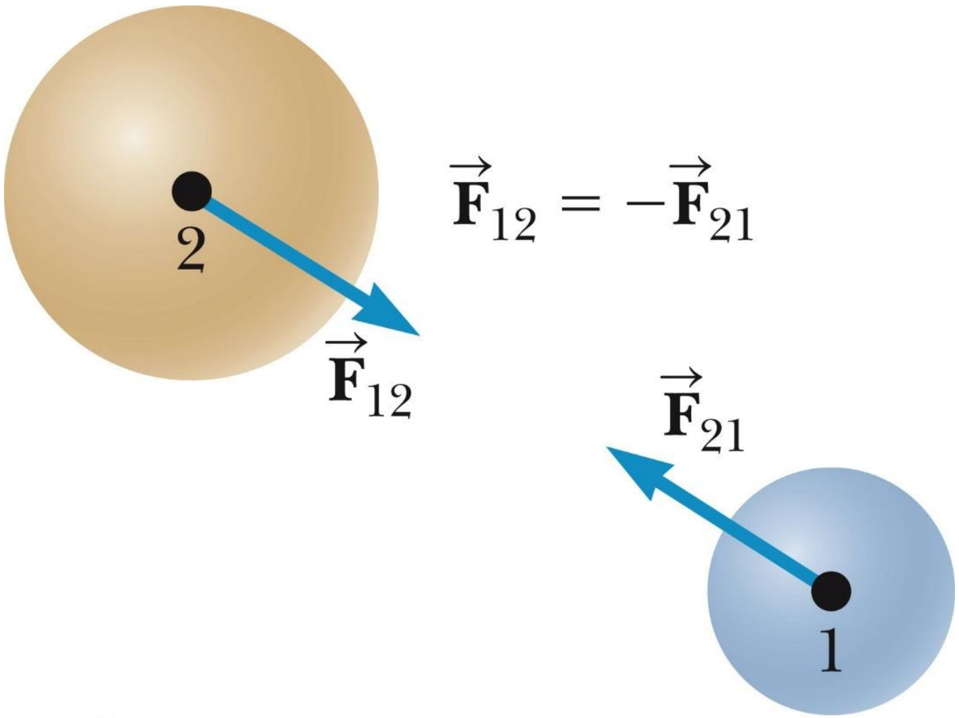
ii) What is the acceleration of the body?

Newton's Third Law

- If object 1 and object 2 interact, the force exerted by object 1 on object 2 is equal in magnitude but opposite in direction to the force exerted by object 2 on object 1.
  - $\vec{\mathbf{F}}_{12} = -\vec{\mathbf{F}}_{21}$
  - Equivalent to saying a single isolated force cannot exist

Newton's Third Law cont.

- F_{12} may be called the *action* force and F_{21} the *reaction* force
  - Actually, either force can be the action or the reaction force
- The action and reaction forces act on **different** objects



Example 4

A car of mass 1200 kg accelerates from rest to 25 m/s in a time span of 10 seconds. Calculate:

i) The acceleration experienced by the car

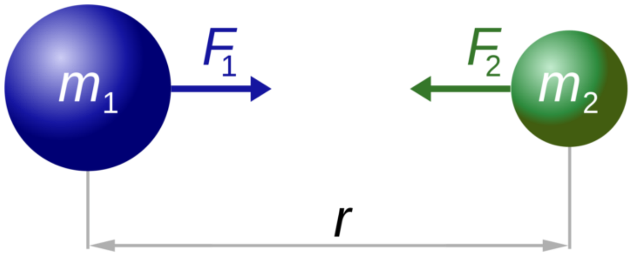
ii) The net force acting on the car during this acceleration

iii) If the force is applied by the car's engine, what is the magnitude of this force?

