Physics 1

Chapter 5 Force & Motion

Isaac Newton, 1642-1727
Philosophiae Naturalis Principia Mathematica
("Mathematical Principles of Physics") 1687

What Causes Acceleration?

Kinematics - description of motion

- Position, displacement, velocity, acceleration

Dynamics - study of causes of motion

- Aristotle's observations (~*350 B.C.*):
  - A body would move only when subjected to a force.
  - Without a force acting on it, a body will come to rest.
- Galileo"s experiments (~*1625*):
  - Moving objects have "inertia" – their motion persists unless something acts on them to change their motion (e.g. friction).
- Newton's 1st Law (*1687*):
  - **An object at rest stays at rest unless acted on by an external force. An object in motion stays in motion unless acted on by an external force.**

What Causes the Acceleration of a Particle?

- **Force**
  - A push or a pull on the particle.
- **Isaac Newton (1642-1727)**
  - Mathematical genius & philosopher
    - Newton's laws relate motion & force
    - Gravitational force
    - Circular motion
    - Properties of light
    - Heat flow
    - Foundations of calculus
- Newtonian Mechanics seemed perfect until the 20th Century!
  - Special Relativity - motion at near the speed of light
  - General Relativity - space & time at very large mass & distance
  - Quantum Mechanics - mechanics on the atomic scale.

Newton’s First Law

- An object at rest stays at rest unless acted on by an external force. An object in motion stays in motion unless acted on by an external force.

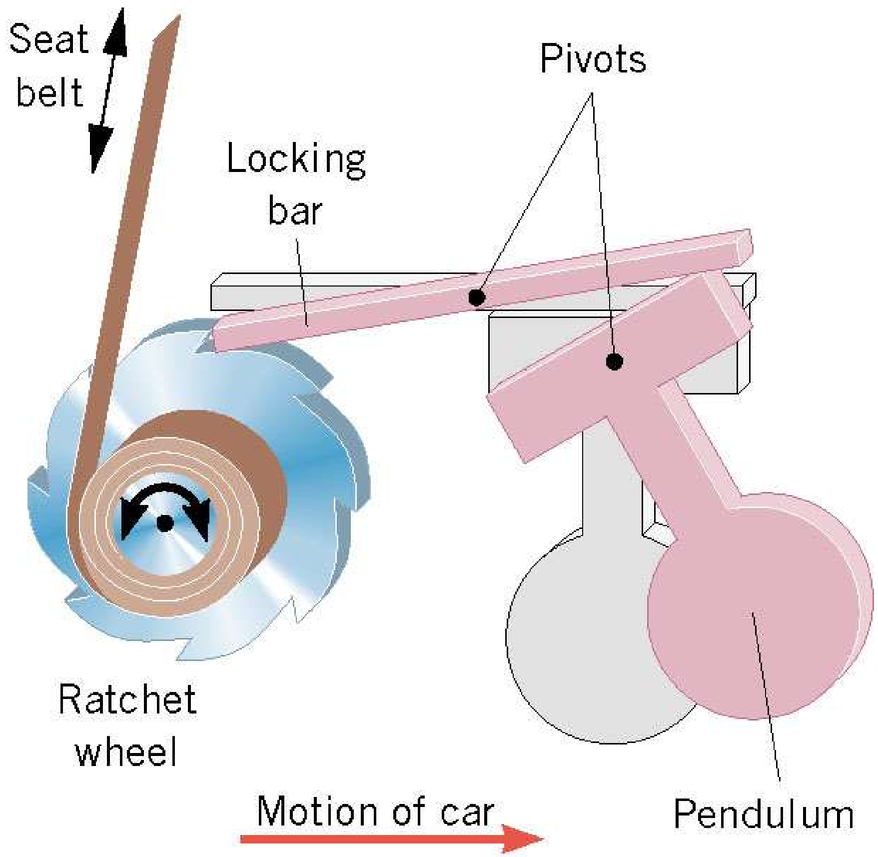
- “If no force acts on a body, then the body’s velocity cannot change; that is, the body cannot accelerate.”
  - aka Galileo’s law of *inertia.*

The bird feeder has ***mass*** - aka "***inertia***"

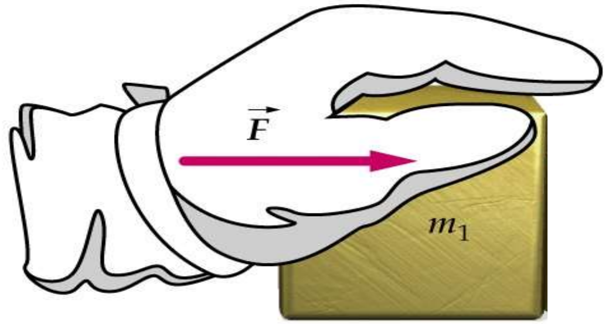
Pull slowly harder and harder
the top string breaks.

Pull hard and fast
the bottom string breaks.

Inertia: When the car stops, the pendulum keeps moving forward!



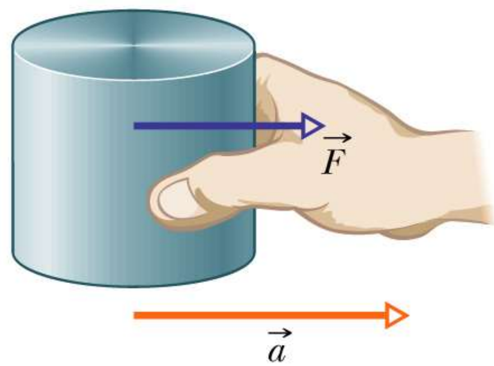
Mass, Motion & Force



Experimental Observations:

- An object acted on by a net force accelerates.
- Accelerates in the same direction as the net force.
- *S*ome objects accelerate slower or faster than others when subjected to the same force - "***inertial mass***"

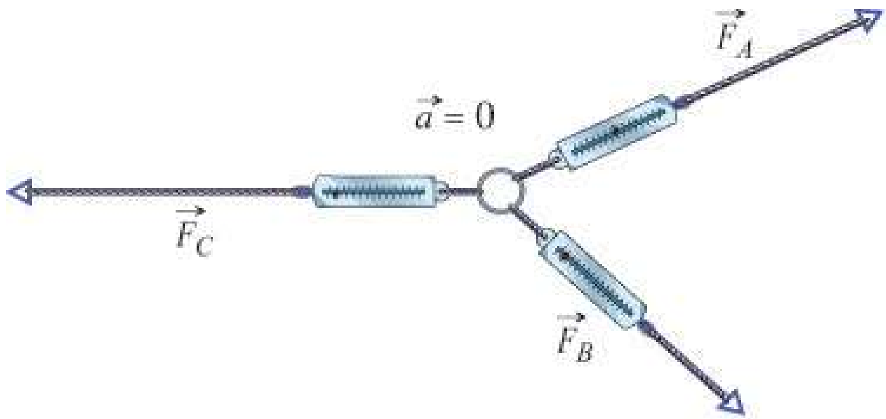
Force & Mass



- **Mass** is an intrinsic property of an object that measures its resistance to acceleration; it is a measure of the object's *inertia*.
- **Acceleration** and **Force** are vectors; mass is a scalar.
  - *Add forces vectorially*
- Principle of Superposition of Forces: a single force with the magnitude and direction of the *net force* has the same effect on a body as all the individual forces acting together.
- Newton's First Law: If no net force acts on a body ($F_{net} = 0$), the the body's velocity cannot change.

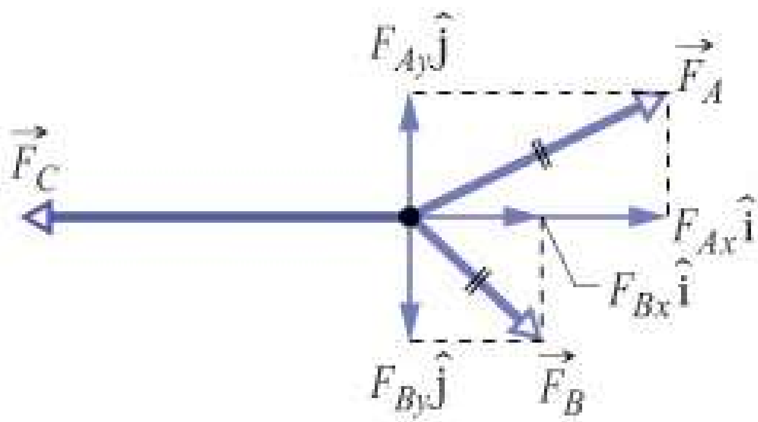
  e.g. a book on a table.

