Celestial Orbits

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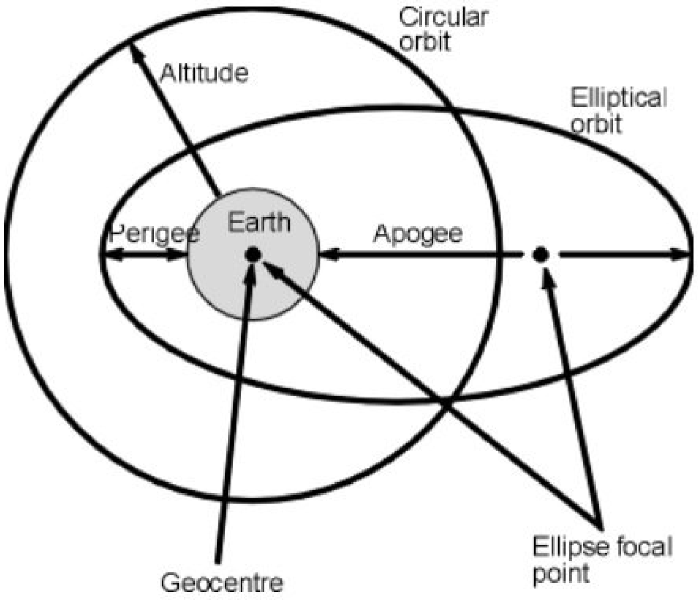
Large Millimeter Telescope Alfonso Serrano, July 2018



Satellite orbits

https://www.radio-electronics.com/info/satellite/satellite-orbits/satellites-orbit-definitions.php

WFW, Cypress Falls Park, May 2018

*Observational astronomer specializing in molecular clouds in nearby galaxies.

Outline

- Definitions
- Motivation
- I. Basic Physics
- II. Orbital Basics and Real Orbits
  - Basics
  - Additional Physical Processes
  - Examples of Real Orbits
- Conclusions?

Definitions

An orbit is the gravitationally curved trajectory of an object,[1] such as the trajectory of a planet around a star or a natural satellite around a planet. Normally, orbit refers to a regularly repeating trajectory, although it may also refer to a non-repeating trajectory. *(https://en.wikipedia.org/wiki/Orbit)*.

Definitions

Bodies are in orbit when they fall around each other due to their mutual gravity. *(W. F. Wall)*

@skydivespain #tracking #tracking #15000ft

5:55 AM - 15 Nov 2016

Motivations:

Why are Orbits Interesting?

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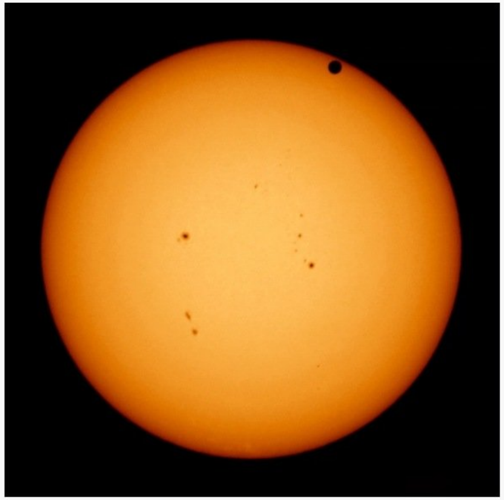
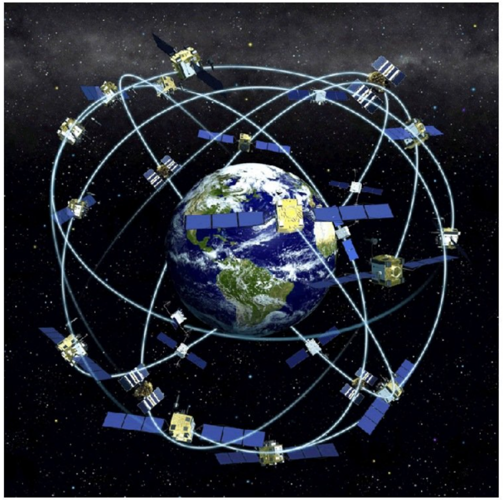
Why are Orbits Interesting?

1) Days, seasons, years, tides, climate, heavenly motions and events (eclipses, occultations, transits, risings, settings).

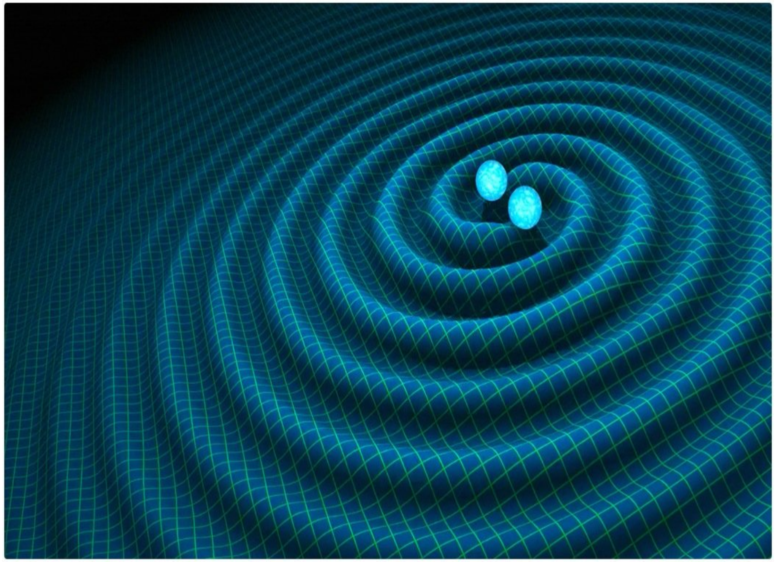
2) Artificial satellites for probing the heavens, the Earth, for communications, for GPS. ***Which have reshaped our worldwide civilization.***



Transit of Venus – Image credit- Wikipedia – http://en.wikipedia.org/wiki/File:2012_Transit_of_Venus_from_SF.jpg – Venus is at the top right of the Sun's disk. Other dark blotches are sunspots.



The orbits of GPS satellites are inclined to the Earth's equator by about 55 degrees. The system is designed to ensure that at least four satellites are visible at least 15 degrees above the horizon at any given time anywhere in the world. (Image: © NOAA)



Artist's conception of two black holes orbiting one another and producing gravitational waves. [Image Credit: NASA]

Motivations: Why are Orbits Interesting?

3) We can do kick-ass science! Exoplanets and gravitational waves, for example.

4) Space travel – exploration (solar system bodies and beyond), exploitation (mining moon and asteroids, inhabiting space).

Motivations:

Why are Orbits Interesting?

5) **Protection of the Earth from Collisions.**

The last days of dinosaurs during the Cretaceous Period, caused by a giant asteroid impact at Chicxulub off the coast of Mexico. | Stocktrek Images via Getty Images

I. BasicPhysics:

I. BasicPhysics:

- Newton's laws of motion
- Newtonian gravity
- Weight vs Mass
- Velocity & Acceleration
  - Linear acceleration
  - Centripetal acceleration
- Fictitious vs True Forces
- Velocity in a circular orbit
- Work and Energy
  - Potential Energy
  - Potential
  - Kinetic Energy
- Total Energy
  - Escape velocity
  - Orbital trajectories

Newton's Laws of Motion

1) A body in motion stays in motion and a body at rest stays at rest unless acted upon by an external unbalanced force. *(Inertia)*

2) Applying such a force to a body results in an acceleration, $\vec{a}$, that is proportional to the force, $\vec{F}$, and inversely proportional to the body's mass, *m*.

$$\vec{F} = m\vec{a}$$

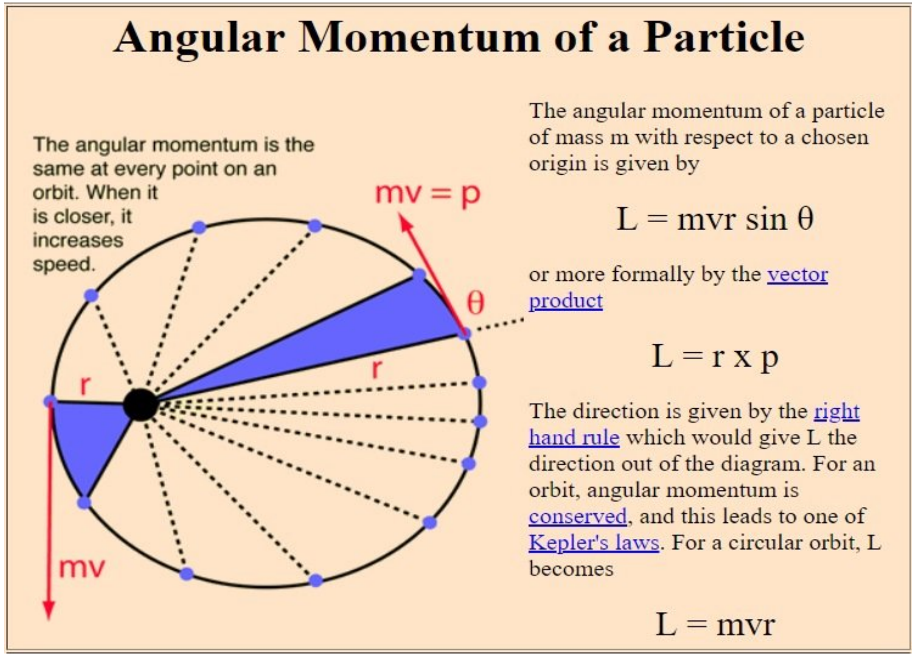
$$W = mg$$

Weight = mass X acceleration due to gravity

Newton's Laws of Motion

3) For every action there is an equal and opposite reaction.

Momentum, $\vec{p} = m\vec{v}$, is conserved.

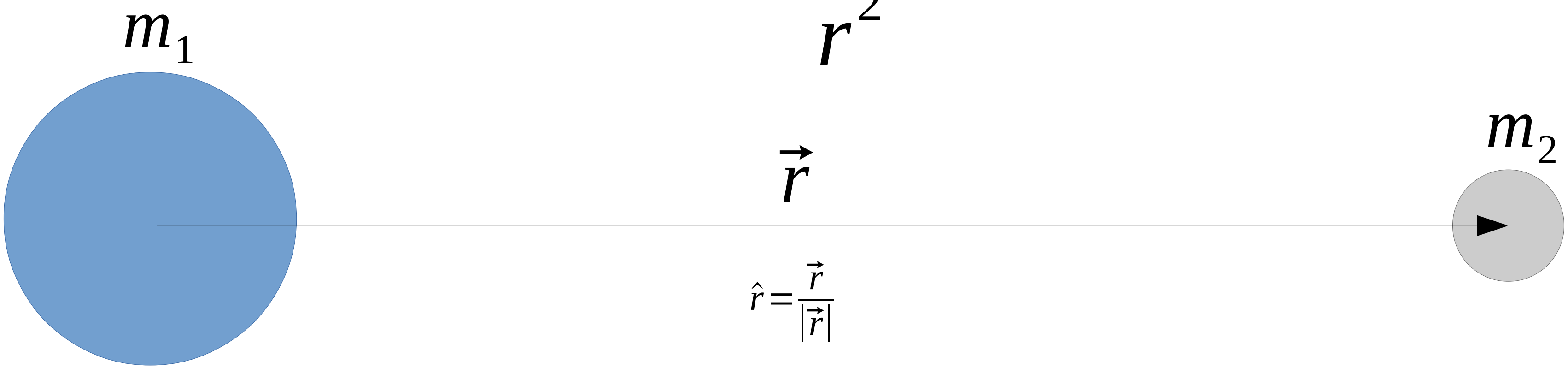


http://hyperphysics.phy-astr.gsu.edu/hbase/amom.html

Newton's Laws of Motion

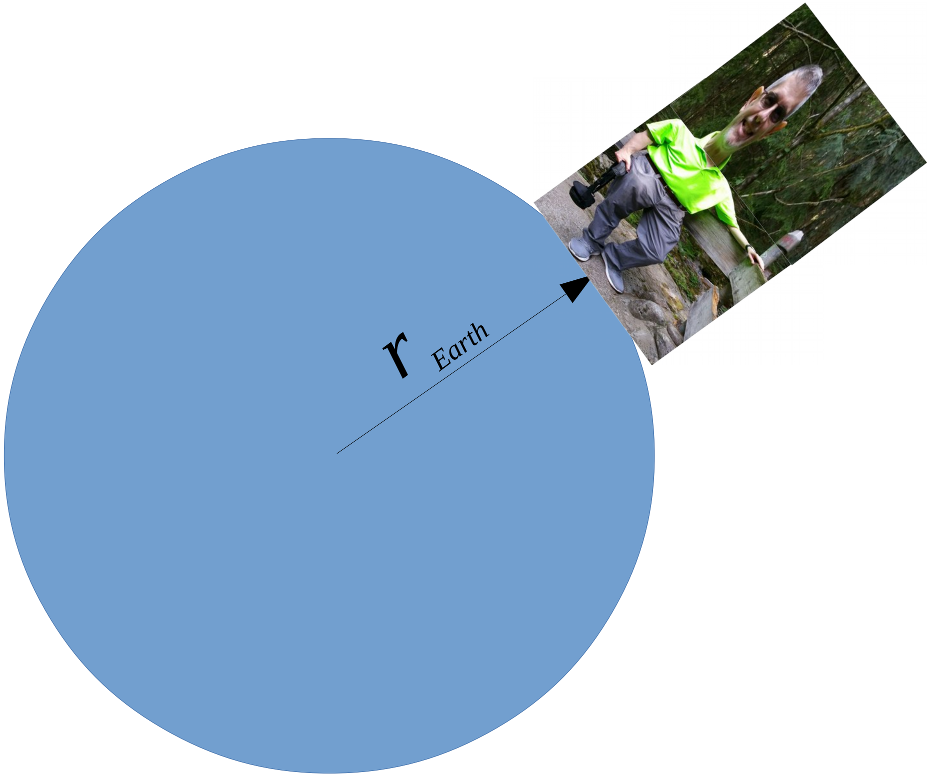
4) The gravitational attraction between two bodies is proportional to the product of their masses and inversely proportional to the square of the distance between them.

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



Newton's Laws of Motion

Let's have fun with Newton's laws. We'll combine #2 with #4:



$$W = F$$

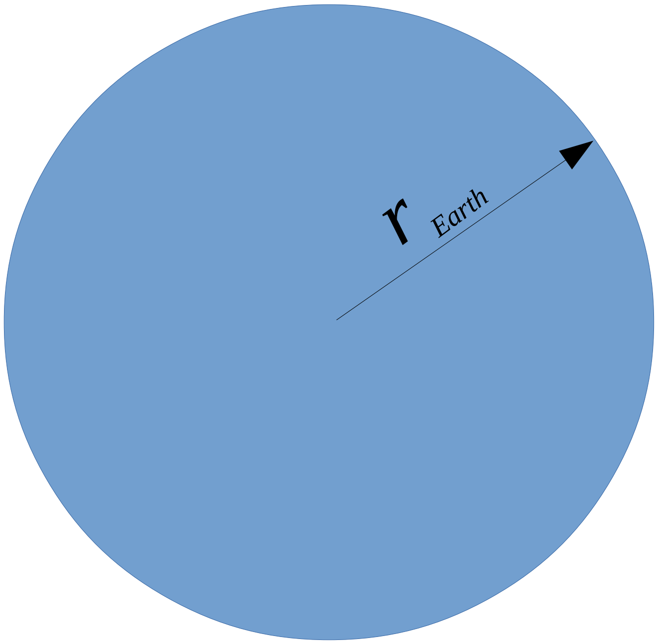
Weight = Force of gravity

$$m_{astronomer}\, g = \frac{G\, M_{Earth}\, m_{astronomer}}{r^{2}_{Earth}}$$

Law #2 = Law #4

Newton's Laws of Motion

Let's be *shocked* by Newton's laws when we combine #2 with #4!!



$$g = \frac{G\,M_{Earth}}{r_{Earth}^{2}}$$

The astronomer is irrelevant!!

Important consequence of the above is that *all <u>free falling</u> bodies accelerate at the same rate as they fall regardless of their masses.*
Feather will free fall like a stone! (WHEN there's no air.)

Free falling = accelerating freely due to gravity with *NO* additional forces present. (*NO* air resistance.)

I realized after taking this photo that I could use it to estimate the radius of the Earth! But I did not have an accurate measure of the camera's height above the lake surface, i.e., 4 to 10 m.

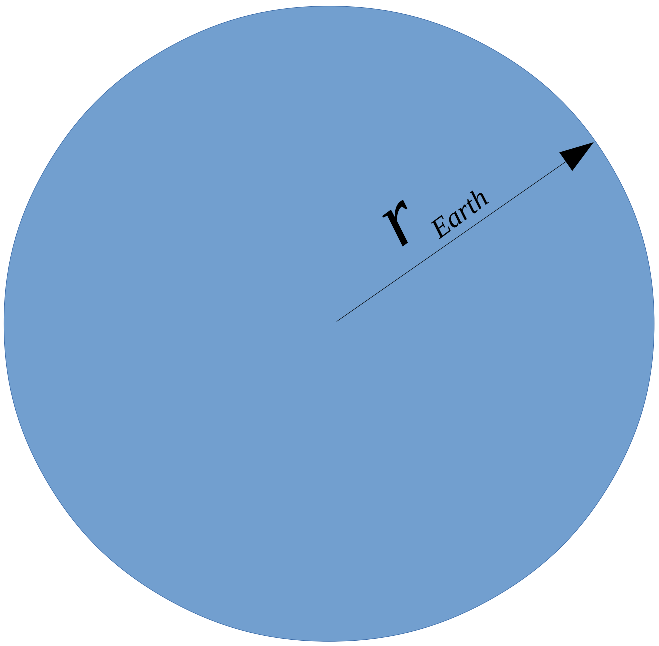
Toronto visible across Lake Ontario from Niagara-on-the-Lake, 2009, WFW

Consequently, my estimate of r_{Earth} was only about 11% accurate: *5930 to 7060 km*. (Correct number is 6371 km.)

Newton's Laws of Motion

Let's be *enlightened* by Newton's laws when we combine #2 with #4!!

The quantities g, G, and r_{Earth} have been measured on the Earth.



$$g = \frac{G M_{Earth}}{r_{Earth}^2}$$

Using $g = 9.807\ m\ s^{-2}$,

$G = 6.673 \times 10^{-11}\ N\ m^2\ kg^{-2}$,

and $r_{Earth} = 6.371 \times 10^6\ m$

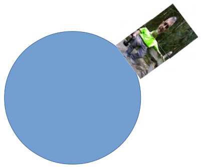
$$M_{Earth} = 5.97 \times 10^{24}\ kg$$

OR about

$$6 \times 10^{21}\ tonnes$$

Six sextillion tonnes! (American)

Six thousand trillion tonnes! (British)



Mass versus Weight

	Person on Earth	Person on the Moon
Système Internationale (SI)	$g = 9.807\ m\ s^{-2}$	$g = 1.625\ m\ s^{-2}$
	Mass = 60 kg	Mass = 60 kg
	Weight = 588 Newtons (N)	Weight = 97.5 N
British Imperial	$g = 32.17\ ft\ s^{-2}$	$g = 5.3313\ ft\ s^{-2}$
	Weight = 132 lb	Weight = 21.9 lb
	Mass = 4.11 slugs	Mass = 4.11 slugs

Mass versus Weight

Mass = *That property of matter that manifests itself as inertia. Or the amount of matter in a body.*

Weight = *The force with which gravity pulls on a body. Or how hard it presses down on a level surface.*

Velocity & Acceleration

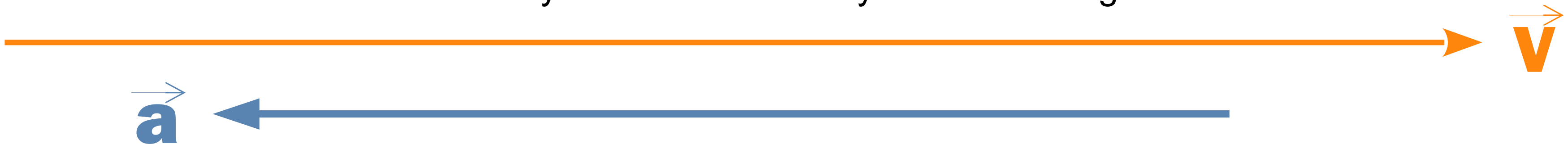
Both are vector quantities having magnitude and direction, but their directions can be distinct.

Only if the acceleration has a non-zero projection onto the velocity vector will it change the magnitude of the velocity vector (*speed*) of the moving body.

Velocity & *Acceleration*

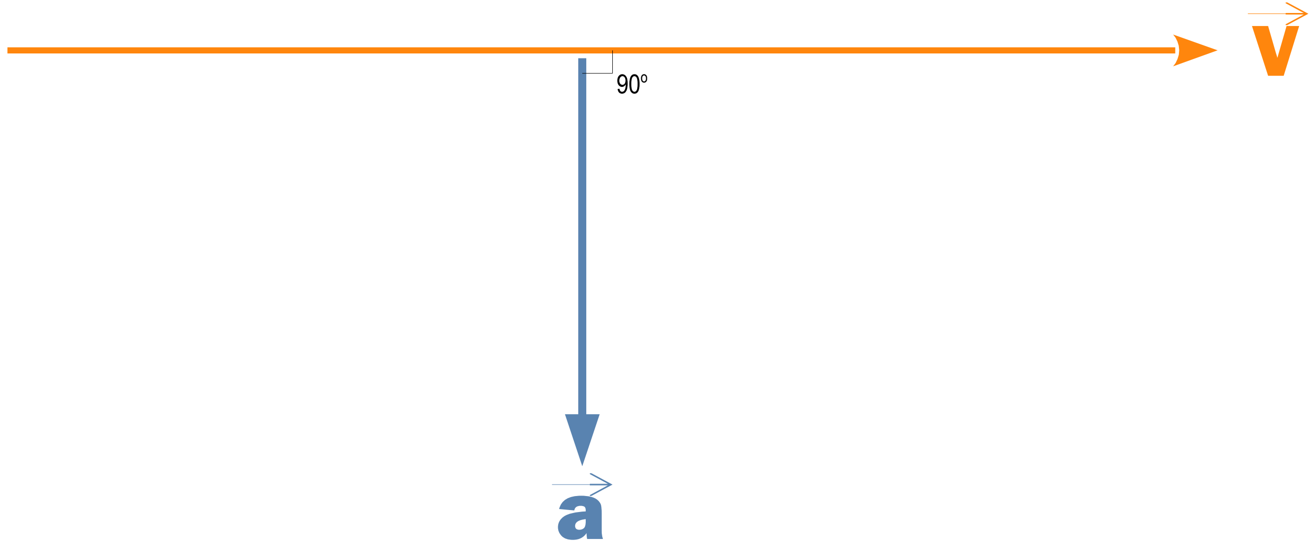
CASE 1: Velocity and acceleration vectors are parallel.   Speed *in*creases, direction is constant.
Conventionally stated as "the body is accelerating."

CASE 2: Velocity and acceleration vectors are *anti*-parallel.   Speed *de*creases, direction is constant.
Conventionally stated as "the body is *de*celerating."

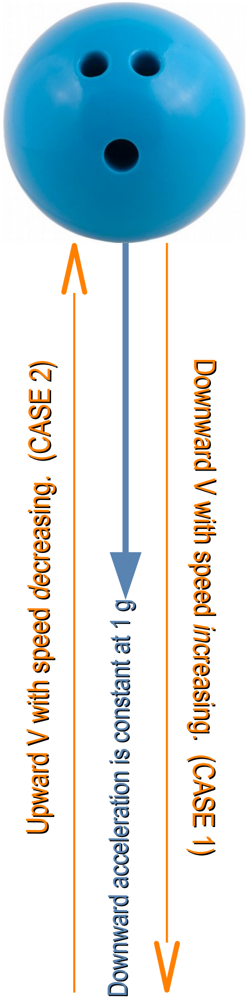


Velocity & Acceleration

CASE 3: Acceleration is *perpendicular* to velocity. Speed is constant, direction changes at constant angular velocity, ω, resulting in *circular motion*.



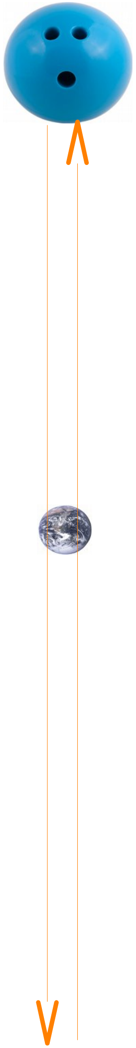
Velocity & *Acceleration*



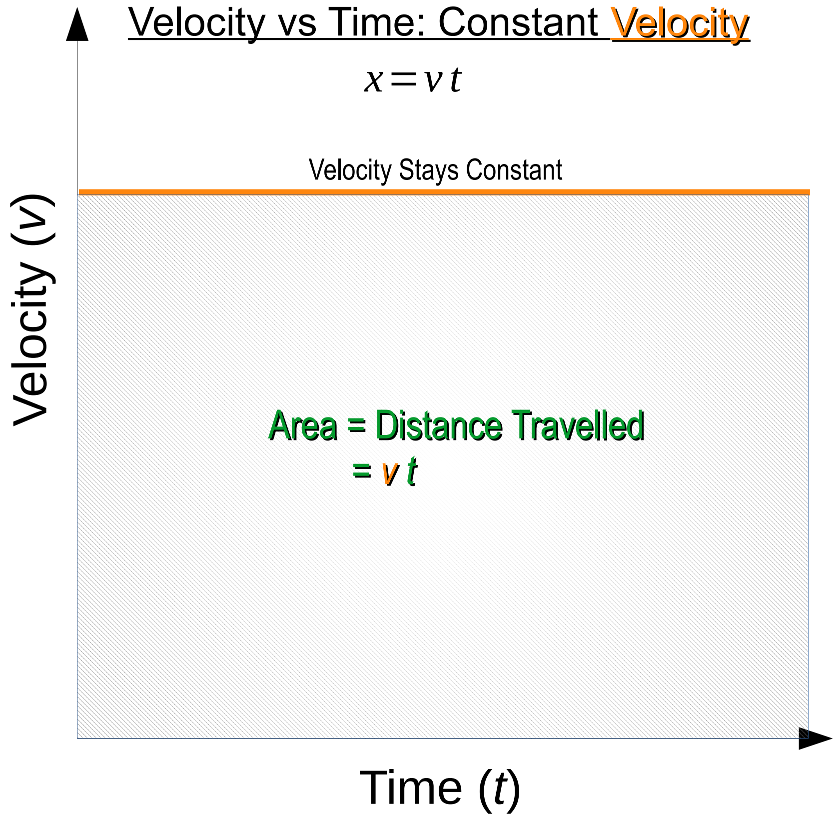
At the top, the speed is zero, but acceleration is still 1 g.

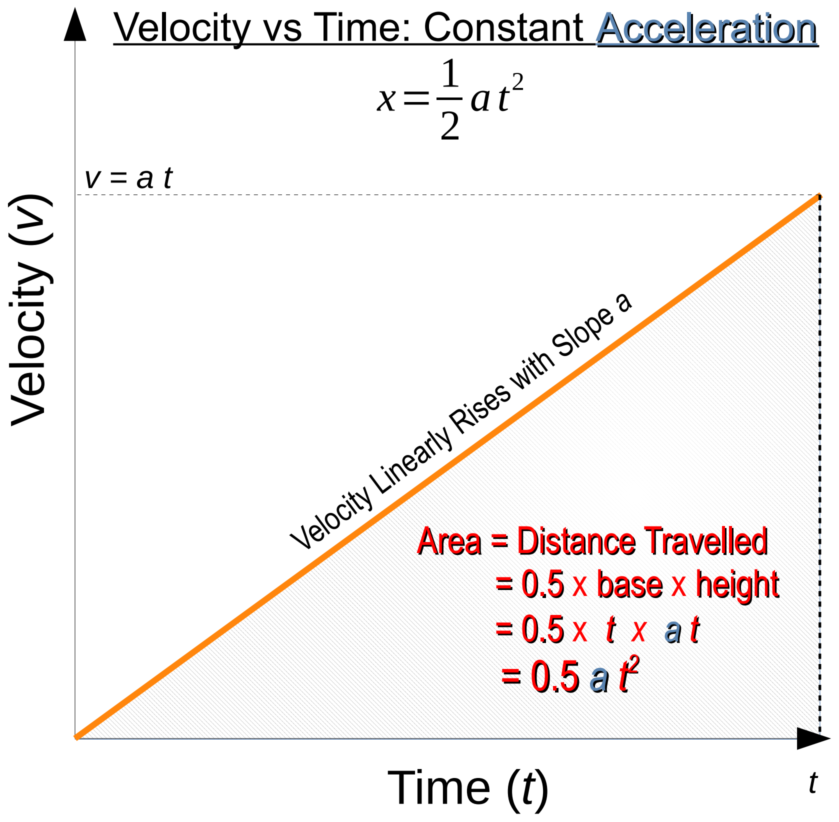
Tossing a ball up and down demonstrates Case 2 and Case 1. The velocity keeps changing, but the acceleration is constant at 1 g (assuming no air resistance).

Repeat the experiment with the Earth shrunken down to a point and the ball is now on a radial ***orbit*** (i.e., zero angular moment).



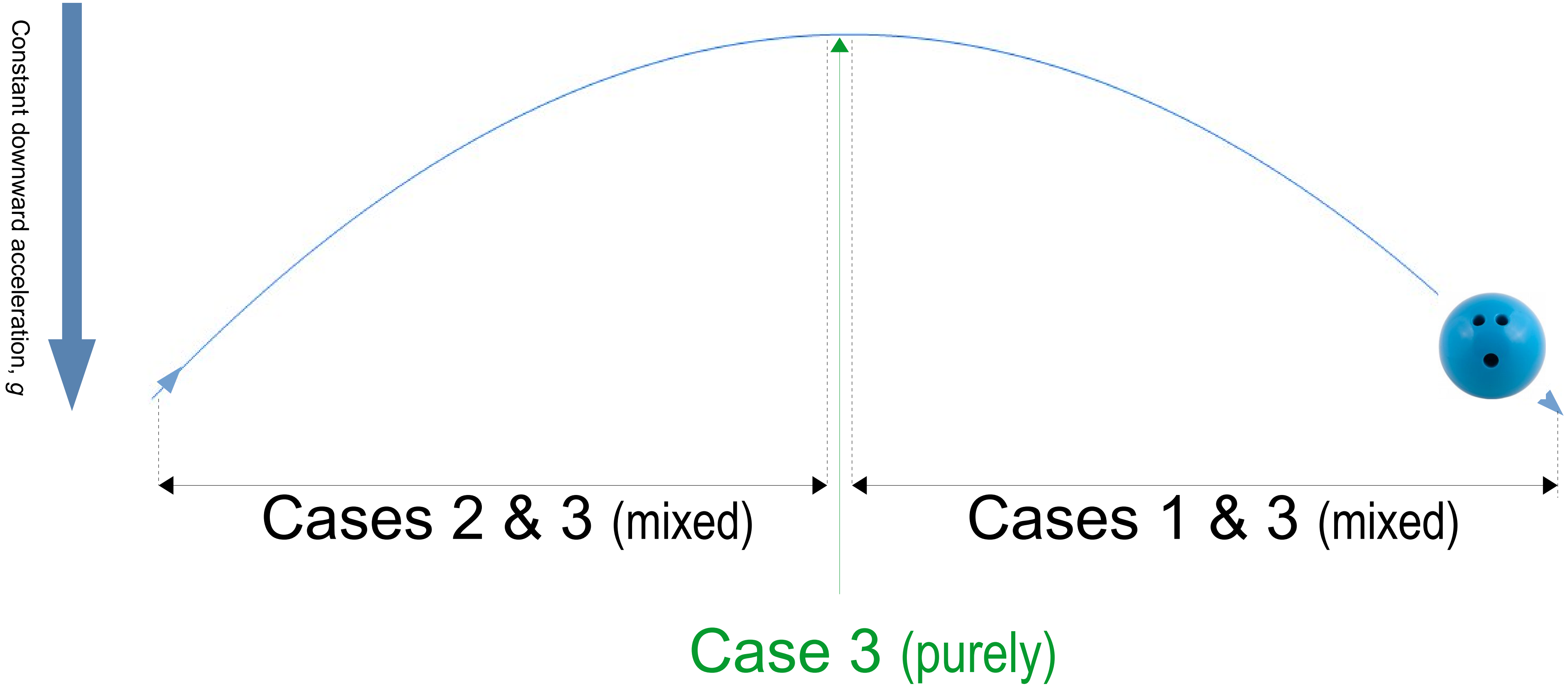
Velocity & Acceleration





Velocity & Acceleration

Projectile Launched* near Earth's Surface: Follows parabolic path in the absence of air resistance.



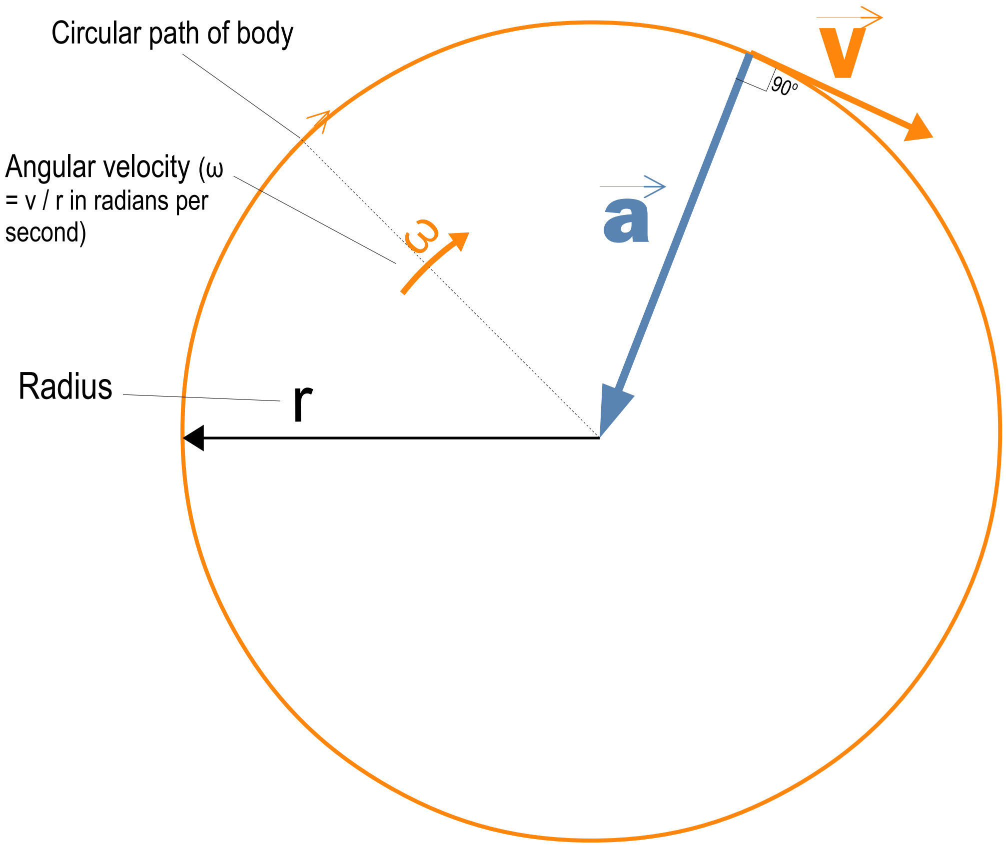
* Ball thrown.

Velocity & Acceleration

That same parabolic path is really part of a highly eccentric ellipse that represents an orbit* around the Earth's centre (visible if the Earth were shrunk down).

* Next time you throw a ball, remember that you're putting that ball into a temporary (decaying) highly eccentric orbit about the Earth's centre.

Velocity & Acceleration



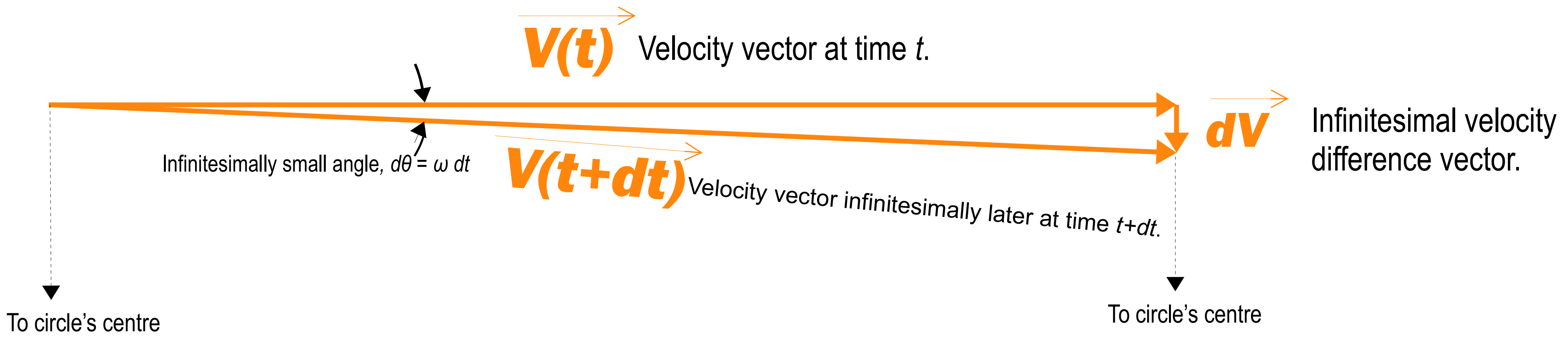
CASE 3: Body is constantly accelerating towards the centre of the circle, i.e., undergoing ***centripetal acceleration*** (which occurs because of some acting ***centripetal force***).

The body never reaches that centre because of the tangential velocity.

This is what occurs in a circular orbit of one celestial body around another.

Velocity & Acceleration

Centripetal Acceleration of Body on Circular Path:



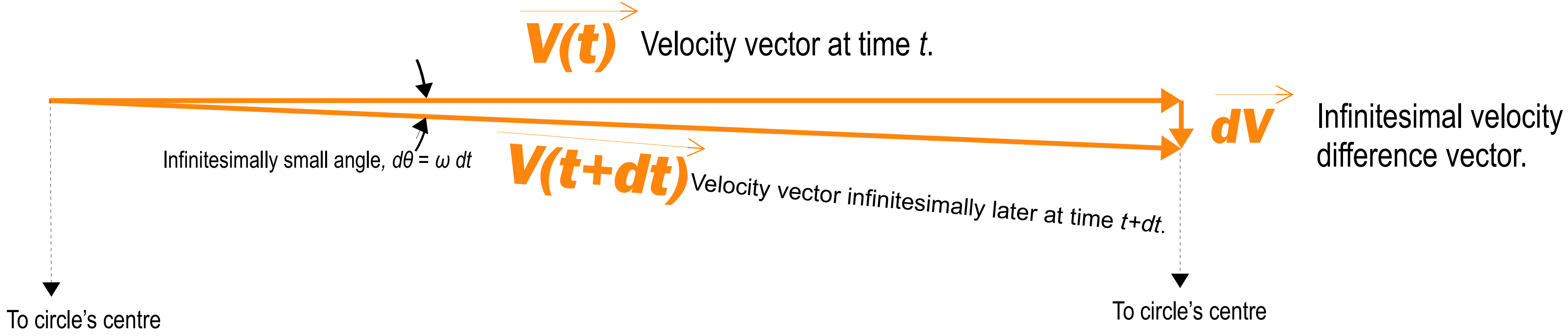
The velocity vectors above are like a thin wedge of pie. So, *dV* is like an infinitesimal arc. Accordingly,

$$dV = V\,d\theta$$

where *dθ* is in radians and dV and V are the magnitudes of the velocity and velocity difference vectors, respectively.

Velocity & Acceleration

Centripetal Acceleration of Body on Circular Path:



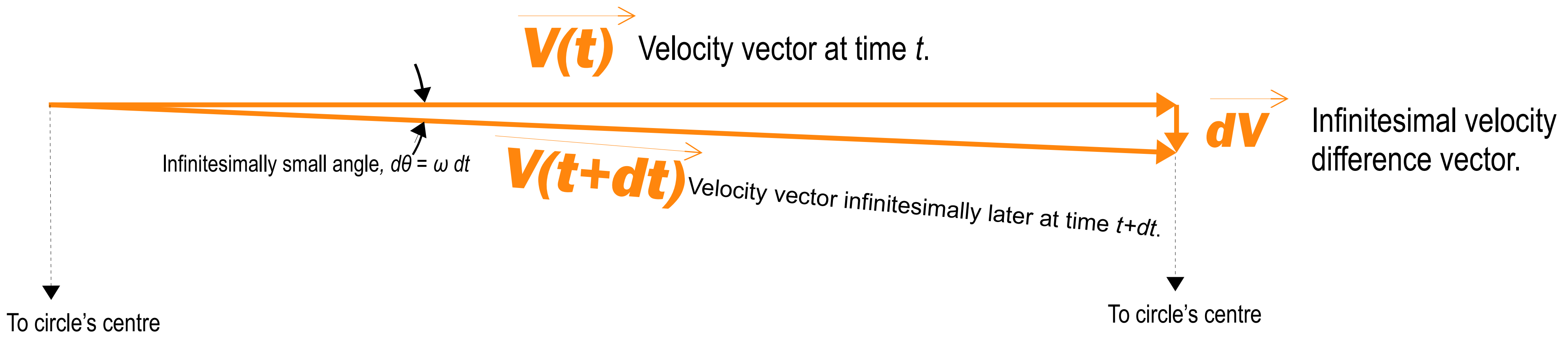
Using $d\theta = \omega\, dt$ and $\omega = V/r$ and remembering that *dV* is really a vector pointing at the circle's centre:

$$\frac{d\vec{V}}{dt} = -\frac{V^2}{r}\hat{r} \quad ,$$

which is the rate of change of velocity, or acceleration.

Velocity & Acceleration

Centripetal Acceleration of Body on Circular Path:



This acceleration is the centripetal acceleration, a_c, so,

$$\vec{a}_c = -\frac{V^2}{r}\hat{r}$$

or

$$\vec{a}_c = -\omega^2 r\,\hat{r} \quad .$$

Velocity & *Acceleration*

Centripetal Acceleration of Body on Circular Path:

- Applying centripetal acceleration formula to real situations.
  - Numerically ...

- Fighter jet in high-g turn:

Speed: 740 km hr^{-1} or 206 m s^{-1}.

Radius: 800 m

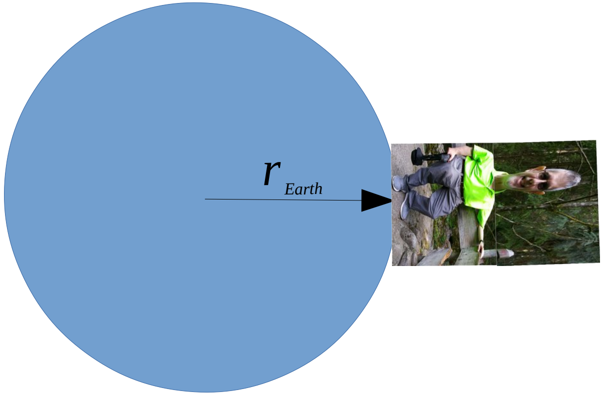
Centripetal a: 53 m s^{-2} or 5.4 g!

- I'm driving home on Hwy #1:

Speed: 70 km hr^{-1} or 19.4 m s^{-1}.

Radius: 290 m

Centripetal a: 1.3 m s^{-2} or 0.13 g.



- I'm standing on equator on spinning Earth:

Angular Speed: 7.272 X 10^{-5} rad s^{-1}.

Radius: 6378 km (equatorial)

Centripetal a: 3.4 cm s^{-2} or 0.0034 g.

Velocity & Acceleration

Centripetal Acceleration of Body on Circular Path:

- Applying centripetal acceleration formula to real situations.
  - Numerically and by noticing its form.

- I'm driving home on Hwy #1:

Speed: 70 km hr^{-1} or 19.4 m s^{-1}.

Radius: 290 m

Centripetal a: 1.3 m s^{-2} or 0.13 g.

- I'm driving home carefully on Hwy #1:

Speed: **50 km hr^{-1}** or **13.9 m s^{-1}**.

Radius: 290 m

Centripetal a: ***0.67 m s^{-2}*** or ***0.068 g***.

Notice that only a moderate change in speed results in a pronounced drop in the centripetal acceleration, making driving on that curve much safer in poor conditions (i.e., icy surface) due to dependence on velocity squared.

(Similarly, collisions are less severe by an amount proportional to velocity squared because the *kinetic energy* of the vehicles is also proportional to that.)

Fictitious vs True Forces

Centrifugal vs Centripetal:

Test it yourself as car *passenger* (**NOT** as driver).

While in the curve, confine your vision to the car's interior (i.e., represented by yellow arrow):

You'll perceive a "force" pushing you toward the outside of the curve, a centrifugal "force."

While in the curve, stare at a distant landmark (i.e., represented by yellow arrow):

You'll perceive your body's inertia attempting to maintain a straight path but is being **forced** into a circular path by a **centripetal force.**

Fictitious vs True Forces

Fictitious Forces: If you and your surroundings (e.g., vehicle) are experiencing acceleration, you're in a ***non-inertial frame of reference***.

The inertia of you and your surroundings will be perceived as "forces," like the centrifugal and coriolis* "forces" that are apparent in rotating frames of reference (e.g., a car in a curve or even the surface of the Earth), but are fictional.


NOAA, GETTY IMAGES

* Resulting in the spinning winds of cyclones and hurricanes.

Fictitious vs True Forces

True Forces: In contrast, a person in an *inertial frame of reference* (i.e., moving at constant velocity) will see the non-inertial frame as accelerating due to an outside true force, e.g., a centripetal force.

True Force(s) in a Circular Orbit

The centripetal and gravitational forces are relevant here. BUT, the gravitational force *is* the centripetal force. There is only *one* force here.

A mass *m* is in a circular orbit of radius *r* around a mass *M*, orbiting at velocity, v_{orb}.

Centripetal Force = Gravitational Force

$$\frac{m v_{orb}^2}{r} = \frac{G M m}{r^2}$$

Note: This expression is not applicable for elliptical orbits because the instantaneous radius of curvature does not necessarily equal the distance between the masses.

True Force(s) in a Circular Orbit

The gravitational force *is* the centripetal force. There is only *one* force here.

After solving for v_{orb} there is no longer a dependence on *m.*

$$v_{orb}=\sqrt{\frac{GM}{r}}$$

Note: This expression is not applicable for elliptical orbits because the instantaneous radius of curvature does not necessarily equal the distance between the masses.

True Force(s) in a Circular Orbit

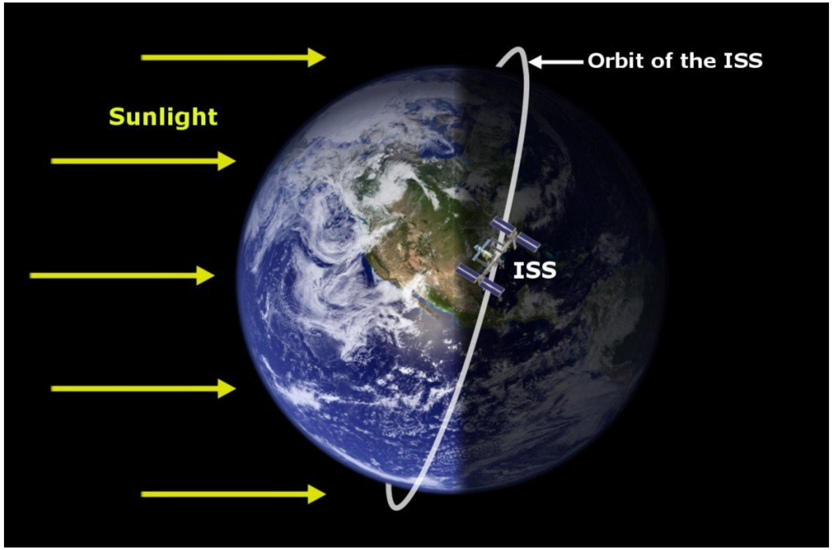
Fun with numbers!

What is v_{orb} for low-Earth orbit, say 200 *km* up?

r = (6371 + 200) *km* = **6.571 × 10⁶ *m***.

M = **5.97 × 10²⁴ *kg***

G = **6.673 × 10⁻¹¹ *N m² kg⁻²***



v_{orb} = **7.79 *km/s***

= **28000 *km/hr***

= 17400 *mi/hr*

True Force(s) in a Circular Orbit

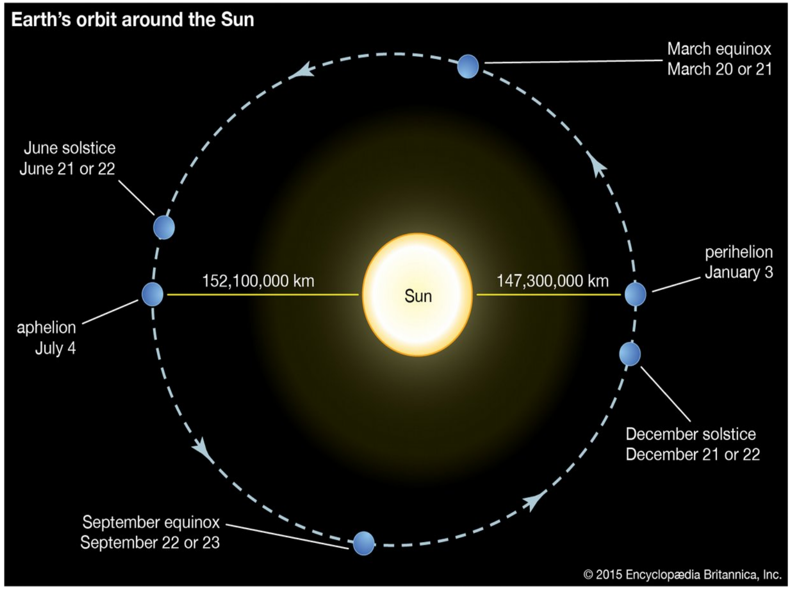
Fun with numbers!

What is v_{orb} for Earth orbiting the sun?

$r_{(average)}$ = 149.6 *million km* = $\mathbf{1.496 \times 10^{11}}$ ***m***.

M = $\mathbf{1.989 \times 10^{30}}$ ***kg***

G = $\mathbf{6.673 \times 10^{-11}}$ ***N m²*** ***kg⁻²***



v_{orb} = **29.8 *km/s***

= **107000 *km/hr***

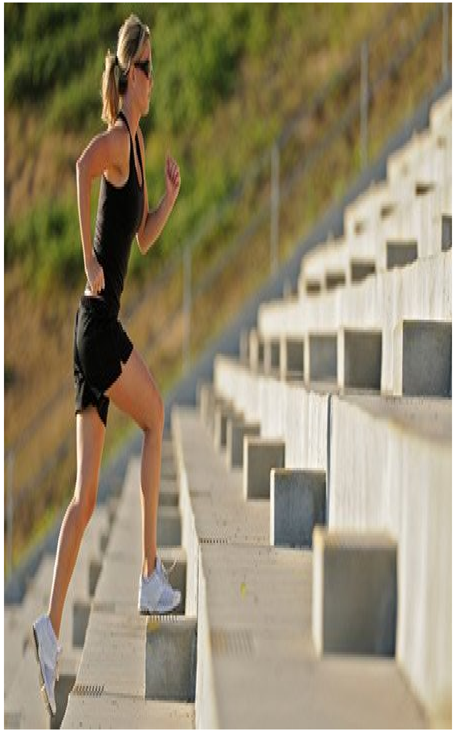
= 66600 *mi/hr*

NEXT: Escape velocity... but first....

Work and Energy

Work: The product of the force and the displacement it produces.

(If not aligned, then the product of the magnitude of the displacement vector and the projection of the force vector onto that displacement vector.)



E.g., a 60 *kg* person walks up one story of stairs. The force is the weight of the person, or 60 *kg* X 9.8 m/s^2, or 588 *N*. One story is 3 m high. So, the work done by climbing that story of stairs is

$$\mathcal{W} = mgh = 1764 \textit{ Joules}.$$

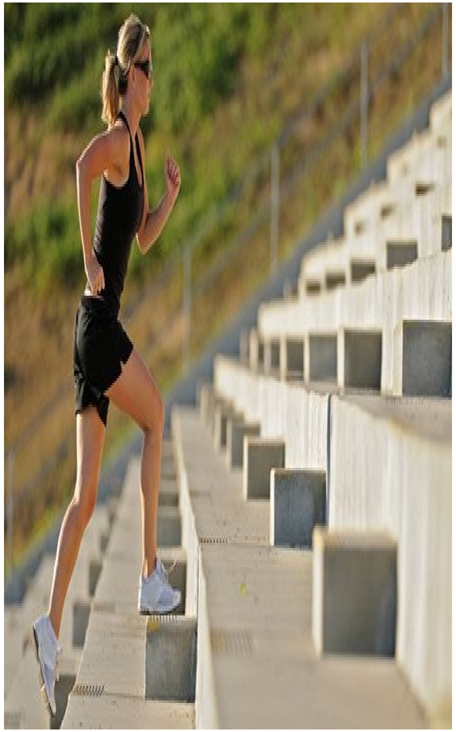
(If done in 7 seconds, the power output is 1764/7 or 252 *Watts*. This is 252/746 or 0.34 *horsepower*.)

Work and Energy

Potential Energy: This is the energy of position within a field, e.g., a mass within a gravitational field (or an electric charge within an electric field).

It is equivalent to the *work* necessary to move a mass (or a charge) to that position within the field.

E.g., that stair-climbing person gained 1764 *Joules* of gravitational potential energy (which would be converted to kinetic energy if he/she then jumped).



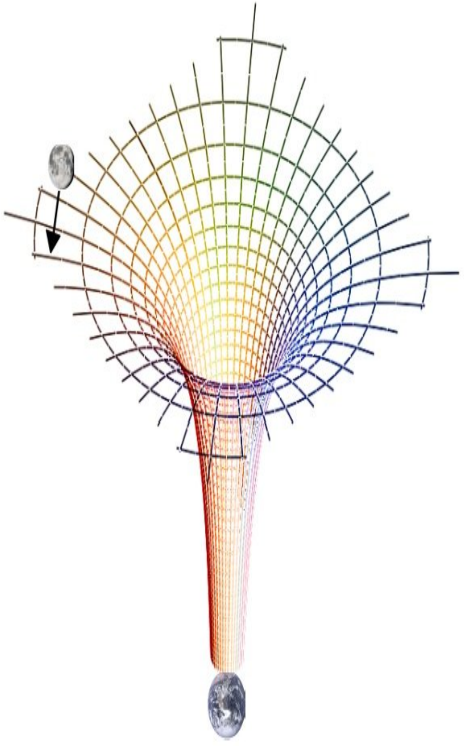
Work and Energy

The Potential: This is the potential energy per unit mass for a gravitational field (in *Joules/kg*).

(For an electric field, it's potential energy per unit charge in *Joules/Coulomb* or *Volts*.)

This is related to the field, which is force per unit mass for a gravitational field (*Newtons/kg* or m/s^2).

(For an electric field, it's *Newtons/Coulomb* or *Volts/metre*.)



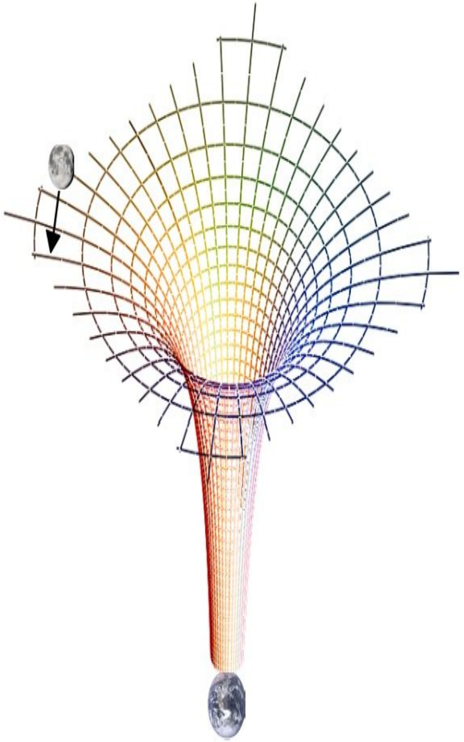
Earth's Gravitational Potential Well

Work and Energy

The field is the negative gradient (i.e., downhill direction) of the potential.

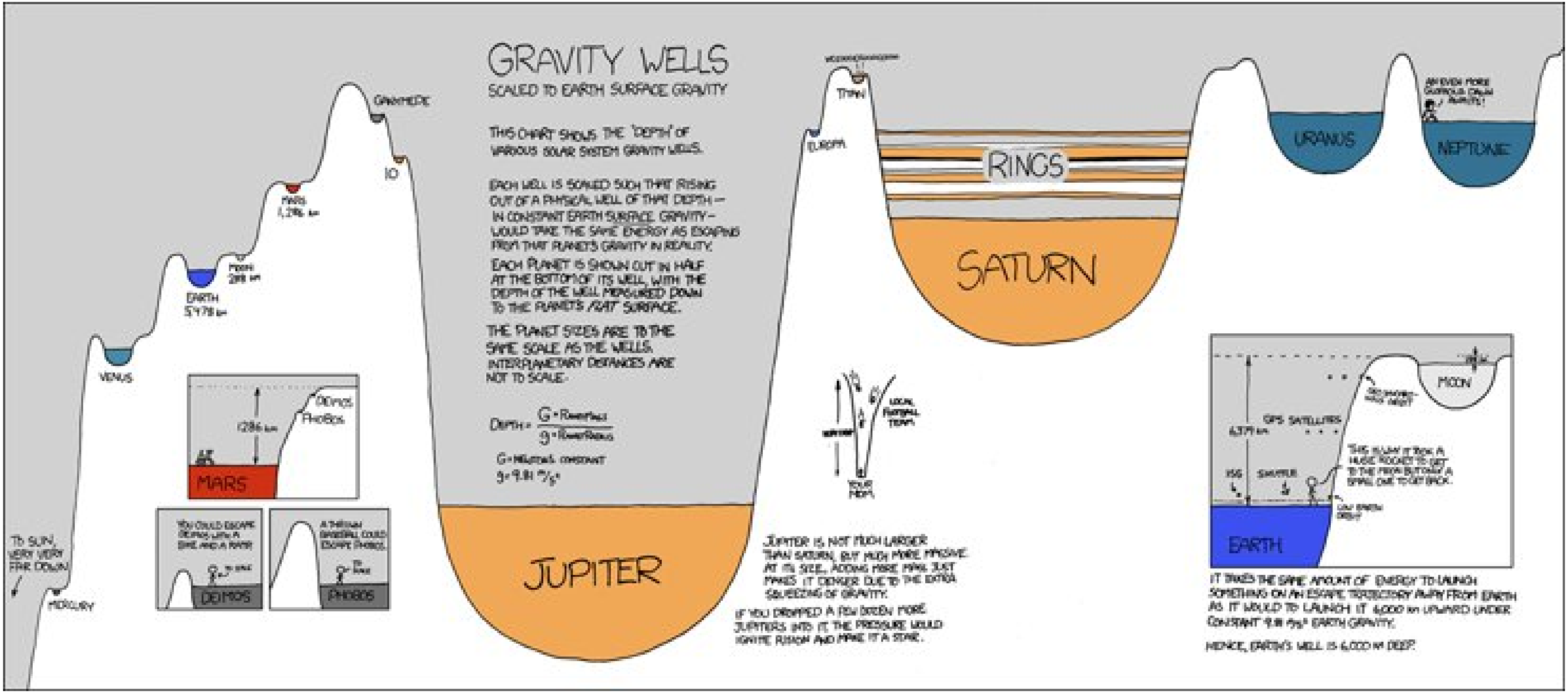
- This is an intuitive way to represent the field, because the potential represents a surface with hills and valleys, and the field would be arrows on that surface that point toward each local downhill direction.

The potential is a *scalar* representation of a *vector* field.

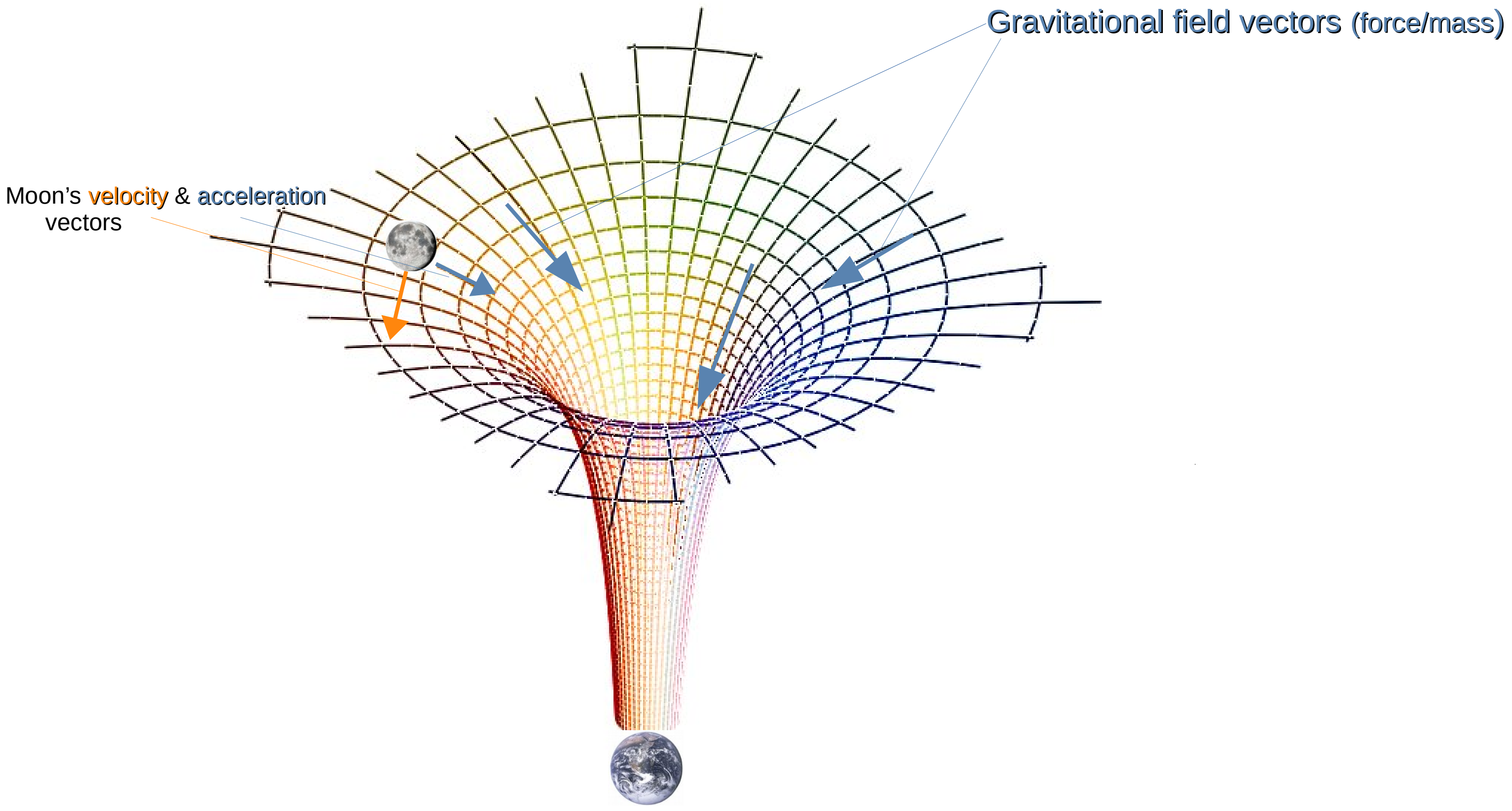


Earth's Gravitational Potential Well

Solar System Potential Well(s)



Planet sizes not to same scale as the distances between them.



Earth's Gravitational Potential Well

Earth's gravitational force:

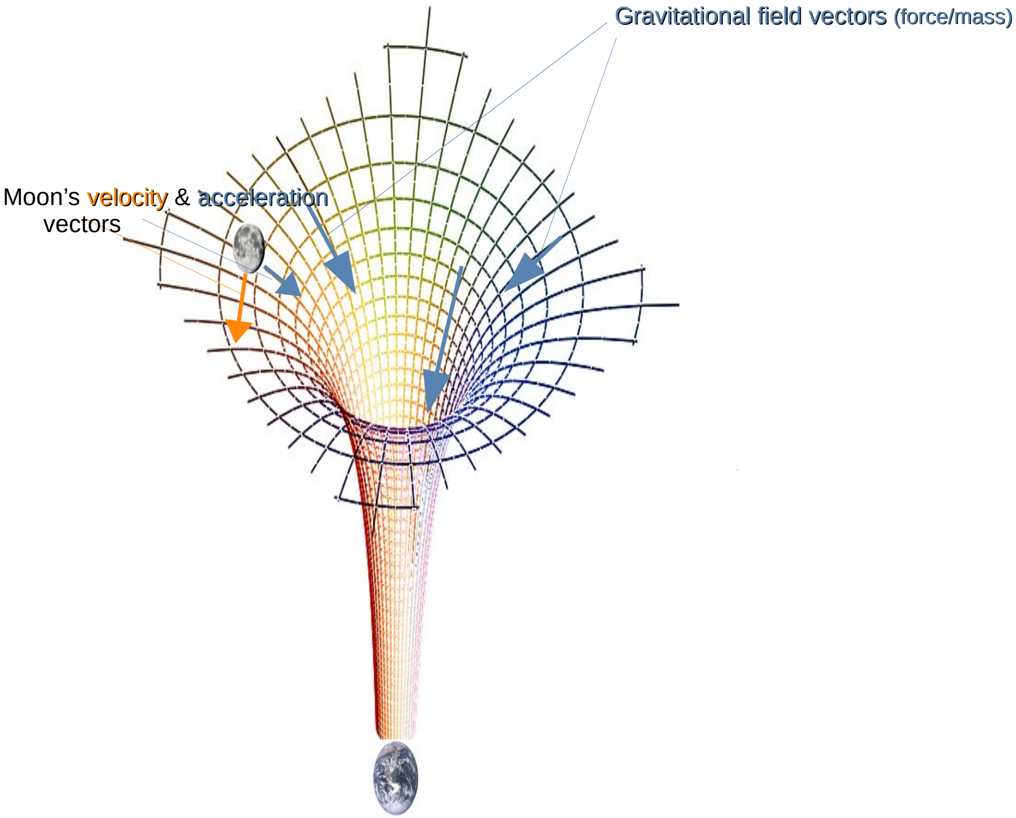
$$\vec{F} = -\frac{G\,M_{Earth}\,m}{r^2}\hat{r}$$

The potential energy at distance *r* is the work of moving a body from *infinity* to *r.* This is equivalent to multiplying the above by *r* (in this case).

Or, more accurately, integrating the force from infinity to r.

The potential energy, Φ, is then ...

$$\Phi = -\frac{G\,M_{Earth}\,m}{r}$$



Earth's Gravitational Potential Well

Accordingly, the Potential, ϕ, is

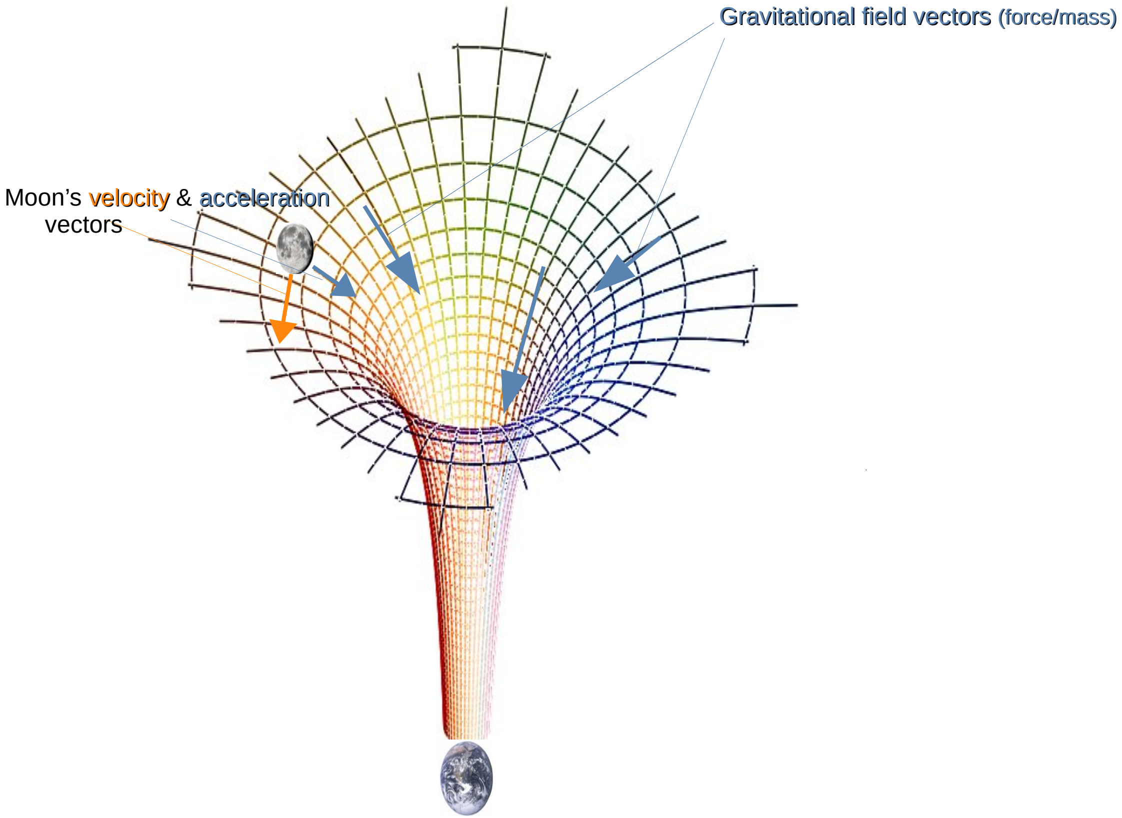
$$\phi = \frac{\Phi}{m}$$

OR

$$\phi = -\frac{G\,M_{Earth}}{r}$$

NOTE: The potential's zero-point occurs at *r = infinity* because the test mass, m, has *escaped* that potential well.

A bound object has negative potential.



Earth's Gravitational Potential Well

NOW! We can have some fun with numbers!!

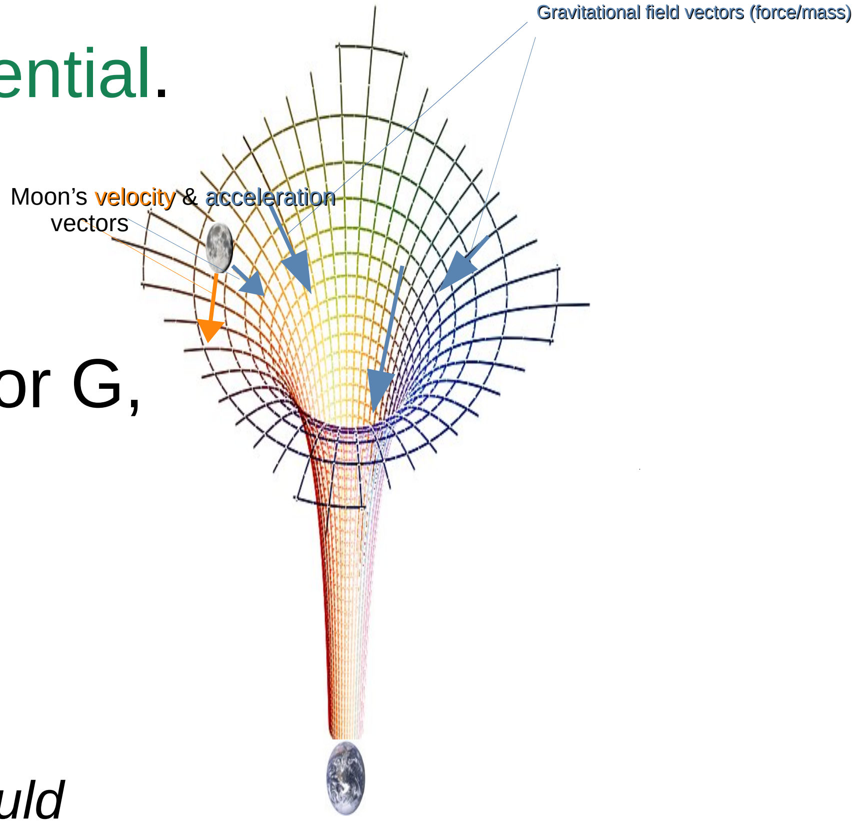
We are all physically bound by that potential.
Exactly how strongly are we bound to the Earth's surface?

Using known values for the Earth and for G, we find

$$\phi = -62.5\ MegaJoules/kg$$

*So, if we were to add more than 62.5 MJ of kinetic energy to each kilogram of your body mass, you could escape the Earth! For a normal-sized adult, this is a few GigaJoules!** ***(Space travel is expensive!)***

** Equivalent to climbing* ***2 MILLION STORIES*** *of stairs!*



Earth's Gravitational Potential Well

Work and Energy

Kinetic energy is the energy of a body due to its motion.

- What is the work required to accelerate mass, *m*, to velocity, *v* ?
- The force is $F = m\,a$ acting over distance $x = 0.5\,a\,t^2$. The work / kinetic energy is then

$$K = \vec{F} \cdot \vec{x} = \frac{1}{2} m a^2 t^2 = \frac{1}{2} m v^2$$

My family on swings, oscillating between peak potential energy and peak kinetic energy.
2019/05/24

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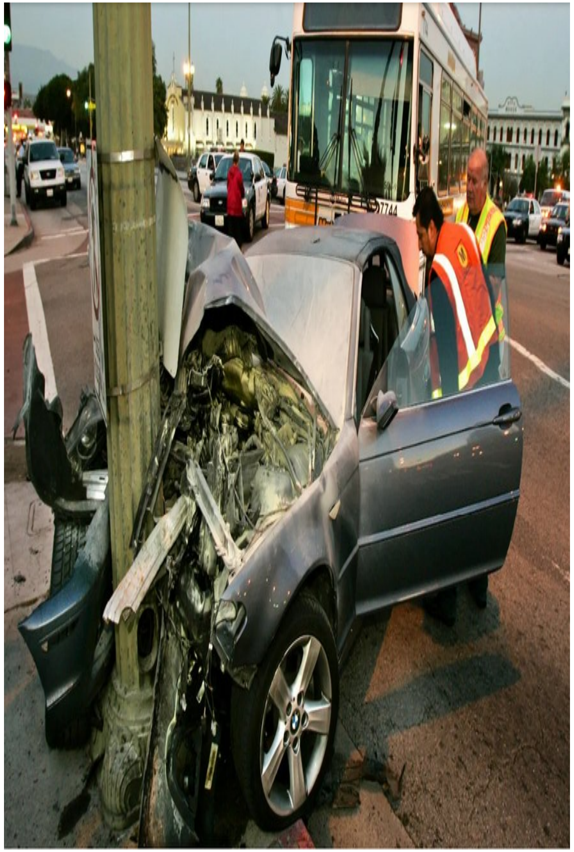
Notice again that dependence on velocity <u>squared</u>. A moderate change in speed will result in a pronounced change in kinetic energy and, therefore, in the damage in collisions! Drive safely/slowly!



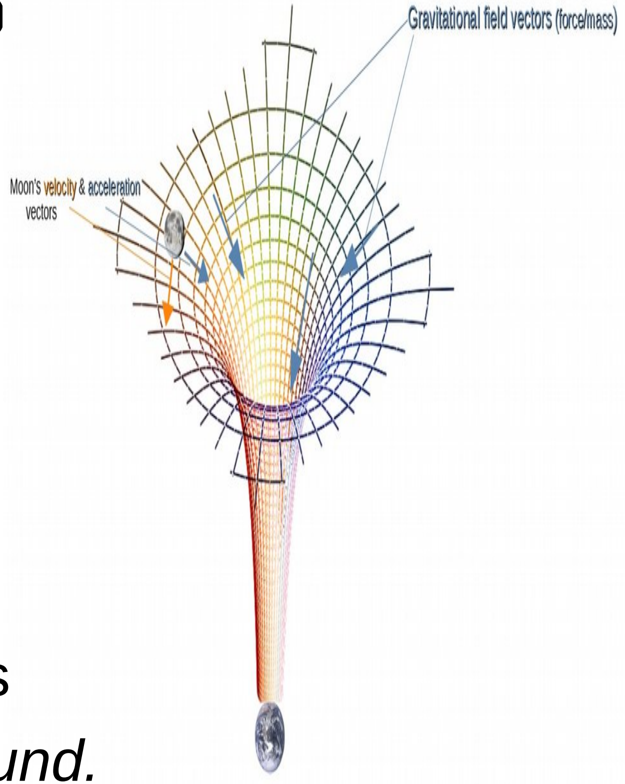
Too much kinetic energy.

Total Energy (Kinetic + Potential)

Adding the kinetic energy of mass *m* to its potential energy yields the total energy, E_{TOT}, of mass *m* within the gravitational field of mass *M*:

$$E_{TOT} = \frac{1}{2} m v^2 - \frac{GMm}{r}$$

- Whether E_{TOT} is negative, zero, or positive determines whether an orbit is *bound, marginally bound, or unbound.*
  - This also determines the orbital trajectory *(elliptical, parabolic, hyperbolic)*.



Earth's Gravitational Potential Well

Total Energy (Kinetic + Potential)

When $E_{TOT} = 0$, the velocity, v, is the escape velocity, v_{esc}, the minimum velocity necessary for m to marginally escape the gravitational field of M:

$$0 = \frac{1}{2} m v_{esc}^2 - \frac{GMm}{r}$$

Solving for v_{esc} yields...

$$v_{esc} = \sqrt{2\frac{GM}{r}}$$

DÉJÀ VU!!

Looks like the expression for v_{orb}!!

In fact, we find...

$$v_{esc} = \sqrt{2}\, v_{orb}$$

Therefore, if you're in orbit, then you only need to increase your velocity by 41% (a factor of 1.41) to escape the gravity of mass M (regardless of r)!

In other words, you already have ***half*** the kinetic energy needed to escape.

Total Energy (Kinetic + Potential)

Fun with numbers!

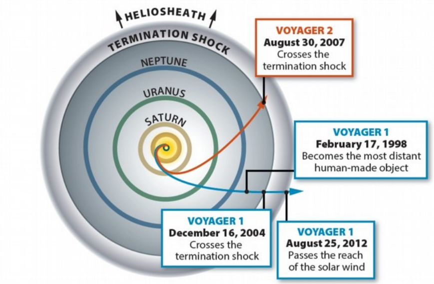
What is v_{esc} for escaping from Earth's surface?

$$v_{esc} = 2^{0.5} \times 7.79\ km/s = \mathbf{11.0\ km/s}$$

= 39660 km/hr

= 24600 mi/hr

What is v_{esc} for escaping from the solar system starting at Earth?



