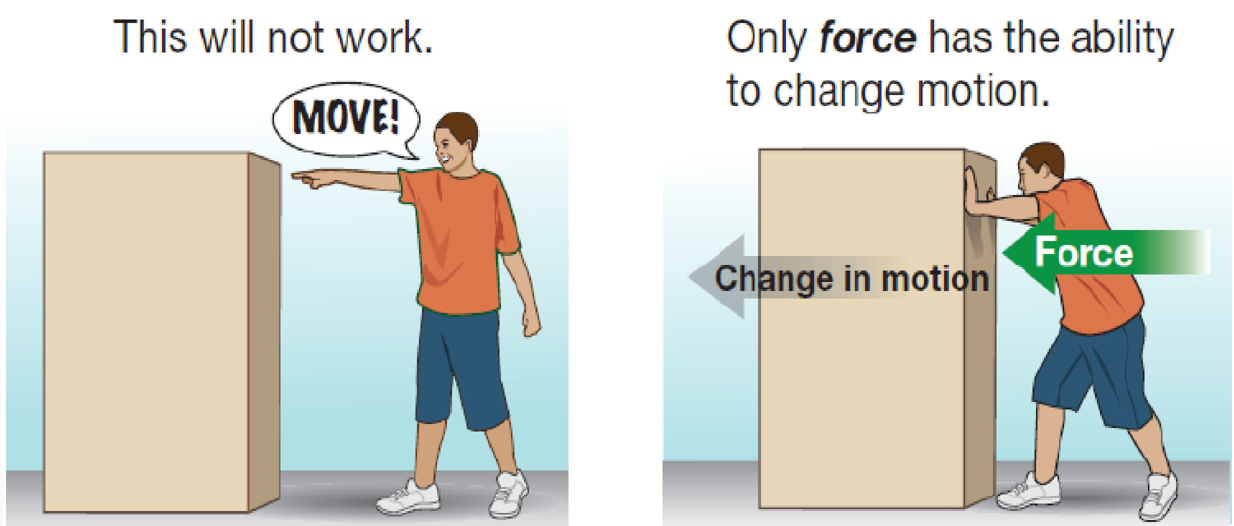
Chapter 5

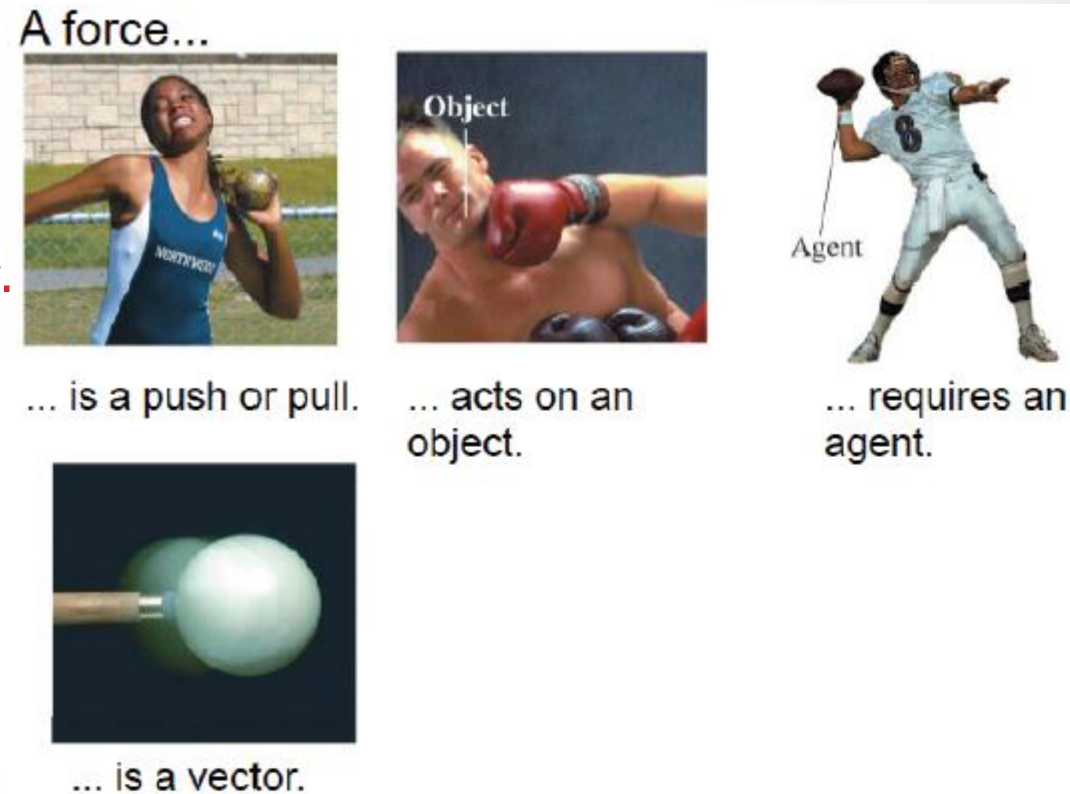
Force and Motion 1



5-1 Newton's First and Second Laws

- A **force**:
  - Is a “push or pull” or any action has the ability to change an object's motion.
  - Causes acceleration

FORCE is a VECTOR quantity.



- We will focus on Newton's three laws of motion:
    - **Newtonian mechanics** is valid for everyday situations
    - It is *not* valid for speeds which are an appreciable fraction of the speed of light
    - It is *not* valid for objects on the scale of atomic structure
    - Viewed as an approximation of general relativity

➢ Forces can be used to increase the speed of an object, decrease the speed of an object, or change the direction in which an object is moving.

Vector Nature of Forces (**Principle of superposition**):

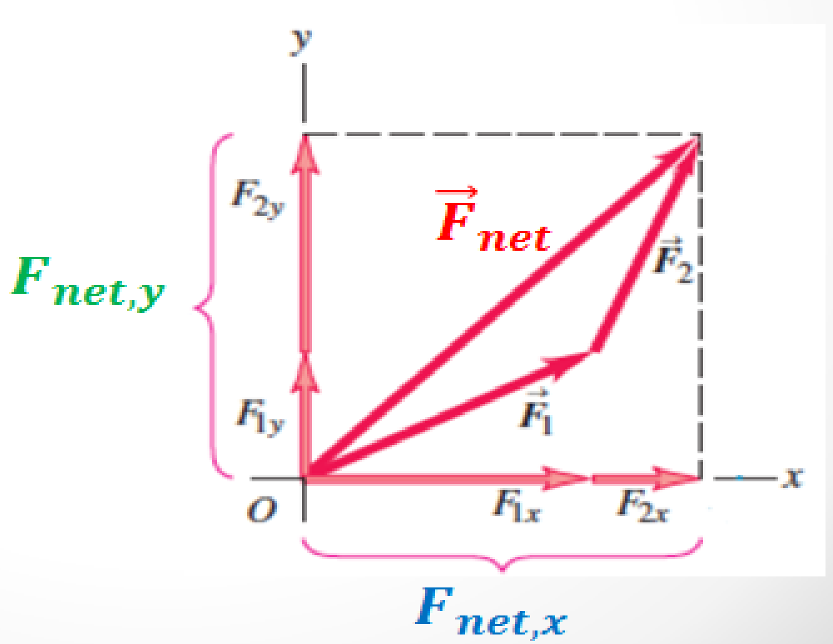
$$\vec{F}_{net} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 + \ \ldots$$

The net force acting on a body is the vector sum, or resultant, of all individual force acting on that body

$$\vec{F}_{net} = F_{net,x}\ \hat{\imath} + F_{net,y}\ \hat{\jmath}$$

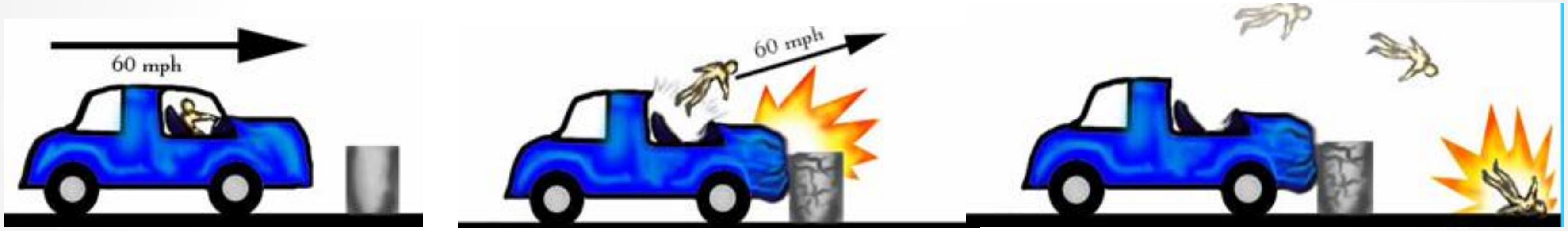
$$F_{net} = \sqrt{(F_{net,x})^2 + (F_{net,y})^2}$$

Only include forces that act *on* that body!



Newton's First Law: If no *net* force acts on a body ($\vec{F}_{net} = 0$), the body's velocity cannot change; that is, the body cannot accelerate.

