Newton's Universe

Classical Mechanics

Ross Dempsey

Department of Physics and Astronomy
Johns Hopkins University

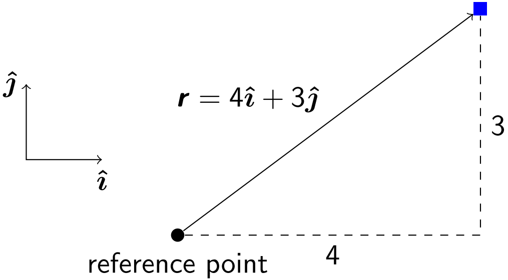
JHU Splash, 2017

Outline

1. Why does the moon stay in orbit?
    - Kinematics
    - Circular Motion
    - Forces
2. Newton's wristwatch
    - Energy
    - Experiment
3. Examples

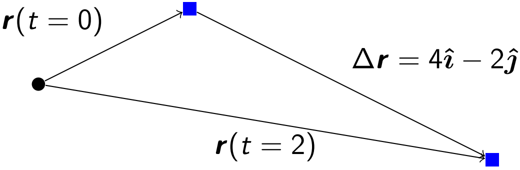
Position

- Position is defined using a reference point and a coordinate system



Velocity

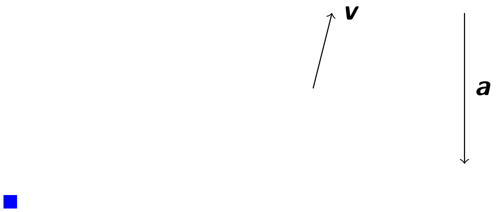
- Velocity is the rate of change of position



$$\boldsymbol{v}_{\text{avg}} = \frac{\Delta \boldsymbol{r}}{\Delta t} = \frac{4\hat{\imath} - 2\hat{\jmath}}{2} = 2\hat{\imath} - \hat{\jmath}$$

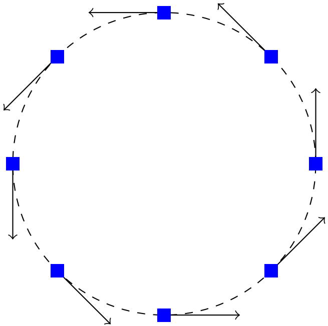
Acceleration

- Acceleration is the rate of change of velocity



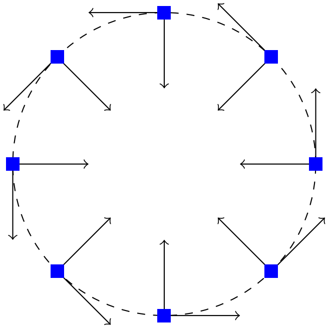
Centripetal and Centrifugal Acceleration

- Velocity changes as an object moves around a circle



Centripetal and Centrifugal Acceleration

- Velocity changes as an object moves around a circle



Computing Centripetal Acceleration

- An object moves with speed v around a circle of radius r

Computing Centripetal Acceleration

- An object moves with speed v around a circle of radius r
- As it rotates, the velocity rotates through a circle of radius v

Computing Centripetal Acceleration

- An object moves with speed v around a circle of radius r
- As it rotates, the velocity rotates through a circle of radius v
- The change in velocity per cycle is $2\pi v$

Computing Centripetal Acceleration

- An object moves with speed v around a circle of radius r
- As it rotates, the velocity rotates through a circle of radius v
- The change in velocity per cycle is $2\pi v$
- The time per cycle is $\frac{2\pi r}{v}$

Computing Centripetal Acceleration

- An object moves with speed v around a circle of radius r
- As it rotates, the velocity rotates through a circle of radius v
- The change in velocity per cycle is $2\pi v$
- The time per cycle is $\frac{2\pi r}{v}$
- The centripetal acceleration is $\frac{\Delta v}{\Delta t} = \frac{v^2}{r}$

Forces

- Forces are physical influences on objects
- Forces come from many different interactions

Forces

- Forces are physical influences on objects
- Forces come from many different interactions
    - Gravitational forces between masses

Forces

- Forces are physical influences on objects
- Forces come from many different interactions
  - Gravitational forces between masses
  - Normal forces keeping objects apart

Forces

- Forces are physical influences on objects
- Forces come from many different interactions
  - Gravitational forces between masses
  - Normal forces keeping objects apart
  - Friction between objects in contact

Forces

- Forces are physical influences on objects
- Forces come from many different interactions
  - Gravitational forces between masses
  - Normal forces keeping objects apart
  - Friction between objects in contact
  - Electrical forces between a balloon and your hair

Newton's Laws

- An object maintains its state of motion unless acted upon by an external force
- Acceleration is proportional to the net force on an object, and inversely proportional to the mass of the object:

$$\boldsymbol{F} = m\boldsymbol{a}.$$

- Objects exert equal and opposite forces on one another:

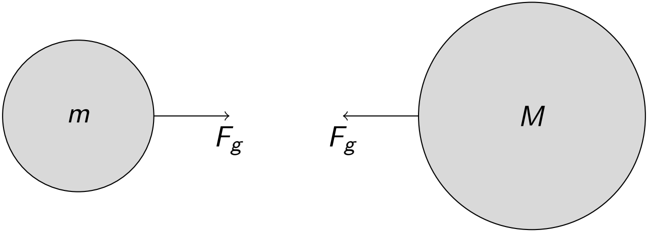
$$\boldsymbol{F}_{a \to b} = -\boldsymbol{F}_{b \to a}.$$

Universal Gravitation

- The force of gravity between two objects depends on their masses and the distance:

$$F_g = -\frac{GMm}{r^2}.$$

- The constant G is a fundamental physical constant

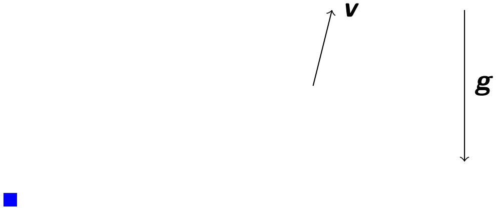


Gravity on Earth

- Compare Newton's second law with the law of universal gravitation:

$$F = ma$$
$$F_g = m\frac{GM}{r^2}$$

- The acceleration of gravity is $g = \frac{GM}{r^2} \approx 9.8\,\mathrm{m/s^2}$ on Earth



Moon Calculations

Gravity

- $G = 6.67 \times 10^{-11}$
- $M = 5.97 \times 10^{24}$
- $r = 3.84 \times 10^{8}$
- Find gravitational acceleration $\frac{GM}{r^2}$

Centripetal Acceleration

- $v = 1.02 \times 10^{3}$
- $r = 3.84 \times 10^{8}$
- Find centripetal acceleration $\frac{v^2}{r}$

Moon Calculations

Gravity

- $G = 6.67 \times 10^{-11}$
- $M = 5.97 \times 10^{24}$
- $r = 3.84 \times 10^{8}$
- Find gravitational acceleration $\frac{GM}{r^2}$
- **Answer:** 2.7×10^{-3}

Centripetal Acceleration

- $v = 1.02 \times 10^{3}$
- $r = 3.84 \times 10^{8}$
- Find centripetal acceleration $\frac{v^2}{r}$
- **Answer:** 2.7×10^{-3}

Freefall

Pendulums

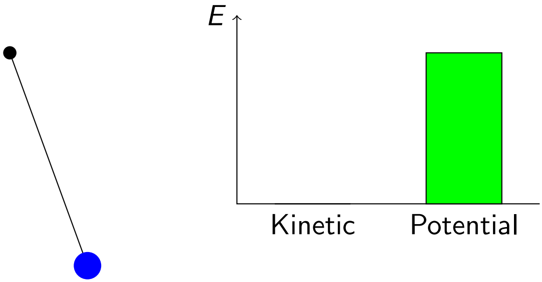
- "the marvelous property of the pendulum, which is that it makes all its vibrations, large or small, in equal times" – Galileo Galilei
- This property is common, and called *simple harmonic oscillation*

Energy

- Two kinds of energy: *kinetic* and *potential*
- Kinetic energy: energy of motion, depends on v
- Potential energy: energy of position, depends on x

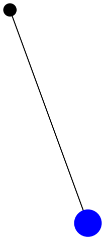
Energy in Pendulums

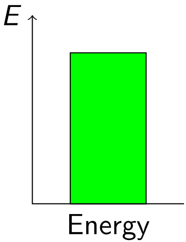
- Pendulums exchange energy between kinetic and potential



Conservation of Energy

- The total energy remains constant





Experiment: Pendulum Period

- The pendulum must swing at a particular rate to conserve energy
- To find the period, let the pendulum swing 10 times back and forth and divide by 10

	20 cm	40 cm	60 cm
Mass 1			
Mass 2			

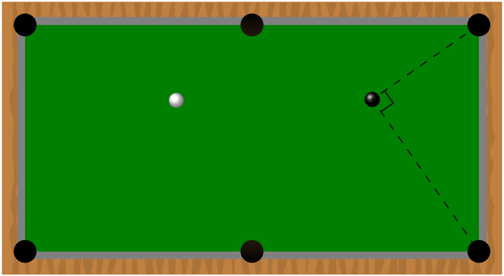
Experiment: Pendulum Period

- The pendulum must swing at a particular rate to conserve energy
- To find the period, let the pendulum swing 10 times back and forth and divide by 10

	20 cm	40 cm	60 cm
Mass 1	0.9 s	1.3 s	1.6 s
Mass 2	0.9 s	1.3 s	1.6 s

Will I Scratch?

- Conservation of momentum requires that billiard balls ricochet at a 90° angle
- You can use this to determine whether the cue ball will reach a pocket



Gravity Train

- A mass falling through a hole in the Earth behaves like a pendulum
- Ignoring extreme temperatures, air drag, etc., the mass would reach the other end in 42 minutes

Foucault Pendulum

- Newton's laws are modified when working in an accelerating frame such as the Earth
- There is an additional *Coriolis force*
- The Coriolis force causes a pendulum to precess

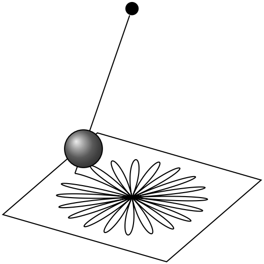


Image credit: Balasubramanian & Dempsey, Mechanics: An Extended Introduction (2016)