Physics 1: Mechanics

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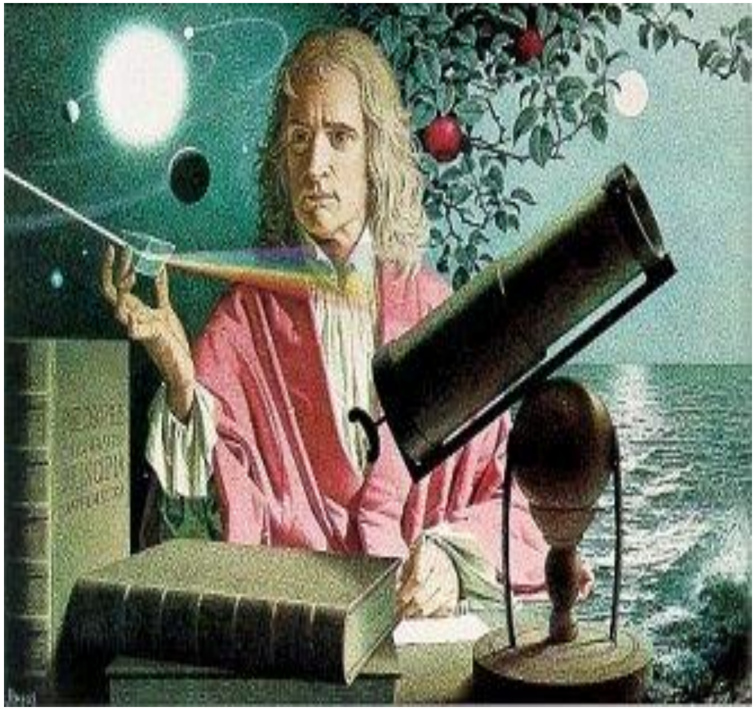
Part A Dynamics of Mass Point

Chapter 2: Force and Motion

Sir Isaac Newton

1. He was born in England on December 25, 1643, died in 1727 (85 years old)
2. He developed the theories of **gravitation** in 1666, when he was only 23 years old.
3. Twenty years later, in 1686, he presented his three laws of motion.



[http://teachertech.rice.edu/Participants/louviere/Newton/index.html]

Newtonian Mechanics

1. The study of **the relation between a force and the acceleration** it causes. Newtonian Mechanics based on Newton's three laws of motion.

2. **Speed (object) < speed of light** ($\sim 3\text{x}10^8$ m/s)

   • If the speed of objects is large, comparable to the speed of light, Newtonian mechanics is replaced by Einstein's special theory of relativity.

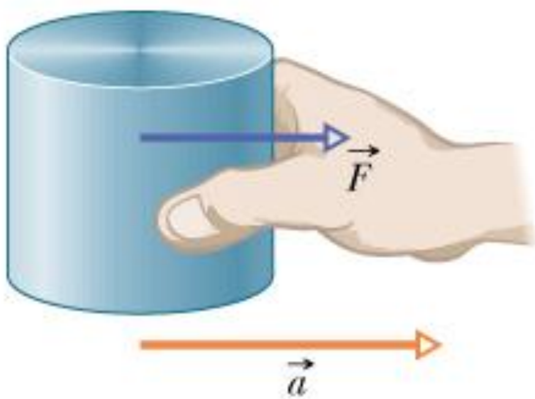
3. **Size (object) >> atomic scale**

   • If the size of objects is comparable to the atomic scale, Newtonian mechanics is replaced by quantum mechanics.

2.1. Newton's First Law and Inertial Frames

Force (N):

If no net force acts on a body, the body's velocity cannot change; that is, the body cannot accelerate.

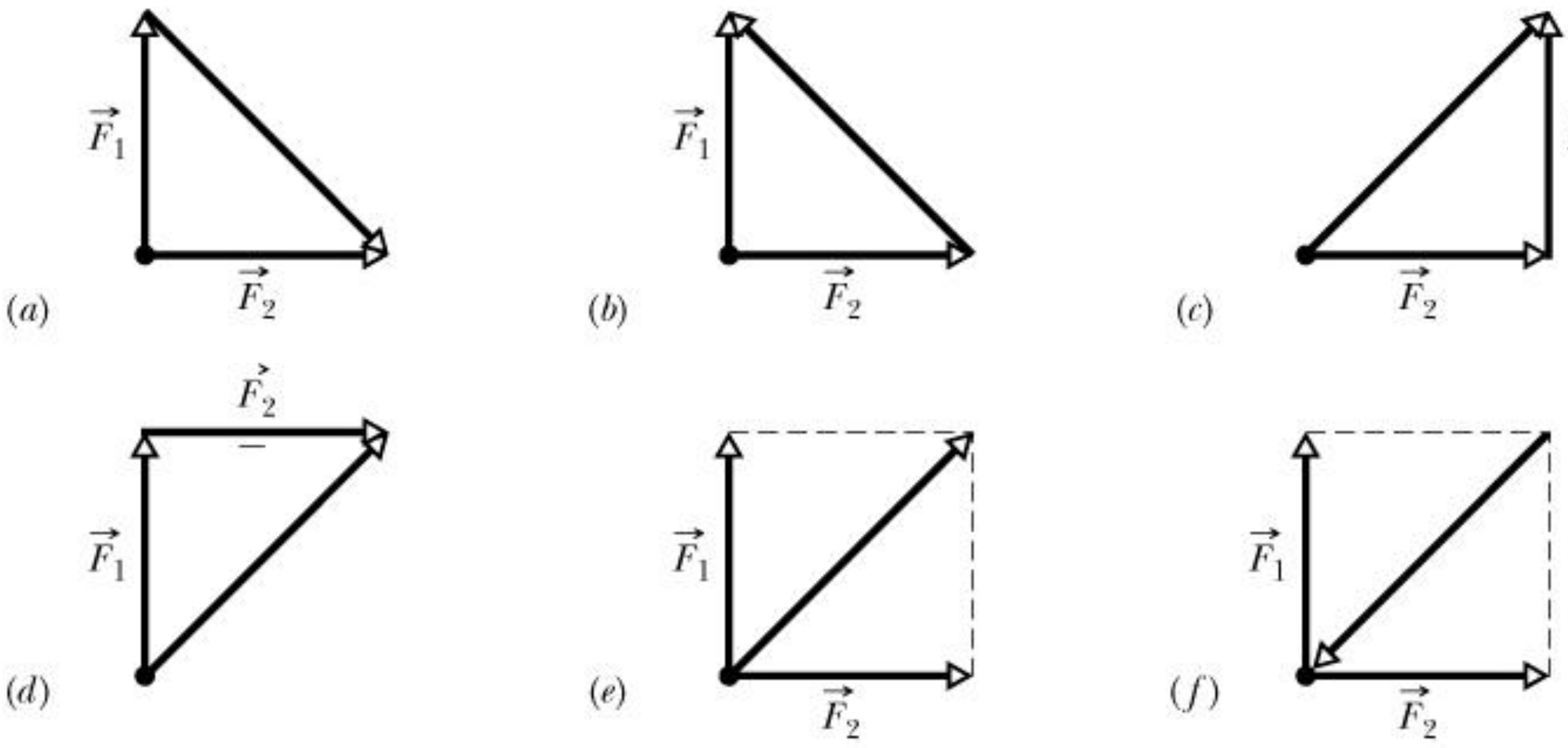


$$\vec{F} = 0 \quad \text{or} \quad \sum_{i=1}^{n} \vec{F}_i = 0$$

Inertial Reference Frames: (Inertial Frames) A reference frame in which there are no accelerations, only zero or uniform motion in a straight line. In other words, an inertial frame is one in which Newton's laws hold.

Example: The ground is an inertial frame if we neglect Earth's astronomical motions (such as its rotation, precession).

Checkpoint 1: **Which of the figure's six arrangements correctly show the vector addition of forces $\vec{F}_1$ and $\vec{F}_2$ to yield the third vector, which is meant to represent their net force $\vec{F}_{net}$?**



2.2. Newton's Second Law

Mass (kg): The mass of a body is the characteristic that relates a force on the body to the resulting acceleration.

