Newtonian Dynamics

Luis Anchordoqui

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 the basis of classical mechanics

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

II. The acceleration of an object is directly proportional to the net force acting on it, and the mass of the object is the constant of proportionality

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

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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

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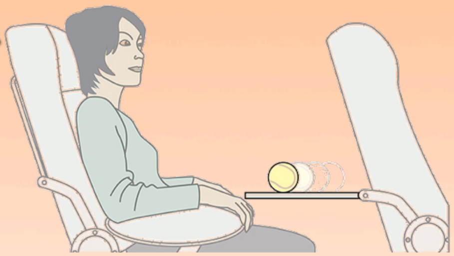
Inertial Reference Frames

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 the plane, the ball will remain at rest as long as the plane continues to fly at constant velocity relative to the ground. Relative to the ground, the ball remains moving with the same velocity as the plane.

Now, suppose the plane suddenly accelerates forward relative to ground. You will observe the ball starts to roll toward the rear of the plane, accelerating relative to the plane even though there is no horizontal force acting on it.



In this accelerating reference frame of the 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 the acceleration of the object remains zero is an inertial reference frame

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Force

Using Newton's first law and the concept of inertial reference frame, we can define a force as an external influence or action on an object that causes the object to change velocity → to accelerate relative to an inertial reference frame.

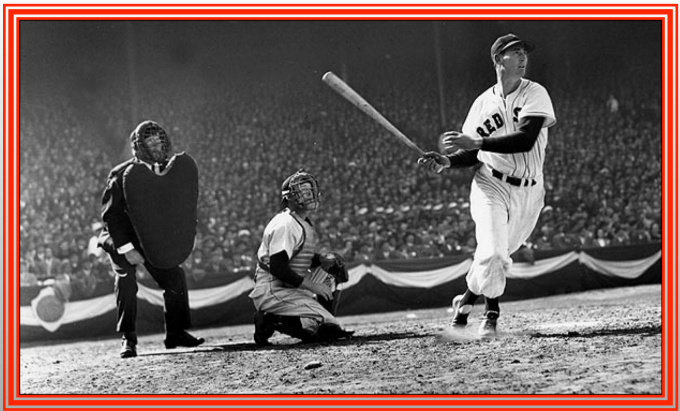
Force is a vector quantity → it has both magnitude and direction

Force unit → $[N]=[kg\ m/s^2]$

Forces are exerted on objects by other objects.

Forces that are due to one object being physically touched by a second object are known as contact forces.

Example → a bat hitting a ball



Forces that act on an object without direct physical contact with a second object are referred to as action-at-a-distance forces.

Example → gravity

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The fundamental interactions in nature

• Gravitational interaction: the long range interaction between particles due to their mass. This interaction is mediated by gravitons.

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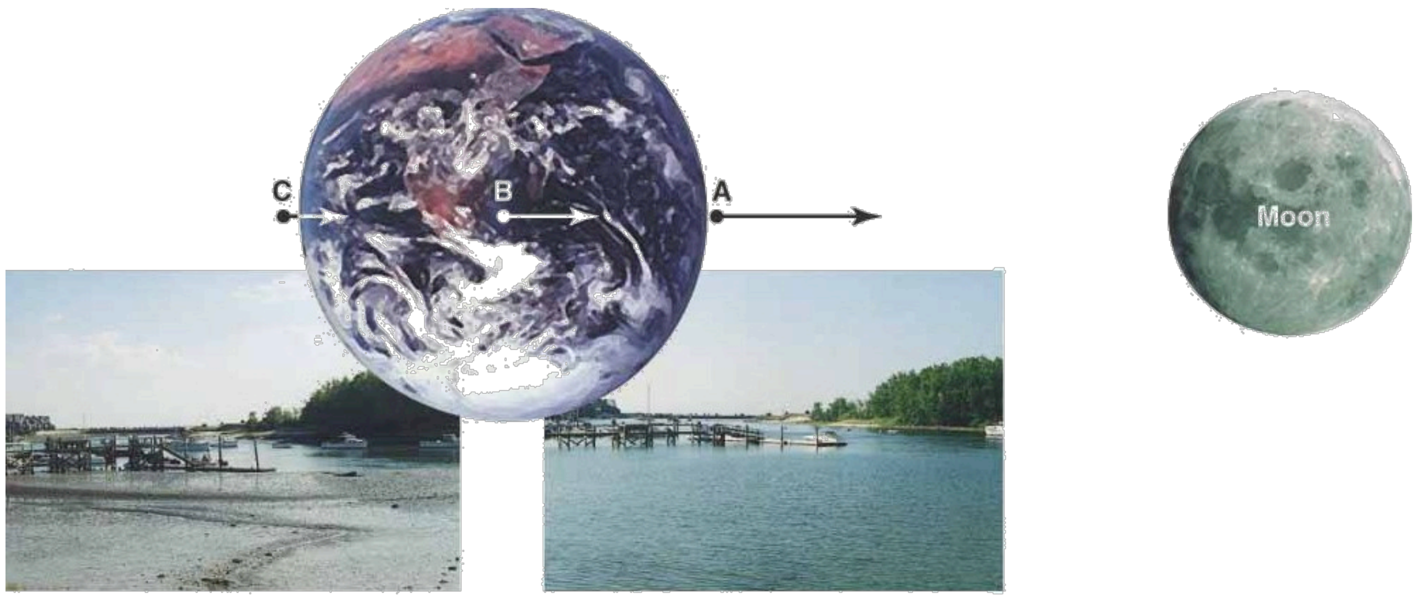

Low tide (as at point B)   High tide (as at points A and C)

The gravitational interaction between Earth and Moon keeps the Moon in its nearly circular orbit around the Earth.
The gravitational forces exerted by the Moon and the Sun on the oceans produce tides

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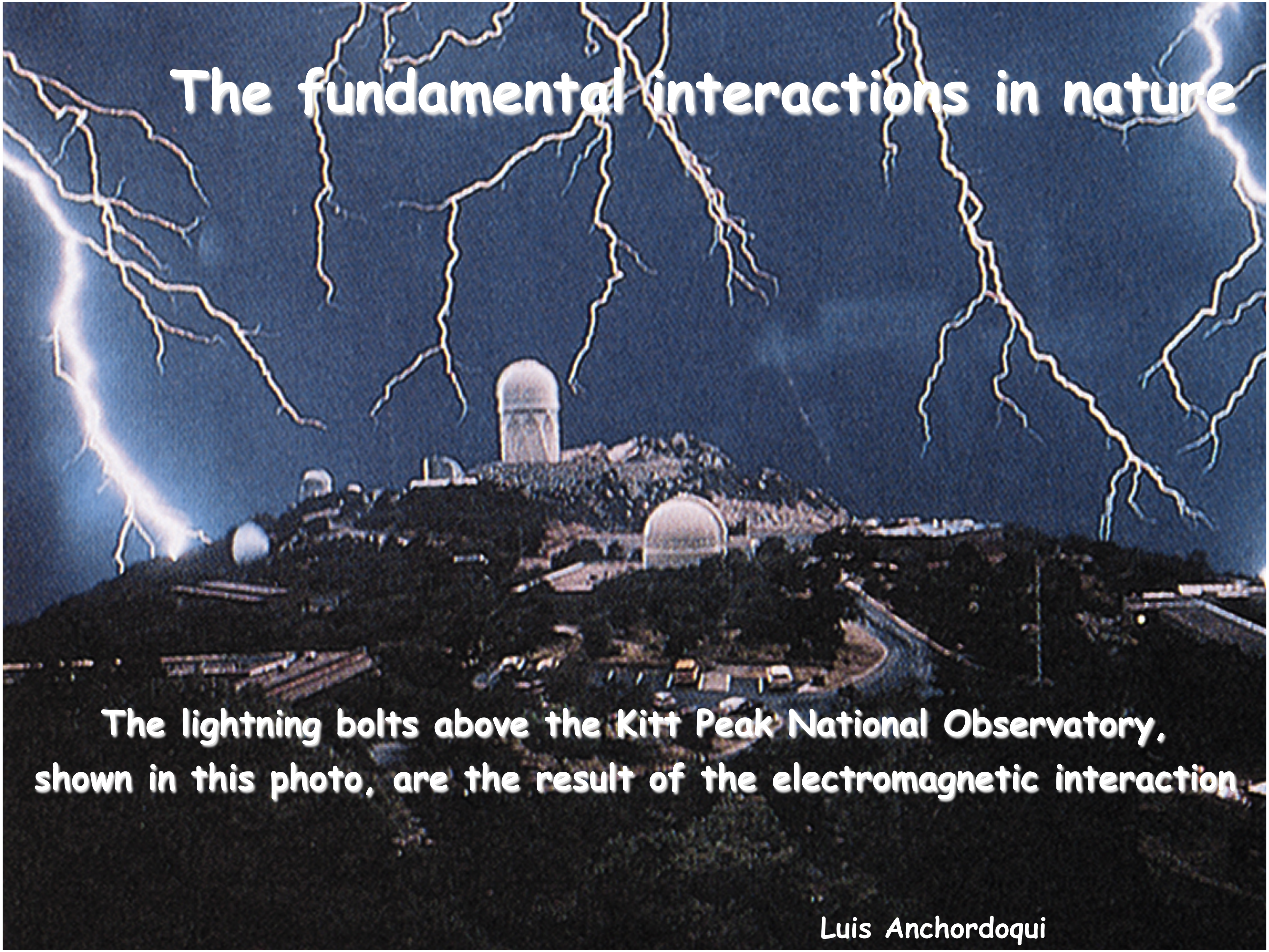
The fundamental interactions in nature

• Gravitational interaction: the long range interaction between particles due to their mass. This interaction is mediated by gravitons.

