Gravitational Force

Unit: Forces in One Dimension

NGSS Standards/MA Curriculum Frameworks (2016): HS-PS2-10(MA)

AP® Physics 1 Learning Objectives/Essential Knowledge (2024): 2.6.A, 2.6.A.1, 2.6.A.1.i, 2.6.A.1.ii, 2.6.A.1.iii, 2.6.A.2, 2.6.A.2.i, 2.6.A.2.ii, 2.6.A.3, 2.6.B, 2.6.B.1, 2.6.B.2, 2.6.C, 2.6.C.1, 2.6.C.2, 2.6.C.3, 2.6.C.4, 2.6.D, 2.6.D.1, 2.6.D.2, 2.6.D.3

Mastery Objective(s): (Students will be able to…)

- Explain gravity as a force field that acts on objects with mass.

Success Criteria:

- Explanation accounts for all terms in the field equation $\vec{F}_g = m\vec{g}$.

Language Objectives:

- Explain the concept of a force field that acts on objects with a certain property.

Tier 2 Vocabulary: gravity, force field

Labs, Activities & Demonstrations:

- Miscellaneous falling objects

Notes:

<u>weight</u>: the gravitational force acting on an object.

The gravitational force is an attractive force between objects that have mass. (This is caused by the action of a theoretical sub-atomic particle called a graviton mediating an interaction among Higgs bosons.) The amount of gravitational force between any two objects with mass can be calculated using the equation:

$$F_g = \frac{Gm_1m_2}{r^2}$$

where:

$F_g =$ gravitational force (N)

$G =$ universal gravitational constant $= 6.67\times10^{-11}\ \frac{\text{N}\cdot\text{m}^2}{\text{kg}^2}$

$m_1 =$ mass of object #1 (kg)

$m_2 =$ mass of object #2 (kg)

$r =$ distance between the objects (m)

Use this space for summary and/or additional notes:

In this equation, suppose object #1 is the Earth and object #2 is some other object that has mass. This means m_1 is the mass of the Earth, m_2 is the mass of the object in question, and *r* is the distance from the center of the Earth* to the surface of the Earth, which means *r* is the radius of the Earth. The gravitation equation is therefore:

$$F_g = \frac{Gm_1 m_2}{r^2} = \frac{Gm_{Earth} m_{object}}{r^2_{Earth}}$$

Gravitational Field

On the surface of the Earth, we can model the gravitational force as a force field.

<u>force field</u>: a region in which a force acts upon objects or that have some particular characteristic or property.

The strength of this force field is based on the gravitational constant *G*, the mass of the Earth and the radius of the Earth. Because those values are all constant in any small region (within a few miles) on the surface of the Earth, we can combine them into a single constant, *g*:

$$g = \frac{Gm_{Earth}}{r^2_{Earth}} \quad \text{which means} \quad F_g = \frac{Gm_{Earth} m_{object}}{r^2_{Earth}} = gm_{object}$$

We can rewrite this equation, replacing m_{object} with just *m*. Also, because force is a vector and the force of gravity on an object is toward the other object (in this case, toward the center of mass of the Earth), we can write the equation in the following format:

$$\vec{\boldsymbol{F}}_g = m\vec{\boldsymbol{g}}$$

At different points on the surface of the Earth, the value of $\vec{\boldsymbol{g}}$ varies from approximately $9.76\,\frac{\text{N}}{\text{kg}}$ to $9.83\,\frac{\text{N}}{\text{kg}}$. In this course, unless otherwise noted, ***we will use the approximation that*** $\vec{\boldsymbol{g}} = 10\,\frac{\text{N}}{\text{kg}}$ ***.***

Don't worry about the equation for gravitation at this point—that concept and equation will be discussed further in the section on *Universal Gravitation,* starting on page 400. The equation $\vec{\boldsymbol{F}}_g = m\vec{\boldsymbol{g}}$ will be sufficient for the gravitational force in this unit.

* This should be the ***center of mass*** of the Earth. For the purposes of this section, we will assume that the Earth's center of mass is in its physical center.

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Other types of force fields include electric fields, in which an electric force acts on all objects that have electric charge, and magnetic fields, in which a magnetic force acts on all objects that have magnetic susceptibility (the property that causes them to be attracted to or repelled by a magnet).

Units for Force Fields

The equation for the force due to any force field is that the force equals the quantity that the field acts on times the strength of the field:

$$\vec{F}_g = m \vec{g}$$

- $\vec{F}_g$: force
- m: quantity that the field acts on
- $\vec{g}$: strength of field

Because force is measured in newtons, the unit for a force field must therefore be newtons divided by the unit for the quantity that the force acts on. This means that the unit for $\vec{g}$ must be $\frac{\text{N}}{\text{kg}}$. Note that $1\frac{\text{N}}{\text{kg}} \equiv 1\frac{\text{m}}{\text{s}^2}$, *i.e.,* the unit $\frac{\text{N}}{\text{kg}}$ is mathematically equivalent to the unit $\frac{\text{m}}{\text{s}^2}$. Thus, a gravitational field of $10\frac{\text{N}}{\text{kg}}$ produces an acceleration of $10\frac{\text{m}}{\text{s}^2}$.