Net Force as a Vector Sum



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

$$\vec{F}_A + \vec{F}_B + \vec{F}_C = 0$$

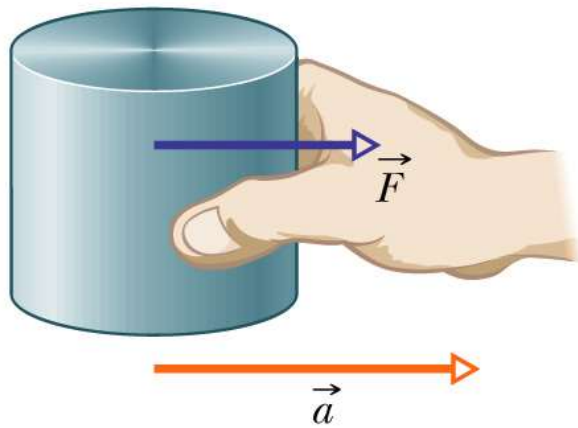


$$F_{Ax} + F_{Bx} + F_{Cx} = 0$$

$$F_{Ay} + F_{By} = 0$$

$$\vec{F}_C = F_{Cx}\vec{i} = -\left(F_{Ax} + F_{Bx}\right)\vec{i}$$

Force



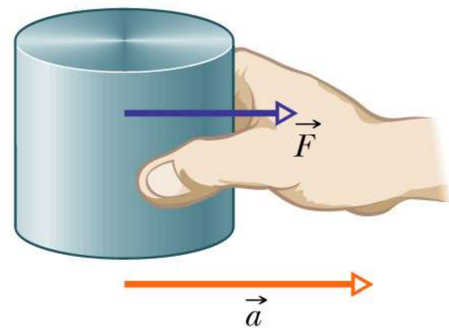
Unit of Force: **1 Newton**

Force needed to accelerate a mass of 1 kilogram at 1 m/s^2.

Newton's Second Law

- The net force on a body is equal to the product of the body's mass and the acceleration of the body:

$$\vec{F}_{net} = m\,\vec{a}$$



Units: $1\,N\,(\text{Newton}) = (1\;kg)\left(1\;{}^{m}\!/_{s^2}\right) = 1\;kg\,\dfrac{m}{s^2}$

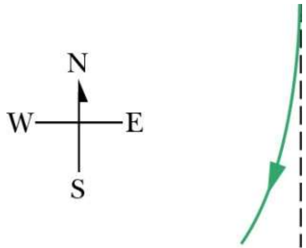
Acceleration and force are vectors; mass is a scalar.

Non-Inertial Reference Frames

A reference frame is called an ***inertial frame*** if Newton's Laws are valid in that frame.

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

A reference frame accelerating relative to an inertial reference frame is ***not*** an inertial reference frame.

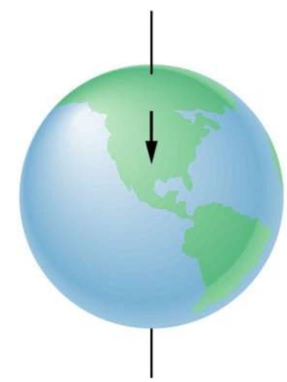


(a)

e.g. an object in an accelerating vehicle will accelerate without a net force acting on it.

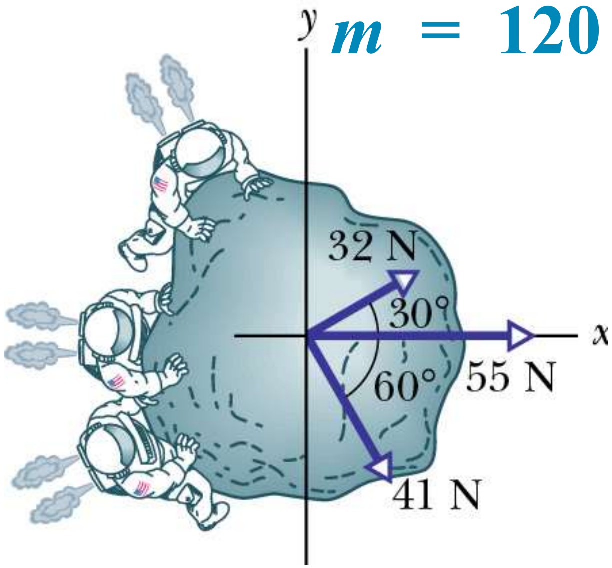
$$\vec{F}_{net} \neq m\vec{a}$$

The rotating earth is not exactly an inertial reference frame.



3 astronauts pushing

$m = 120$ kg



$$\vec{F}_1 = (32\,N)\left(\cos 30^0\,\vec{i} + \sin 30^0\,\vec{j}\right)$$

$$\vec{F}_2 = (55\,N)\vec{i}$$

$$\vec{F}_3 = (41\,N)\left(\cos(-60^0)\vec{i} + \sin(-60^0)\vec{j}\right)$$

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

$$(103\,N)\vec{i} - (19.5\,N)\vec{j} = (120\,kg)\vec{a}$$

$$\vec{a} = \left(0.86\,{}^{m}/_{s^2}\right)\vec{i} - \left(0.16\,{}^{m}/_{s^2}\right)\vec{j}$$

$$|\vec{a}| = 0.88\,{}^{m}/_{s^2} \quad @ \quad \theta = \tan^{-1}\frac{a_y}{a_x} = -11^0$$

The Gravitational Force

- If we drop a body near the Earth's surface, it accelerates toward the center of the Earth:

g = free-fall acceleration

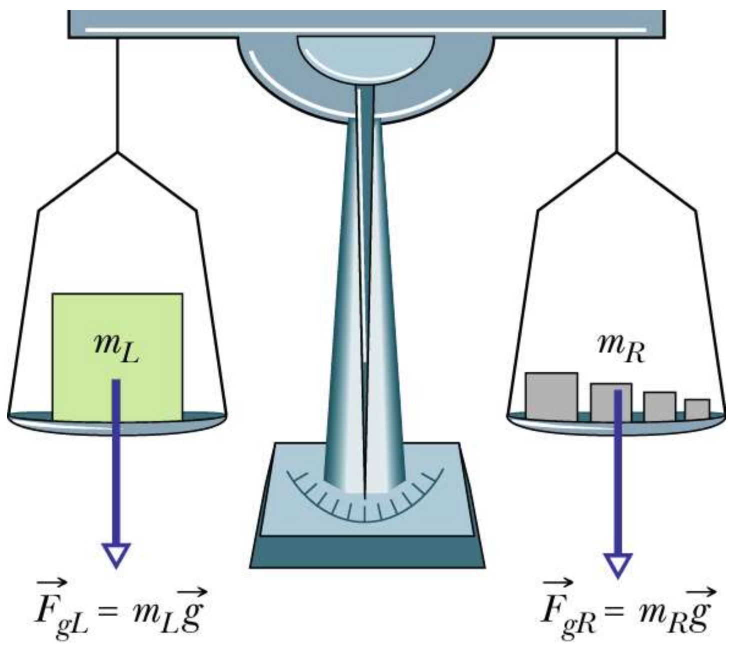
Newton's Second Law: $\vec{F}_g = m\,\vec{g}$

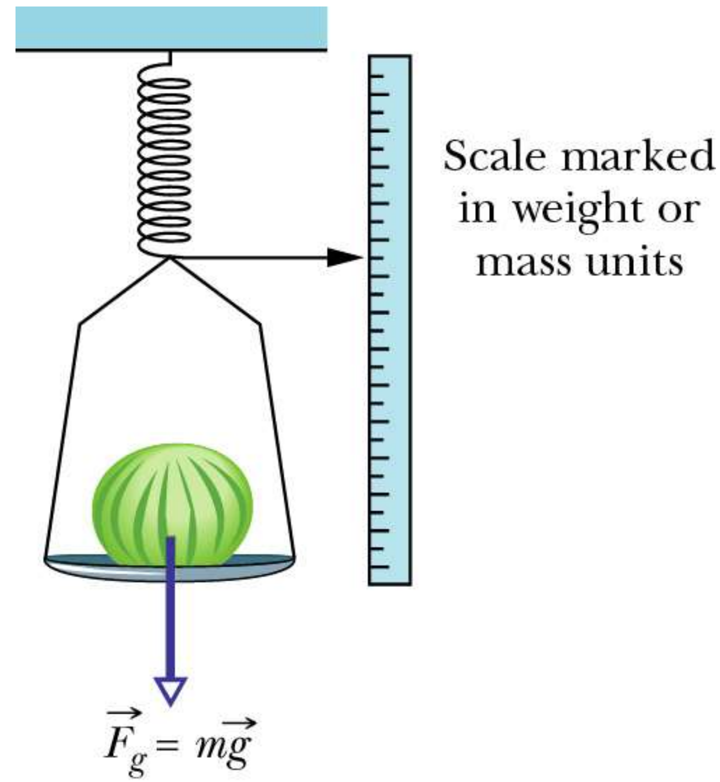
- Weight of a body is the magnitude of the net force required to prevent the body from falling freely:

