

The background features a dark blue gradient with a starry pattern. On the left side, there are several overlapping circular elements. A prominent one is a large scale with tick marks and numbers ranging from 140 to 260. Other circles contain curved arrows, suggesting motion or rotation. The overall aesthetic is scientific and technical.

# NEWTON'S LAW OF UNIVERSAL GRAVITATION

PES 1000 – PHYSICS IN EVERYDAY LIFE

# NEWTON'S APPLE AND THE MOON

- Isaac Newton, while in a friend's apple orchard, observed an apple falling, and also the moon in orbit, and concluded that they were both under the same gravitational influence
- He knew some basic facts about the moon:
  - Period (1 month)
  - Approximate distance (60 Earth radii)
  - Speed of the moon (circumference of the orbit divided by period,  $d \div t$ )



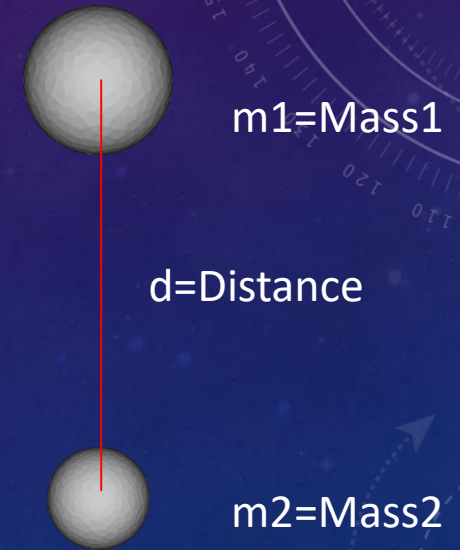
# NEWTON'S APPLE AND THE MOON

- He knew that gravity accelerates objects toward Earth:
  - Apple near the surface:  $g = 9.81 \text{ m/s}^2$
  - Moon far from Earth:  $g = ?$
- He had his second law of motion:  $F = m \cdot a$
- He knew centripetal acceleration is related to speed and radius:  $a_{\text{cent}} = v^2 / r$
- He wanted a gravitational force formula that worked both near and far from Earth



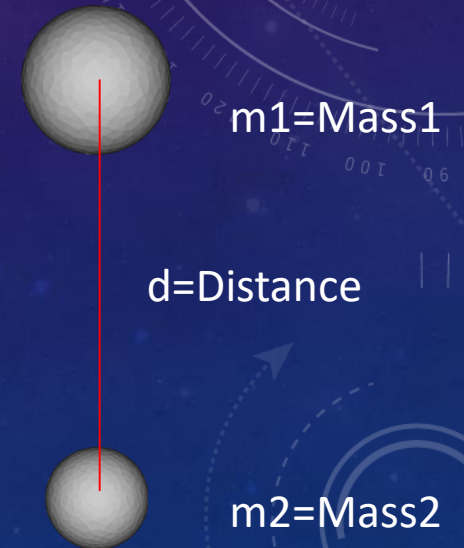
# THE UNIVERSAL LAW OF GRAVITY

- Newton supposed that the force of gravity depended on these quantities:
  - **Mass of object 1** (the Earth in his problem)
  - **Mass of object 2** (the apple or the moon in his problem)
  - The **distance between the centers** of the objects (the radius of the Earth for the apple and the radius of the moon's orbit for the moon)



# THE UNIVERSAL LAW OF GRAVITY

- He tried various relationships and came to the following conclusion:
  - Gravitational force is proportional to both mass 1 and mass 2, and **inversely proportional to the square of the distance between them**. **Double** the distance and the gravitational force is **quartered**.
  - The equation is:  $F_G = \frac{G*m1*m2}{d^2}$
  - G is the Universal Gravity constant, which makes the units come out right. Its value is  $G = 6.67 \times 10^{-11} \text{ N*m}^2/\text{kg}^2$
  - The smallness of G means that it takes a huge mass to cause any significant force.



# CHECKING THE LAW WITH THE APPLE AND THE MOON

- Newton knew that the mass of the falling/orbiting object didn't matter, if drag is ignored.
  - Both the moon and the apple are accelerated toward the Earth by gravity
  - He knew the apple's acceleration (**9.81 m/s<sup>2</sup>**)
- Newton knew this about the Moon:
  - The Moon is 60 times as far from Earth's center as the apple is from the Earth's center.
  - So the moon's centripetal acceleration (if his law was correct) should be **1/60<sup>2</sup>** that of the apple.
  - He knew from his Moon facts that  $a_{\text{cent\_moon}} = \mathbf{9.81/3600 \text{ m/s}^2}$
  - The law ( $F_G = \frac{G*m*M}{d^2}$ ) checked out!
- The values of G and M (mass of the Earth) were determined later (by Cavendish)
  - Note: he **doesn't need to know the mass of the moon** for his calculation.
- The Universal Law is true at all scales throughout the universe (solar system, galaxy, galactic clusters)