In physics, we use $\vec{g}$ to represent ***both*** the strength of the gravitational force near the surface of the Earth (in $\frac{\text{N}}{\text{kg}}$) ***and*** the acceleration due to gravity near the surface of the Earth (in $\frac{\text{m}}{\text{s}^2}$). Therefore, what $\vec{g}$ actually means *and the units used for it* depend on context!

Sample Problem:

Q: What is the weight of (*i.e.,* the force of gravity acting on) a 7 kg block?

A: weight = $\vec{F}_g = m\vec{g} = (7)(10) = 70\,\text{N}$

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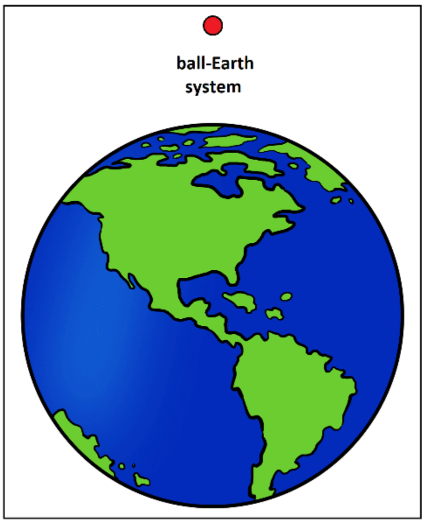
Force Fields and Systems

For the purposes of this course, we usually think of a force field as external to a system, which means the field can be considered to act on the system as a whole, as well as every component of the system that the field acts upon. (In the case of the gravitational field, this means every component of the system that has mass.)

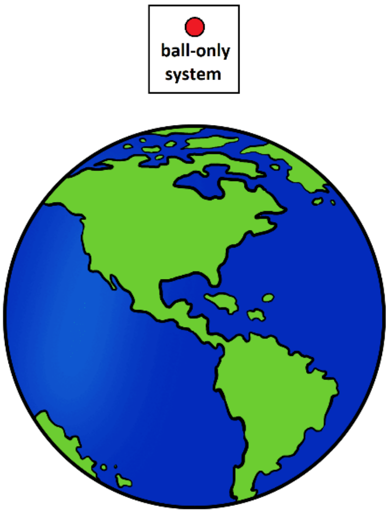
When we define a system of objects in order to make a situation or problem easier to understand (see *Systems* on page 264), the system can either include or exclude the Earth. This means that we would only use the force field definition for a single object or for a system that does not include the Earth.

If the system includes the Earth, we need to consider the gravitational force to be a force between two objects, one of which is the Earth.



two objects (one of which is Earth)

$$F_g = \frac{Gm_{Earth}m_{object}}{r^2_{Earth}} = mg$$



gravitational field

$$F_g = mg$$

Note that the gravitational force is the same no matter which way we calculate it. This is important—the strength of the gravitational force cannot depend on how we choose to look at it!

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Apparent Weight and g-Forces

<u>apparent weight</u>: the magnitude of the normal force on a system

It may surprise you to learn that you cannot feel the force of gravity. When you pick up an object and "feel" its weight, what you are actually feeling is the normal force that you have to apply to it.

However, the normal force is not always the same as the object's weight. Some examples:

- If you are standing on the bottom of a swimming pool, the buoyant force from the water is partially holding you up, so your apparent weight (what it "feels" like you weigh) is the net force that results from your weight combined with buoyant force.

  $$\vec{\boldsymbol{W}}_{app} = \vec{\boldsymbol{F}}_g + \vec{\boldsymbol{F}}_b$$

  Note that the forces are vectors. The vectors are mathematically added, but they will have opposite signs because they are in opposite directions.
- If you are riding on a roller coaster with a vertical drop, your apparent weight drops to zero (you feel weightless) because you and the roller coaster are accelerating downwards at the same rate, so there is no normal force from the roller coaster holding you up.
- If you're riding in an elevator, your apparent weight increases when the elevator accelerates upwards and decreases when the elevator accelerates downwards.

Apparent weight is often described in terms of "g-force". The "g-force" represents the apparent weight as a fraction/multiple of Earth's gravity. A force of 1 g is equivalent to the $10\,\frac{\text{N}}{\text{kg}}$ force of gravity near the surface of the Earth.

$$g \text{ force} = \frac{F_N}{F_g}$$

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Vertical Frame of Reference Accelerations*

g-force	Description
−5	limit of sustained human tolerance
−2	severe blood congestion; throbbing headache; reddening of vision (redout)
−1	congestion of blood in head
0	free fall; orbit (apparent weightlessness)
+⅙	surface of the moon (not accelerating)
+⅓	surface of Mars (not accelerating)
+1	surface of the Earth (not accelerating)
+4.5	roller coaster maximum at bottom of first dip
+3.4–4.8	partial loss of vision (grayout)
+3.9−5.5	complete loss of vision (blackout)
+4.5−6.3	loss of consciousness for most people

Horizontal Frame of Reference Accelerations*

g-force	Description
0	at rest or moving at constant velocity
0.4	maximum acceleration of typical American car
0.8	maximum acceleration in a high-performance sports car
2	"Extreme Launch" roller coaster at start
3	space shuttle, maximum at takeoff
8	limit of sustained human tolerance
60	chest acceleration limit during car crash at 30 mph with airbag
3400	impact acceleration limit of "black box" flight data recorder

* Data are from the Physics Hypertextbook, https://physics.info

Use this space for summary and/or additional notes: