Physics 111: Mechanics
Lecture 14

Bin Chen

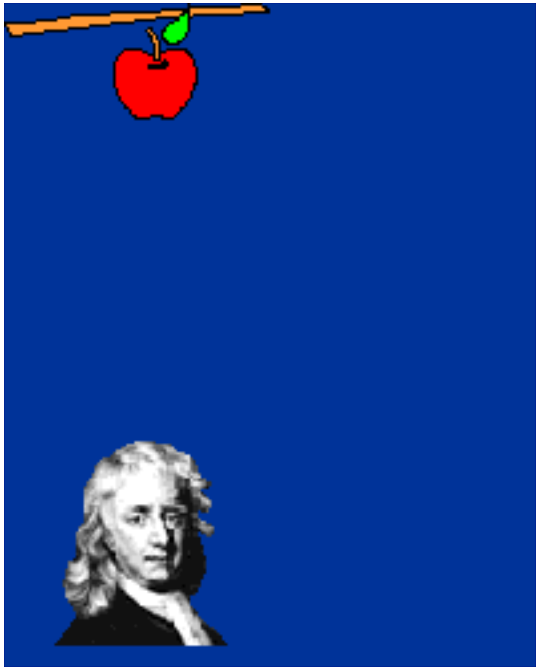
NJIT Physics Department

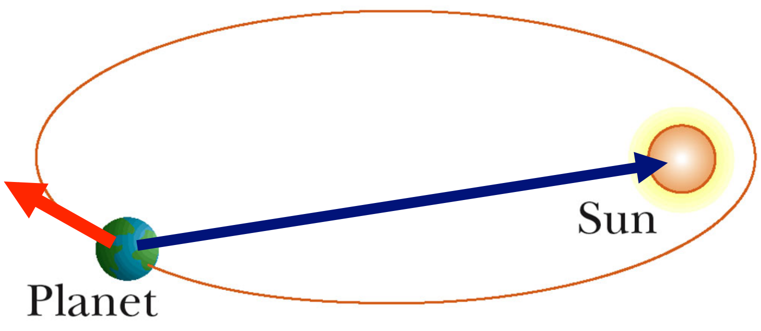
Chapter 13 Gravitation

- 13.1 Newton's Law of Gravitation
- 13.2 Weight
- 13.3 Gravitational Potential Energy
- 13.4 The Motion of Satellites
- 13.5 *Kepler's Law and Motion of Planets
- 13.6* Spherical Mass Distributions
- 13.7* Apparent Weight and the Earth's Rotation
- 13.8* Black Holes