• Electromagnetic interaction: the long range interaction between electrically charged particles involving the exchange of photons.


The fundamental interactions in nature
The lightning bolts above the Kitt Peak National Observatory,
shown in this photo, are the result of the electromagnetic interaction
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The fundamental interactions in nature

• Gravitational interaction: the long range interaction between particles due to their mass. This interaction is mediated by gravitons.

• Electromagnetic interaction: the long range interaction between electrically charged particles involving the exchange of photons.

• Weak interaction: the extremely short range (10^{-18} m) interaction between subnuclear particles involving the exchange or production of W and Z bosons.
The electromagnetic and weak interactions are now viewed as a single unified interaction called the electroweak interaction.

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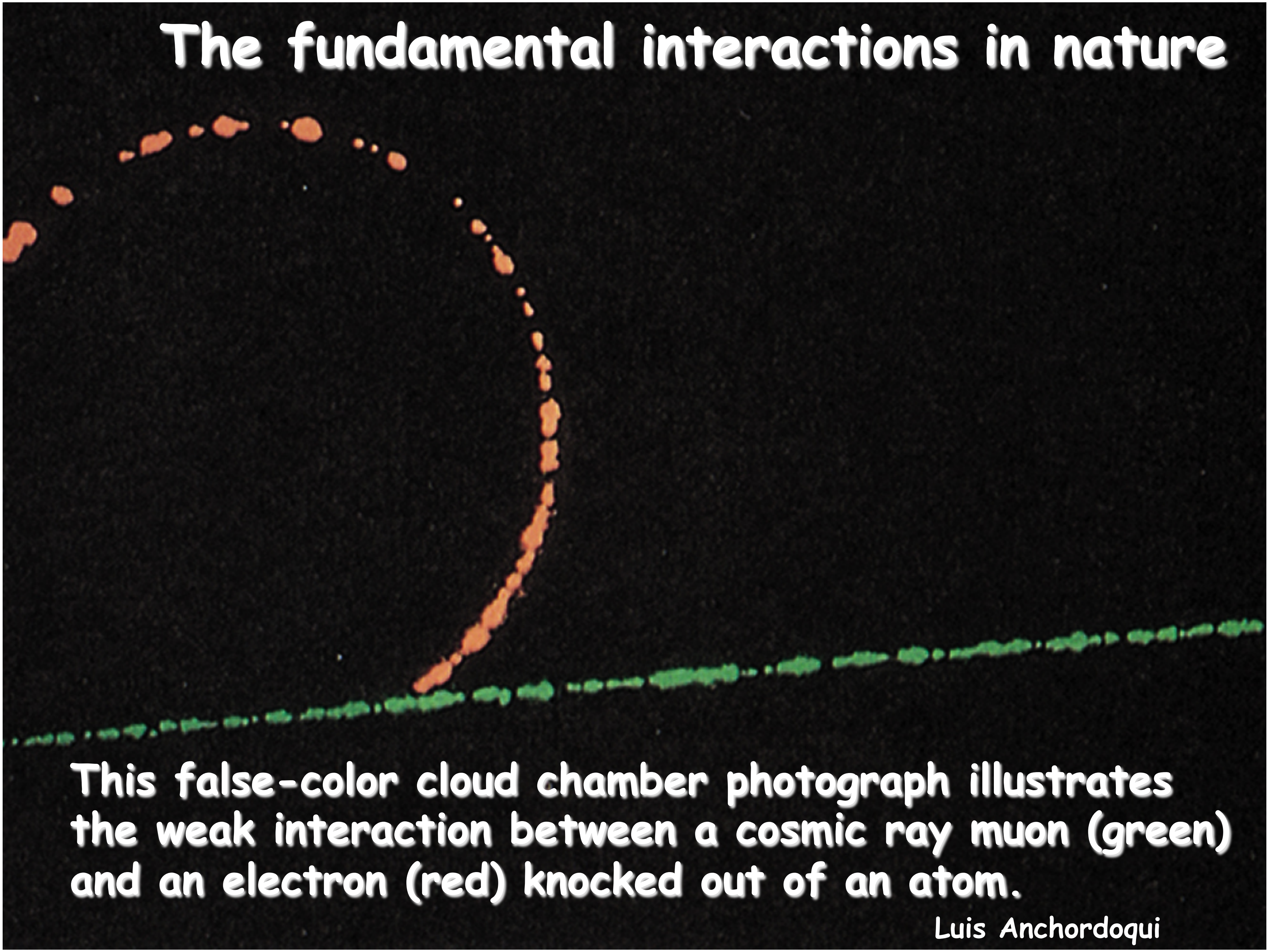
The fundamental interactions in nature



This false-color cloud chamber photograph illustrates the weak interaction between a cosmic ray muon (green) and an electron (red) knocked out of an atom.

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The fundamental interactions in nature

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- Strong interaction: the short range (10^{-15} m) interaction between hadrons, which themselves consist of quarks, that binds protons and neutrons together to form the atomic nuclei. It involves the exchange of gluons between quarks.

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The fundamental interactions in nature

The hydrogen bomb explosion shown here illustrates the strong nuclear interaction

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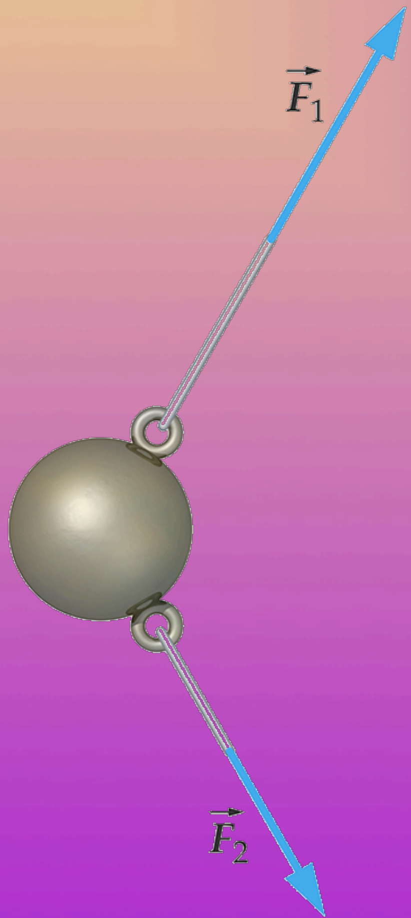
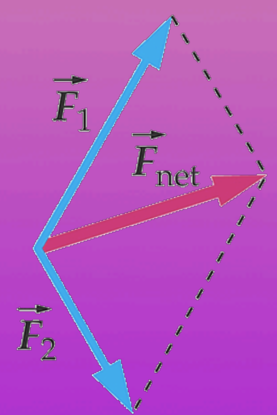
Combining forces

If two or more individual forces simultaneously act on an object, the result is as if a single force, equal to the sum of the individual forces, acts in place of the individual a forces





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Mass

Objects intrinsically resist being accelerated.
Imagine kicking both a soccer ball and a bowling ball.
The bowling ball resist being accelerated much more than does the soccer ball $\longrightarrow$ as would be evidenced by your sore toes.
This intrinsic property is called the object's mass.
It is a measure of the object's inertia

The greater an object's mass
the more the object resists being accelerated

Newton's second law

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

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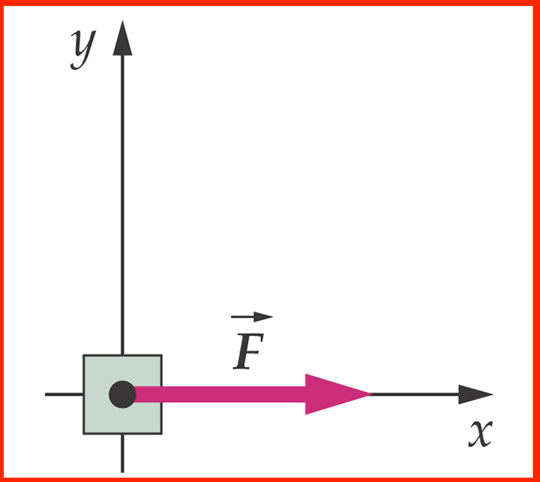
A Walk in Space

You're stranded in space away from your spaceship. Fortunately, you have a propulsion unit that provides a constant net force for 3 s.
After 3 s, you have moved 2.25 m.
If your mass is 68 kg, find the magnitude and direction of the force.