$$\vec{W} - \vec{F}_g = m(0)$$

$$\left|\vec{W}\right| = m\left|\vec{g}\right| = m\,g$$

Mass versus Weight





$\boldsymbol{m}_{\mathrm{L}} = \boldsymbol{m}_{\mathrm{R}}$

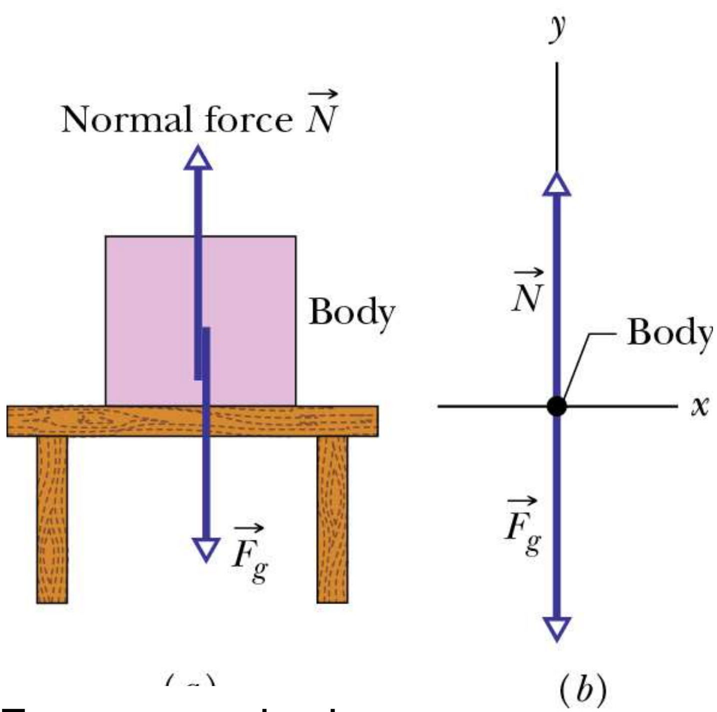
weight

Free-fall acceleration on earth (g) = $9.8\ m / s^2$

Free-fall acceleration on the moon = $1.7\ m / s^2$

The Normal Force

When a body presses against a surface, the surface pushes back on the body with a force that is perpendicular to the surface (the *normal force*).



Forces on a body Resting on a table.

The free-body diagram

Newton's Second Law:

$$\vec{F}_{net} = m\vec{a}$$
$$\vec{N} - \vec{F}_g = m\vec{a}$$
$$N - mg = ma_y$$
$$N = m(a_y + g)$$

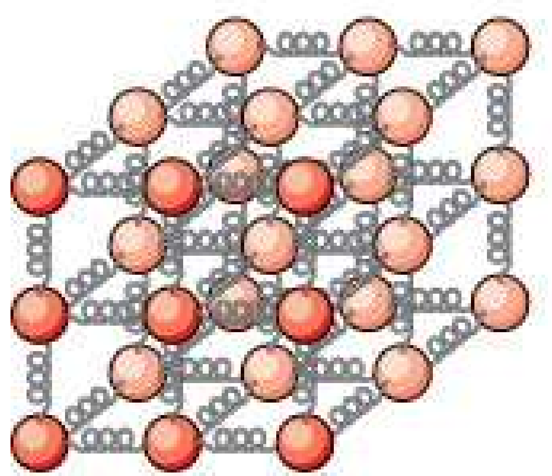
The body is at rest: $a_y = 0$

$$\therefore N = mg$$

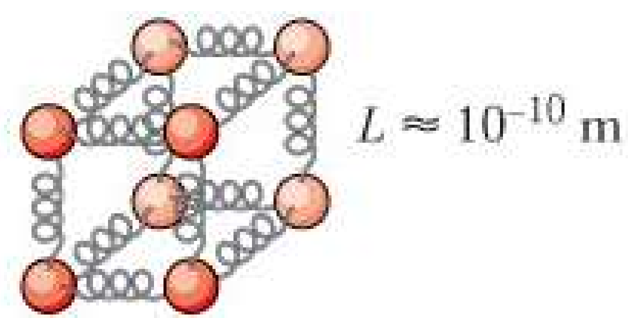
Solids and the Normal Force

Idealized Model of Solids Made of Atoms

Atoms in a solid held together by “springs”.



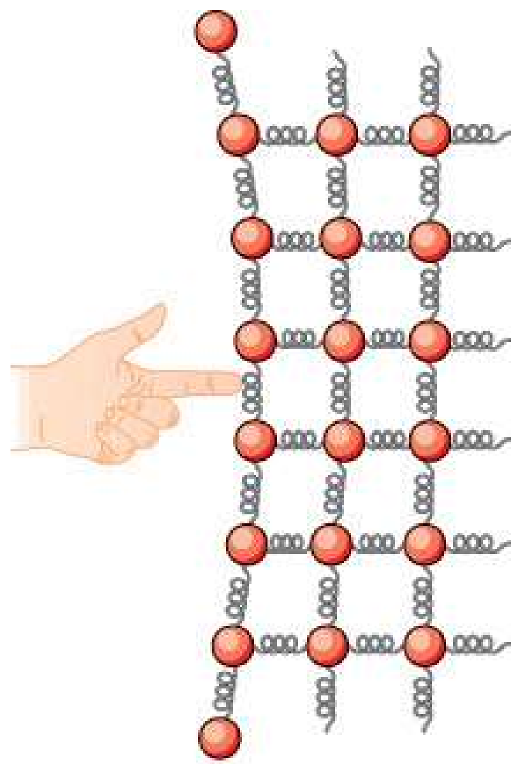
Atoms are very small”.



“springs” between the atoms ➔ electric attraction between atoms

“The Normal Force”

Finger applying a force on a surface of a solid



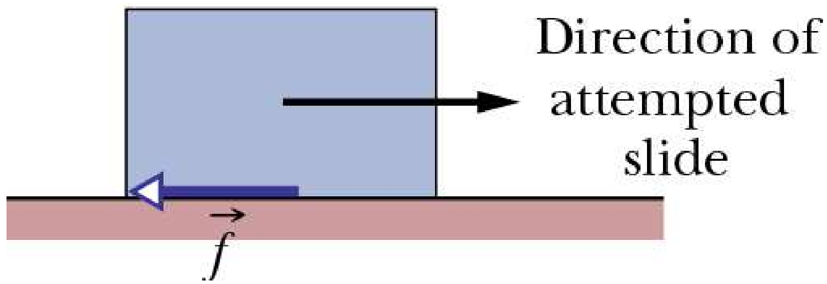
Reaction force from the surface on the finger due to the “springs” between the atoms.

The surface of the solid is deformed by the force.

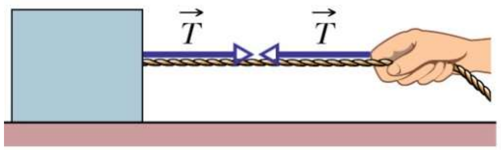
The electrons in the atoms of my finger repel the electrons in the atoms of the surface.

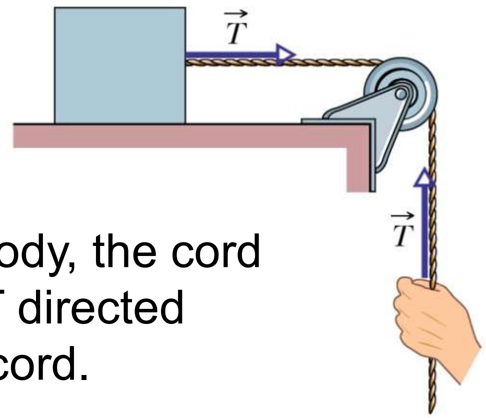
The Friction Force

The resistance encountered if one slides or attempts to slide a body over a surface is called the *friction force*.

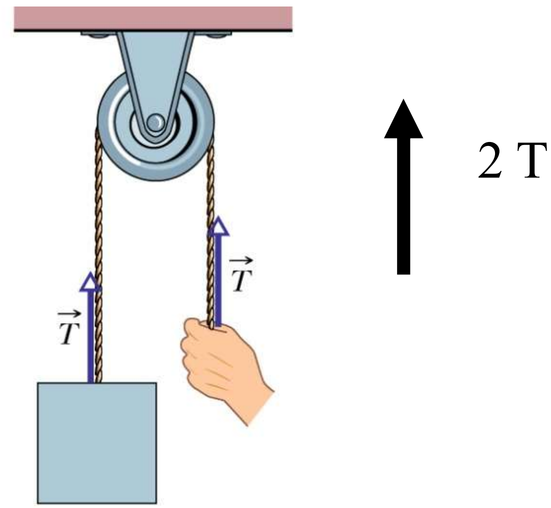


Tension Force





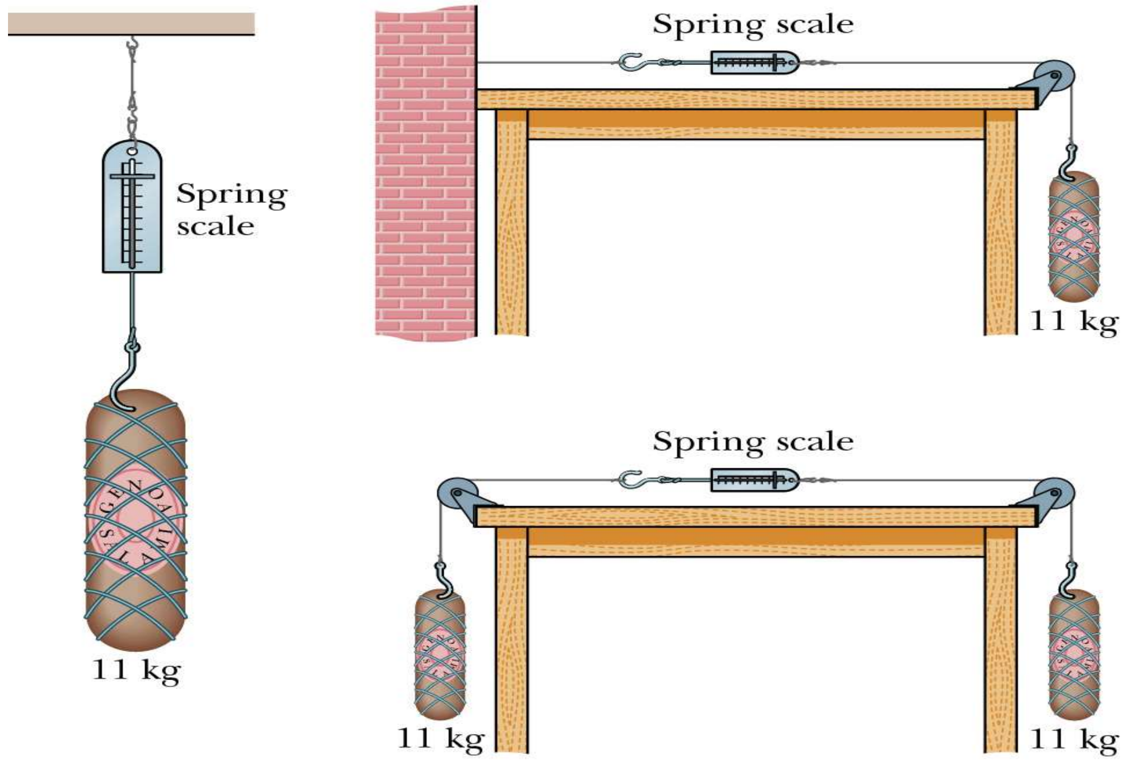
When a cord is attached to a body, the cord pulls on the body with a force T directed away from the body along the cord.



(c)

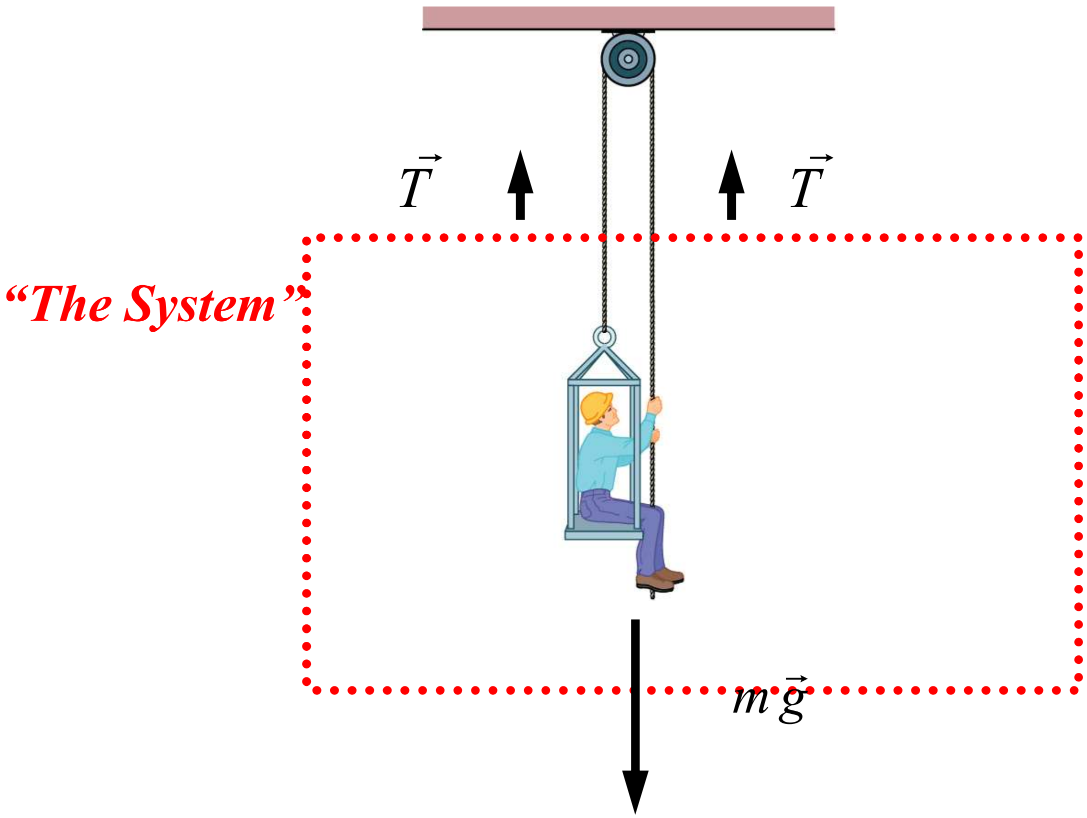
A cord is considered massless and unstretchable.
A pulley is considered massless and frictionless.

the hanging salami



The scale always reads 108 newtons!!!!

A free ride?

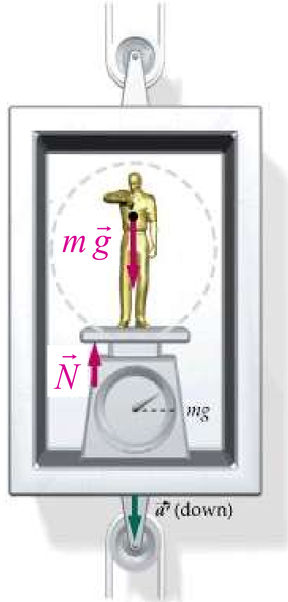


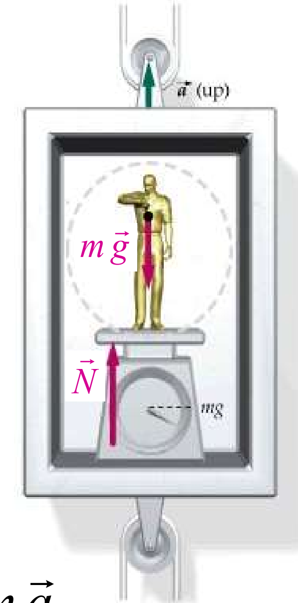
$$\vec{F}_{net} = m\vec{a}$$

$$T + T - mg = 0$$

$$\boxed{T = \tfrac{1}{2}mg}$$

How much do you weigh on an accelerating elevator?





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

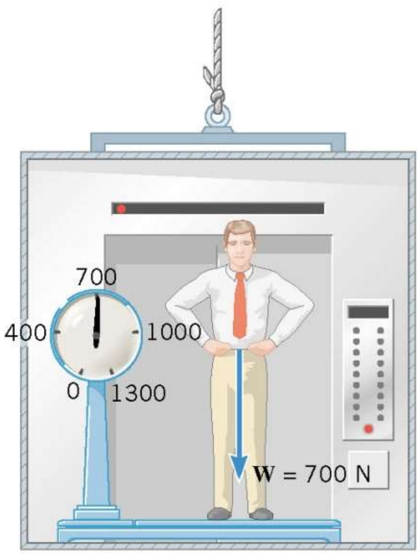
$$\vec{N} - m\vec{g} = m\vec{a}$$

$$N - mg = -ma$$
$$N = m(g - a)$$

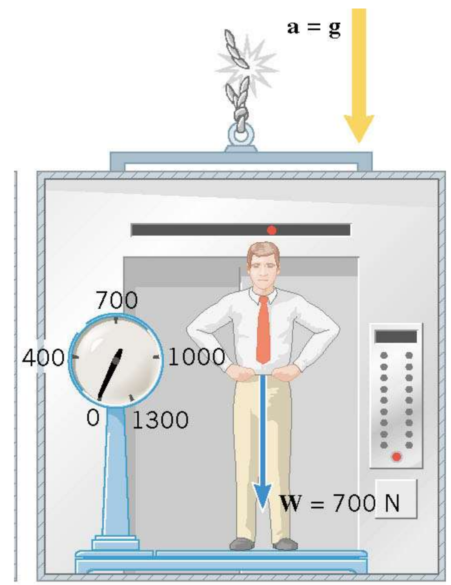
$$N - mg = +ma$$
$$N = m(g + a)$$

More on a person's weight in an elevator

$$\vec{N} - m\vec{g} = m\vec{a}$$



(*a*) No acceleration (**v** = constant)



(*d*) Free-fall

$$|\vec{a}| = 0 \qquad N = mg = W$$

$$\vec{a} = -\vec{g} \qquad N = 0$$

Classroom Excercise

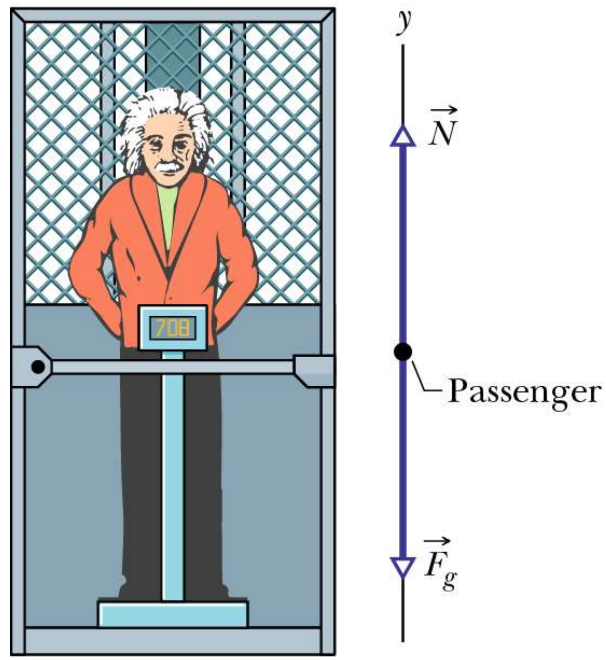
m = 72.2 kg

Apparent weight

$a = 0$

$a = + 3.20\ m/s^2$

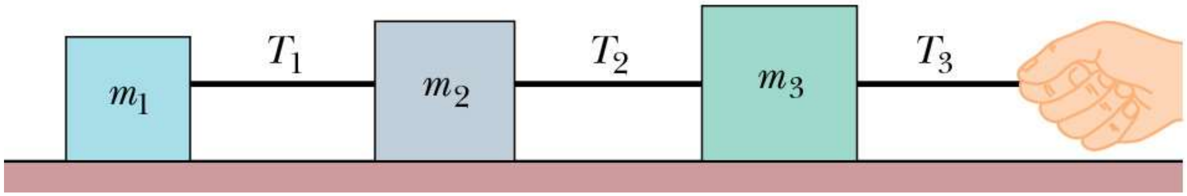
$a = - 3.20\ m/s^2$



(a) (b)

Sliding blocks on a frictionless surface

$m_1 = 12$ kg $\quad m_2 = 24$ kg $\quad m_3 = 31$ kg



$T_3 = 65$ N

Acceleration = ???

a) "The System": $m_1 + m_2 + m_3$

$$F_{net} = m\,a$$

$$T_3 = (m_1 + m_2 + m_3)\,a$$

$$a = \frac{65}{67}\ {}^{m}\!/\!_{s^2}$$

This is the acceleration of the system as a ***whole***.

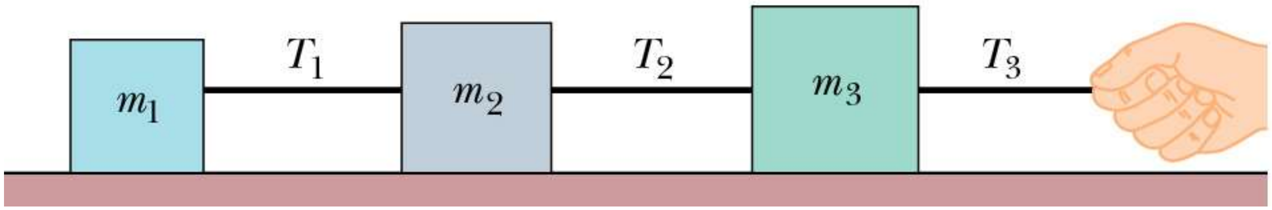
This also is the acceleration of the ***first block***,

the ***second block.***

and the ***third block!***

sliding blocks on a frictionless surface

$m_1 = 12$ kg $m_2 = 24$ kg $m_3 = 31$ kg



$T_3 = 65$ N

a) "The System": $m_1 + m_2 + m_3$

$$a = \frac{65}{67}\,{}^{m}\!/\!{}_{s^2} = 0.97\,{}^{m}\!/\!{}_{s^2}$$

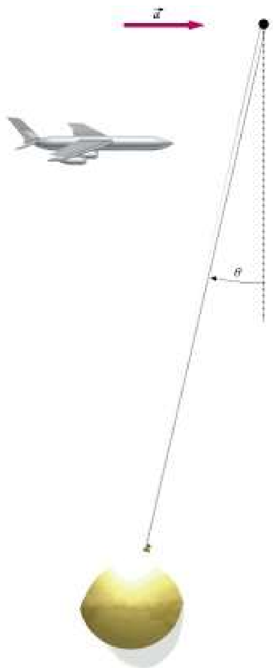
b) "The System" is Block #1:

$$F_{net} = m\,a$$
$$T_1 = m_1\,a = (12\,kg)(0.97\,{}^{m}\!/\!{}_{s^2}) = 11.6\,N$$

c) "The System" is Blocks 1 and 2:

$$F_{net} = m\,a$$
$$T_2 = (m_1 + m_2)\,a = (36\,kg)(0.97\,{}^{m}\!/\!{}_{s^2}) = 34.9\,N$$

Weight hanging by a string on an accelerating airplane.



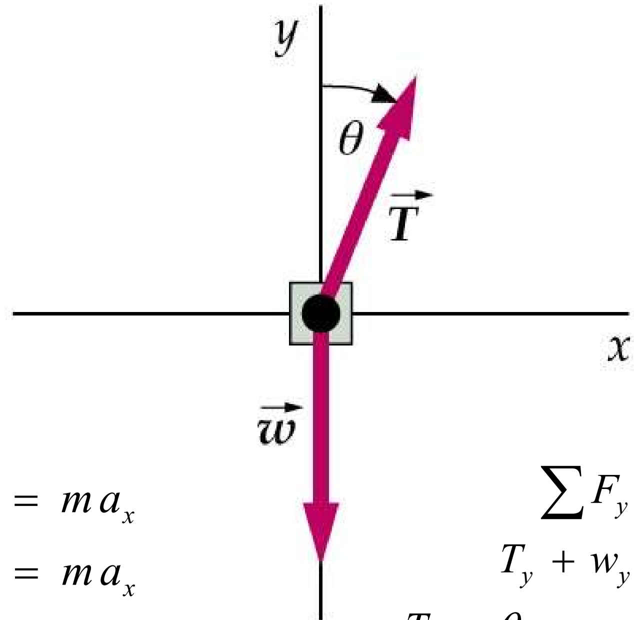
$\theta = 22^0$

$m = 40\,g$
$= 0.04\,kg$

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

$$\sum F_x = m a_x$$

$$\sum F_y = m a_y$$



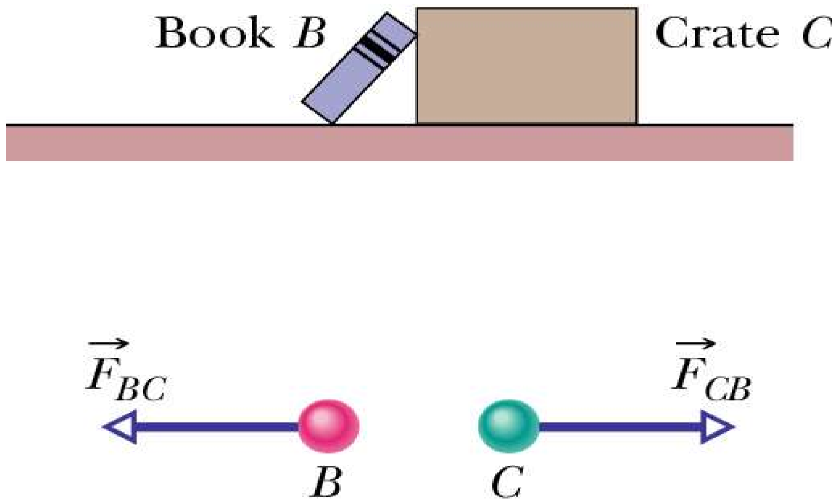
$$\sum F_x = m a_x$$
$$T_x + w_x = m a_x$$
$$T\sin\theta + 0 = m a_x$$
$$T\sin\theta = m a_x$$

$$\sum F_y = m a_y$$
$$T_y + w_y = m a_y$$
$$T\cos\theta - m g = m a_y = 0$$
$$T\cos\theta = m g$$

$$a_x = g\tan\theta$$

Newton's Third Law

- When two bodies interact, the forces on the bodies from each other are always equal and opposite.



Book pushes on crate.
Crate pushes on book.

$$\vec{F}_{BC} = -\vec{F}_{CB}$$

Newton's 3rd Law

action-reaction forces due to an object resting on a table

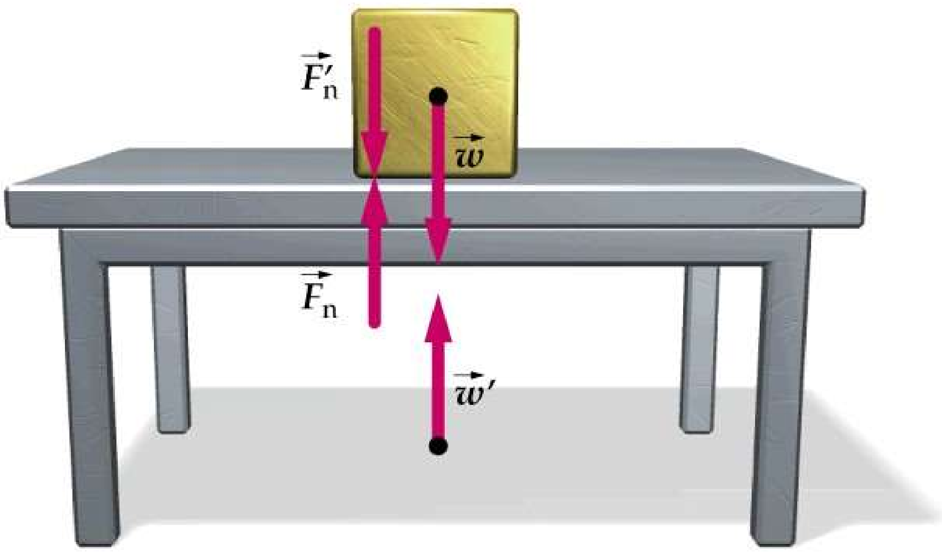
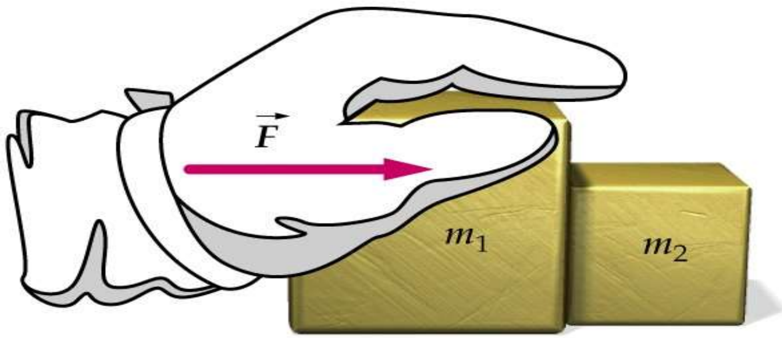


table resting on the floor

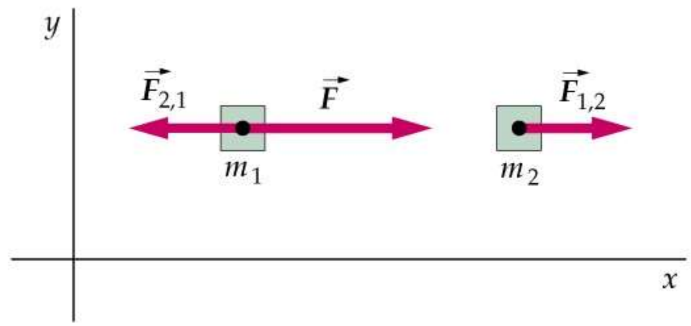
floor resting on the building

Earth

blocks pushing blocks



Forces acting on the boxes



Newton's 3rd Law:

$$\vec{F}_{2,1} = -\vec{F}_{1,2}$$

Newton's 2nd Law:

$$\vec{F}_{net} = m\,\vec{a}$$

"The System" is $\boldsymbol{m_1} + \boldsymbol{m_2}$: $F = (m_1 + m_2)\,a$

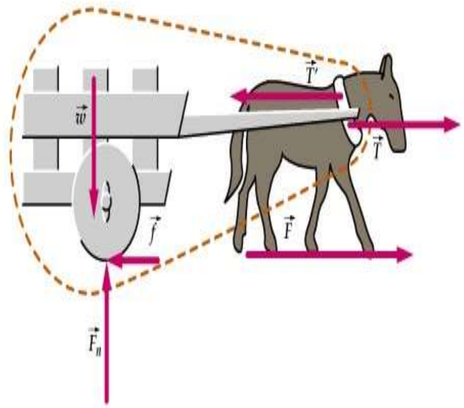
"The System" is Block #2: $F_{1,2} = m_2\,a = m_2\left(\dfrac{F}{m_1 + m_2}\right)$

Problem Solving Tactics

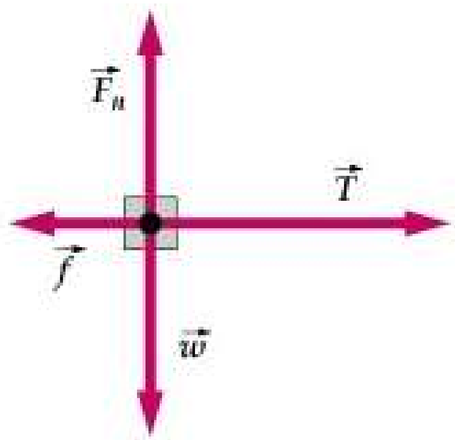
- Read the Problem!
    - What's given and what's asked for?
    - Usually every word is important!
- Draw rough picture, showing the forces and masses.
    - Which are the external forces?
- What is the *system* that the problem is referring to?
- Draw *free-body diagrams* showing the external forces on each body.
- Choose a *convenient coordinate system* to describe the components of the forces.
- Add vectors vectorially! Add scalars arithmetically!

Free Body Diagram

Total System:



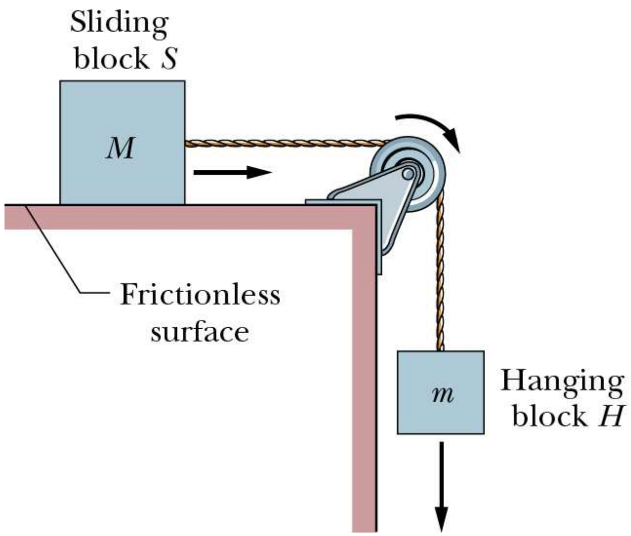
The System of interest is the cart:

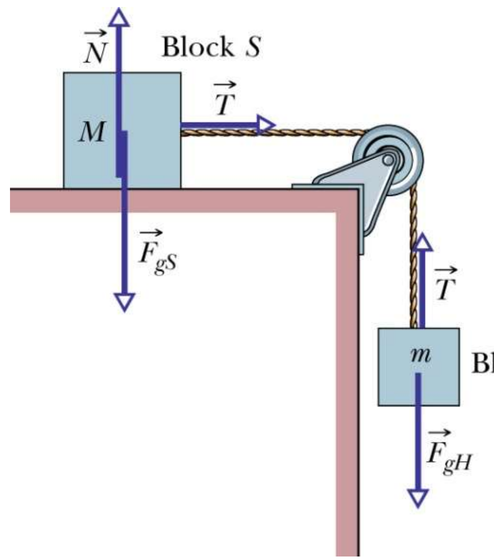


Forces on the cart:

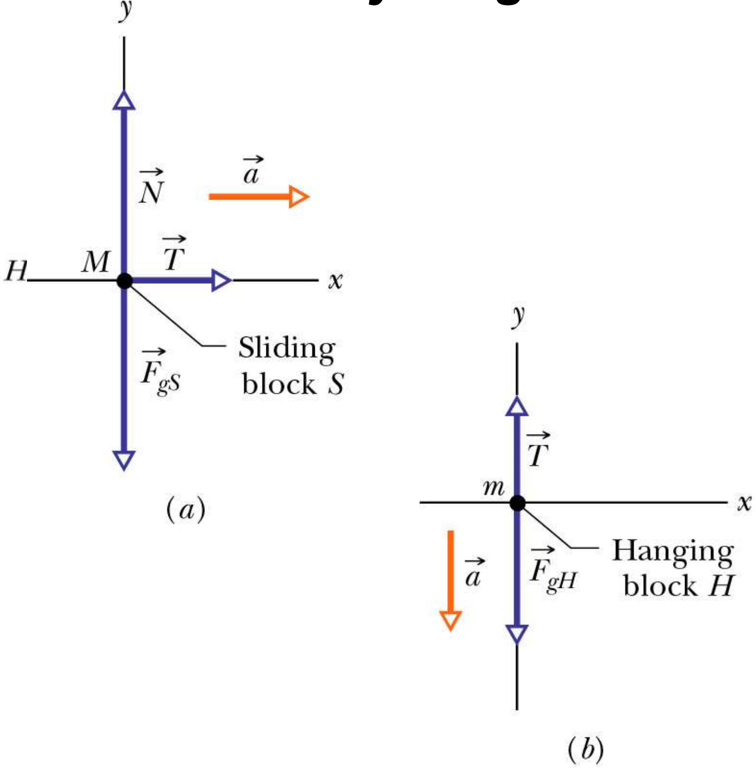
Sample Problem

The Forces



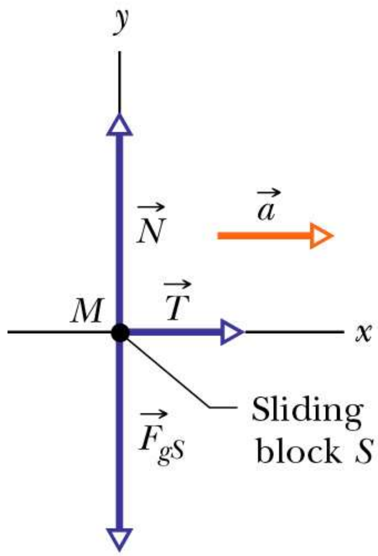


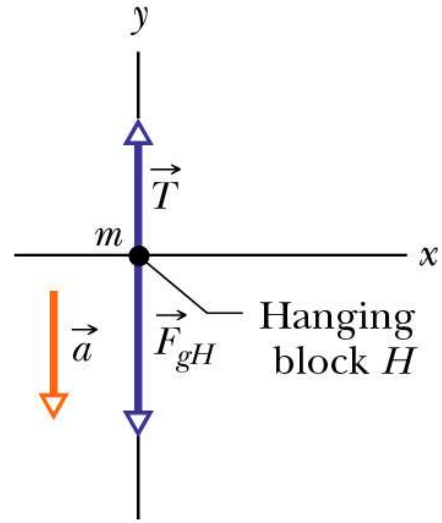
Free-Body Diagrams



What's going to happen?

Sample Problem : ***The Equations***





$$\sum F_y = M a_y$$
$$N + F_{gS} = 0$$
$$N = -F_{gS} = M g$$

$$\sum F_x = M a_x$$
$$T = M a$$

$$\sum F_y = m a_y$$
$$T - F_{gH} = -m a$$
$$T - m g = -m a$$
$$T = m(g - a)$$

$$T = M a = m(g - a)$$

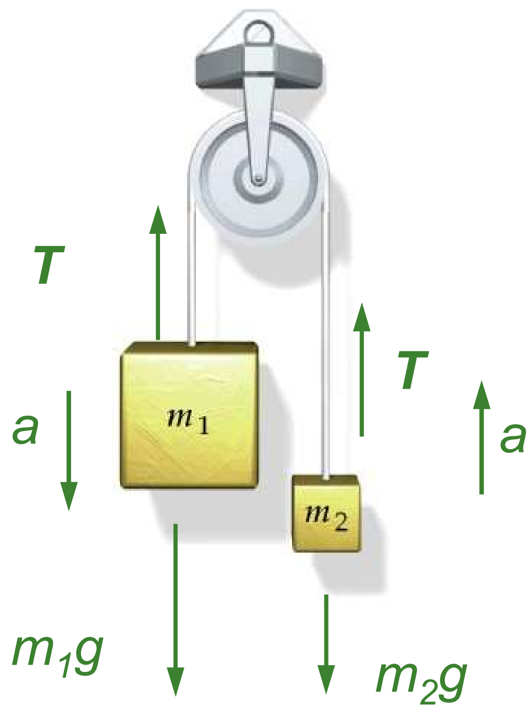
$$a = \frac{m}{M + m} g \qquad T = \frac{M m}{M + m} g$$

Study the sample problems!

Atwood's Machine

$$\sum F_x = 0$$

$$\sum F_y = m_1 a_y$$



$$T - m_1 g = -m_1 a$$

$$T - m_2 g = +m_2 a$$

$$a = \frac{m_1 - m_2}{m_1 + m_2} g$$

$$T = \frac{2 m_1 m_2}{m_1 + m_2} g$$

Newton's 2nd Law isn't quite correct, but it can still be used!

Albert Einstein
(1979 – 1955)

<u>Newton</u>:

- "Absolute, true, and mathematical ***time***, of itself and from its own nature, flows equably without relation to anything external … '
- "Absolute ***space***, in its own nature, without relation to anything external, remains always similar and immovable."

<u>Einstein</u>: ***Special Theory of Relativity*** (1905)

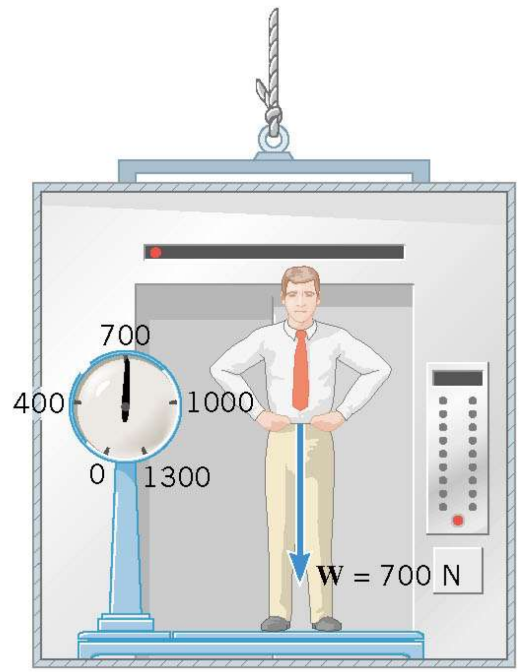
Newton not correct for motion at speeds near the speed of light.

<u>Einstein</u>: ***General Theory of Relativity*** (1915)

Newton not correct about space & time - a 4D-space curved by the presence of mass!

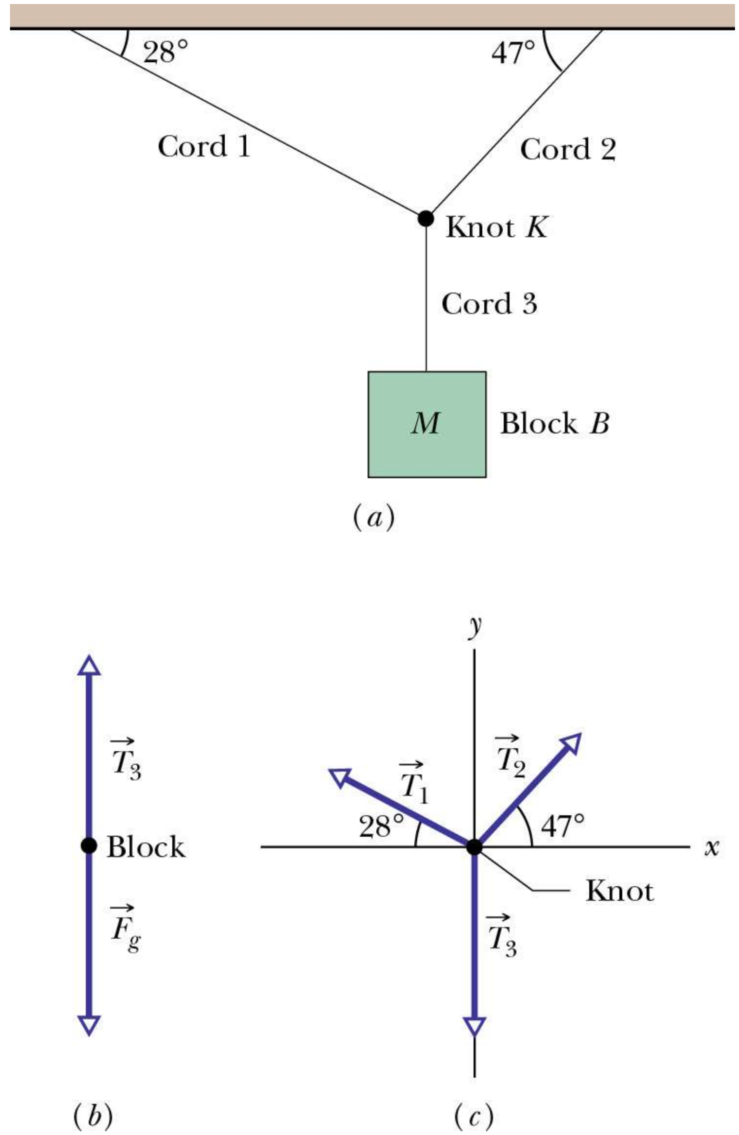
General Theory of Relativity

***Einstein*:** There is no experiment that the person in a windowless box can perform to distinguish between an accelerating elevator and a box just sitting near a massive object (e.g. the Earth).