Launched in 1977, Voyager 1 (blue) has exited the solar system, with Voyager 2 (red) to follow. To leave the solar system, the Voyagers only needed to reach the escape velocity at the last planet from which a gravity assist was received: Saturn and Neptune, respectively.
Astronomy: Roen Kelly

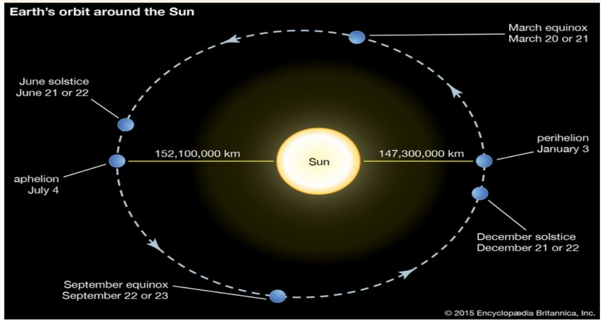
$$v_{esc} = 2^{0.5} \times 29.8\ km/s = \mathbf{42.1\ km/s}$$

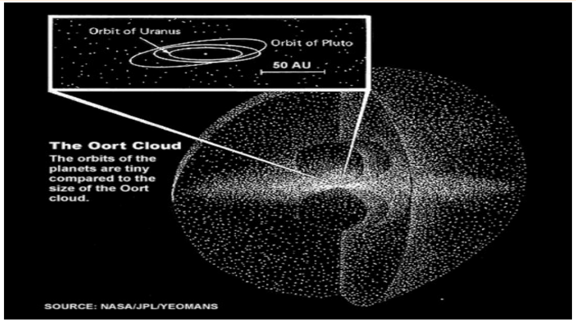
= 152000 km/hr

= 94300 mi/hr

Total Energy (Kinetic + Potential)

	$E_{TOT} < 0$	$E_{TOT} = 0$	$E_{TOT} > 0$
Orbit Type	Bound	Marginally bound	***Un***bound
Trajectory	Elliptical	Parabolic	Hyperbolic
Eccentricity	$0 \leq e < 1$	$e = 1$	$e > 1$
Examples	Earth orbiting sun (e=0.0167086) Short-period comets	Long- “Period” Comets	1I/ ’Oumuamua (e = 1.19951±0.00088) 2I/ Borisov (e = 3.3575±0.0004)





Representación artística de 'Oumuamua. Crédito: ESO/M. Kornmesser / nagualdesign

I. BasicPhysics:

- Newton’s laws of motion
- Newtonian gravity
- Weight vs Mass
- Velocity & Acceleration
  - Linear acceleration
  - Centripetal acceleration
- Fictitious vs True Forces
- Velocity in a circular orbit
- Work and Energy
  - Potential Energy
  - Potential
  - Kinetic Energy
- Total Energy
  - Escape velocity
  - Orbital trajectories

II. Orbital Basics and Real Orbits:

NEWTON'S CANNON

Dad and Dylan at Fort George, Niagara-on-the-Lake, Ontario, Canada, Jan /2006, Photo: Narissa Wall

NEWTON'S CANNON

NEWTON'S CANNON

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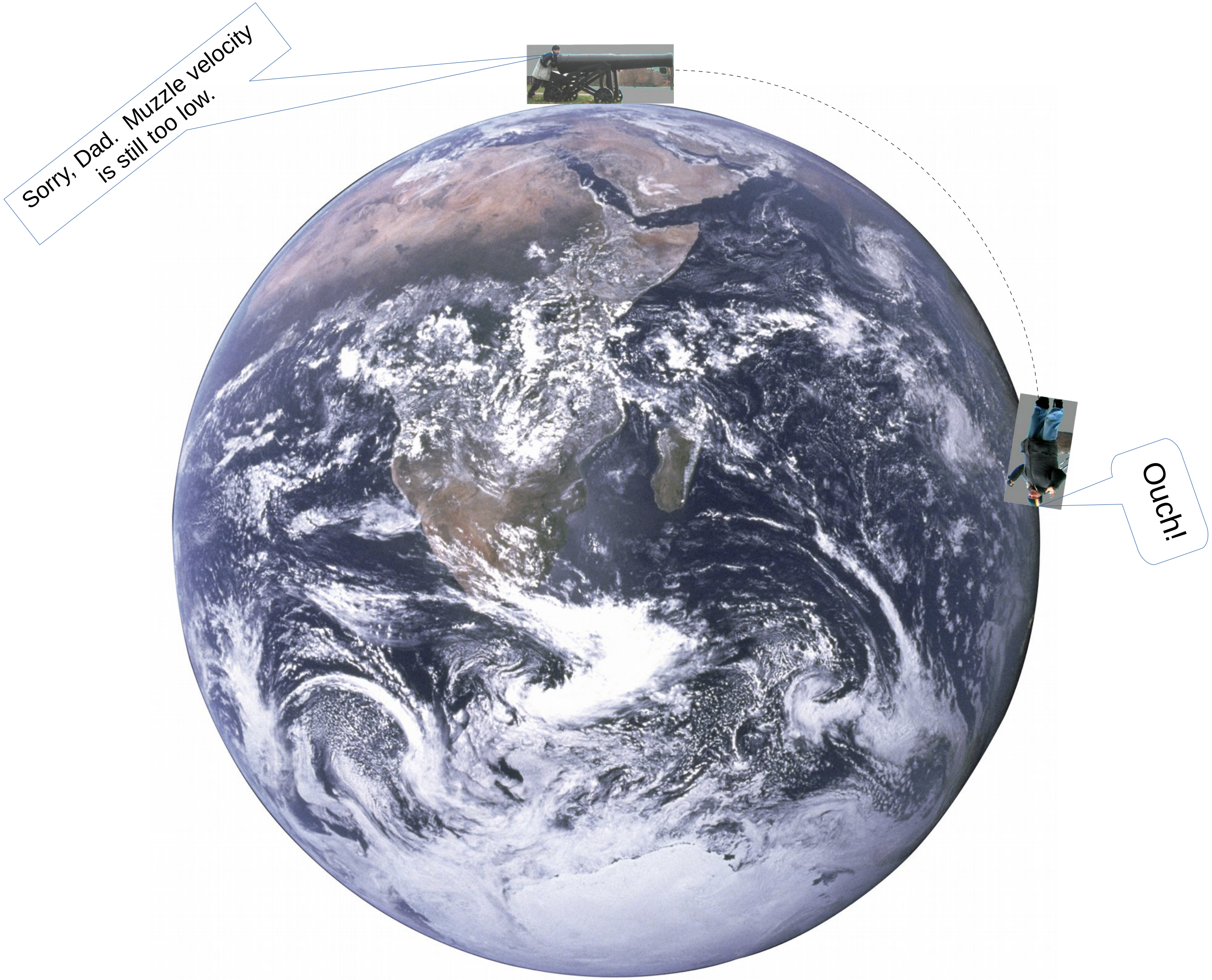
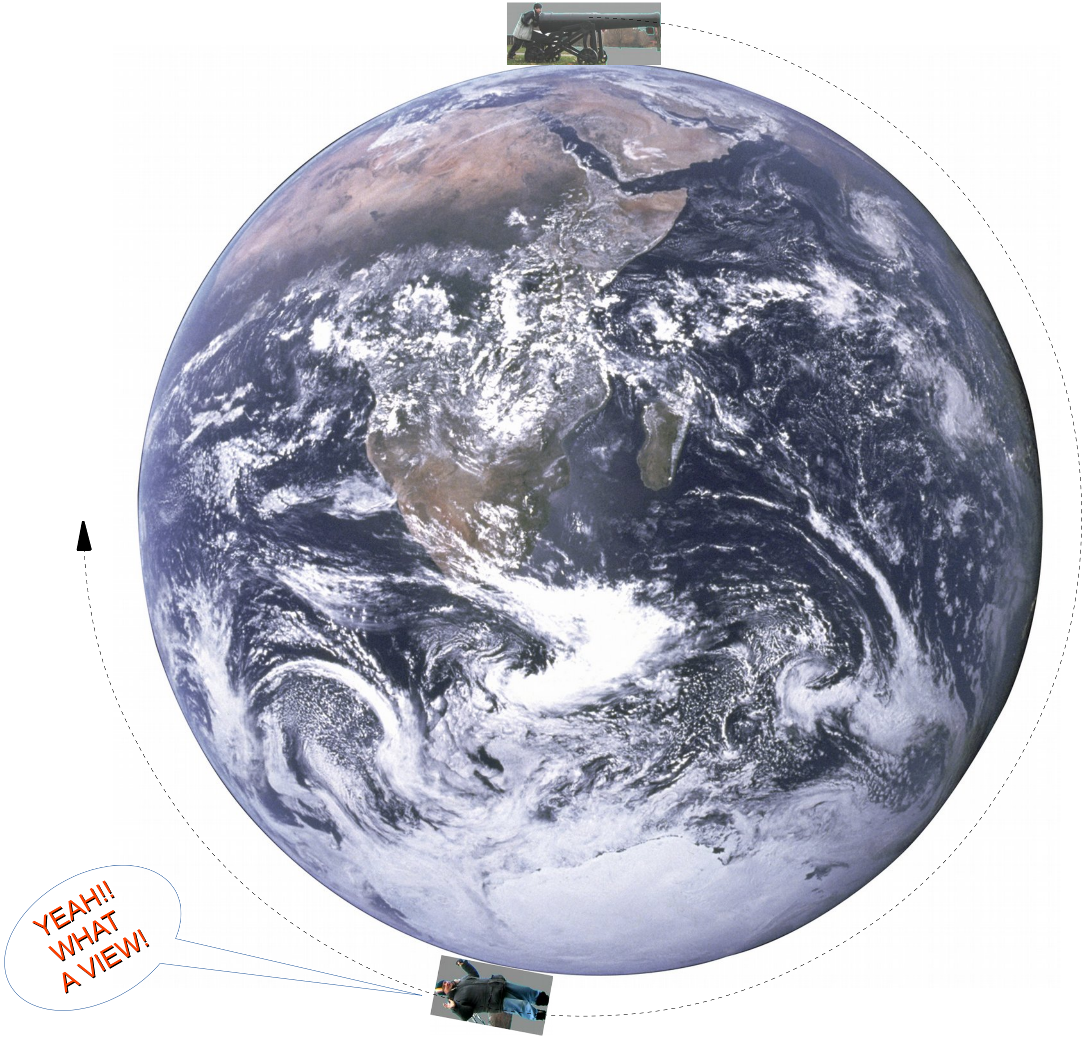


NEWTON'S CANNON



Kepler's Laws of Planetary Motion

1) The orbit of a planet is an ellipse with the sun at one of the two foci.
2) A line segment joining a planet and the Sun sweeps out equal areas during equal intervals of time. *(Conservation of angular momentum.)*
3) The square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit. $T^2 \propto a^3$

- Kepler’s Laws of Orbital Motion – Newton’s law of gravitational motion.
  - Newton’s Cannon – free fall and weightlessness.

- Orbits and their elements – elliptical, parabolic, hyperbolic orbits
  - Periasis, apasis points
  - Discussion of eccentricity
  - Use blender 3D model to demonstrate.

- Complications in real orbits
  - non-negligible masses – orbit common centre of mass
  - non-spherical and extended
  - more than 2 bodies
  - Poynting-Robertson effect
  - Yarkovsky effect

- Examples of real orbits -
  - artificial satellites
  - moon around earth
  - earth around sun
  - other planets around sun
  - exoplanets

- Additional considerations of orbits (might be combined with above)-
  - Tides
  - Lagrangian points
  - Seasons
  - Observations of solar system from Earth – retrograde loops
  - Precession
  - Eclipses
  - Occultations
  - Milankovitch cycles

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