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

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

$$F_{net,\,x} = ma_x, \quad F_{net,\,y} = ma_y, \quad F_{net,\,z} = ma_z$$

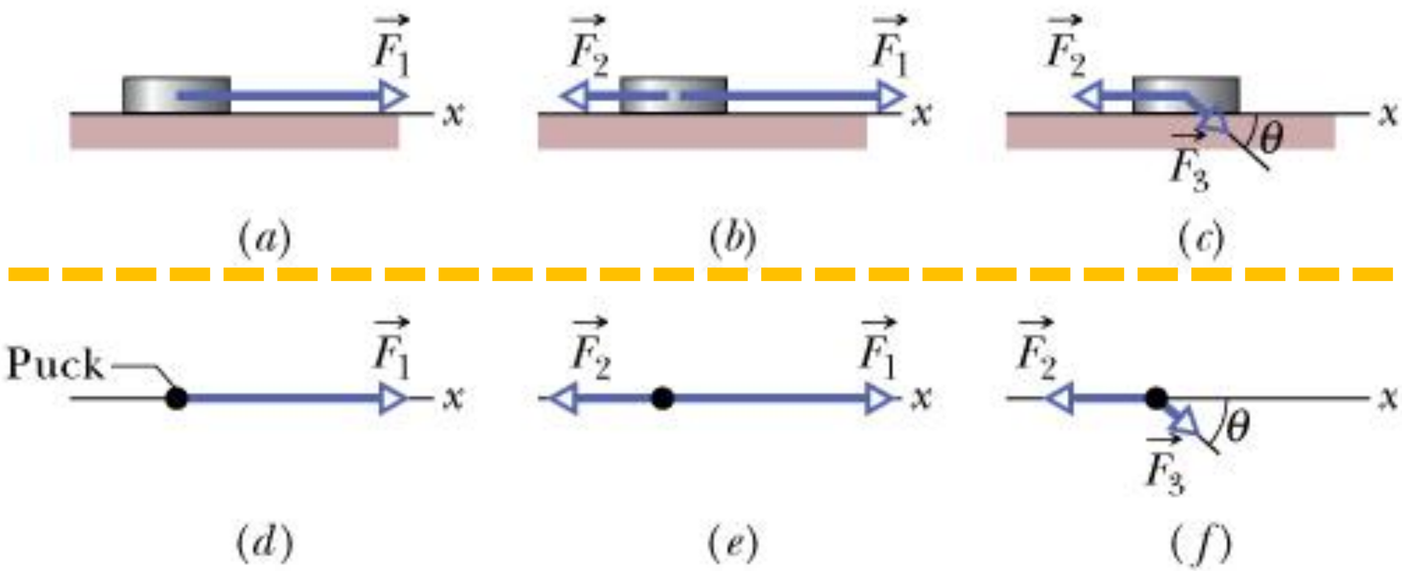
Note: If a system consists of two or more bodies, we only consider the net external force on the system to its acceleration. We do not include internal forces from bodies inside the system.

System	Force	Mass	Acceleration
SI	Newton (N)	kg	m/s^2
CGS	dyne	g	cm/s^2

$1\ N = 1\ kg.m/s^2$; $1\ dyne = 1\ g.cm/s^2$

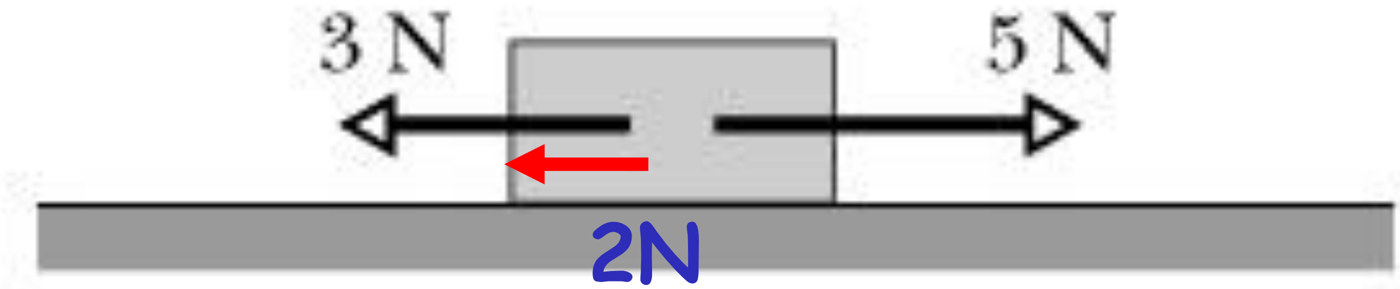
To solve problems with Newton's second law, we often draw a free-body diagram:

- The body is presented by a dot
- Each force on the body is drawn as a vector arrow with its tail on the body
- A coordinate is usually included
- You can show the acceleration of the body as a vector



Free-body diagram

Checkpoint 2: The figure here shows two horizontal forces acting on a block on a frictionless floor. If a third horizontal force $\vec{F}_3$ also acts on the block, what are the magnitude and direction of $\vec{F}_3$ when the block is (a) stationary and (b) moving to the left with a constant speed of 5 m/s?

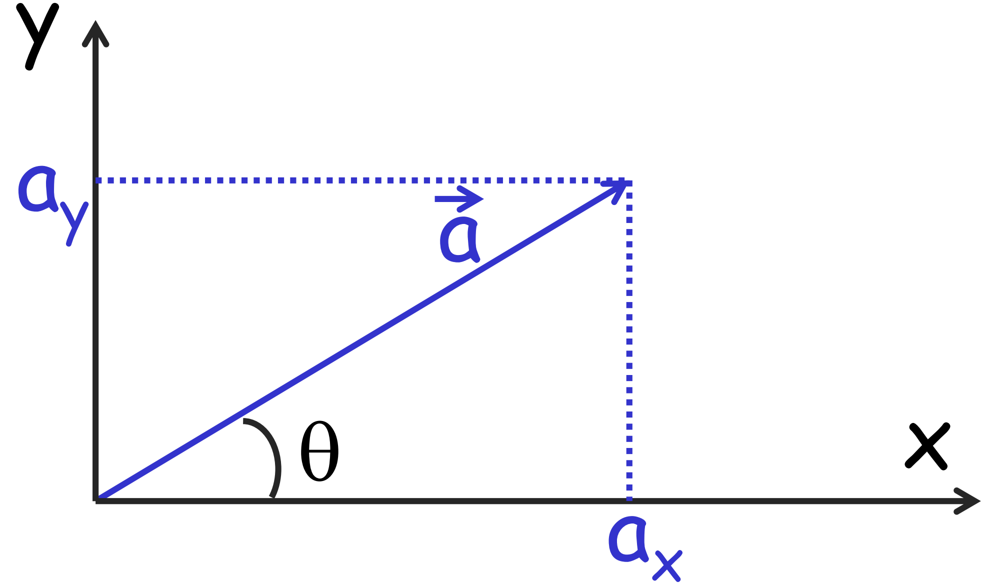


*(acceleration is zero in each situation)

Example (P. 108). If the 1 kg standard body has an acceleration of 2.00 m/s^2 at 20.0^0 to the positive direction of an x axis, what are (a) the x component and (b) the y component of the net force acting on the body, and (c) what is the net force in unit-vector notation?

$$F_x = m\,a_x = m\,a\cos\theta$$

$$F_y = m\,a_y = m\,a\sin\theta$$



$$\vec{F}_{net} = F_x\hat{i} + F_y\hat{j} = m\,a(\cos\theta\,\hat{i} + \sin\theta\,\hat{j})$$

2.3. Some Particular Forces. The Gravitational Force and Weight

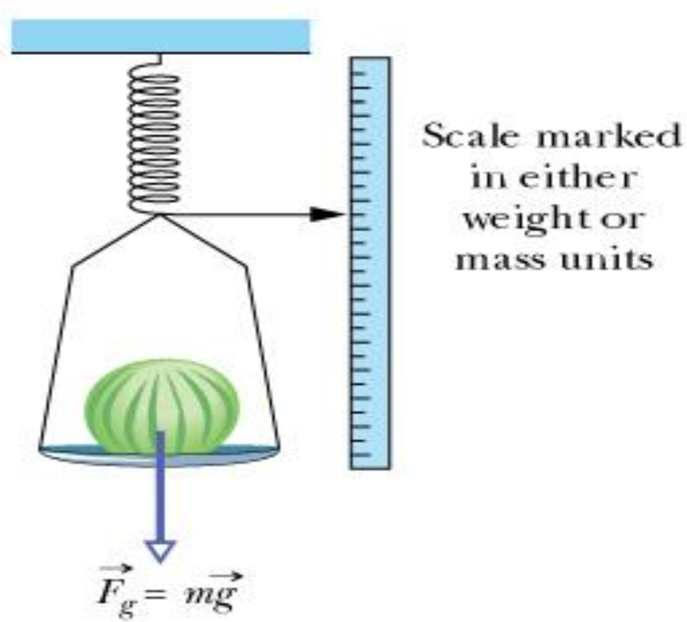
The gravitational force: The force of attraction between any two bodies.

$$F_g = G\frac{m_1 m_2}{r^2}$$

$G = 6.67\times10^{-11}\ N.m^2.kg^{-2}$ is the gravitational constant.

Weight: The weight of a body is equal to the magnitude Fg of the gravitational force on the body.

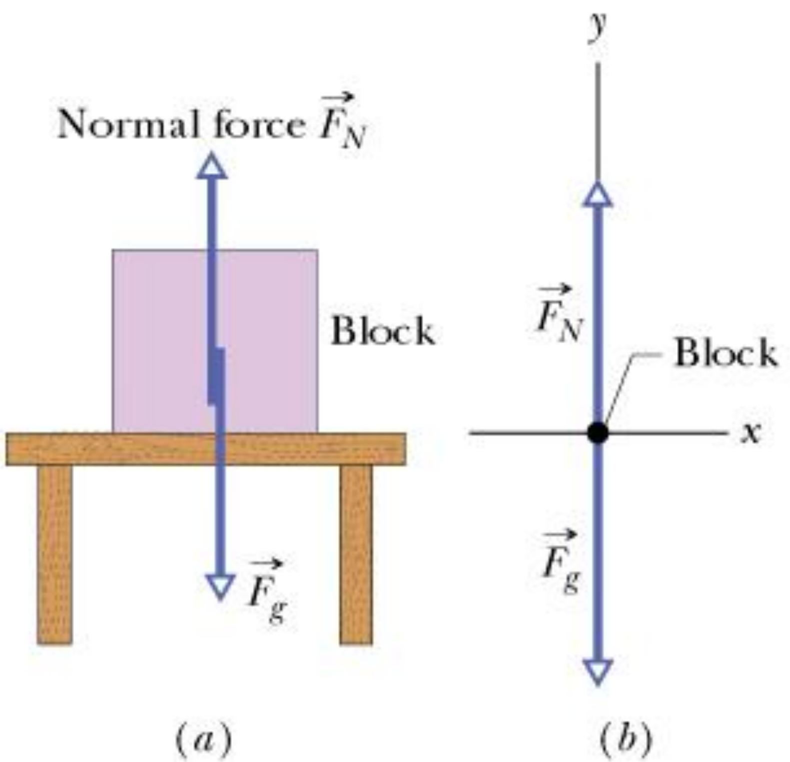
$$W = mg$$



Note: A body's weight is not its mass. weight depends on g.
For example, a ball of 7 kg is ~70 N on Earth but only ~12 N on the Moon since g_{Moon}=1.7 m/s².