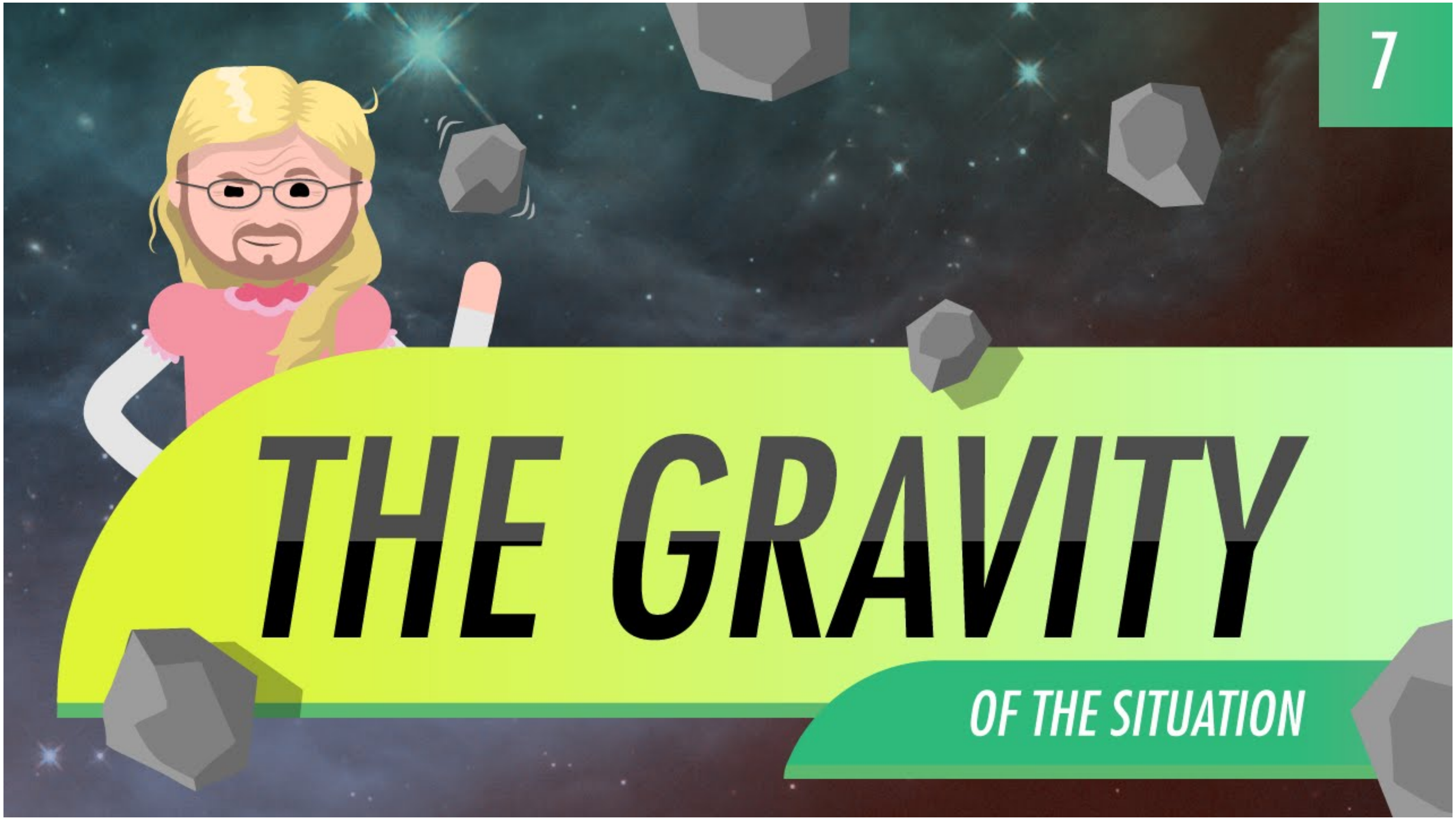
Newton's Law of Universal Gravitation

- The apple was attracted to the Earth
- All objects in the Universe were attracted to each other in the same way the apple was attracted to the Earth
- The force law governing the motion of planets was the same as the force law that attracted a falling apple the Earth





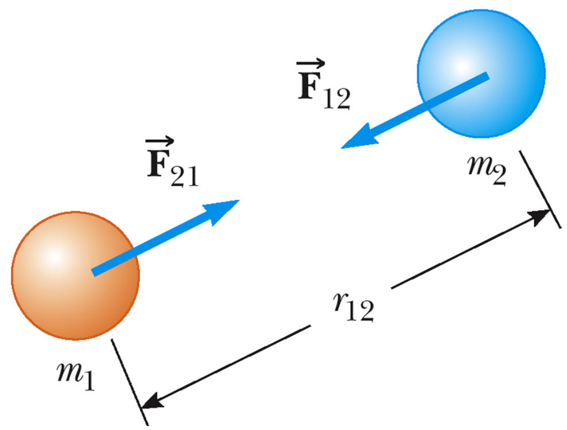
Phil Plait's Crash Course on Gravity



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 and inversely proportional to the square of the distance between them.

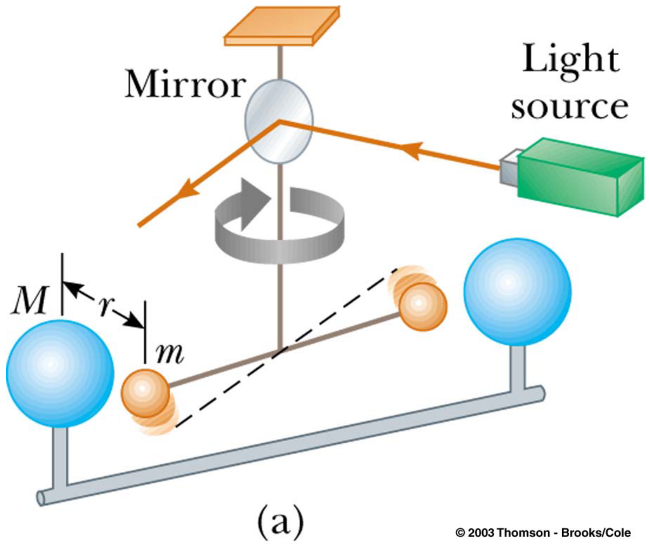
$$F = G\frac{m_1 m_2}{r^2}$$



Universal Gravitation

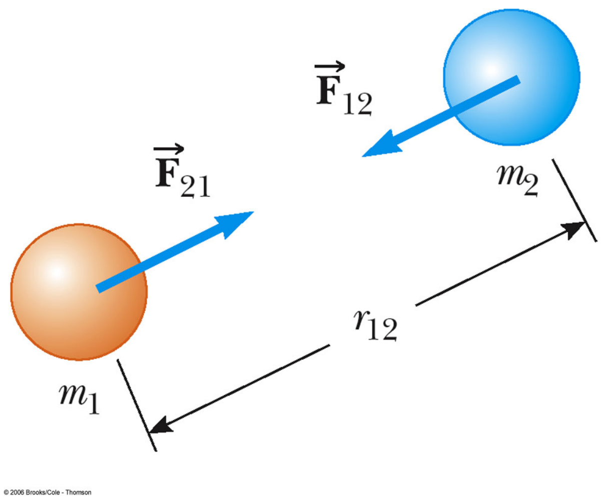
- G is the constant of universal gravitation
- $G = 6.673 \times 10^{-11}$ N m² /kg²
- This is an example of an *inverse square law*
- Determined experimentally
- Henry Cavendish in 1798

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



Universal Gravitation

- The force that mass 1 exerts on mass 2 is equal and opposite to the force mass 2 exerts on mass 1
- The forces form a Newton's third law action-reaction



- The gravitational force exerted by a uniform sphere on a particle outside the sphere is the same as the force exerted if the entire mass of the sphere were concentrated on its center

Gravitational force

- A ball falls to the ground. Which of the following statements is **not** true?

A) The force that the ball exerts on Earth is equal in magnitude to the force that Earth exert on the ball

B) The force that the ball exerts on Earth is opposite in direction to the force that Earth exert on the ball

C) The ball undergoes a larger acceleration than the Earth

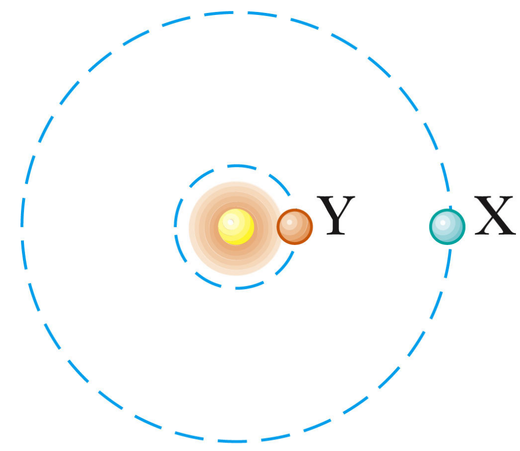
D) Earth pulls much harder on the ball than the ball pulls on Earth, so the ball falls while Earth remains at rest

Gravitational Force

- A planet has two moons of equal mass. Moon Y is in a circular orbit of radius r. Moon X is in a circular orbit of radius 2r. The magnitude of the gravitational force exerted by the planet on Moon X is

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

A) Four times as large as that on Moon Y
B) Twice as large as that on Moon Y
C) Equal to that on Moon Y
D) Half as large as that on Moon Y
E) one-fourth as large as that on Moon Y



(a)

Free-Fall Acceleration and Gravitational Force

- Consider an object of mass m near the Earth's surface

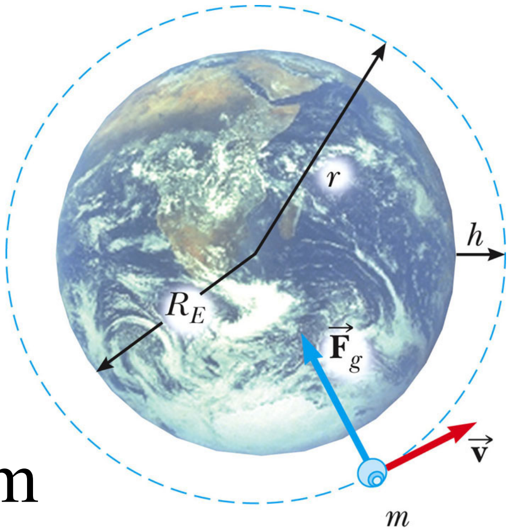
$$F = G\frac{m_1 m_2}{r^2} = G\frac{mM_E}{R_E^{\ 2}}$$

- Acceleration a_g due to gravity

$$F = G\frac{mM_E}{R_E^{\ 2}} = ma_g$$

- Since

$$M_E = 5.9742\times10^{23}\ \text{kg} \quad R_E = 6378.1\,\text{km}$$



- Near the Earth's surface

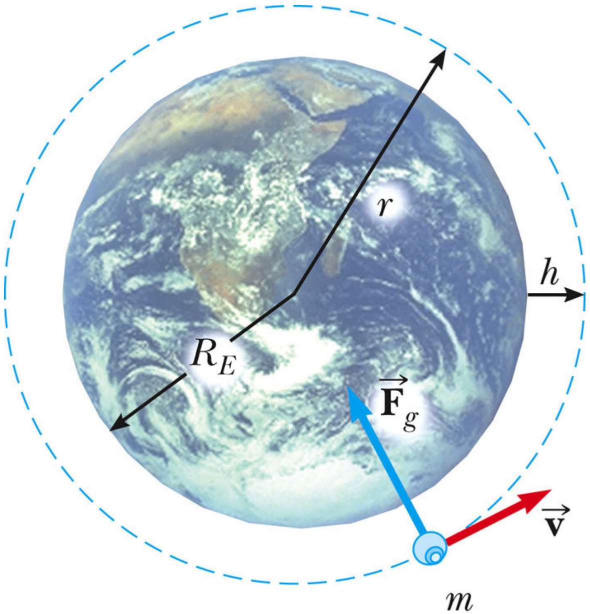
$$a_g = G\frac{M_E}{R_E^2} = 9.8\ \text{m/s}^2$$

- a_g also known as ***gravitational field***, which depends on not only the **massive object**, but also the **location**.

Free-Fall Acceleration and the Gravitational Force

- Consider an object of mass m at a height h above the Earth's surface

$$F = G\frac{m_1 m_2}{r^2} = G\frac{mM_E}{(R_E + h)^2}$$



- Acceleration a_g due to gravity

$$F = G\frac{mM_E}{R_E^{\,2}} = ma_g$$

- a_g will vary with altitude

$$a_g = G\frac{M_E}{(R_E + h)^2}$$

Free-Fall Acceleration

- Superman stands on top of a very tall mountain and throws a baseball horizontally with a speed such that the baseball goes into a circular orbit around the Earth. While the baseball is in orbit, what is the magnitude of the acceleration of the ball?

$$a_g = G\frac{M_E}{(R_E + h)^2}$$

A) It depends on how fast the baseball is thrown.

B) It is zero because the ball does not fall to the ground

C) It is slightly less than 9.80 m/s^2

D) It is equal to 9.80 m/s^2

E) It is slightly larger than 9.80 m/s^2

Variation of *g* with Altitude

TABLE 7.1

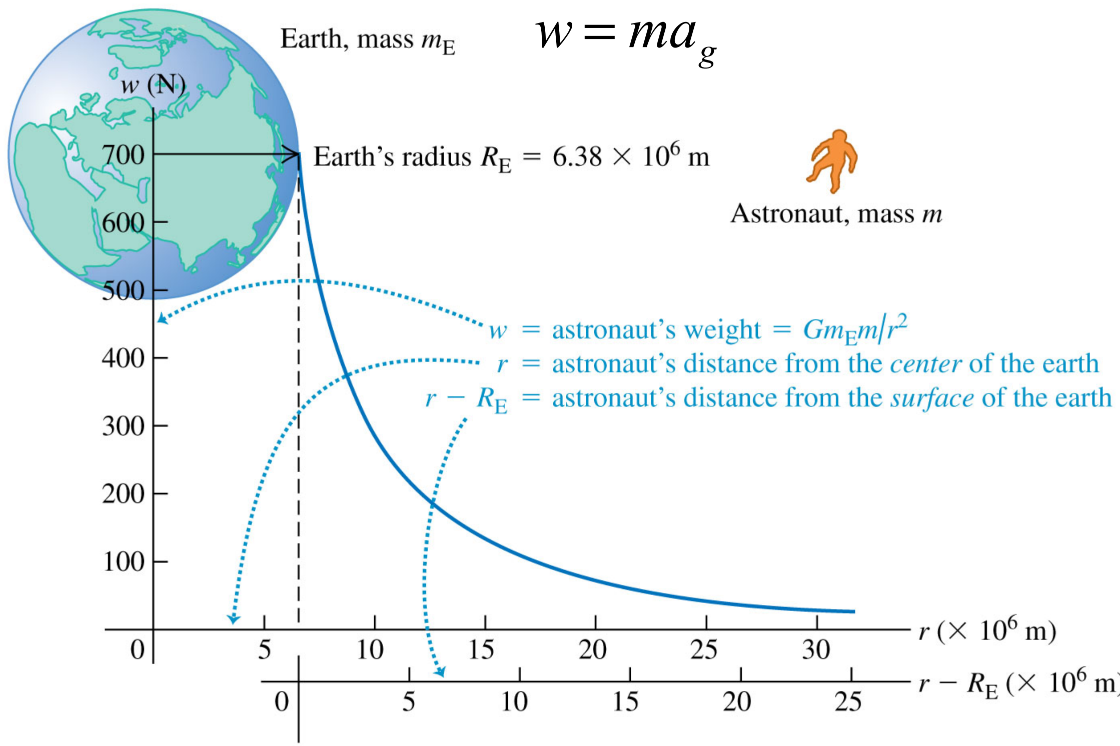
Free-Fall Acceleration *g* at Various Altitudes