We choose the x-direction to be in the direction of the force

$$\vec{F} = F_x \, \hat{i} \rightarrow F_x = m a_x$$



$$\vec{F} = 34 \text{ N} \, \hat{i}$$

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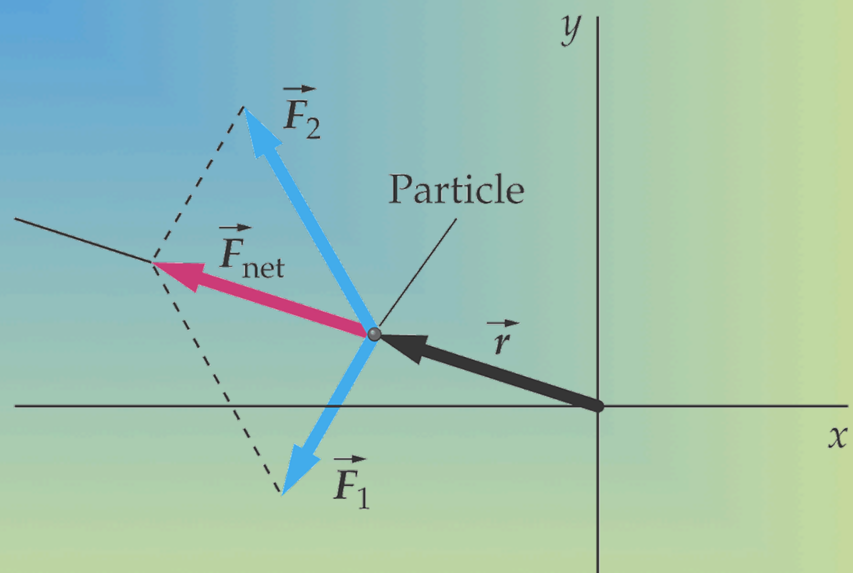
A particle subjected to Two Forces

A particle of mass 0.400 kg is subjected simultaneously to two forces

$$\vec{F}_1 = -2.00\ \mathrm{N}\,\hat{\imath} - 4.00\ \mathrm{N}\,\hat{\jmath} \text{ and } F_2 = -2.60\ \mathrm{N}\,\hat{\imath} + 5.00\ N\,\hat{\jmath}$$



If the particle is at the origin and starts at rest at t =0 find

(a) Its position $\vec{r}$ at t = 1.60 s

$$\vec{r} = -14.7\ \mathrm{m}\,\hat{\imath} + 3.20\ \mathrm{m}\,\hat{\jmath}$$

(b) Its velocity $\vec{v}$ at t = 1.60 s

$$\vec{v}(1.6\ \mathrm{s}) = -18.4\ \mathrm{m/s}\,\hat{\imath} + 4.00\ \mathrm{m/s}\,\hat{\jmath}$$

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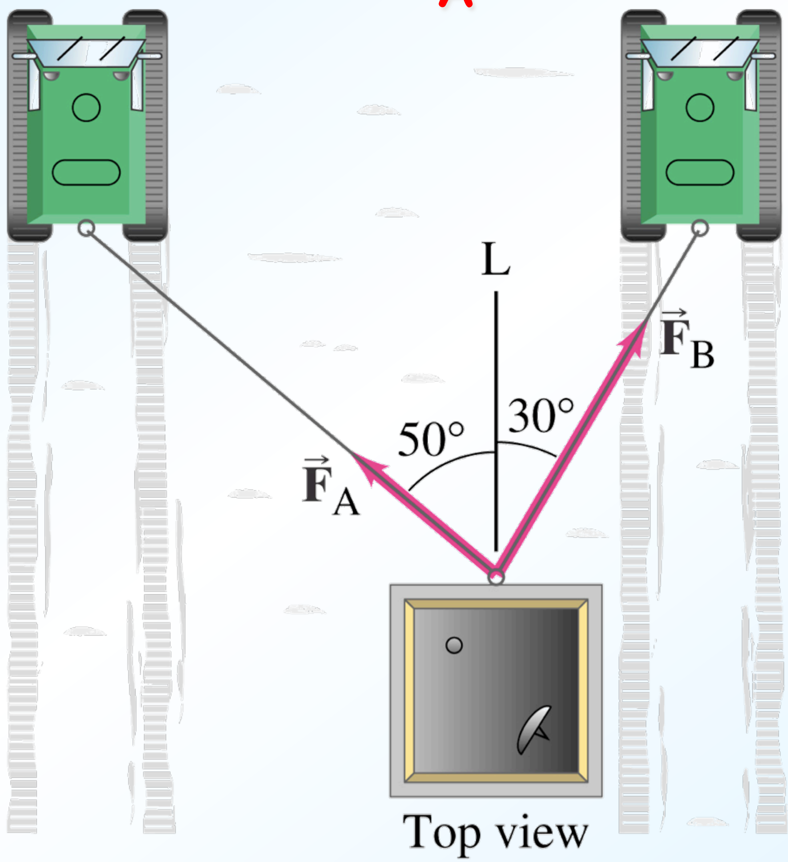
Two snowcats tow a housing unit to a new location at the IceCube base in Antarctica.

The sum of the forces exerted on the unit by the horizontal cables is parallel to the line L, and F_A = 4500 N. Determine F_B .



F_B = 6900 N

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Weight

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

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

The force causing this acceleration is the gravitational force exerted by the Earth on the object

The weight of the object is the magnitude of the gravitational force on it

If the gravitational force is the only force acting on an object the 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 the gravitational force

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

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

$g = 9.81\ N/kg = 9.81\ m/s^2 = 32.2\ ft/s^2$ Luis Anchordoqui

Contact Forces: Normal Force

If a surface is pushed against, it pushes back

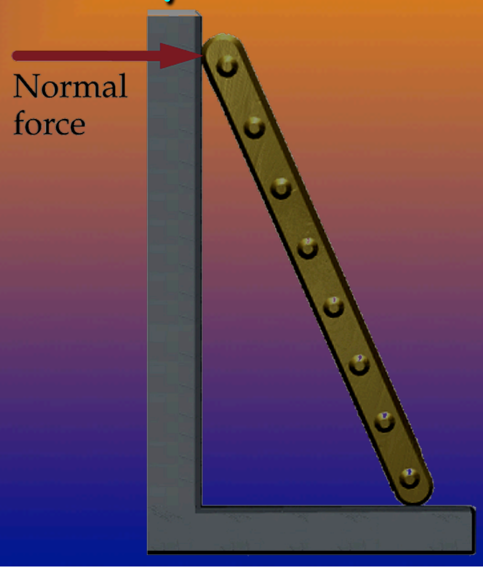
Consider a ladder leaning against a wall

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

The compressed molecules in the wall pushes back on the ladder with a horizontal force

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

The wall bends slightly in response to a load though this is rarely noticeable to the unaided eye



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Contact forces: Frictional force

Surfaces in contact can exert forces on each other
that are parallel to the contacting surfaces
Consider a large block on the floor as shown in the figure

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

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

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

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

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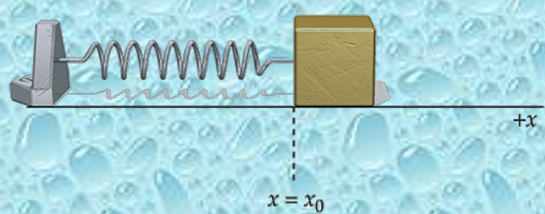
Contact Forces: springs

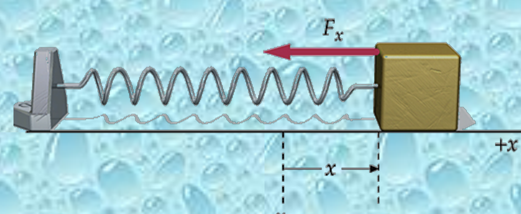
Hooke's Law

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

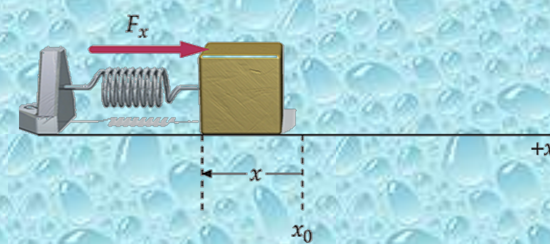
the positive constant k (or spring constant) is a measure of the stiffness of the spring



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



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



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

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

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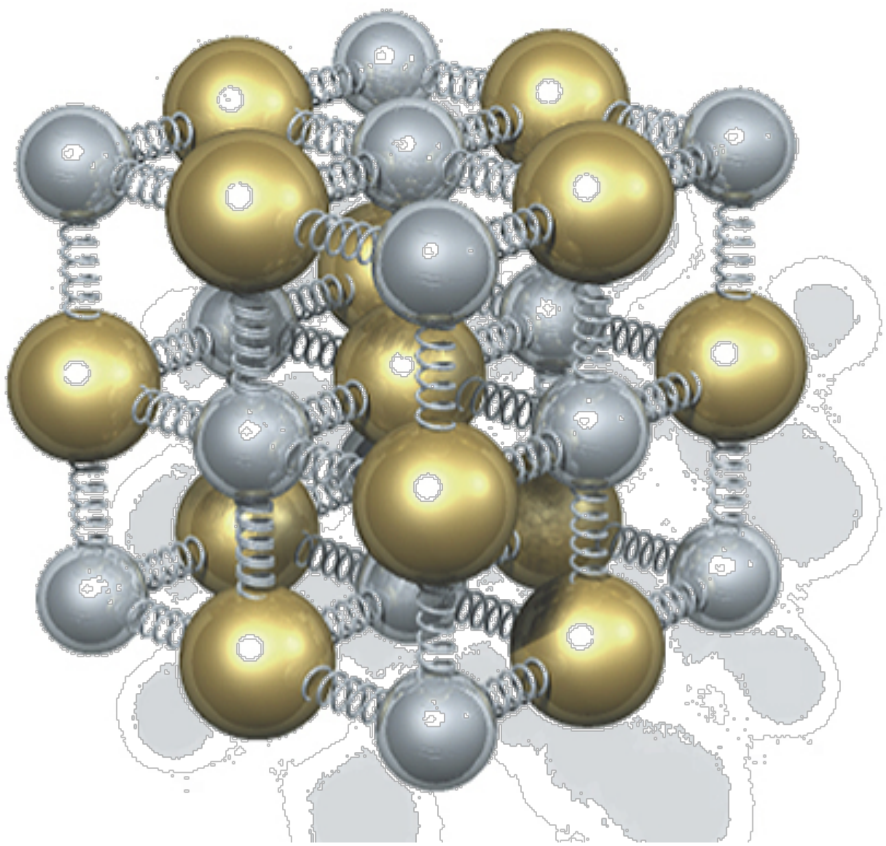
Solids

The molecular force of attraction between atoms in a molecule or solid varies much like that of a spring.
We can therefore use two masses on a spring to model a diatomic molecule, or a set of masses connected by springs to model a solid



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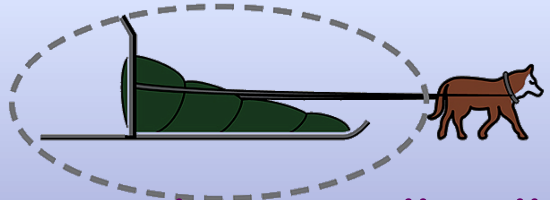
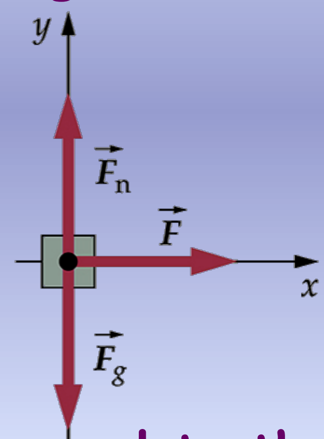
Free body diagramans

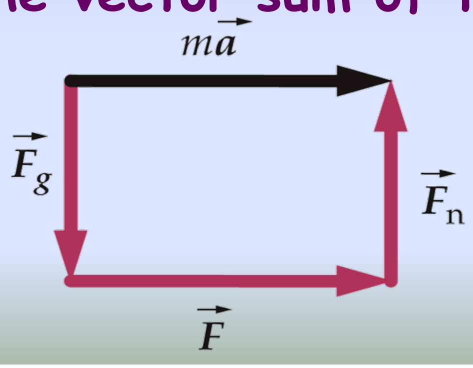
Imagine a sled being pulled across icy ground by a led dog.
The dog pulls on a rope attached to the sled with a horizontal force causing the sled to gain speed. (Friction is negligible.)



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



The vector sum of the forces in a free-body diagram is equal to the mass times the acceleration



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A Dogsled Race

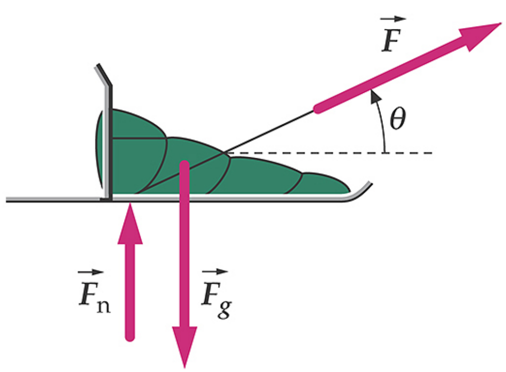
During your winter break, you enter a dogsled race in which students replace dogs.
Wearing cleats for traction, you begin the race by pulling on a rope attached to the sled with a force of 150 N at 25 degrees above the horizontal.

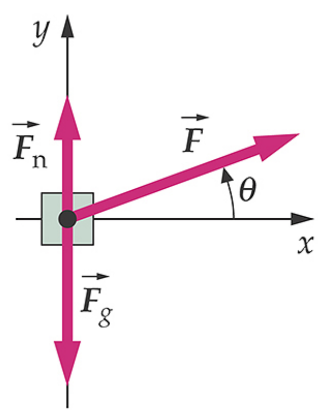
The mass of the sled-passenger-rope particle is 80 kg
and
there is negligible friction between the sled runners and the ice.

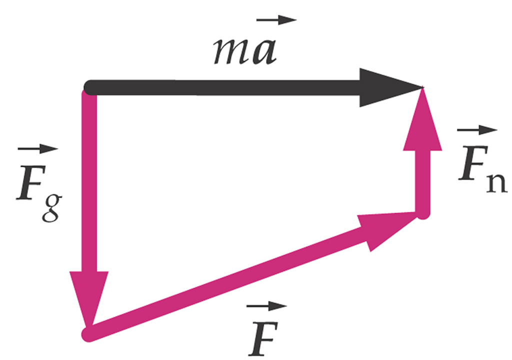
(a) Find the acceleration of the sled $a_x = 1.7\ m/s^2$

(b) find the magnitude of the normal force exerted by the surface on the sled

$F_n = 720$ N







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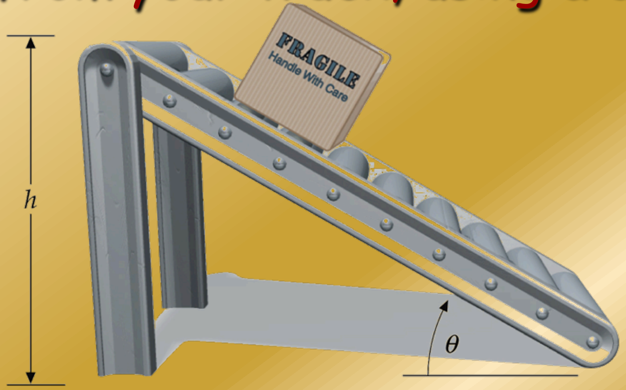
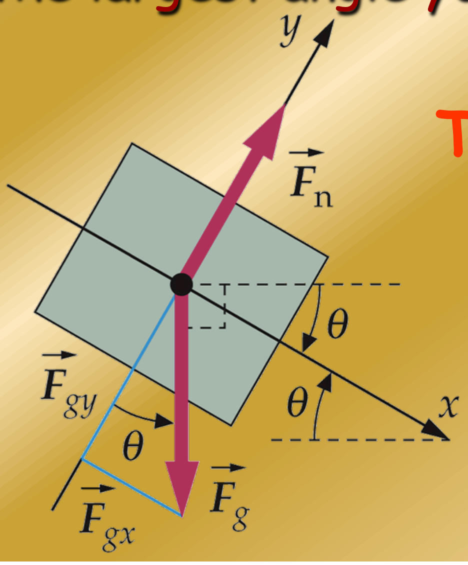
Unloading a Truck

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



If the downward component of the velocity of the package when it reaches the bottom of the ramp is greater than 2.5 m/s, the package will break. What is the largest angle you can safely unload? The ramp is 1 m high.



The maximum angle is 34.4 degrees

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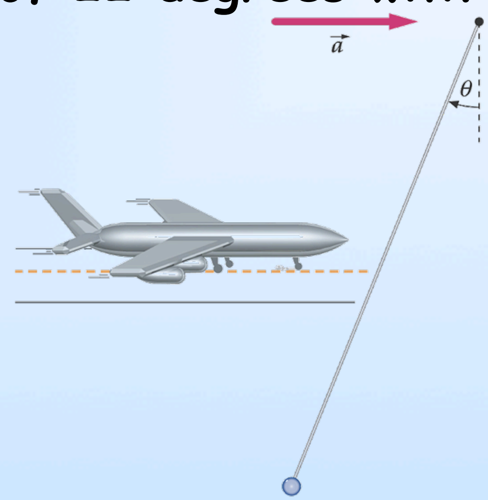
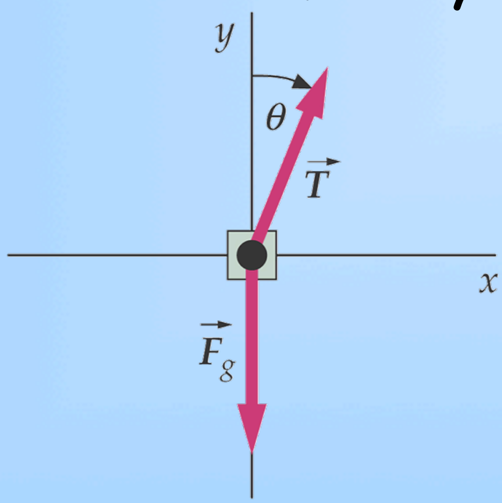
An accelerating jetplane

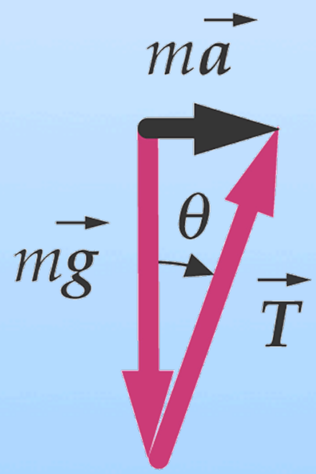
As your jet plane speeds down the runway on takeoff, you decide to determine its acceleration, so you take out your yo-yo and note that when you suspend it, the string makes an angle of 22 degrees with the vertical.



(a)What is the acceleration of the plane?

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





$a_x = 3.96\ m/s^2$

$T = 0.423\ N$

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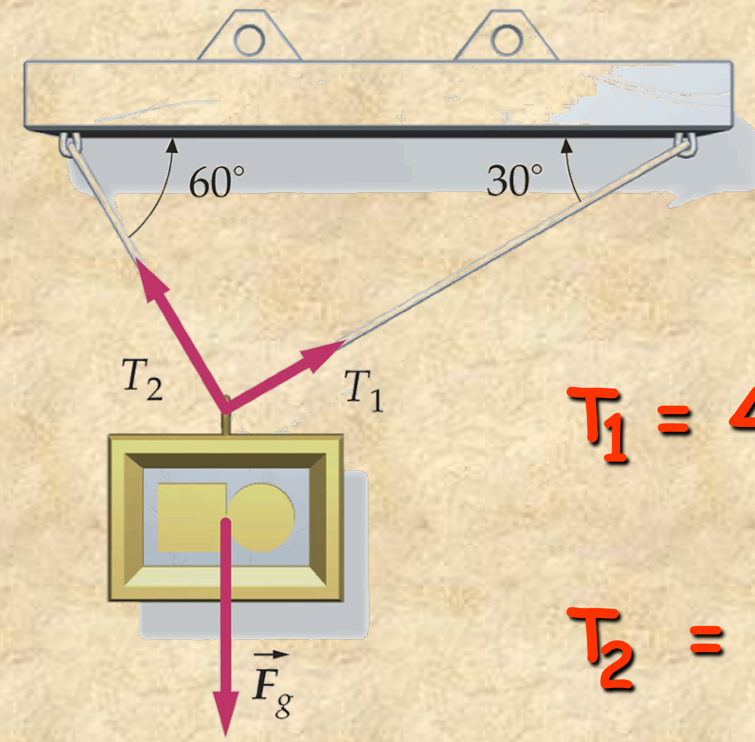
Picture Hanging: 1st Equilibrium Condition

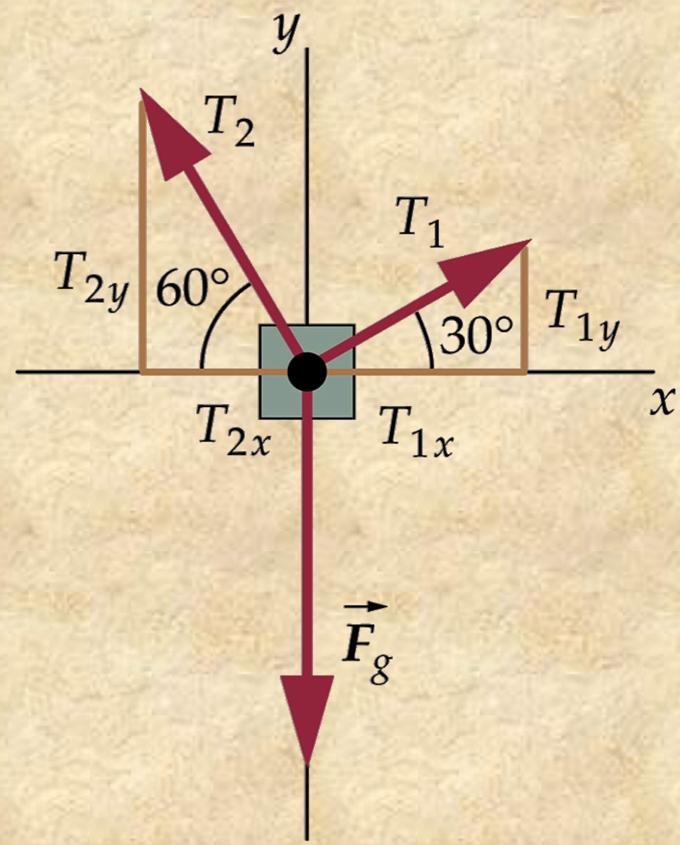
A picture weighing 8.0 N is supported by two wires with tensions T_1 and T_2

Find each tension.



T_1 = 4 N

T_2 = 6.9 N



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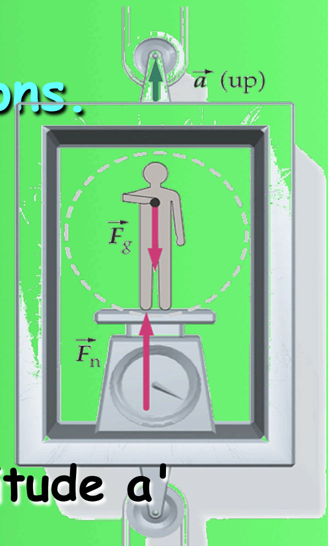
" Weighing " Yourself in an Elevator

Suppose that your mass is 80 kg and you are standing on a scale fastened to the floor of an elevator.

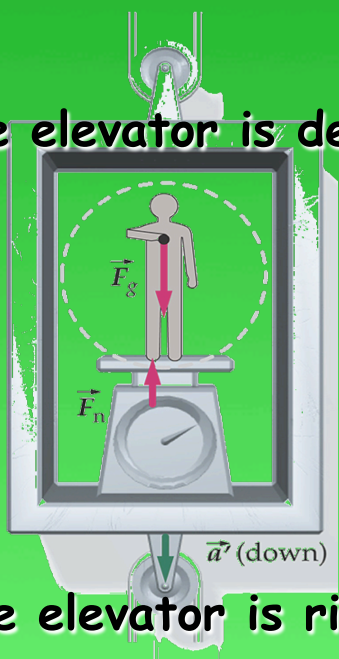
The scale measures force and is calibrated in newtons.

What does the scale reads when



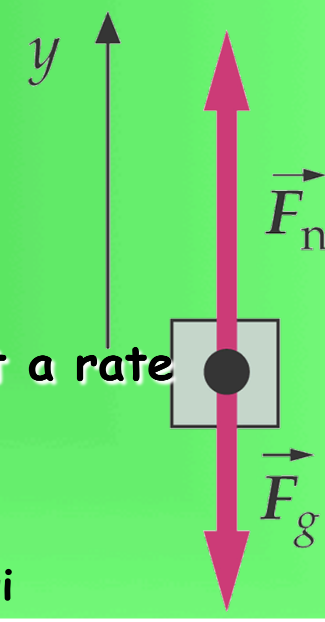
(a) the elevator is rising with upward acceleration of magnitude a

$$F_n = m\,(g+a)$$



(b) the elevator is descending with downward acceleration of magnitude a'

$$F_n = m\,(g-a')$$



(c) the elevator is rising at 20 m/s and its speed is decreasing at a rate of 8.0 m/s^2?

$$F_n = 144.8\ N$$

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Newton's Third Law

When two bodies interact, the force $\vec{F}_{BA}$ exerted by object B on object A is equal in magnitude an opposite in direction to the 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 the pair as an action and the other one as reaction.

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

The two forces occur simultaneously

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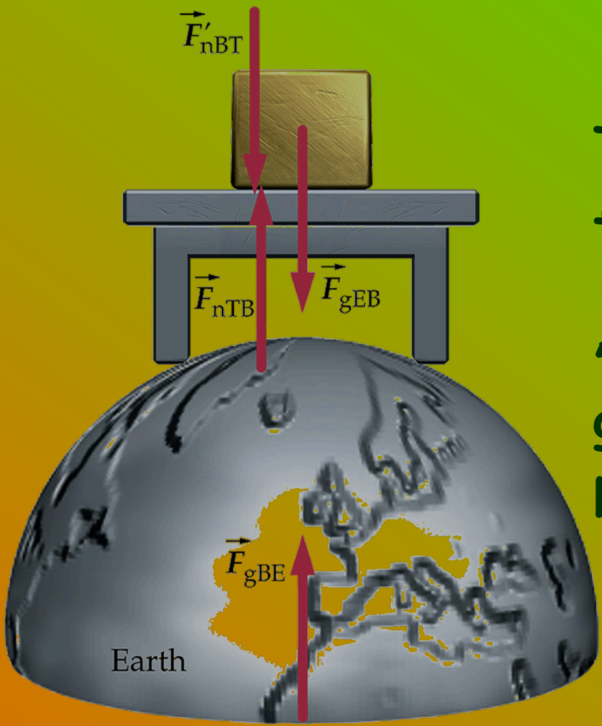
Newton's Third Law



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

An equal and opposite force $\vec{F}_{gBE}$ is the gravitional force exerted on the Earth by the block. These forces form an action-reaction pair

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

The upward force $\vec{F}_{nTB}$ by the table on the block balances the gravitional force on the block

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

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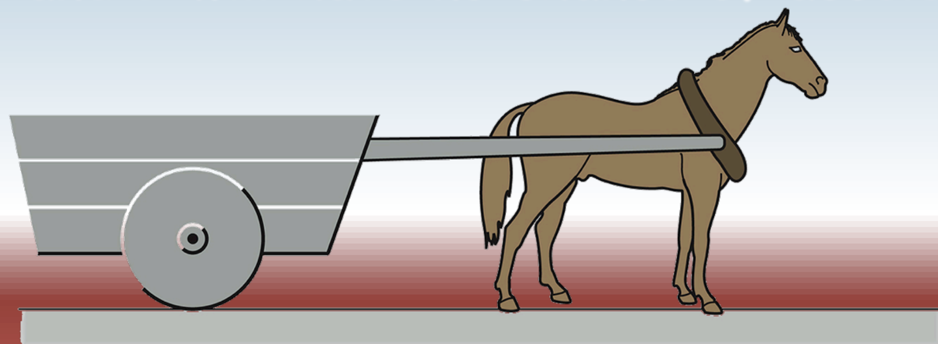
The Horse Before the Cart

A horse refuses to pull a cart. The horse reasons:
"According to Newton's third law, whatever force I exert on the cart, the cart will exert an equal and opposite force on me, so the net force will be zero and I will have no chance of accelerating the cart"



What is wrong with this reasoning?

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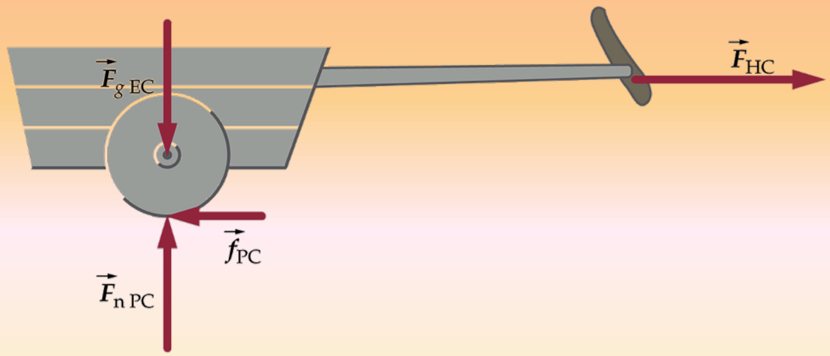
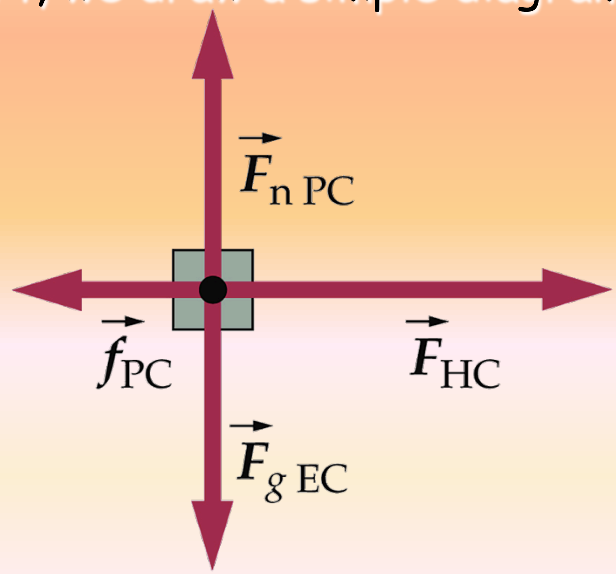
The Horse Before the Cart (cont'd)

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





The force exerted by the horse on the cart, is actually exerted on the harness. Because the harness is attached to the cart, we consider it part of the cart.

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

Because the cart doesn't accelerate vertically➔ the vertical forces must sum to zero

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

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The Horse Before the Cart (cont'd)

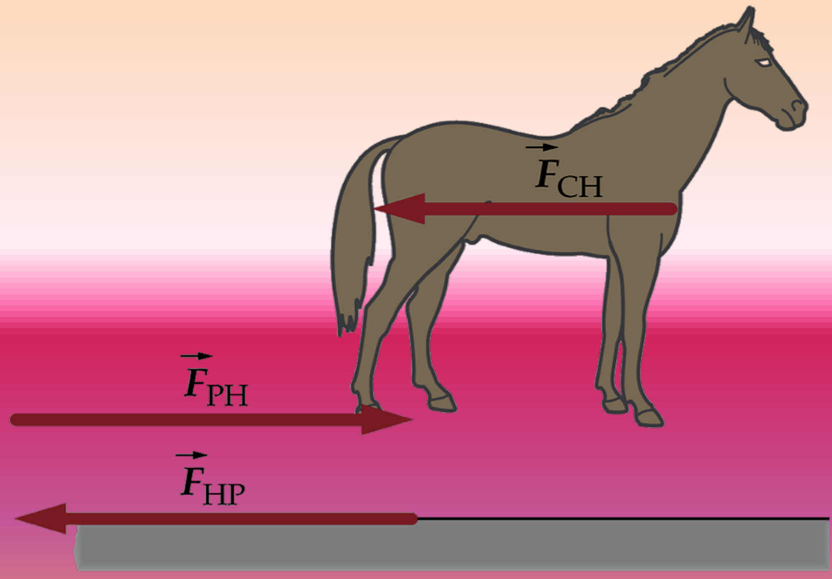
Note that the reaction to $\vec{F}_{HC}$ (which we call $\vec{F}_{CH}$)

is exerted on the horse not on the cart

Because the reaction force is exerted on the horse

it has no effect on the motion of the cart

This is the flaw in the horses reasoning



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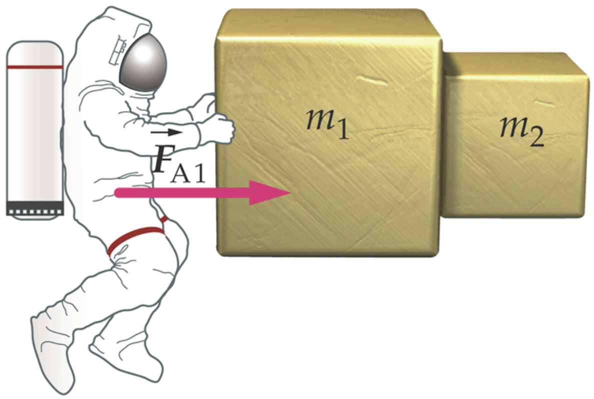
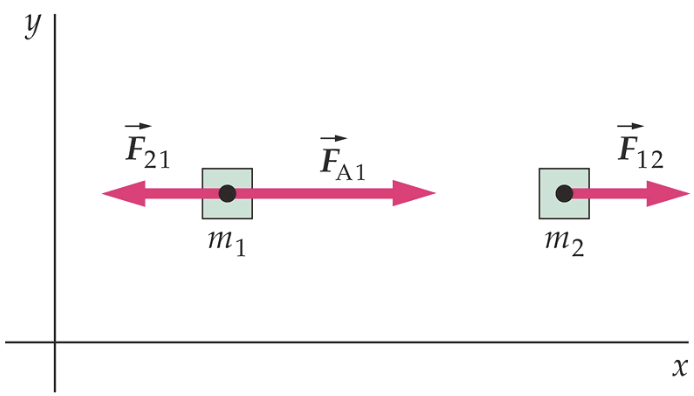
Building a space station

You are an astronaut constructing a space station, and you push a box of mass m_1 with force A1. The box is in direct contact with a second box of mass m_2



(a)What is the acceleration of the boxes?

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



$$a_x = F_{A1} / (m_1+m_2)$$

$$F = m_2 F_{A1} / (m_1 + m_2)$$

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Friction

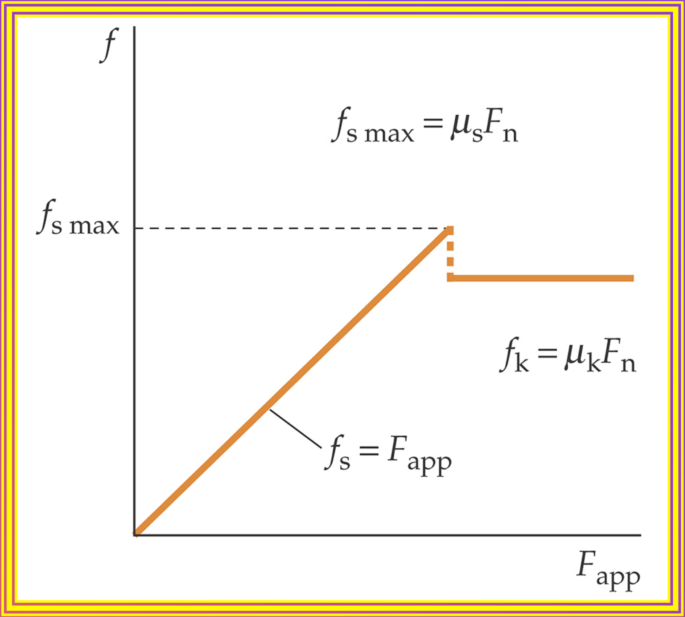
Static friction is the frictional force that acts when there is no sliding between the two surfaces in contact → It is the force that keeps the box from sliding.

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 the strength of the forces pressing the two surfaces: $f_{s,\,max} = \mu_s F_n$

Kinetic friction is the force that opposes to the motion

The magnitude of this force is also proportional to the microscopic contact area and the strength of the forces pressing the two surfaces: $f_k = \mu_k F_n$



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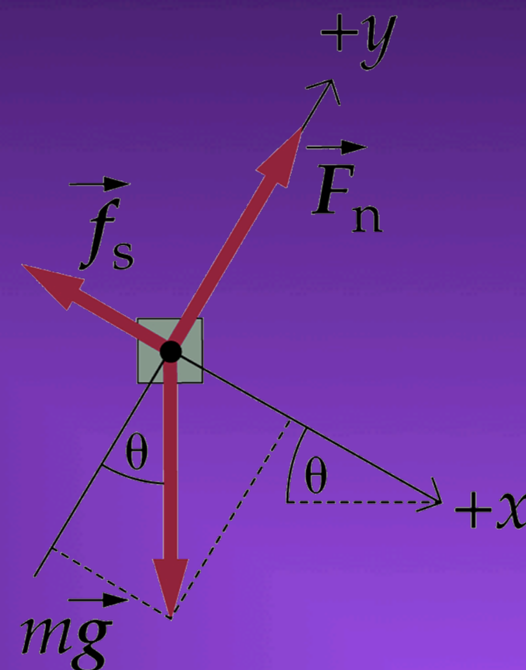
Approximate values of frictional coefficients

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

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 the book until the coin starts to slide.

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



$$\mu_s = \tan \Theta_{max}$$

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Erosion due to a stream cutting across a beach

Even though the edge weaves in and out, the angle of the slope remains constant

The angle of the slope is the angle of repose for the granular material.

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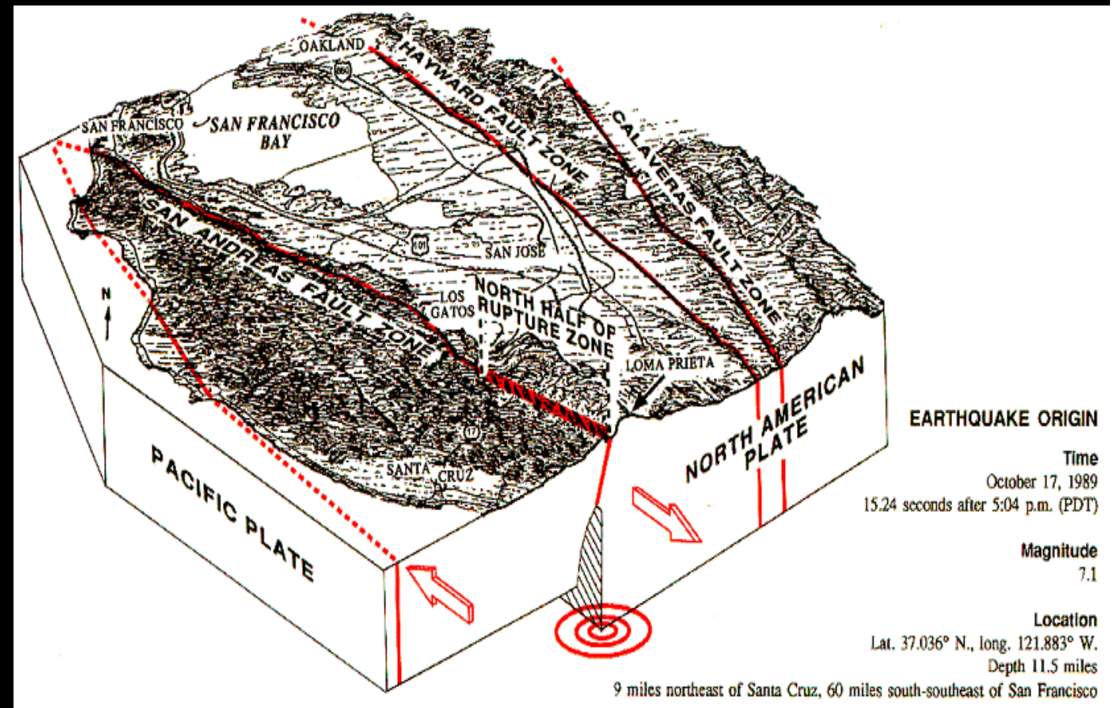
If the horizontal acceleration produced by an earthquake is "a" and if an object is going to ``hold its place'' on the ground show that the coefficient of static friction must beat least $\mu_s = a/g$



The famous Loma Prieta earthquake that stopped the 1989 World Series produced ground accelerations of up to 4 m/s^2 in the San Francisco Bay Area

Would a chair have started to slide on a linoleum floor with coefficient of static friction = 0.25?