The normal force:

When a body presses against a surface, the surface deforms and pushes on the body with a normal force $\vec{F}_N$ that is perpendicular to the surface.



Example: A block of mass m presses down on a table, if the table and block are accelerating with a_y:

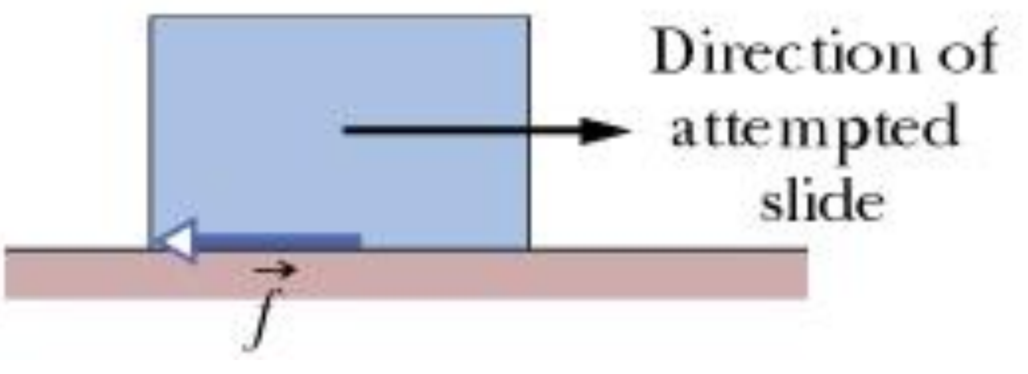
$$F_N - mg = ma_y$$

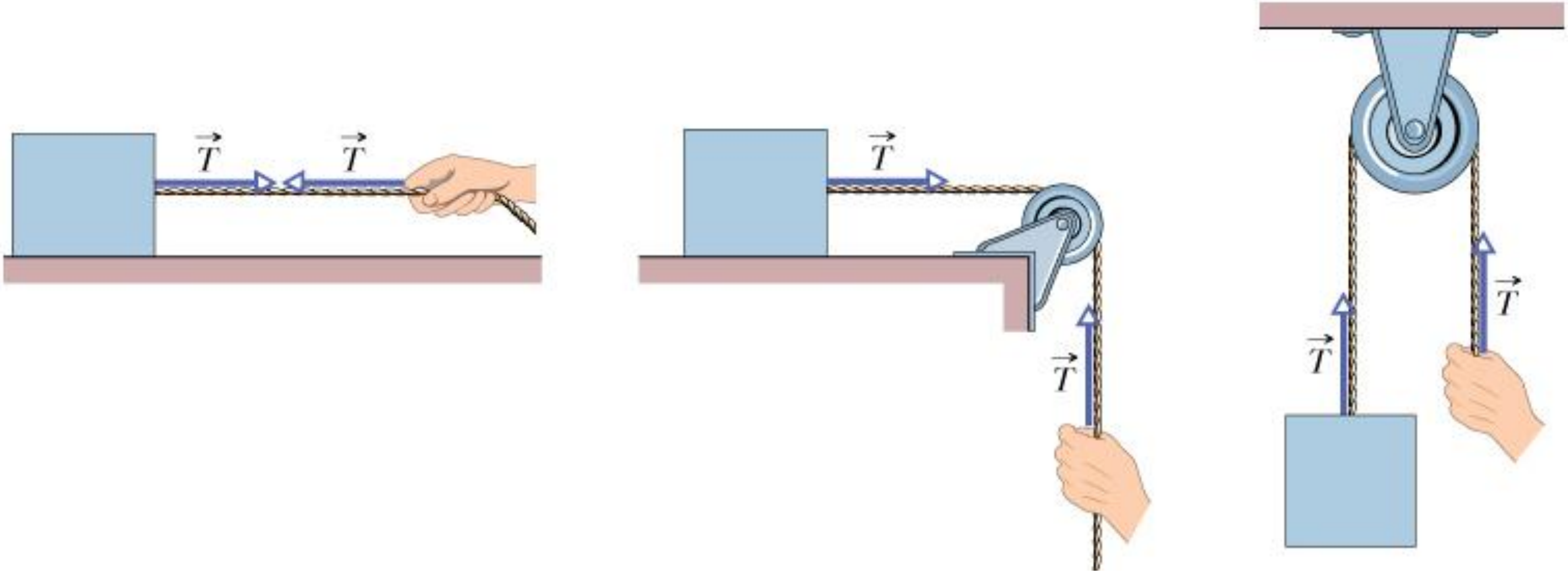
So,

$$F_N = m\,(g + a_y)$$

Friction: The force resists the attempted slide of a body over a surface.

$\vec{f}$: frictional force





Tension:

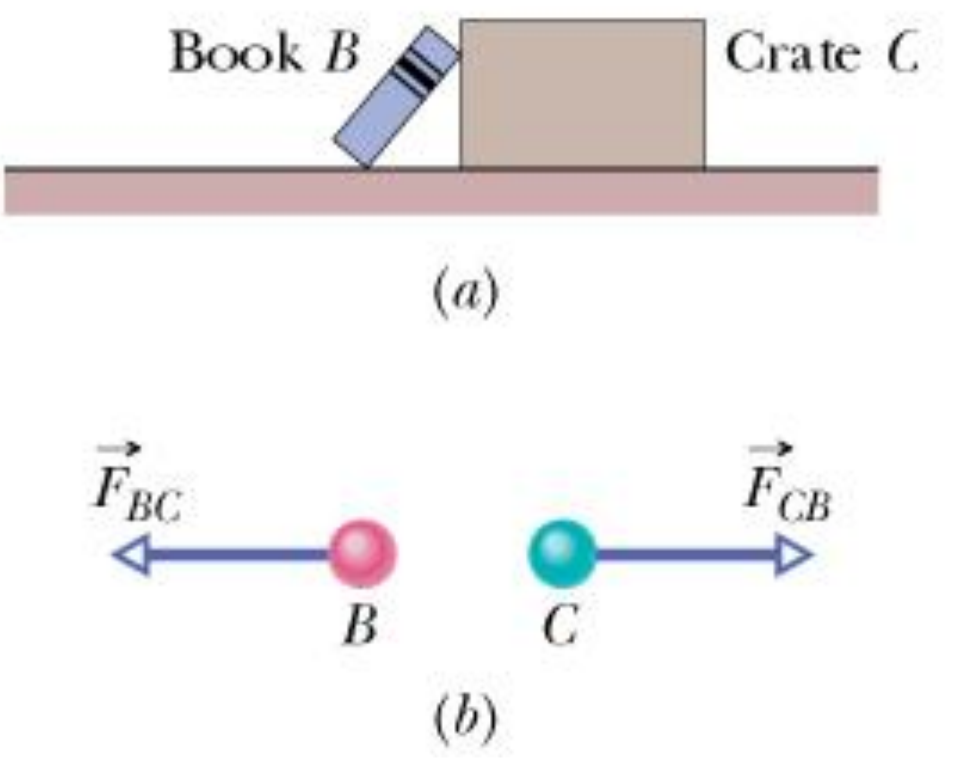
$\vec{T}$: the tension force is directed away from the body and along the cord;

2.4. Newton's Third Law

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

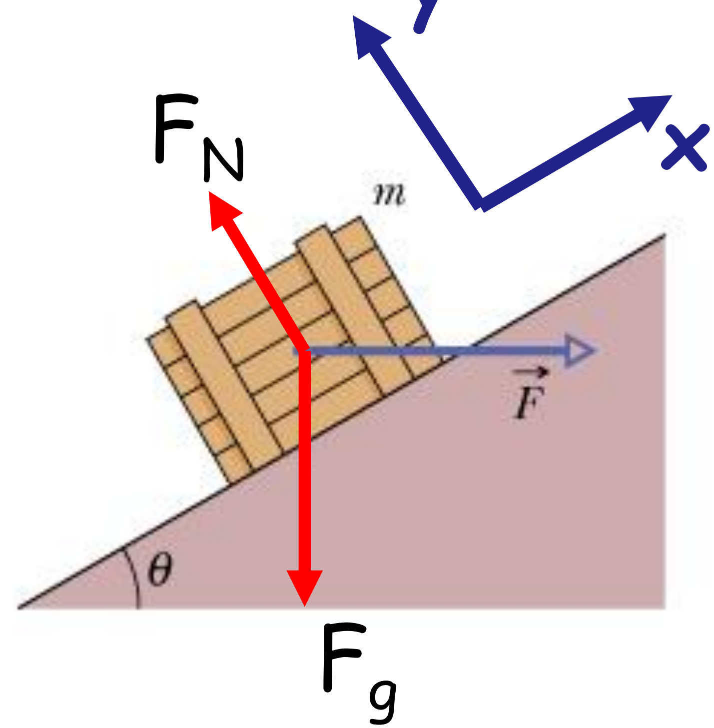
$$F_{BC} = F_{CB}$$

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



- The forces between two interacting bodies are called a third-law force pair.

Example (P.110). **In the figure below, a crate of mass m=115 kg is pushed at constant speed up a frictionless ramp (θ=30.0^0) by a horizontal force. What are the magnitudes of (a) $\vec{F}$ and (b) the force on the crate from the ramp?**



(a) The crate moves with a constant speed, so the net force acting on the crate is zero.

Along the x axis:

$$F\cos\theta - mg\sin\theta = ma$$

+ a = 0 (constant speed):

$$F\cos\theta = mg\sin\theta \rightarrow F = 651\ (N)$$

(b) Along the y axis:

$$F_N - mg\cos\theta - F\sin\theta = 0$$

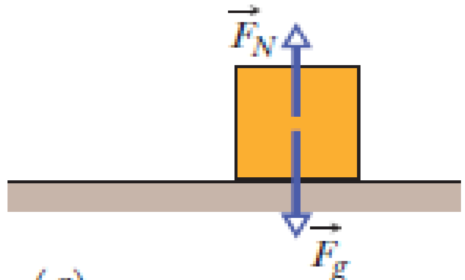
$$F_N = mg\cos\theta + F\sin\theta \rightarrow F_N = 1302\ (N)$$

Homework: 5, 7, 13, 15, 45, 49, 50, 53, 57, 59

Page 108 – 112 in the book Principles of Physics

2.5. Friction and Properties of Friction.

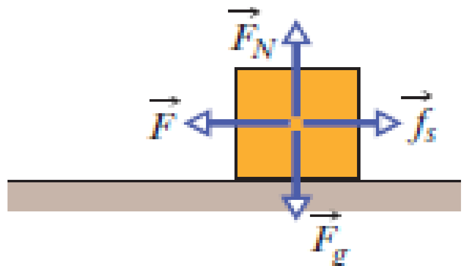
There is no attempt at sliding. Thus, no friction and no motion.



(a)

Frictional force = 0

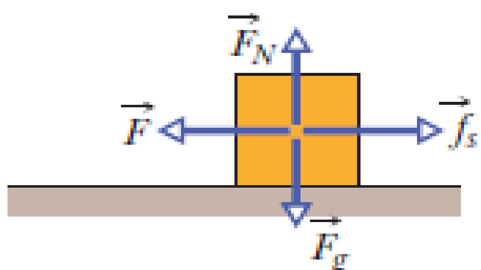
Force $\vec{F}$ attempts sliding but is balanced by the frictional force. No motion.



(b)

Frictional force = F

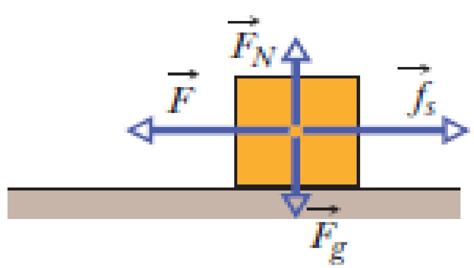
Force $\vec{F}$ is now stronger but is still balanced by the frictional force. No motion.



(c)

Frictional force = F

Force $\vec{F}$ is now even stronger but is still balanced by the frictional force. No motion.

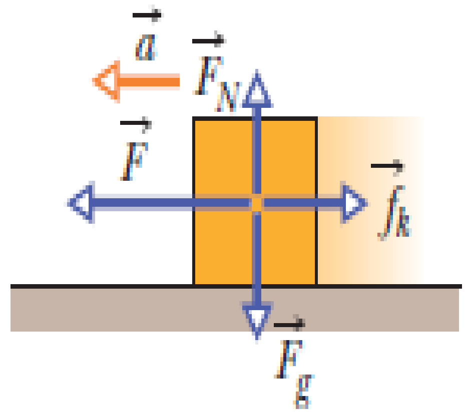


(d)

Frictional force = F

2.5. Friction and Properties of Friction.

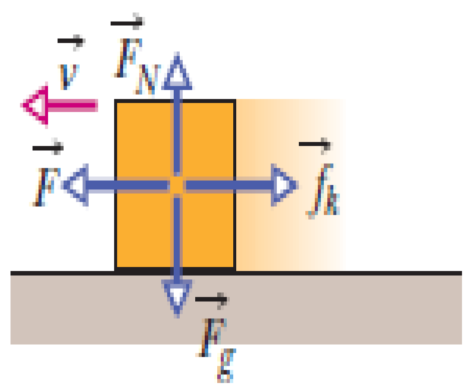
Finally, the applied force has overwhelmed the static frictional force. Block slides and accelerates.



(e)

Weak kinetic frictional force

To maintain the speed, weaken force $\vec{F}$ to match the weak frictional force.



(f)

Same weak kinetic frictional force

2.5. Friction and Properties of Friction.

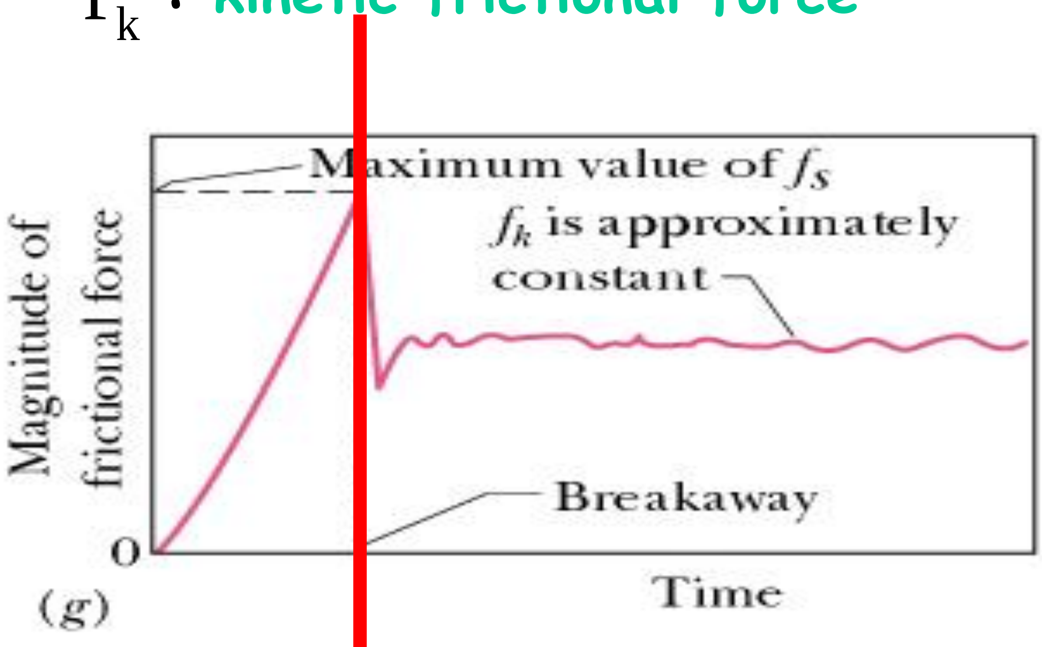
- **Friction:**

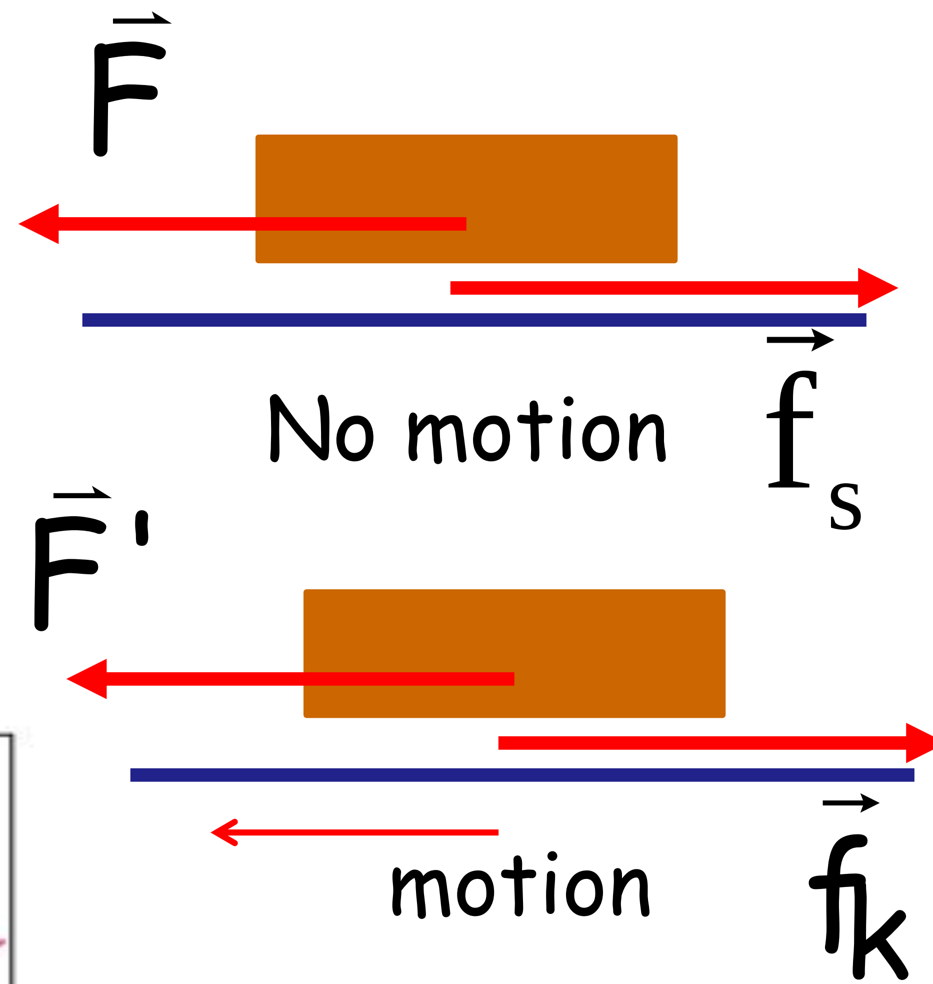
- No motion of the block:

  $\vec{f}_s$: static frictional force

- Motion of the block:

  $\vec{f}_k$: kinetic frictional force





$$\left|\vec{f}_k\right| < \left|\vec{f}_{s,max}\right|$$

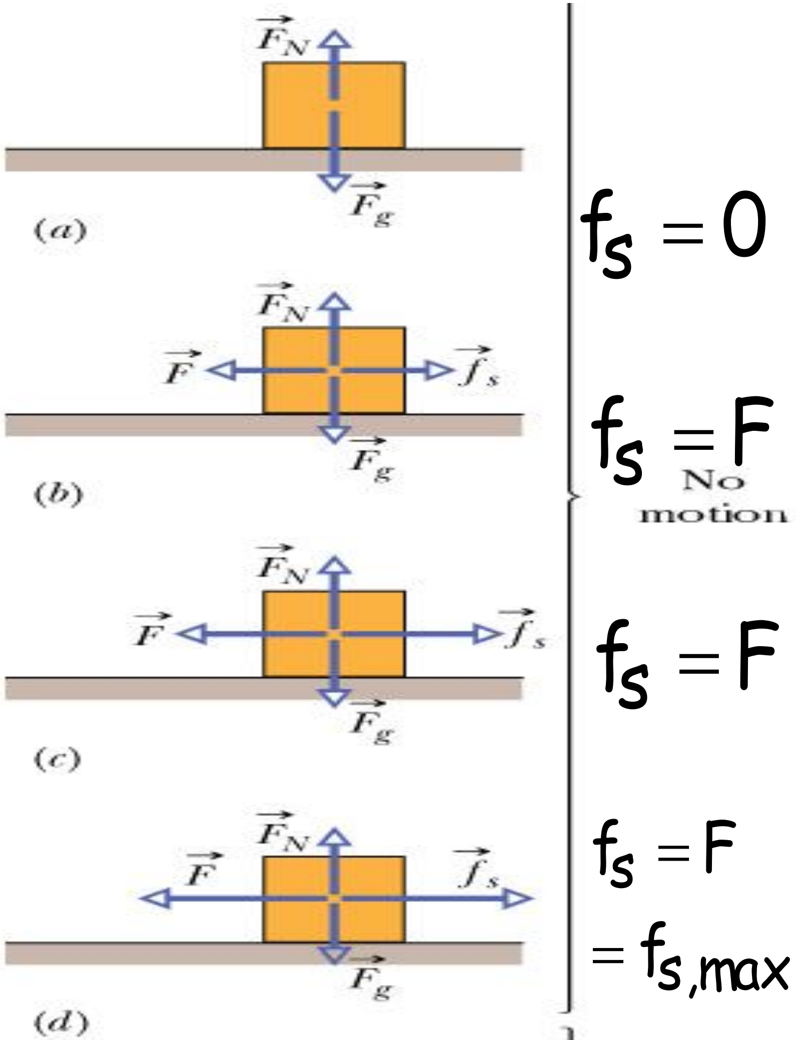
- **Properties of friction:**

Property 1: If the body does not move, $\vec{f}_s$ and the component of $\vec{F}$ that is parallel to the surface are equal in magnitude and opposite in direction.

Property 2: The magnitude of $\vec{f}_s$ has a **maximum value** computed by:

$$f_{s,max} = \mu_s F_N$$

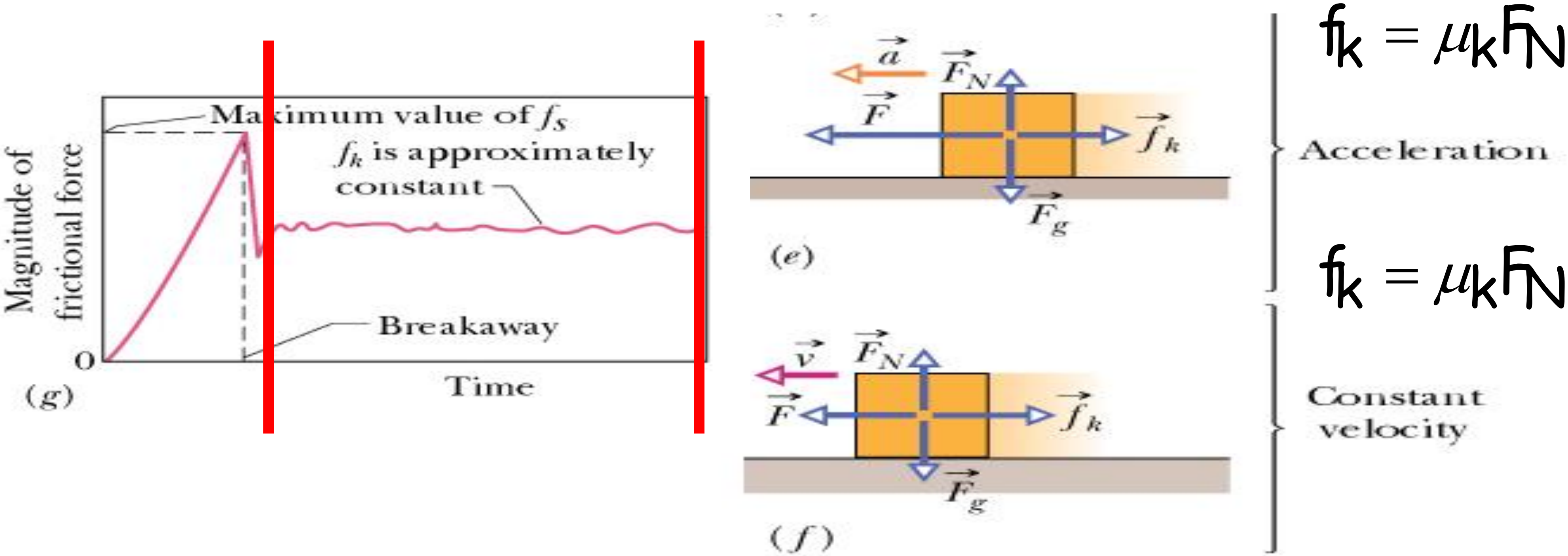
μ_s is the coefficient of static friction.
F_N is the magnitude of the normal force on the body from the surface.



Property 3: **If the body moves, the magnitude of the frictional force decreases to a value f_k calculated by:**

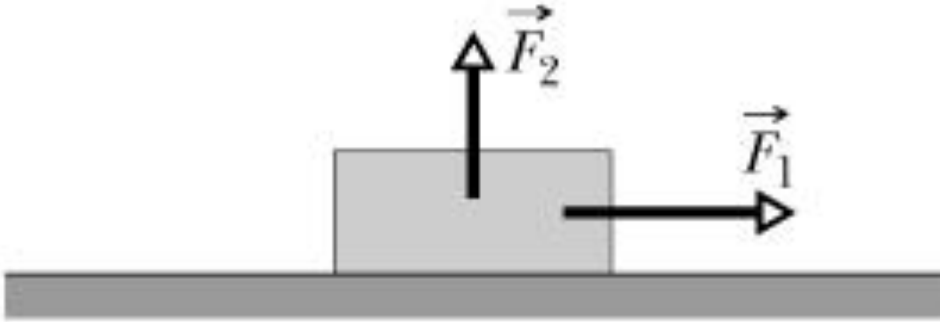
$$f_k = \mu_k F_N$$

μ_k **is the coefficient of kinetic friction**



- **Checkpoint:**

F_1=10 N, F_2 increases from 0. Before the box begins to slide, do the following quantities increase, decrease or stay the same:
(a) f_s; (b) F_N; (c) $f_{s,max}$



(a) the same;

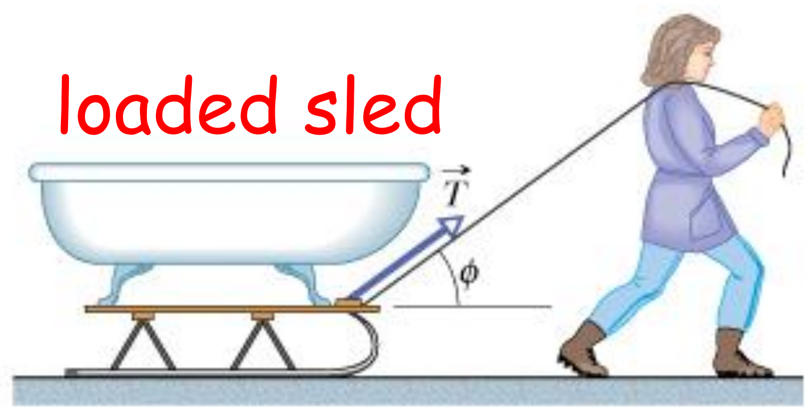
(b) $F_N + F_2 = mg$ → F_N decreases;

(c) $f_{s,max} = \mu_s F_N$, so $f_{s.max}$ decreases

- **Sample Problem:**

A woman pulls a loaded sled of $m=75$ kg at constant speed; $\mu_k=0.10$; $\phi=42^0$; determine:

(a) $|\vec{T}|$ (b) T increases, how about f_k?