Gravitational Force

- Mutual force of attraction between any two objects
- Expressed by Newton's Law of Universal Gravitation:
  - Every particle in the Universe attracts every other particle with a force that is directly proportional to the product of the masses of the particles and inversely proportional to the square of the distance between them

$$F_g = G\frac{m_1 m_2}{r^2}$$



In SI units, $G = 6.67 \times 10^{-11}$ N/kg^2.m^2

Weight

- Gravity gives weight to physical objects on Earth. The magnitude of the gravitational force acting on an object of mass *m* near the Earth's surface is called the weight *w* of the object

  $W = m.g$ is a special case of Newton's Second Law

    - g is the acceleration due to gravity, $g = 9.8\ m/s^2$
- g can also be found from the Law of Universal Gravitation

Exercise: A body of mass 6.0 kg is dropped out of a window. What force does the body experience? (ignore air resistance)

Answer: All bodies falling freely close to the Earth's surface experience the same acceleration. That acceleration is directed towards the center of the Earth.

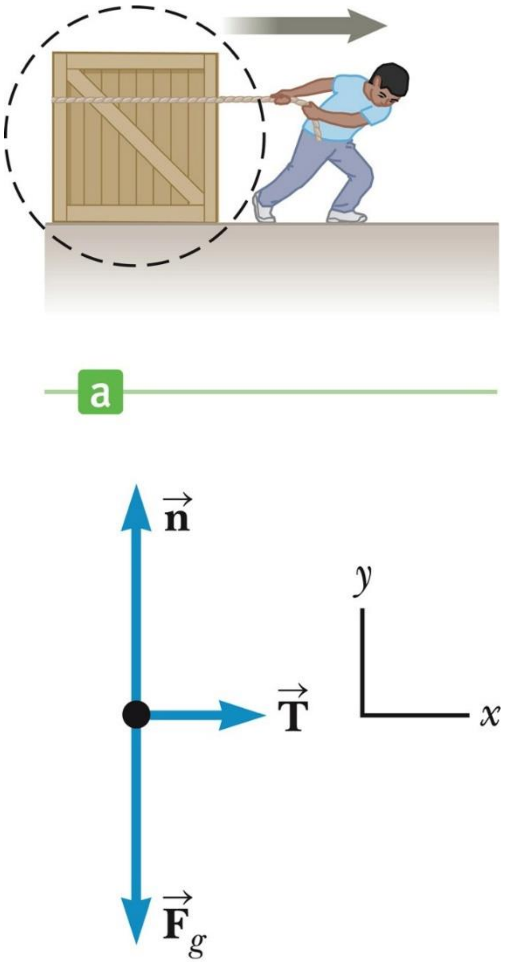
Using $F = W = mg = 6.0 \times 9.8 = 59$ N

Example 5

An object is dropped, with no initial velocity, above the surface of planet Alpha and falls 12.5 m in 3 seconds. The radius of planet Alpha is 6.2×10^6 m. What is the mass of planet Alpha?

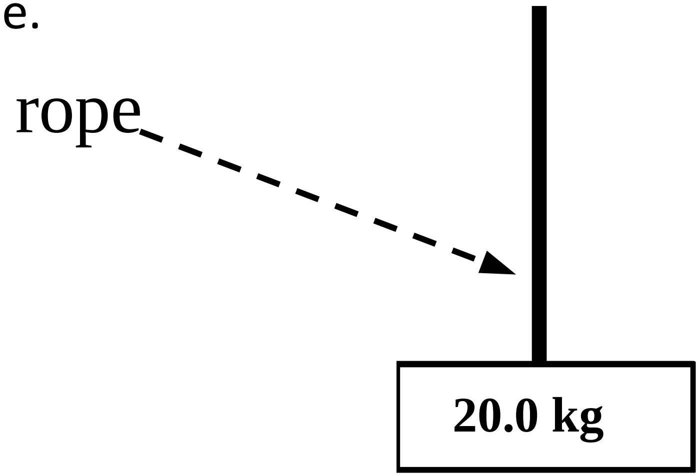
Free-Body Diagram

- A diagram of the forces acting on an object
- Must identify all the forces. If the free body diagram is incorrect, the solution will likely be incorrect.
- The magnitude of force **T** is the tension acting on the box
- $\vec{\mathbf{n}}$ and $\vec{\mathbf{F}}_g$ are the forces exerted by the ground and the Earth, respectively.



Example 6

The tension in the rope shown in the figure below is such that the body accelerates upwards with an acceleration of 1.5 m/s^2. Calculate the value of the tension in the rope.



New concept: Ropes

- The magnitude of the force exerted along the rope is called the **tension**
- If the mass of the rope is ignored, the tension is the same at all points in the rope