# SURFACE GRAVITY ON A PLANET

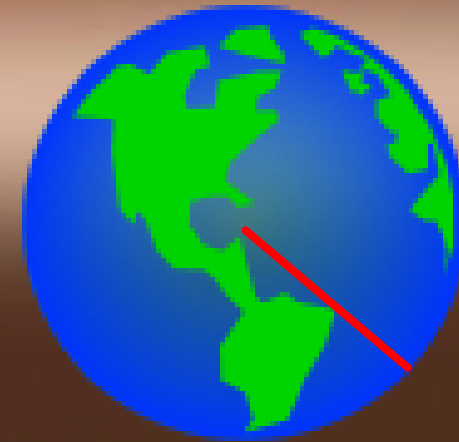
- The acceleration of a falling object near the surface of Earth can be obtained from Newton's Law of Universal Gravitation

- $d = \text{radius of Earth} = 6378136 \text{ m}$

- $M = 5.98 \times 10^{24} \text{ kg}$

- $G = 6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2 / \text{kg}^2$

- $g = F_G / m = \frac{G \cdot M}{d^2} = 9.81 \text{ m/s}^2$



d=Distance=radius

- We can apply this to any astronomical body:

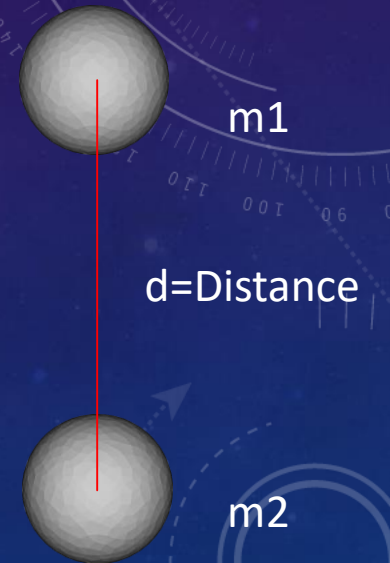
- Moon:  $M = 1/80$  mass of Earth,  $d = 1/5$  radius of Earth, so  $g = 1/6$  of Earth's

- Jupiter:  $318 \cdot$  Earth mass,  $11 \cdot$  Earth radius  $\rightarrow 2.1 \cdot$  Earth's gravity (1 Earth Gravity = 1 Gee)



# GRAVITATIONAL FORCE BETWEEN TWO OBJECTS

- Two large, spherical objects are brought near each other. What is the amount of gravitational attraction between them?
  - Let's assume they are both made of lead. If the spheres are **1 meter** in diameter, each mass would be **5940 kg**.
  - If we place their centers **1 meter** apart, then the law of gravity would be:
  - $F_G = \frac{G*m_1*m_2}{d^2} = \frac{G*5940*5940}{1^2} = G * 35283600$
  - But remember, G is very small! So the total force is only  **$F_G = 0.0024 \text{ N}$**  !
    - This is the weight of 1/10 of a penny!



# GRAVITATIONAL FORCE BETWEEN TWO OBJECTS

- Earth/Moon example

- $F_{Earth\ on\ Moon} = \frac{G * EarthMass * MoonMass}{d^2}$

- $= \frac{G * MoonMass * EarthMass}{d^2} = F_{Moon\ on\ Earth}$

- Forces are equal and opposite (Newton's 3<sup>rd</sup> Law), but acceleration effects are not.
- The Moon accelerates more for the same force because it has less mass (Newton's 2<sup>nd</sup> Law).
  - Both Earth and Moon orbit a common center of mass (which is within the Earth), but the Moon's orbit is larger in size.



# GRAVITATIONAL FORCE SIMULATION

- Link to simulation: [https://phet.colorado.edu/sims/html/gravity-force-lab/latest/gravity-force-lab\\_en.html](https://phet.colorado.edu/sims/html/gravity-force-lab/latest/gravity-force-lab_en.html)
- Some things to try:
  - Double mass one and/or mass two. Look at how the force changes
  - Move the distance to half and note the change in the force
  - Try to make the force as big as you can make it. What did you have to do?

The screenshot shows the Gravity Force Lab 2.0.3 simulation in a Mozilla Firefox browser window. The interface includes a ruler at the bottom with a scale from 0 to 10 meters. Two masses, m1 (blue) and m2 (red), are positioned on the ruler. m1 is at approximately 3.5 meters and m2 is at approximately 7.5 meters. Two human figures are standing on either side of the masses, holding them. Above the masses, two force vectors are shown: a blue arrow pointing up from m1 labeled "Force on m1 by m2 = 0.000 000 041 712 N" and a red arrow pointing up from m2 labeled "Force on m2 by m1 = 0.000 000 041 712 N". Below the ruler, there are two control panels for "Mass 1" and "Mass 2". The "Mass 1" panel has a slider set to 50 kg and a "1" button. The "Mass 2" panel has a slider set to 200 kg and a "1" button. To the right of these panels are two checkboxes: "Show Values" (checked) and "Constant Radius" (unchecked). A "Reset" button is located at the bottom right of the control area. The PhET logo is visible in the bottom right corner of the simulation window.

# CONCLUSION

- Newton's Law of Universal Gravity relates the **masses** of two objects and their separation **distance** to the force of gravity between them.
- Force **increases with more mass**, and **decreases with the square of the distance** between them.
- The **Universal Gravitational constant**,  $G$ , is very small, and requires a large mass to have any significant effect.
- This law applies between any two objects in the universe, regardless of scale.