(a)

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

Constant speed requires a = 0, so:

- For the x axis:

$$T\cos\Phi - f_k = 0; f_k = \mu_k F_N$$

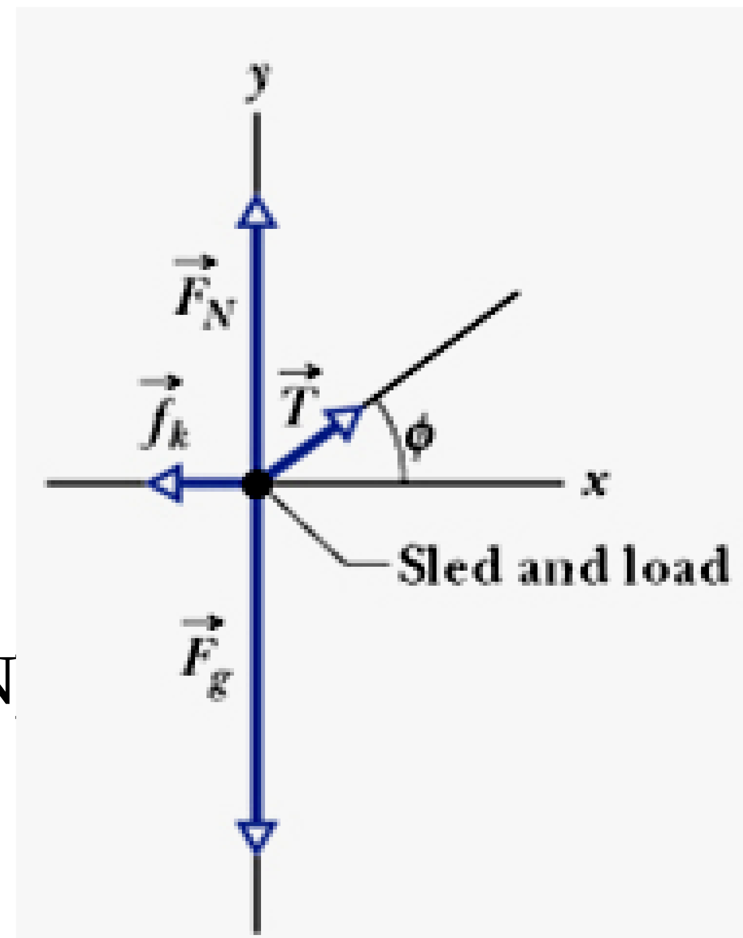
$$T\cos\Phi - \mu_k F_N = 0 \ (1)$$

- For the y axis:

$$T\sin\Phi + F_N - mg = 0 \ (2)$$

$$(1) \& (2) \Rightarrow T = \frac{\mu_k mg}{\cos\Phi + \mu_k \sin\Phi} = 90.7 \ (N$$

$$F_N = mg - T\sin\Phi$$



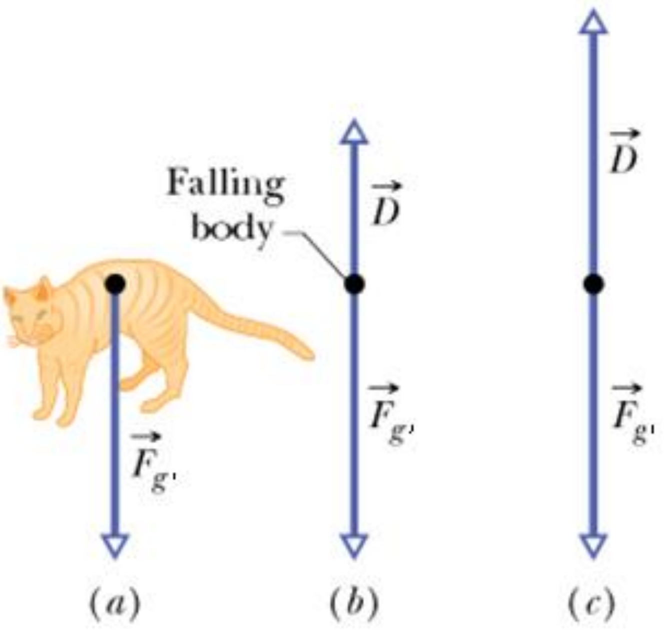
➔ If T increases, F_N will decrease ➔ f_k decreases

➔ On the x axis: T increases, but f_k decreases ➔ speed change

Motion in the Presence of Resistive Forces:

If a body moves through a fluid (gas or liquid), the body will experience a drag force $\vec{D}$ (due to air or viscous resistance) that opposes the relative motion.

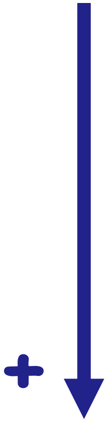
- Drag at high velocity: $D = \frac{1}{2} C\rho A v^2$



ρ is the density of the fluid
v is the speed of the body relative to the f
A is the effective cross-sectional area
C is the drag coefficient

For a body falling through air:
$F_{g'} - D = ma$

D increases until $D = F_{g'}$, and the body falls at a constant speed, called the terminal speed V_t:



$$F_g' - \frac{1}{2} C\rho A v_t^2 = 0$$

$$\Rightarrow v_t = \sqrt{\frac{2F_g'}{C\rho A}}$$

- **Drag at low velocity:** $$D = bv$$

b is a constant, depending on the properties of the fluid and the dimension of the body v is the speed of the body

$$mg - F_{buoyant} - bv = ma \quad (1)$$

D increases until the acceleration a=0:

$$mg - F_{buoyant} = bv_t \quad (2)$$

$$(1) \text{ and } (2) \Rightarrow b(v_t - v) = ma \text{ or } b(v_t - v) = m\frac{dv}{dt}$$

$$\frac{dv}{v - v_t} = -\frac{b}{m}dt \Rightarrow \int_0^v \frac{dv}{v - v_t} = -\frac{b}{m}\int_0^t dt$$

$$\ln\frac{v_t - v}{v_t} = -\frac{b}{m}t \Rightarrow v = v_t(1 - e^{-\frac{b}{m}t}) \quad (3)$$

$$(1) \Rightarrow v_t = \frac{mg - F_{buoyant}}{b} = \frac{mg'}{b} \Rightarrow v = \frac{mg'}{b}\left(1 - e^{-\frac{b}{m}t}\right);$$

$$(3) \rightarrow \quad y = v_t t + v_t \frac{m}{b}\left(e^{-\frac{b}{m}t} - 1\right)$$

$$a = g' e^{-\frac{b}{m}t}$$

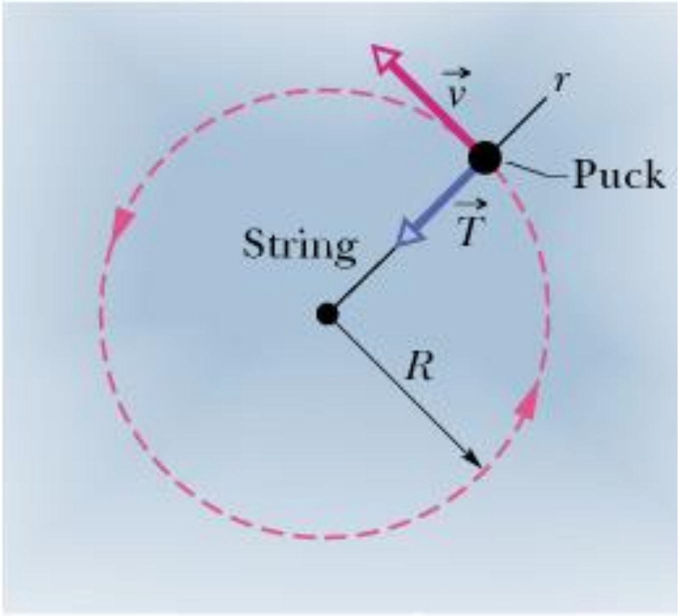
$$\tau = \frac{m}{b} : \text{the characteristic time}$$

$$v = v_t\left(1 - e^{-\frac{t}{\tau}}\right)$$

$$a = g' e^{-\frac{t}{\tau}}$$

$$y = v_t t + v_t \tau\left(e^{-\frac{t}{\tau}} - 1\right)$$

2.6. Uniform Circular Motion and Non-uniform Circular Motion



Uniform circular motion

Centripetal (radial) acceleration:

$$a = \frac{v^2}{R}$$

Centripetal (radial) force:

$$F = ma = m\frac{v^2}{R}$$

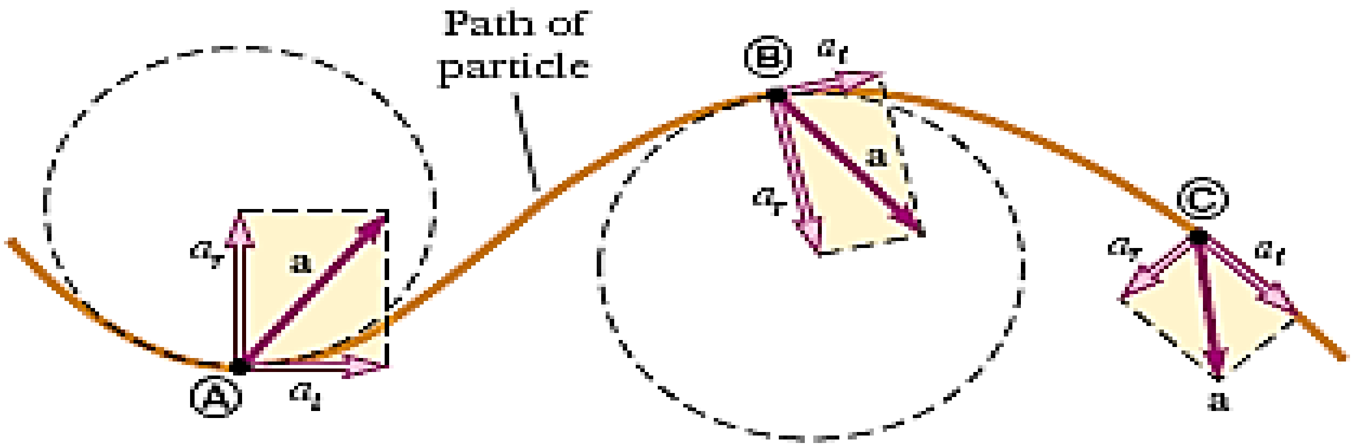
$$T = m\frac{v^2}{R}$$

Note: A centripetal force accelerates an object by changing its velocity direction without changing its speed.

Non-uniform circular motion

$$\vec{a} = \vec{a}_r + \vec{a}_t$$

Radial (centripetal) acceleration — Tangential acceleration



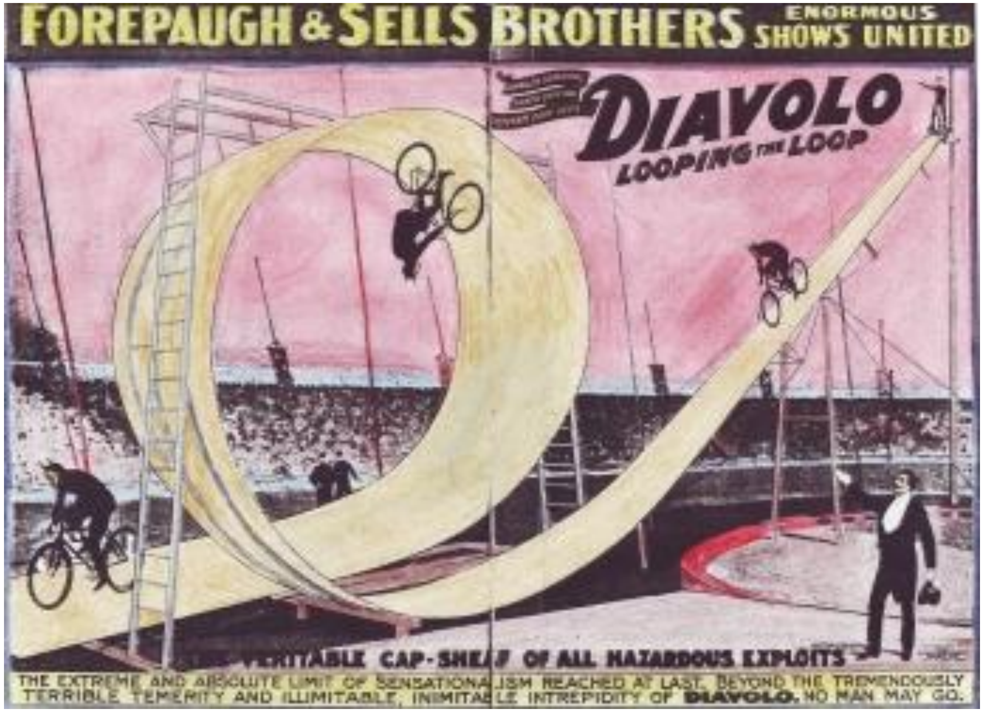
$$\vec{F} = m\vec{a} = m(\vec{a}_r + \vec{a}_t) = m\vec{a}_r + m\vec{a}_t$$

$$\vec{F}_r = m\vec{a}_r; \vec{F}_t = m\vec{a}_t$$

$$F_r = m\frac{v^2}{R}; F_t = m\frac{dv}{dt}$$

Sample Problem (p. 125)

Di is riding a bike in a loop, assuming the loop is a circle with R = 2.7 m, what is the least speed v Di can have at the top of the loop to remain in contact with it there?



$$-F_N - F_g = m(-a) = -m\frac{v^2}{R}$$

$$F_N + mg = m\frac{v^2}{R}$$

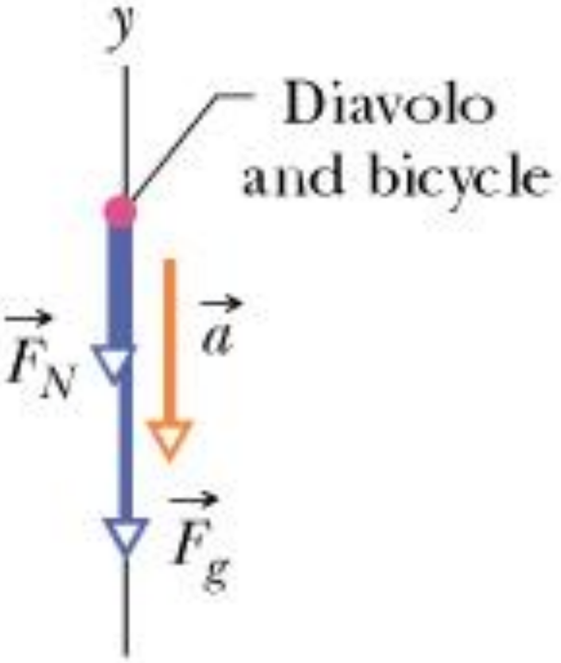
To remain in contact with the loop:

$$F_N \geq 0$$

the least speed needed for the Diavolo and his bike:

$$F_N = 0 \Rightarrow v_{min} = \sqrt{gR}$$

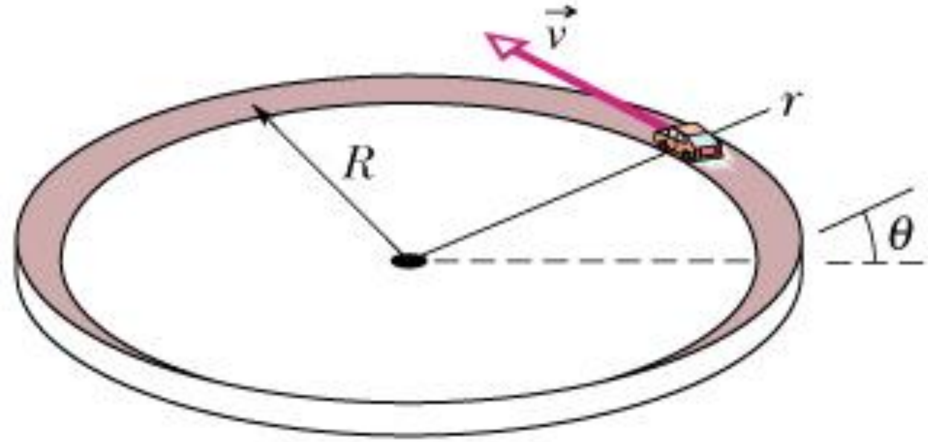
$$v_{min} = \sqrt{9.8 \times 2.7} = 5.1(m/s)$$

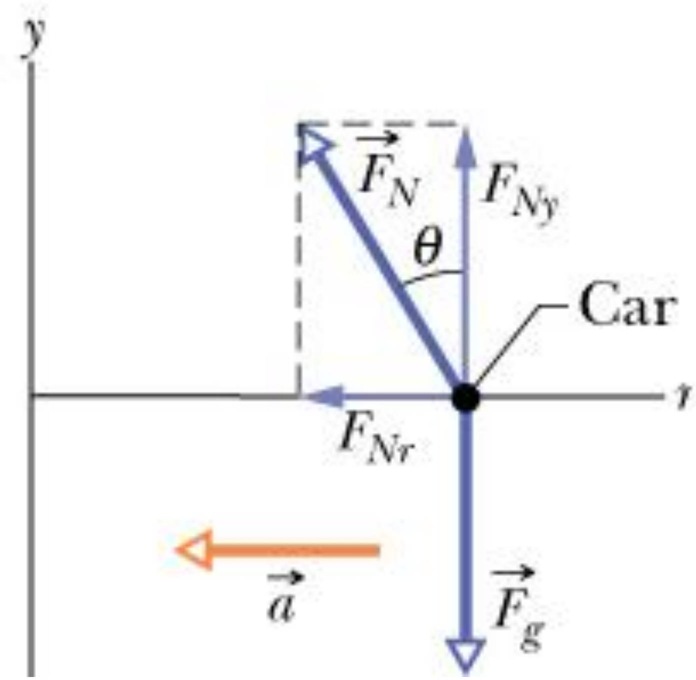


A free-body diagram

Sample Problem (p. 128)

Curved portions of highways are tilted to prevent cars from sliding off the highways. If the highways are wet, the frictional force from the track is negligible. What bank angle θ prevents sliding?