Sample Problem

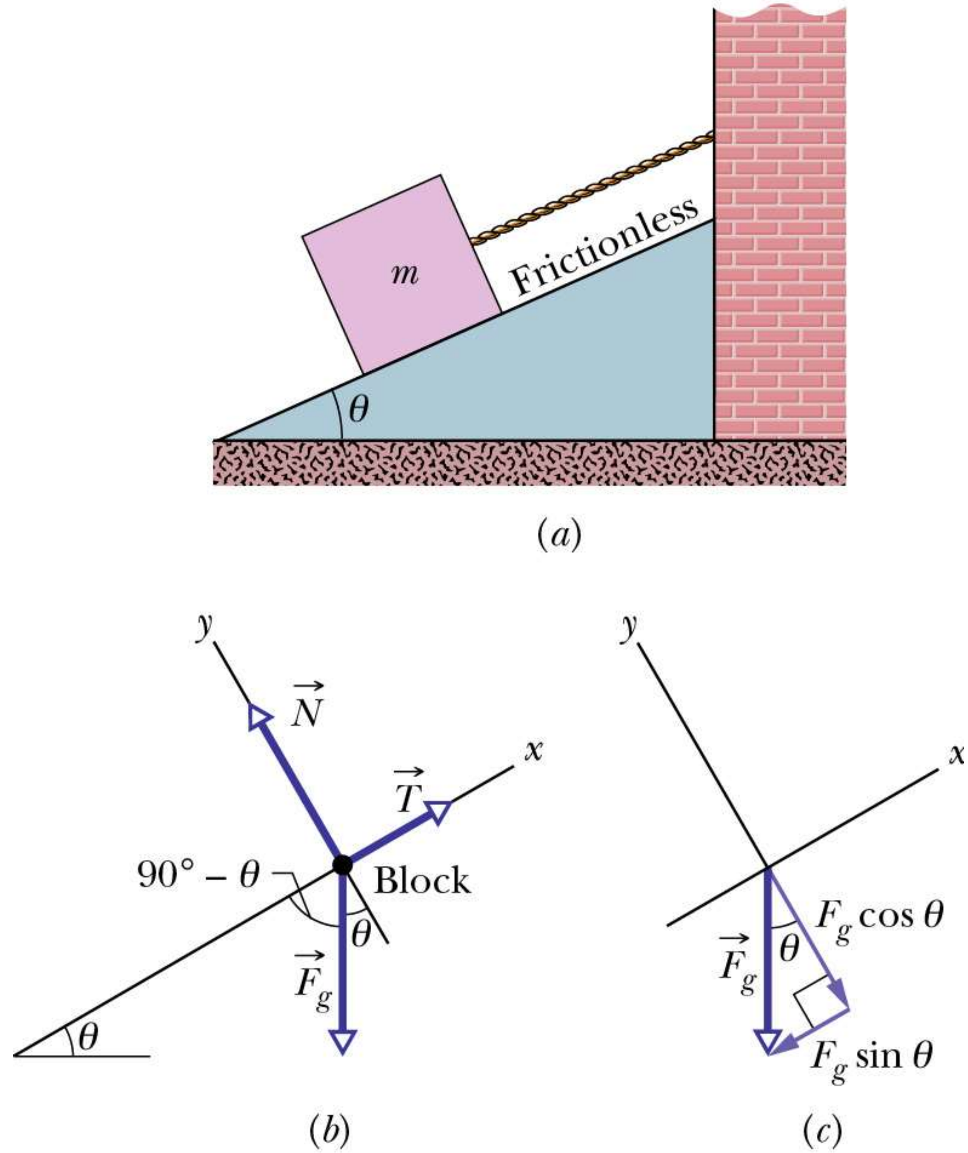
M = 15.0 kg
What are tensions in 3 cords?



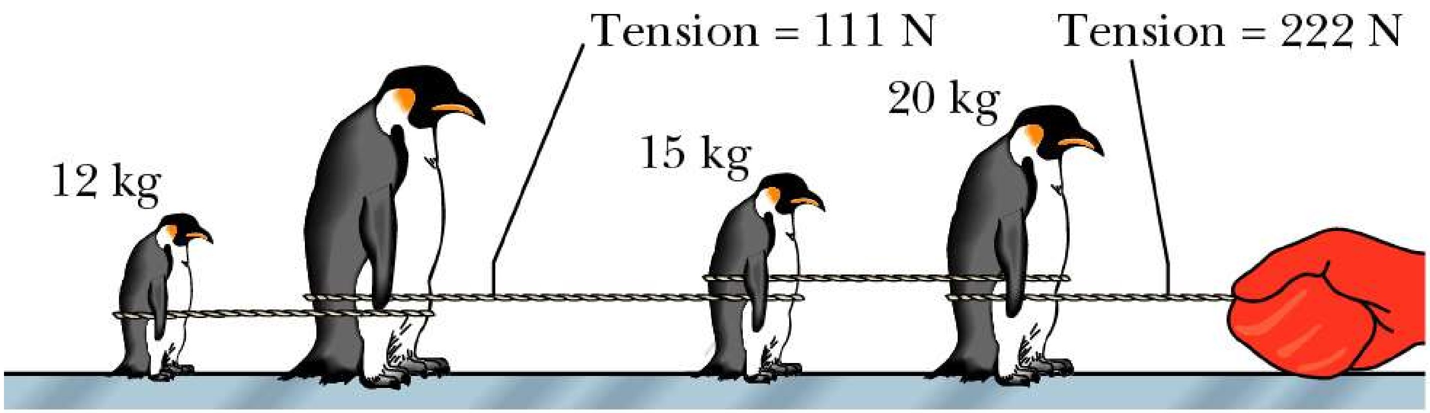
Sample Problem

M = 15.0 kg, θ = 27^0
T on block from cord ?
N on block from plane ?

Cut the cord. Does the block accelerate?



What's the mass of the big penguin?



$$m_4 \quad m_3 \quad m_2 \quad m_1$$

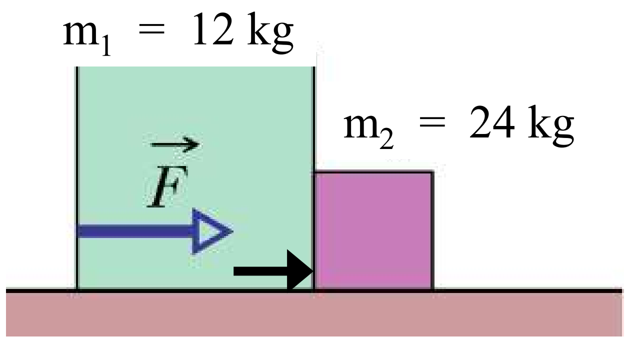
$$F_{net} = m\,a$$
$$F_{net} = (m_3 + m_4)a$$
$$111\,N = (m_3 + 12\,kg)a$$

$$F_{net} = m\,a$$
$$F_{net} = (m_1 + m_2 + m_3 + m_4)a$$
$$222\,N = (20\,kg + 15\,kg + m_3 + 12\,kg)a$$

$$m_3 = 23\,kg$$

blocks pushing blocks

$$f_{12} = ?$$



$$\vec{F}_{net} = m\,\vec{a}$$

"The System": $\boldsymbol{m}_1 + \boldsymbol{m}_2$ $\quad F = (m_1 + m_2)\,a$

"The System" is Block #2: $\quad f_{12} = m_2\,a = m_2\left(\dfrac{F}{m_1 + m_2}\right)$

"The System" is Block #1: $\quad F - f_{21} = m_1\,a = m_1\left(\dfrac{F}{m_1 + m_2}\right)$