Altitude (km)[a]	g (m/s^2)
1 000	7.33
2 000	5.68
3 000	4.53
4 000	3.70
5 000	3.08
6 000	2.60
7 000	2.23
8 000	1.93
9 000	1.69
10 000	1.49
50 000	0.13

[a]All figures are distances above Earth's surface.

$$a_g = G\frac{M_E}{r^2} = G\frac{M_E}{(R_E+h)^2}$$

$$w = ma_g$$



Astronaut in Orbit

- I weigh 600 N on the surface of the earth. If I travel on a space shuttle orbiting at a distance of 3 times the Earth's radius above ground. What is my mass in kg at the space shuttle?

a. 37.5 b. 150 c. 15.0 d. 3.83 e. 61.2

Mass is an intrinsic measure of the object, and does not change with distance!

Astronauts in Orbit

- Have you heard this claim:
  - Astronauts are weightless in space, therefore there is no gravity in space?
- It is true that if an astronaut on the International Space Station (ISS) tries to step on a scale, he/she will weigh nothing.
- It may seem reasonable to think that if $\text{weight} = mg$, since $\text{weight} = 0$, $g = 0$, but this is NOT true.
- If you stand on a scale in an elevator and then the cables are cut, you will also weigh nothing ($ma = N - mg$, but in free-fall $a = g$, so the normal force $N = 0$). This does not mean $g = 0$!
- Astronauts in orbit are in free-fall around the Earth, just as you would be in the elevator. They do not fall to Earth, only because of their very high tangential speed.

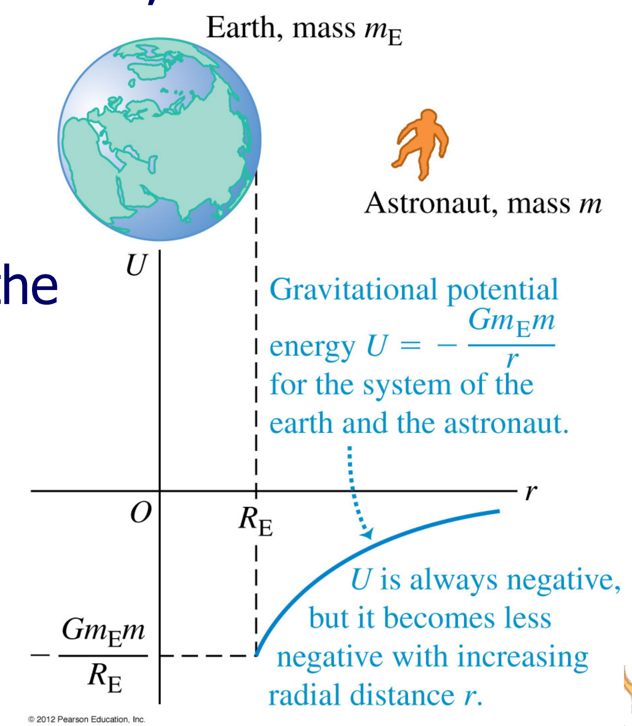
Gravitational Potential Energy

- $U = mgy$ is valid only near the earth's surface
- For objects high above the earth's surface, an alternate expression is needed

$$U = -G\frac{M_E m}{r}$$

  - Zero reference level is infinitely far from the earth, so potential energy is everywhere negative!
- Energy conservation

$$E = K + U = \frac{1}{2}mv^2 - G\frac{M_E m}{r}$$



Escape Speed

- The escape speed is the spee object to soar off into space a

$$E = K + U = \frac{1}{2}mv^2 - G\frac{M_E m}{r} = 0$$

- For the earth, v_{esc} is about 11.
- Note, v is independent of the object

$$v_{esc} = \sqrt{\frac{2GM_E}{R_E}}$$

TABLE 7.2

Escape Speeds for the Planets and the Moon

Planet	v_e (km/s)
Mercury	4.3
Venus	10.3
Earth	11.2
Moon	2.3
Mars	5.0
Jupiter	60.0
Saturn	36.0
Uranus	22.0
Neptune	24.0
Pluto	1.1