To prevent sliding, the component F_{Nr} of the normal force along the radial axis r provides the necessary centripetal force and radial acceleration:

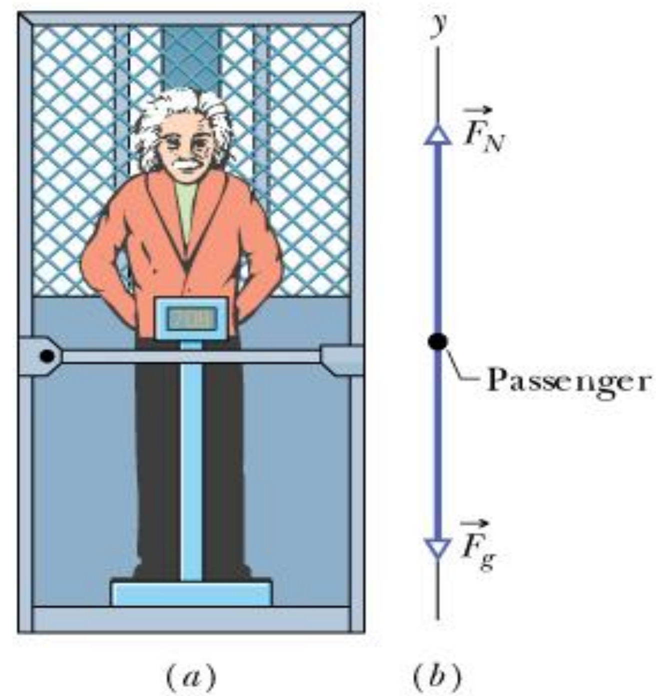
$$F_{Nr} = -F_N \sin\theta = m\left(-\frac{v^2}{R}\right)$$

$$F_N \cos\theta = mg$$

$$\theta = \tan^{-1}\frac{v^2}{gR}$$ ➔ to prevent sliding

2.5. Motion in Accelerated Frames

Accelerated (no inertial) reference frames: in which Newton's laws of motion do not hold.



Example: An elevator cab is moving with an acceleration $\vec{a}_0$ ➔ the cab is not an inertial frame.

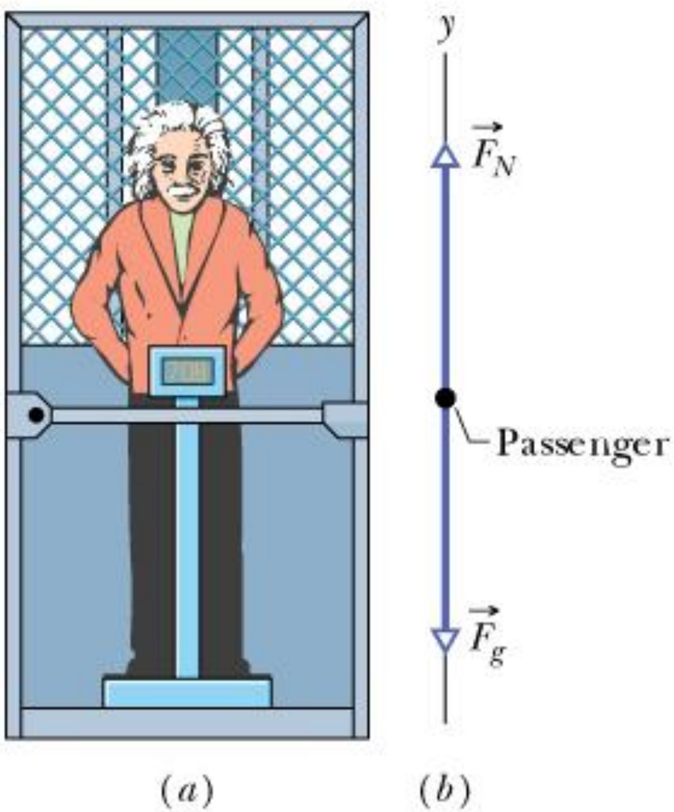
+ We choose the ground to be our inertial frame (stationary), so using Newton's second law for the passenger with a mass m

$$\vec{F}_N + \vec{F}_g = m\vec{a}_0$$

+ However, if we choose the cab (non-inertial frame, accelerated with $\vec{a}_0$) to be our frame, the passenger's acceleration is zero in this frame, so

~~$$\vec{F}_N + \vec{F}_g = 0$$~~

In this case, to use Newton's second law, we must add an inertial (fictitious) force:



$$\vec{F}_{fictitious} = -m\vec{a}_0$$

Therefore:

$$\vec{F} + \vec{F}_g - m\vec{a}_0 = 0$$

If the passenger moves with an acceleration $\vec{a}$ in the cab:

$$\vec{F} + \vec{F}_g - m\vec{a}_0 = m\vec{a}$$

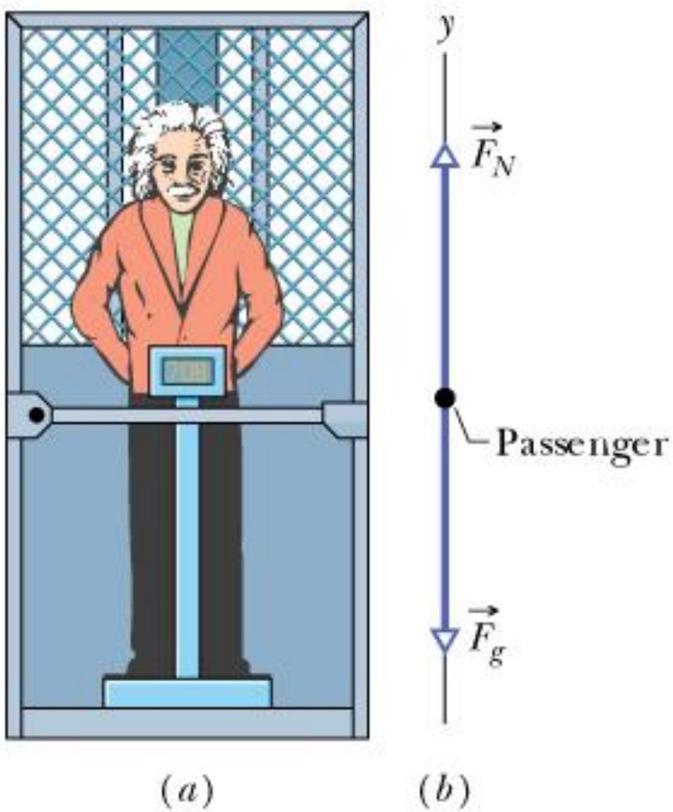
In a noninertial frame, Newton's second law is:

$$\sum \vec{F} - m\vec{a}_0 = m\vec{a}$$

Sample Problem (p.103): In the figure below, a passenger of mass m=72.2 kg stands on a platform scale in an elevator cab. We are concerned with the scale readings when the cab is stationary and when it is moving up or down.

(a) Find a general solution for the scale reading, whatever the vertical motion of the cab. The scale reading is equal to the magnitude of the normal force acting on the passenger.

$$F_N - mg = ma \Rightarrow F_N = m(g + a)$$



(b) What does the scale read if the cab is stationary or moving upward at a constant 0.50 m/s?

$$a = 0 \Rightarrow F_N = m(g + a) = 72.2 \times 9.8 \approx 708\ (N)$$

(c) What does the scale read if the cab accelerates upward at 3.20 m/s² and downward at 3.20 m/s²?

$$F_N = m(g+a) = 72.2 \times (9.8 + 3.2) \approx 939 \text{ (N)}$$

$$F_N = m(g+a) = 72.2 \times (9.8 - 3.2) \approx 477 \text{ (N)}$$

(d) During the upward acceleration in part (c), what is the magnitude F_{net} of the net force on the passenger, and what is the magnitude $a_{p,cab}$ of his acceleration as measured in the frame of the cab?

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

$$F_{net} = F_N - F_g = 939 - 708 = 231 \text{(N)}$$

The passenger is stationary in the elevator, so: $a_{p,cab} = 0$

The cab is not an inertial frame, hence Newton's second law is not applicable in the frame of the cab:

$$F_{net} \neq m a_{p,cab}$$

If we want to use Newton's second law, we need to include a fictitious force:

$$F_{net} + F_{fictitious} = F_{net} - m\underbrace{a_{cab,ground}}_{=0} = m\underbrace{a_{p,cap}}_{=0}$$

Homework:

5, 9, 19, 25, 31, 34, 39, 49, 51, 70

Page.130-137 in the book Principles of Physics

Review chapter 2: Force and Motion

Newton's Laws

1. $\vec{F} = 0$ or $\sum_{i=1}^{n} \vec{F}_i = 0$ 2. $\vec{F}_{net} = m\vec{a}$ 3. $\vec{F}_{BC} = -\vec{F}_{CB}$

Some particular forces: gravitational, normal, tension and frictional forces

Friction and Properties of Friction:

$f_{s,max} = \mu_s F_N$ μ_s is the coefficient of static friction

$f_k = \mu_k F_N$ μ_k is the coefficient of kinetic friction

Uniform Circular Motion and Non-uniform Circular Motion:

- Uniform circular motion: $a = \frac{v^2}{R}$ $F = ma = m\frac{v^2}{R}$
- Non-uniform circular motion:

$$\vec{a} = \vec{a}_r + \vec{a}_t$$

$$F_r = m\frac{v^2}{R}; F_t = m\frac{dv}{dt}$$