$a/g = 0.41 > 0.25 \longrightarrow$ the chair will slide

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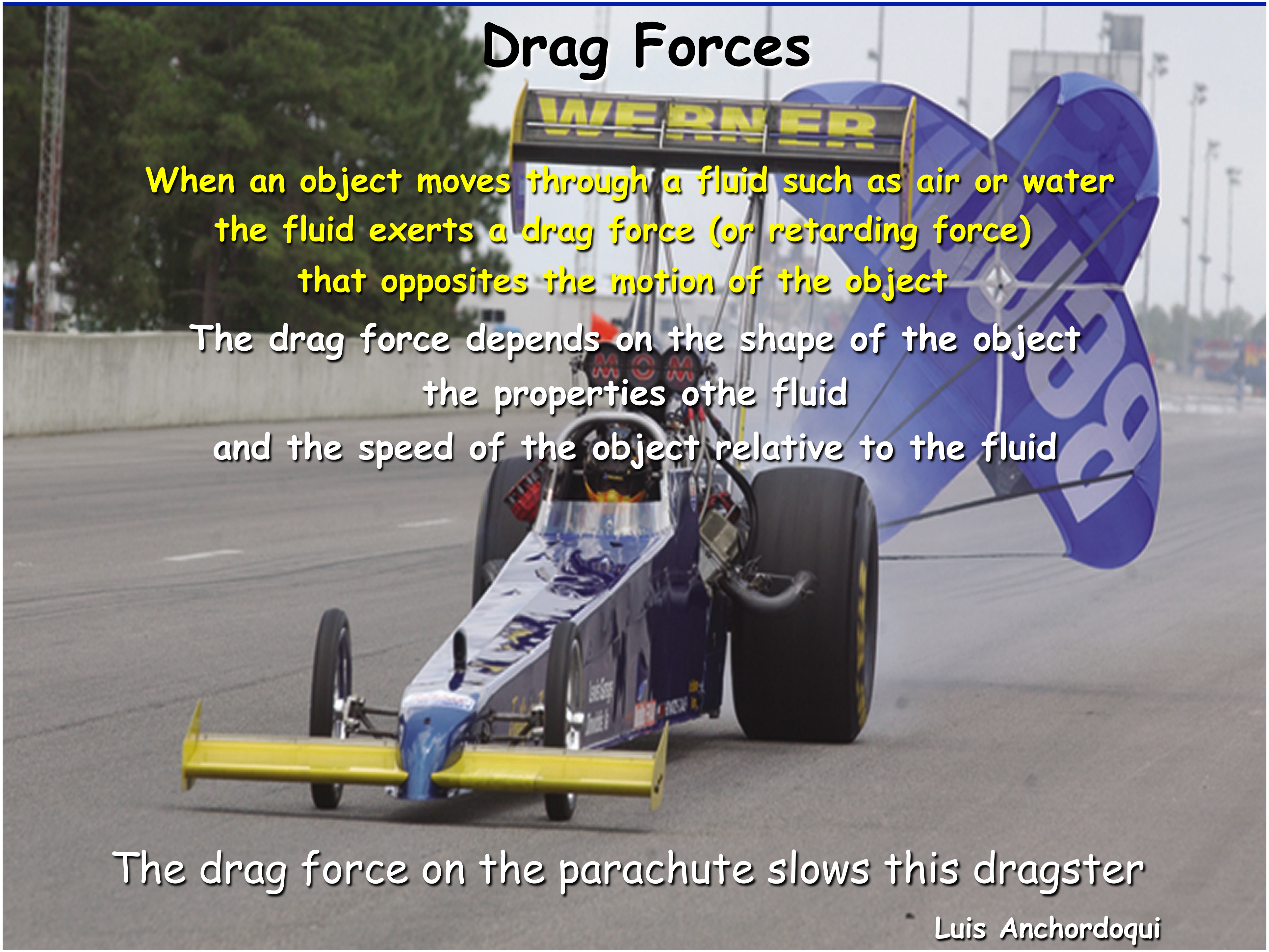
Drag Forces

When an object moves through a fluid such as air or water
the fluid exerts a drag force (or retarding force)
that opposites the motion of the object

The drag force depends on the shape of the object
the properties othe fluid
and the speed of the object relative to the fluid



The drag force on the parachute slows this dragster

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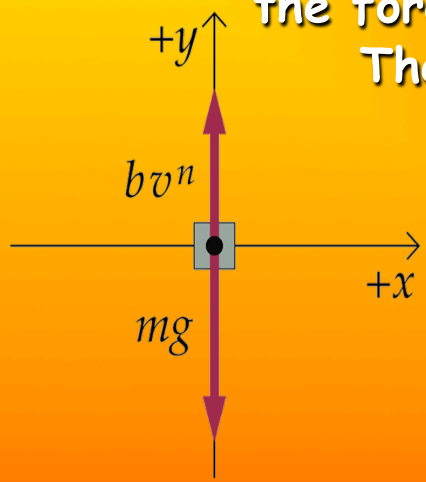
Drag Forces (cont'd)

Consider an obejct dropped from rest and falling under the influence of the force of gravity (which we assume to be constant)



The magnitude of the drag force is $F_d = b\,v^n$

$$mg - b\,v^n = m\,a_y$$

solving this equation for the acceleration gives

$$a_y = g - b\,v^n/m$$

The speed is zero at t=0 ⟶ at t=0 the drag force is zero and the acceleration is g downwards

As the speed of the object increases the drag force increases so the acceleration decreases

Eventually the speed is great enough for the magnitude of the drag force to approach the force of gravity

At terminal speed $b\,v_T^n = mg$

↓

$$v_T = (m\,g/b)^{1/n}$$

The larger the constant b the smaller the terminal speed

A parachute is designed to maximize b so that the terminal speed is small

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Terminal Velocity

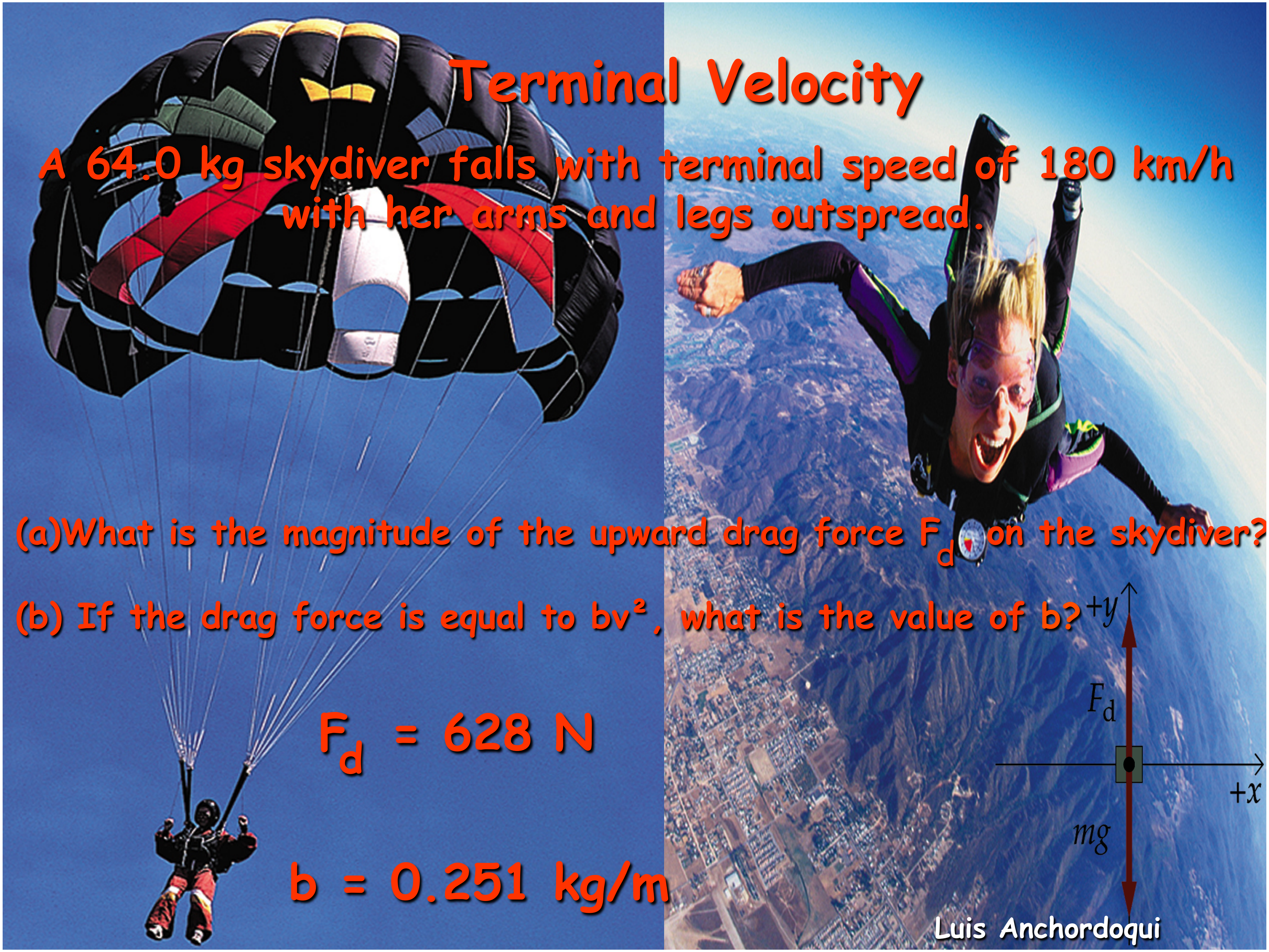
A 64.0 kg skydiver falls with terminal speed of 180 km/h with her arms and legs outspread.

(a)What is the magnitude of the upward drag force F_d on the skydiver?

(b) If the drag force is equal to bv^2, what is the value of b?

$$F_d = 628 \text{ N}$$

$$b = 0.251 \text{ kg/m}$$



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