Lesson 3

Physics 168

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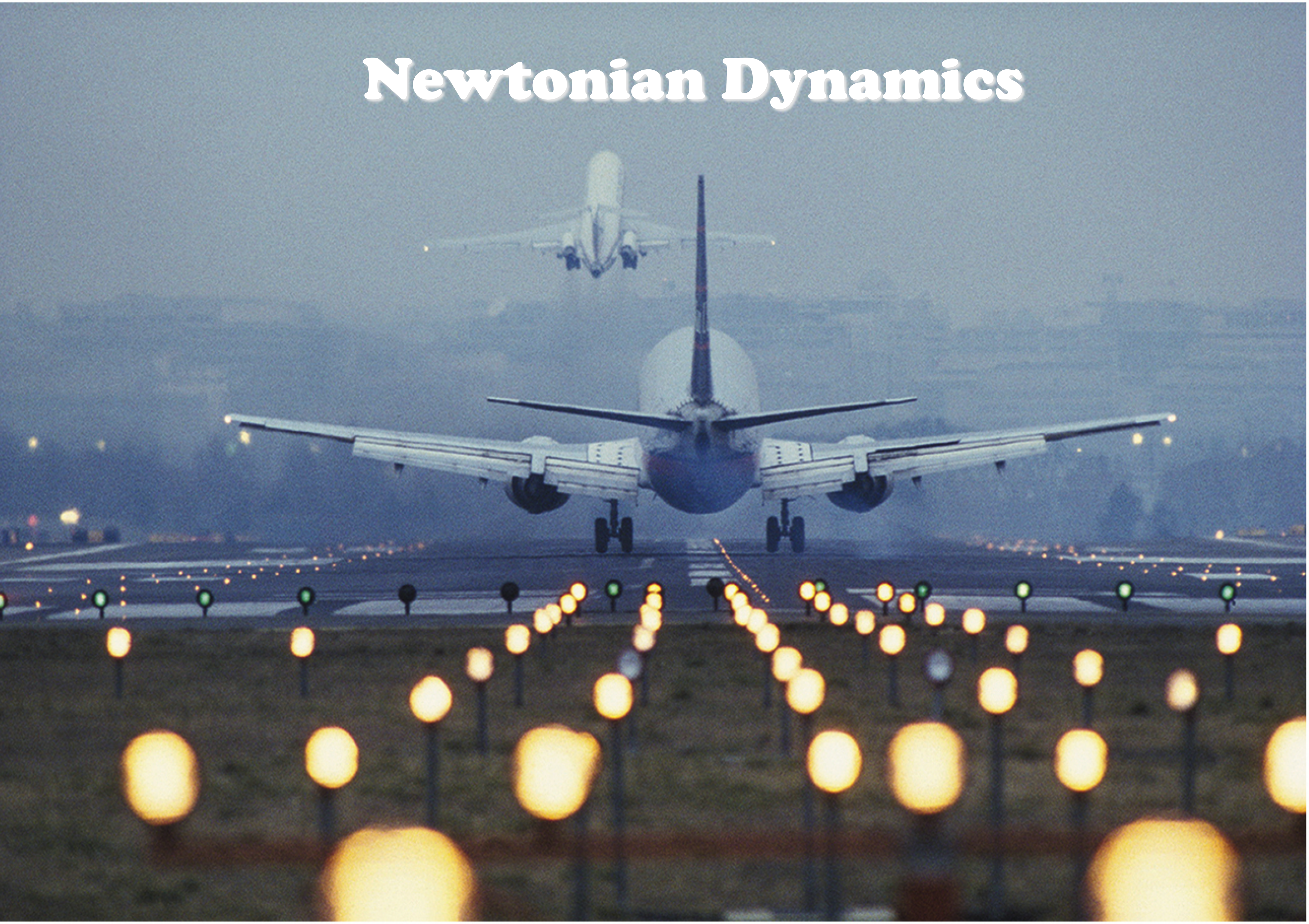
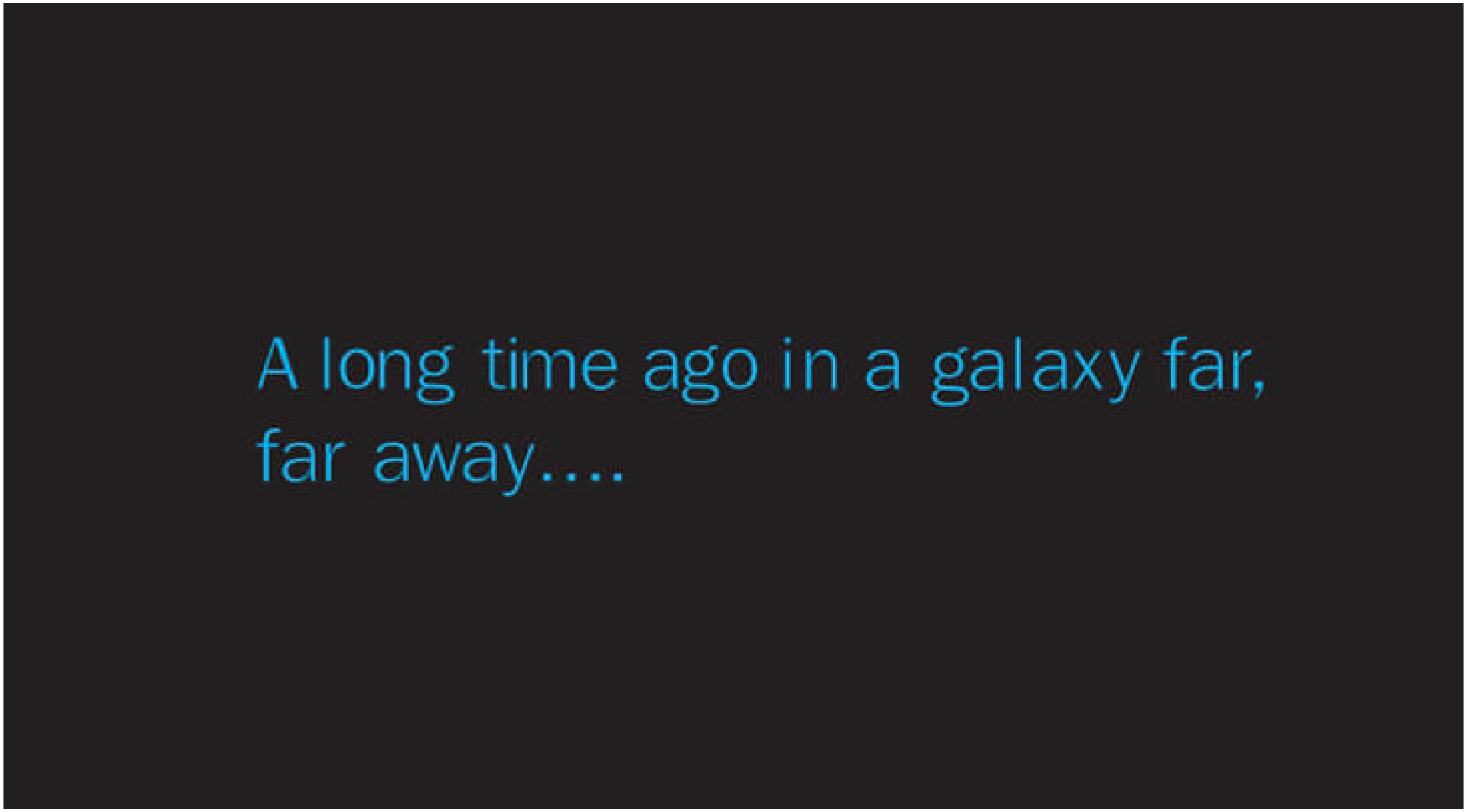

Newtonian Dynamics

We have see that ...

- Everything is in motion
- Even stuff that appears to be motionless moves
- But of course ☞ motion is relative
- E.g. ☞ while you are listening this lecture
  you are moving at about $107,000$ km/hr relative to Sun
  you are moving even faster relative to center of Galaxy
- When we discuss motion of something
  we describe motion with respect to something else
- To describe motion of something we need:
  - a reference point ☞ sometimes called the origin
  - a reference of time

E.g.



Newton's Laws

Now that we have studied how objects move we can ask the questions:

Why do objects start to move?

What causes a moving object to change speed or change direction?

Sir Isaac Newton answered these questions

his three basic laws of motion form basis of classical mechanics

I. A body remains at rest or in uniform motion unless acted upon by a force

II. Acceleration of an object is directly proportional to net force acting on it and mass of object is constant of proportionality

III. If two bodies exert forces on each other these forces are equal in magnitude and opposite in direction

Inertial Reference Frames

Newton's first law makes no distinction between object at rest and object moving with constant (non-zero) velocity

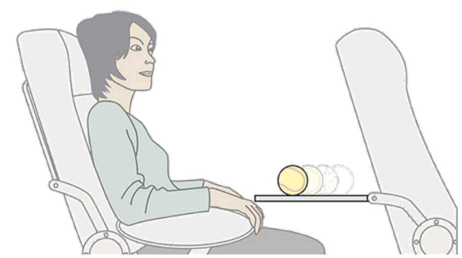
Whether object remains at rest or remains moving with constant velocity depends on reference frame in which object is observed

Inertial Reference Frames (cont'd)

Suppose you are a passenger on an airplane that is flying along a straight path at constant altitude and you carefully place a tennis ball on your seat tray. Relative to plane, ball will remain at rest as long as plane continues to fly at constant velocity relative to ground. Relative to ground, ball remains moving with same velocity as plane.

Now, suppose plane suddenly accelerates forward relative to ground.

You will observe ball starts to roll toward rear of plane, accelerating relative to plane even though there is no horizontal force acting on it.



In this accelerating reference frame of plane, Newton's 1st-law does not apply.

Newton's 1st-law applies only in reference frames known as inertial frames.

If no forces act on an object, any reference frame for which acceleration of object remains zero is an inertial reference frame

Mass

Objects intrinsically resist being accelerated

Imagine kicking both a soccer ball and a bowling ball

Bowling ball resist being accelerated much more than does soccer ball → as would be evidenced by your sore toes.

This intrinsic property is called the object's mass.

It is a measure of object's inertia

Greater an object's mass more the object resists being accelerated

Newton's second law

$$\vec{a} = \frac{\vec{F}_{\text{net}}}{m} \Leftrightarrow \vec{F}_{\text{net}} = \sum_i \vec{F}_i$$

Weight

If you drop an object near Earth's surface → it accelerates toward Earth

If air resistance is negligible → all objects fall with same acceleration called free-fall acceleration $\vec{g}$

Force causing this acceleration is gravitational force exerted by Earth on object. Weight of object is magnitude of gravitational force on it

If gravitational force is only force acting on an object object is said to be in free-fall

We can apply Newton's second law to an object of mass m that is in freefall to obtain an expression for gravitational force

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

Near Earth surface magnitude of acceleration of gravity is found to be

$$g = 9.81\,\mathrm{N/kg} \;=\; 9.81\,\mathrm{m/s^2} \;=\; 32.2\,\mathrm{ft/s^2}$$

Contact Forces: Normal Force

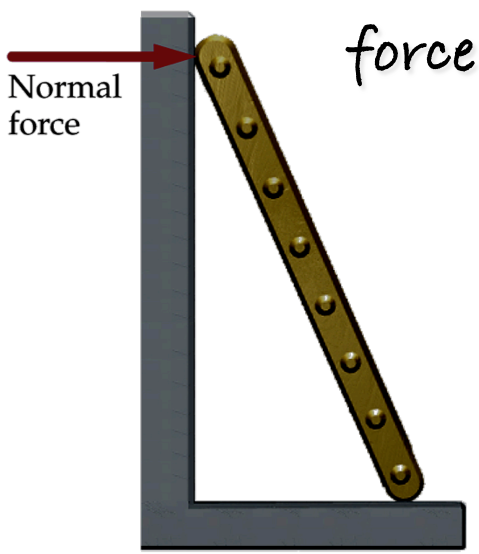
If a surface is pushed against, it pushes back

Consider a ladder leaning against a wall

At region of contact ladder pushes against wall with horizontal force compressing distance between molecules in surface of wall

Compressed molecules in wall pushes back on ladder with a horizontal force

Such force perpendicular to contacting surfaces is called normal force (the word normal means perpendicular)



Wall bends slightly in response to a load though this is rarely noticeable to unaided eye

Contact Forces: Frictional Force

Surfaces in contact can exert forces on each other that are parallel to contacting surfaces

Consider a large block on floor as shown in figure

If block is pushed sideways with gentle enough force, it will not slide
Surface of floor exerts a force back on block opposing its tendency to slide in direction of push

If block if pushed sideways with sufficiently large force ➤ it will start to slide

To keep block sliding, it is necessary to continue to push it
If push is not sustained contact force will slow the motion of the box until it stops

A component of contact force that opposes sliding, or tendency to slide is called a frictional force ➤ it acts parallel to contracting surfaces

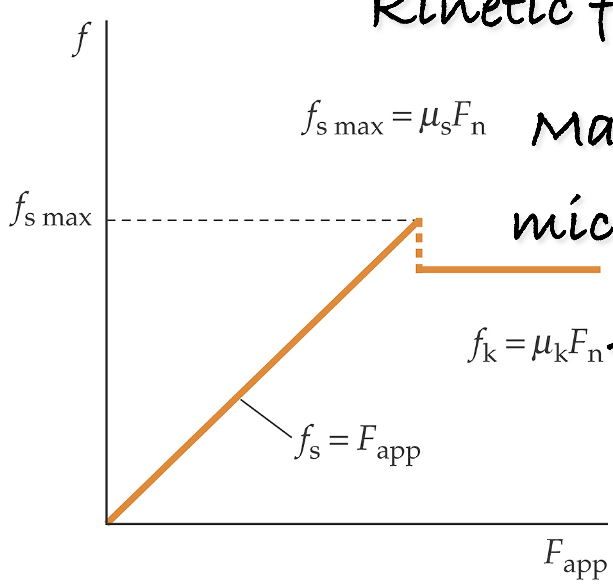
Friction

Static friction is frictional force that acts when there is no sliding between two surfaces in contact → It is force that keeps box from sliding

This force can vary in magnitude from zero to some maximum value $F_{s,\,\max}$ depending on how hard you push

Experimental data show that $F_{s,\,\max}$ is proportional to strength of forces pressing two surfaces: $F_{s,\,\max} = \mu_s F_n$

Kinetic friction is force that opposes to motion



Magnitude of this force is also proportional to microscopic contact area and strength of forces pressing two surfaces: $F_k = \mu_k F_n$

Approximate values of frictional coefficients

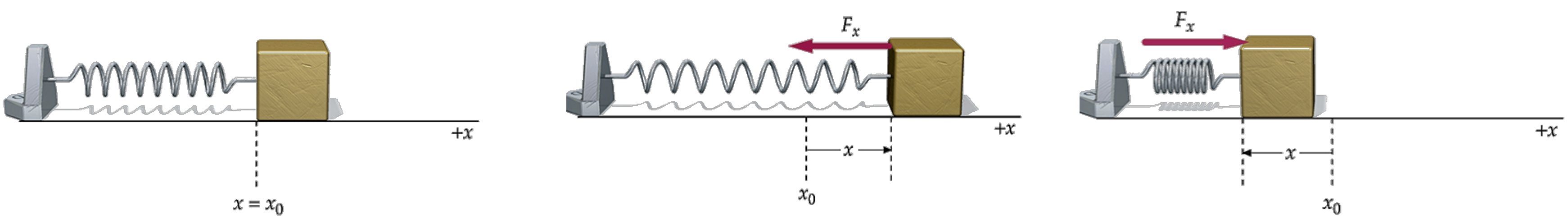
Materials	μ_s	μ_k
Steel on steel	0.7	0.6
Brass on steel	0.5	0.4
Copper on cast iron	1.1	0.3
Glass on glass	0.9	0.4
Teflon on Teflon	0.04	0.04
Teflon on steel	0.04	0.04
Rubber on concrete (dry)	1.0	0.80
Rubber on concrete (wet)	0.30	0.25
Waxed ski on snow (0°C)	0.10	0.05

Contact Forces: springs

Hooke's Law

When a spring is stretched from its unstressed length by a distance x force it exerts is found experimentally to be $F_x = -kx$

Positive constant k (or spring constant) is a measure of stiffness of spring



$F_x = -kx$ is negative (because Δx is positive).

$F_x = -kx$ is positive (because Δx is negative).

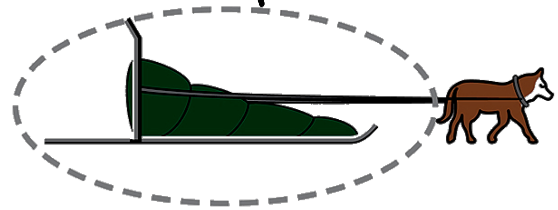
A negative value means spring has been compressed a distance $|x|$ from its unstressed length

Negative sign in Hooke's law signifies that when spring is stretched (or compressed) in one direction, force it exerts is in opposite direction

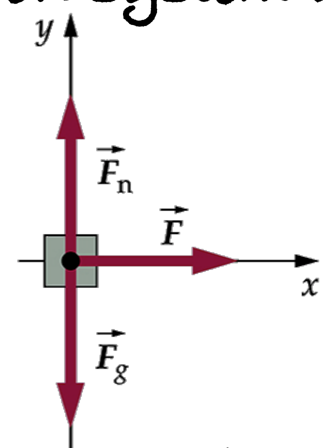
Free body diagramans

Imagine a sled being pulled across icy ground by a led dog

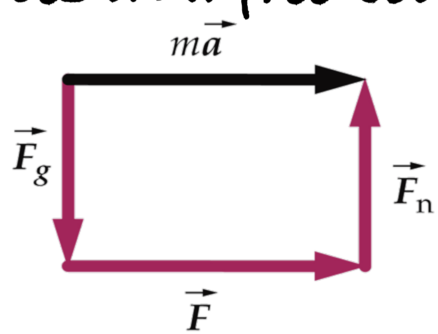
Dog pulls on a rope attached to sled with a horizontal force causing sled to gain speed (Friction is negligible)



A diagram that shows schematically all forces acting on system is called a free-body diagram

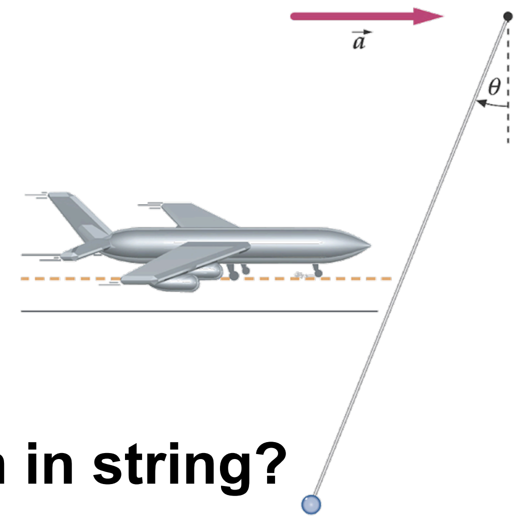


Vector sum of forces in a free-body diagram is equal to mass times acceleration



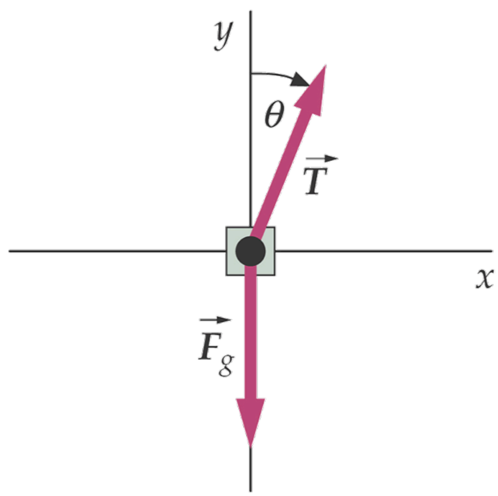
An accelerating jet plane

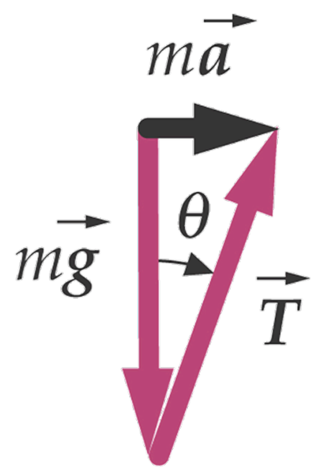
As your jet plane speeds down runway on takeoff, you decide to determine its acceleration, so you take out your yo-yo and note that when you suspend it, string makes an angle of 22 degrees with vertical



(a) What is acceleration of plane?

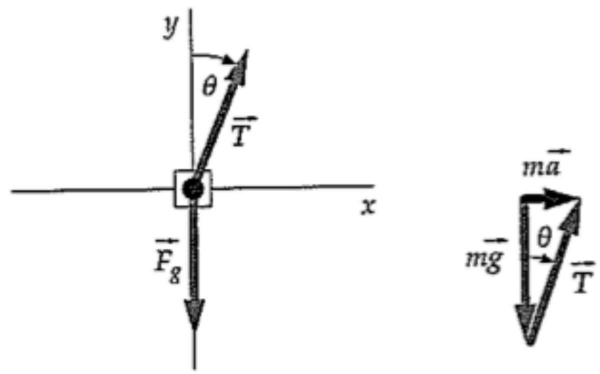
(b) If mass of yo-yo is 40.0 g, what is tension in string?





Draw free body diagram for yo-yo

Choose +x direction to be direction of yo-yo acceleration vector



$$T_x + F_{g_x} = ma_x \Rightarrow T\sin\theta = ma_x$$

$$T_y + F_{g_y} = ma_y \Rightarrow T\cos\theta = mg$$

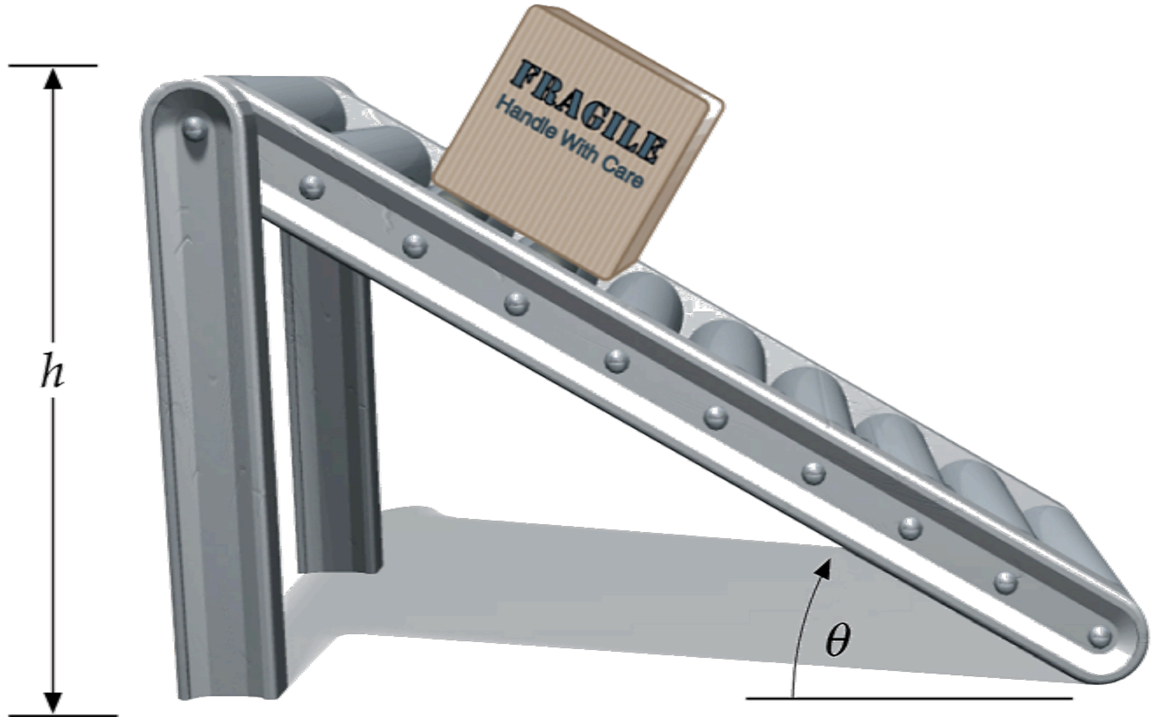
$$\tan\theta = a_x/g$$

$$a_x = g\tan\theta = 3.96 \text{ m/s}^2$$

$$T = mg/\cos\theta = 0.42 \text{ N}$$

Unloading a truck

You are working for a big delivery company and must unload large fragile package from your truck using a delivery ramp



If downward component of velocity of package when it reaches bottom of ramp is greater than 2.5 m/s package will break

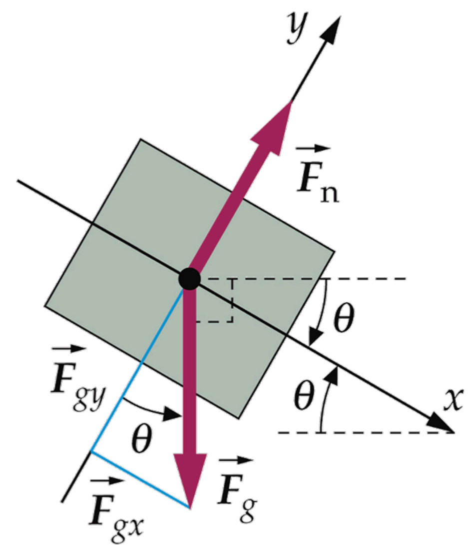
What is largest angle you can safely unload? Ramp is 1 m high

$$F_g \sin\theta = mg\sin\theta = ma_x \Rightarrow a_x = g\sin\theta$$

$$F_n - F_g\cos\theta = 0$$

$$v_x = a_x t$$

$$\Delta x = \tfrac{1}{2}a_x t^2 \Rightarrow t = \sqrt{2\Delta x / a_x}$$



$$\Delta x \, \sin\theta = h \Rightarrow v_x = \sqrt{2\Delta x g \sin\theta} = \sqrt{2gh}$$

$$v_{\text{downward}} = v_x \sin\theta = \sqrt{2gh}\sin\theta$$

$$\sin\theta = \frac{v_{\text{downward}}}{\sqrt{2gh}} \Rightarrow \theta_{\text{max}} = 34.4^\circ$$

Newton's Third Law

When two bodies interact, force $\vec{F}_{BA}$ exerted by object B on object A is equal in magnitude an opposite in direction to force $\vec{F}_{AB}$ exerted by object A on object B

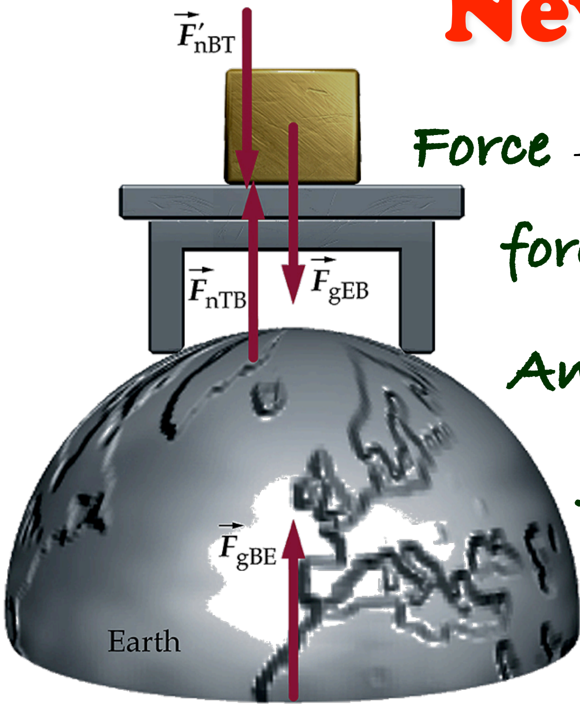
$$\vec{F}_{BA} = -F_{AB}$$

It is common to refer to one force in pair as an action and other one as reaction

This terminology is unfortunate because it sounds like one force "reacts" to other that is not case

Two forces occur simultaneously

Newton's Third Law



Force $\vec{F}_{gEB}$ acting downward on block is gravitional force by Earth on block

An equal and opposite force $\vec{F}_{gBE}$ is gravitional force exerted on Earth by block

These forces form an action-reaction pair

If they were only forces present block would accelerate downward because it will have only a single force acting on it (and Earth would accelerate upward from same reason)

Upward force $\vec{F}_{nTB}$ by table on block balances gravitional force on block

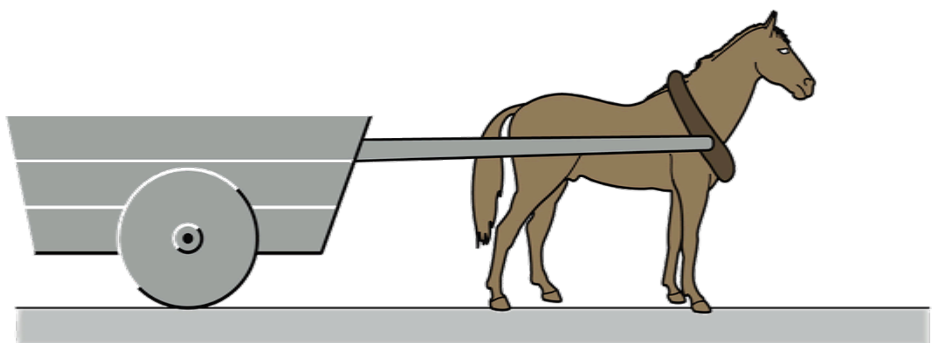
There is also a downward force $\vec{F}_{nBT}$ by block on table

Horse before cart

A horse refuses to pull a cart

Horse reasons:

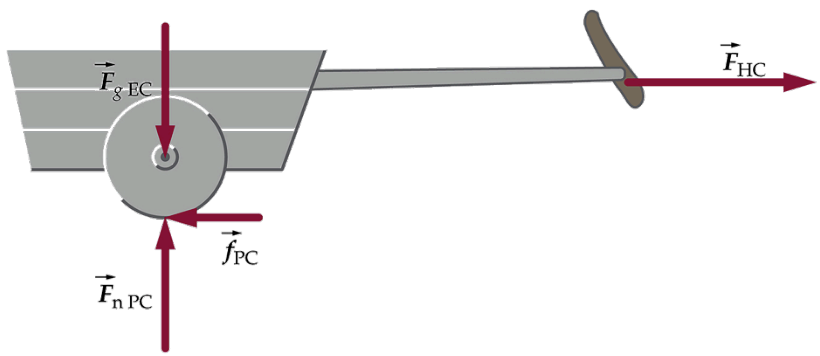
"According to Newton's third law, whatever force I exert on cart, cart will exert an equal and opposite force on me, so net force will be zero and I will have no chance of accelerating cart"

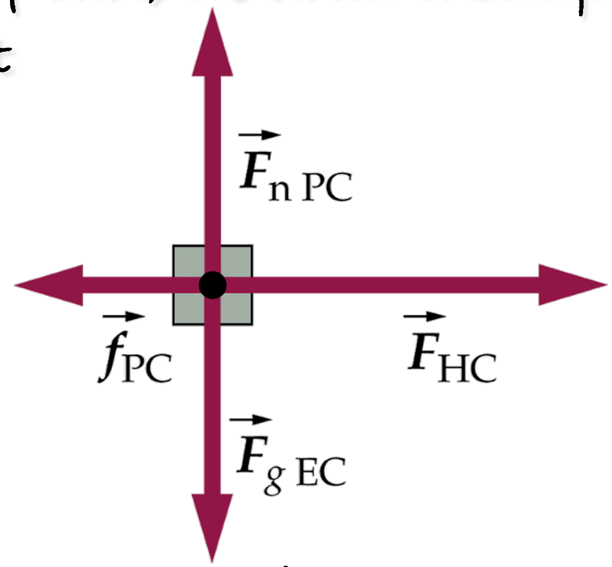


What is wrong with this reasoning?

Horse before cart (cont'd)

Because we are interested in motion of cart, we draw a simple diagram for it





Force exerted by horse on cart, is actually exerted on harness

Because harness is attached to cart, we consider it part of cart

Other forces acting are the gravitational force of the Earth on cart normal force of pavement on cart and frictional force exerted by pavement on cart

Because cart doesn't accelerate vertically → vertical forces must sum to 0

Cart will accelerate to right if force exerted by horse on cart is greater than frictional force

Horse before cart (cont'd)

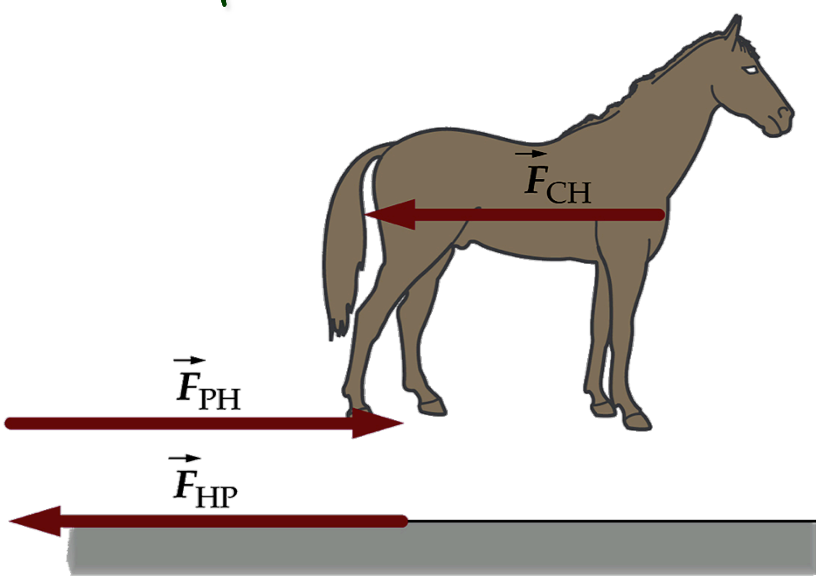
Note that reaction to $\vec{F}_{HC}$ (which we call $\vec{F}_{CH}$)

is exerted on horse not on cart

Because reaction force is exerted on horse

it has no effect on motion of cart

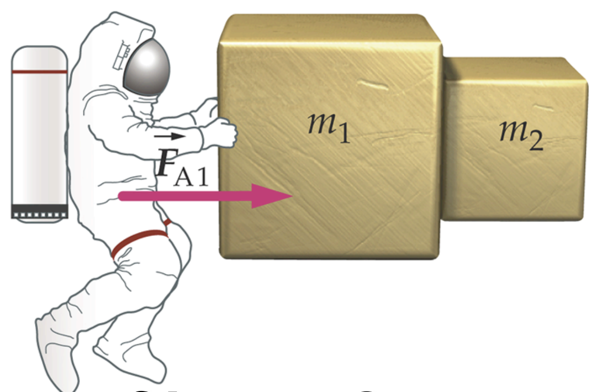
This is flaw in horses reasoning



Building a space station

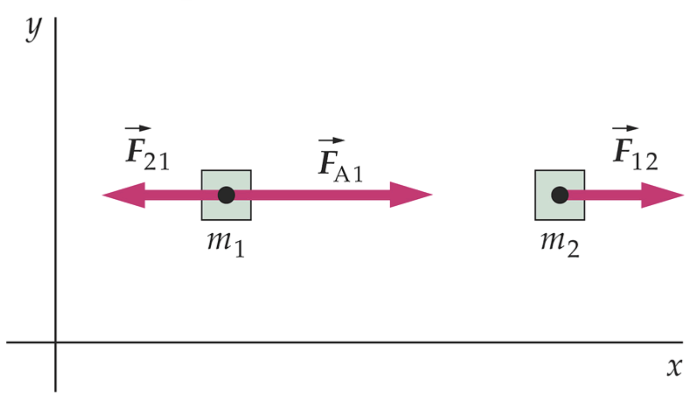
You are an astronaut constructing a space station, and you push a box of mass m with force A1.

Box is in direct contact with a second box of mass m

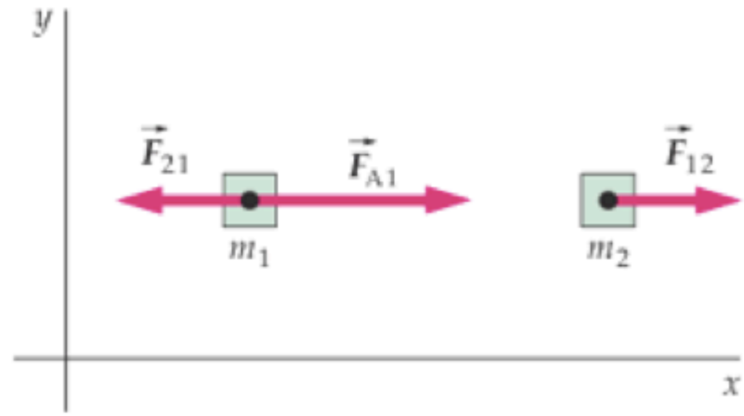


(a) What is acceleration of boxes?

(b) What is magnitude of force each box exerts on other?



Draw free body diagram for two boxes



$$\text{Apply } \sum \vec{F} = m\vec{a} \text{ to box 1} \Rightarrow F_{A1} - F_{21} = m_1 a_{1_x}$$

$$\text{Apply } \sum \vec{F} = m\vec{a} \text{ to box 2} \Rightarrow F_{12} = m_2 a_{2_x}$$

Accelerations are equal because speeds are equal at all times so rate of change of speeds are equal

$$a_{1_x} = a_{2_x}$$

$$\text{Newton 3rd law force pair} \Rightarrow F_{21} = F_{12} = F$$

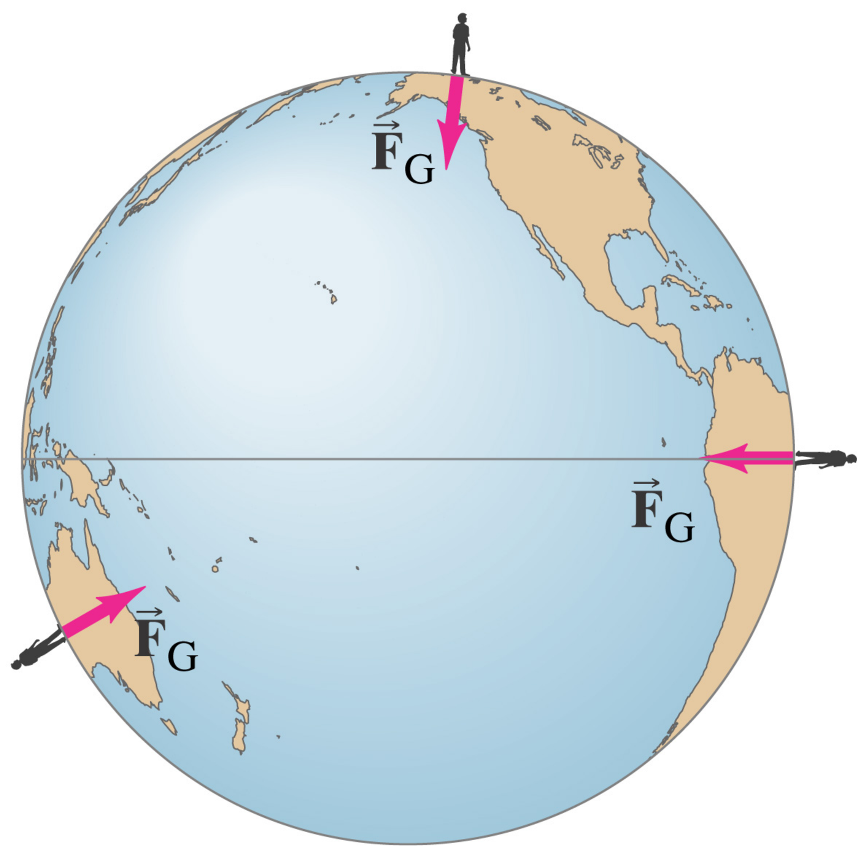
$$a_x = \frac{F_{A1}}{m_1 + m_2} \qquad F = \frac{m_2}{m_1 + m_2} F_{A1}$$

Newton's Law of Universal Gravitation

If force of gravity is being exerted on objects on Earth,
what is origin of that force?

Newton's realization was that force must come from Earth

He further realized that this force must be what keeps Moon in its orbit

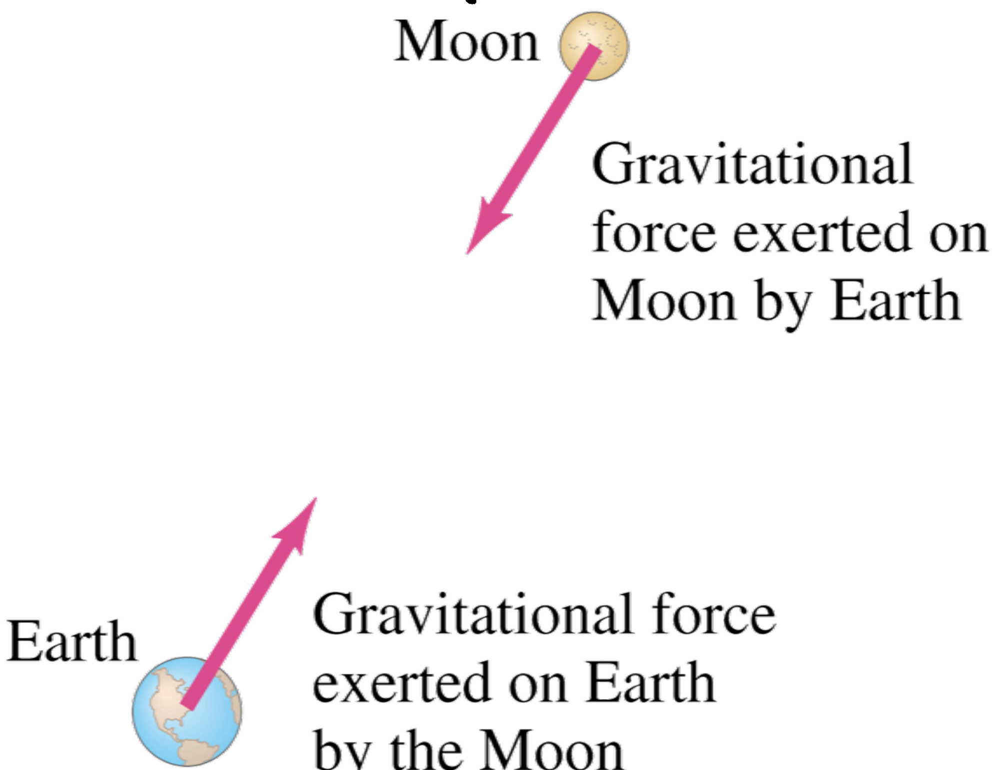


Newton's Law of Universal Gravitation

Gravitational force on you is one-half of a Third-Law pair:

Earth exerts a downward force on you and you exert an upward force on Earth

When there is such disparity in m's reaction force undetectable but for bodies more equal in mass it can be significant



Newton's Law of Universal Gravitation

Gravitational force must be proportional to both masses

By observing planetary orbits

Newton also concluded that gravitational force must decrease

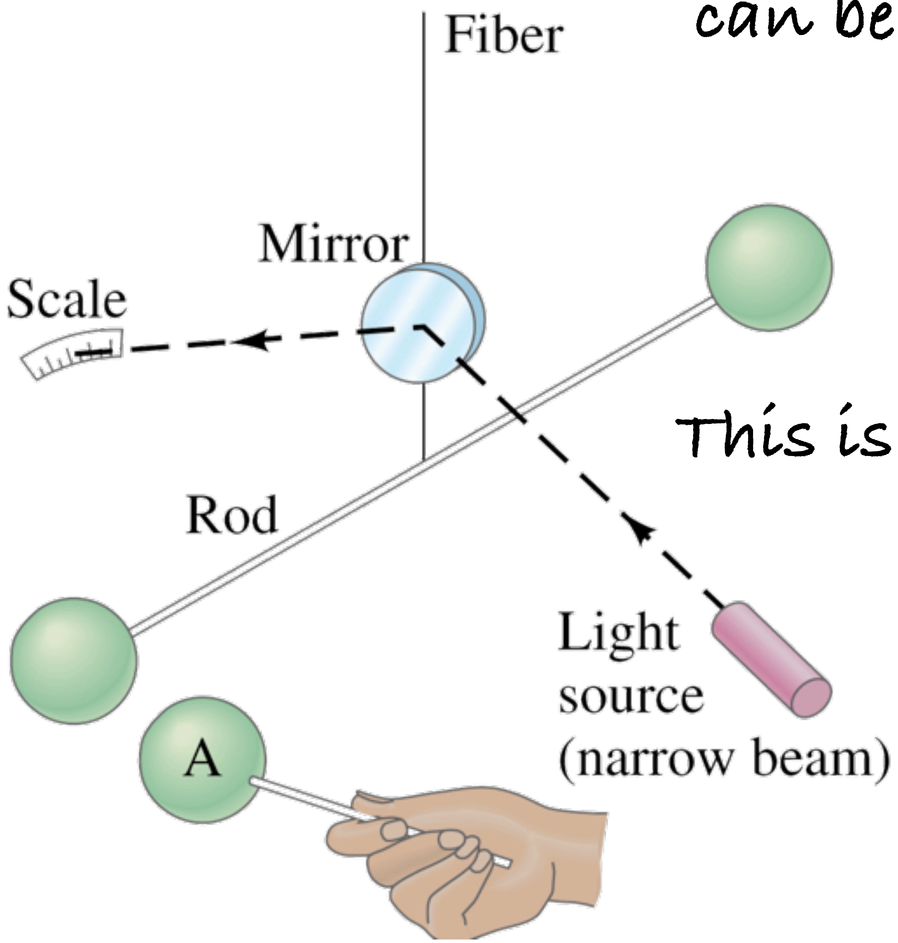
as inverse of square of distance between masses

In its final form Law of Universal Gravitation reads:

$$\vec{F}_{12} = G \frac{m_1 m_2}{r_{12}^2} \hat{r}_{12}$$

Newton's Law of Universal Gravitation

Magnitude of gravitational constant G can be measured in laboratory



This is ☛ **Cavendish experiment**

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

Gravity Near Earth's Surface: Geophysical Applications

Relate gravitational constant to local acceleration of gravity

We know that, on surface of Earth

$$mg = G\frac{m\,m_E}{r_E^2}$$

Solving for g gives

$$g = G\frac{m_E}{r_E^2}$$

Knowing g and radius of Earth, mass of Earth can be calculated:

$$m_E = \frac{gr_E^2}{G} = \frac{(9.80\ m/s^2)(6.38\ \times\ 10^6\ m)^2}{6.67\ \times\ 10^{-11}\ N\ \cdot\ m^2/kg^2} = 5.98\ \times\ 10^{24}\ kg$$

Gravity Near Earth's Surface: Geophysical Applications

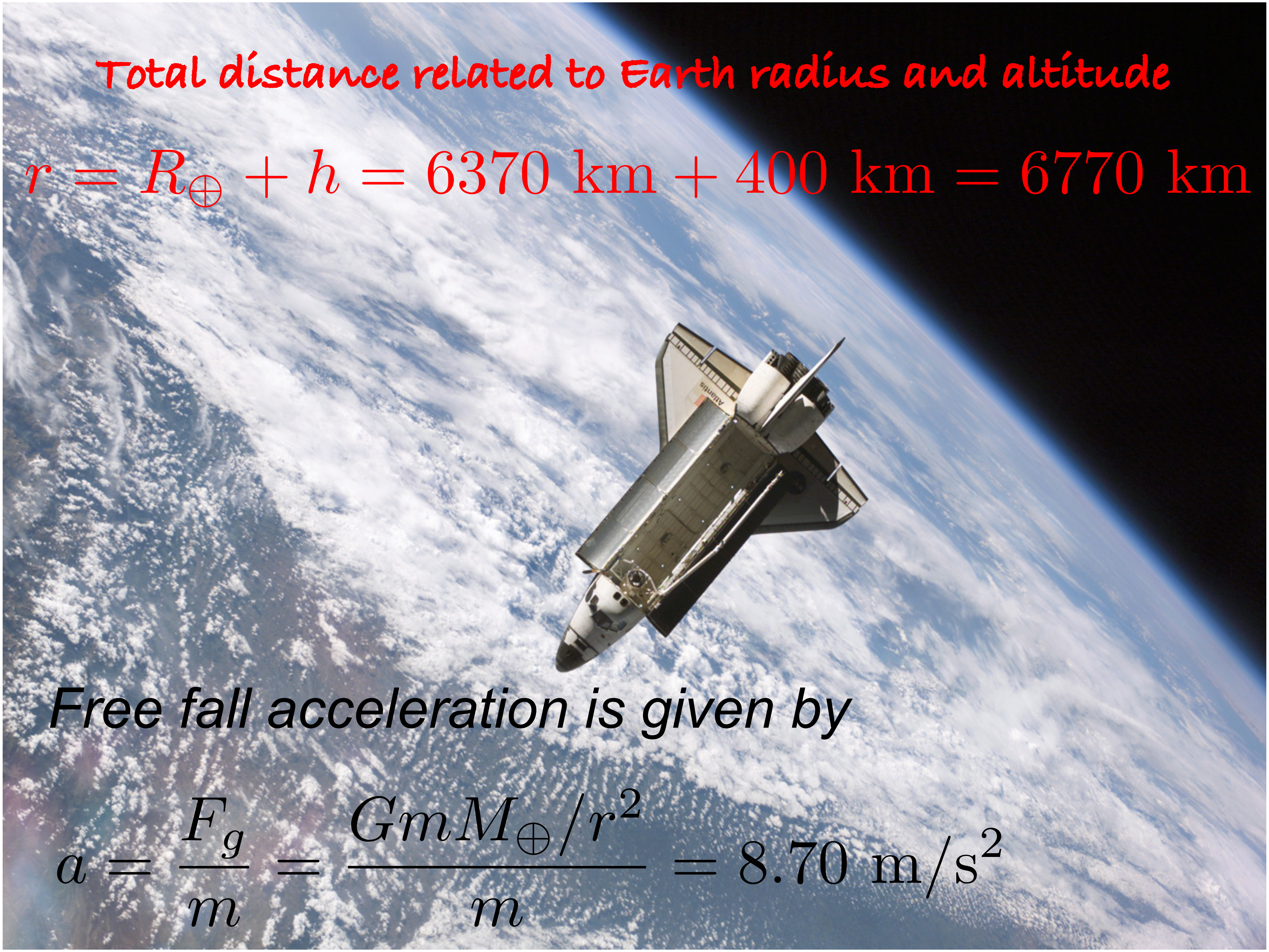
Acceleration due to gravity varies over Earth's surface due to altitude, local geology, and shape of Earth, which is not quite spherical

Acceleration Due to Gravity at Various Locations on Earth

Location	Elevation (m)	g (m/s^2)
New York	0	9.803
San Francisco	0	9.800
Denver	1650	9.796
Pikes Peak	4300	9.789
Sydney, Australia	0	9.798
Equator	**0**	**9.780**
North Pole	0	9.832

Falling to Earth

What is acceleration of an object at altitude of space shuttle's orbit, above 400 km above Earth surface



Total distance related to Earth radius and altitude

$$r = R_{\oplus} + h = 6370 \text{ km} + 400 \text{ km} = 6770 \text{ km}$$

Free fall acceleration is given by

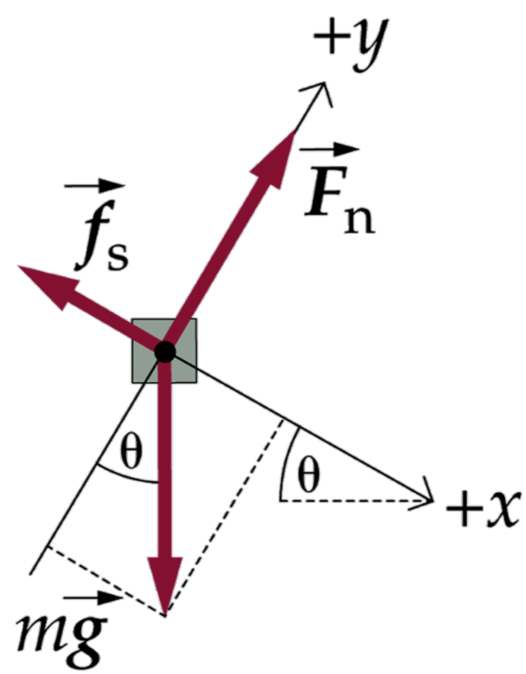
$$a = \frac{F_g}{m} = \frac{GmM_{\oplus}/r^2}{m} = 8.70 \text{ m/s}^2$$

A sliding coin

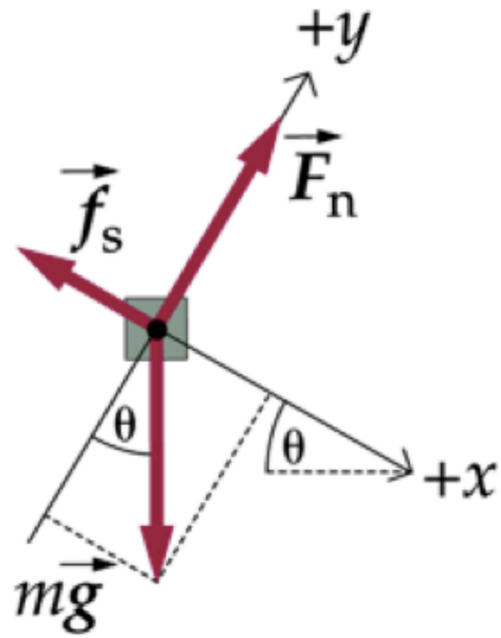
A hard cover book is resting on a tabletop with its front cover facing upward

You place a coin on this cover and very slowly open book until coin starts to slide

Angle θ_{max} (known as the angle of repose) is angle front cover makes with horizontal just as coin starts to slide.



Draw free body diagram for coin when book cover inclined @ $\theta \le \theta_{\mathrm{max}}$



Coefficient of static friction relates frictional and normal forces according to $f_{\mathrm{s}} \le \mu_{\mathrm{s}} F_{\mathrm{n}}$

Apply $\sum F_y = ma_y \Rightarrow F_n - mg\cos\theta = 0 \Rightarrow F_n = mg\cos\theta$

$$f_{\mathrm{s}} \le \mu_{\mathrm{s}} F_{\mathrm{n}} \Rightarrow f_{\mathrm{s}} \le \mu_{\mathrm{s}} mg\cos\theta$$

Apply $\sum F_x = ma_x \Rightarrow -f_{\mathrm{s}} + mg\sin\theta = 0 \Rightarrow f_{\mathrm{s}} = mg\sin\theta$

$$\tan\theta \le \mu_{\mathrm{s}} \Rightarrow \mu_{\mathrm{s}} = \tan\theta_{\mathrm{max}}$$