Zero acceleration →→ $\vec{v}$ is constant in magnitude and direction

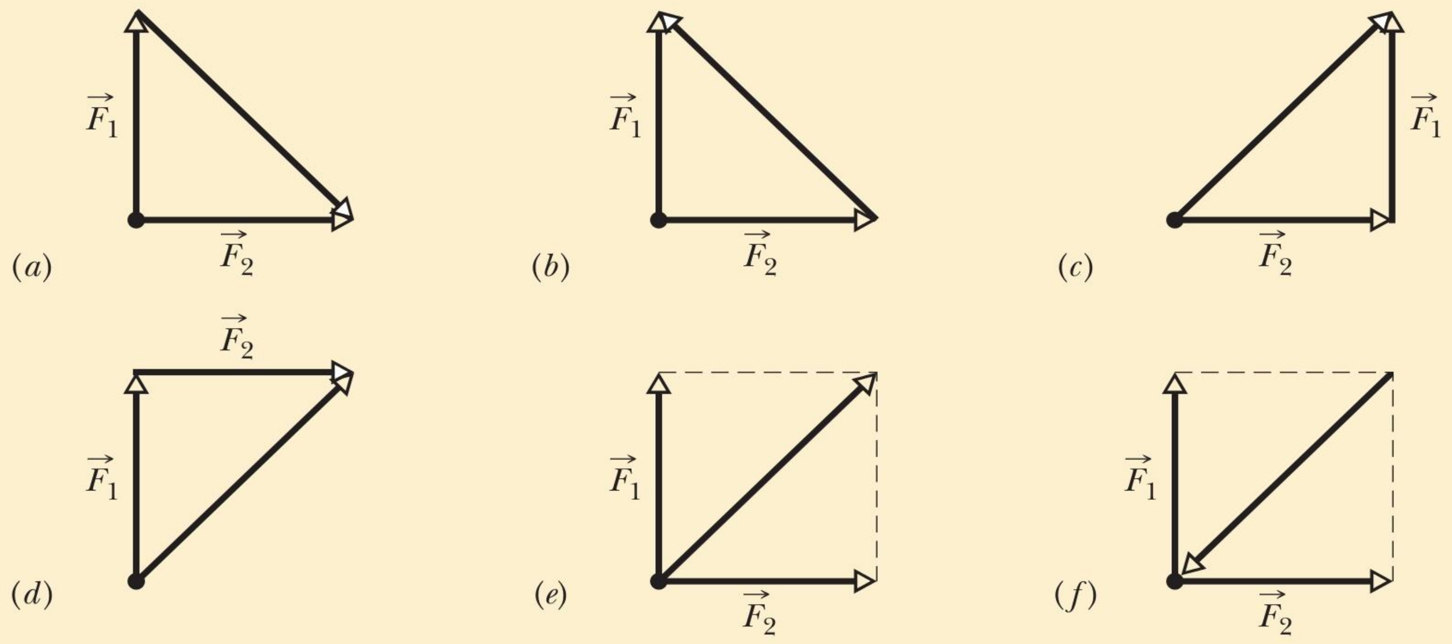


- **Inertial frames (Newtonian Mechanics):**

An inertial reference frame is one in which Newton's laws hold.

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 $\vec{F}_{net}$?



Answer: (c), (d), (e)

Newton's Second Law The net force $\vec{F}_{net}$ on a body with mass m is related to the body's acceleration $\vec{a}$ by

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

which may be written in the component versions **(They are Independent)**

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

The second law indicates that in SI units

$$1 \text{ N} = 1 \text{ kg} \cdot \text{m/s}^2$$

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

The acceleration component along a given axis is caused *only by* the sum of the force components along that *same* axis, and not by force components along any other axis.

- What is mass?
  - *"the mass of a body is the characteristic that relates a force on the body to the resulting acceleration".*
  - *Scalar quantity*
  - Mass is a measure of a body's resistance to a change in motion (change in velocity)

Example Apply an 8.0 N force to various bodies:

- Mass: 1kg → acceleration: 8 m/s^2
- Mass: 2kg → acceleration: 4 m/s^2
- Mass: 0.5kg → acceleration: 16 m/s^2
- Acceleration: 2 m/s^2 → mass: 4 kg

- If the net force on a body is zero:
  - Its acceleration is zero
  - The forces and the body are in *equilibrium*
  - *But* there may still be forces!

- Units of force:

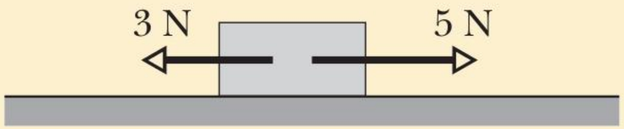
Table 5-1 Units in Newton's Second Law (Eqs. 5-1 and 5-2)

System	Force	Mass	Acceleration
SI	newton (N)	kilogram (kg)	m/s^2
CGS[a]	dyne	gram (g)	cm/s^2
British[b]	pound (lb)	slug	ft/s^2

[a] $1 \text{ dyne} = 1 \text{ g} \cdot \text{cm/s}^2$.

[b] $1 \text{ lb} = 1 \text{ slug} \cdot \text{ft/s}^2$.

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?

Answer:

$$\vec{F}_{net} = 0$$

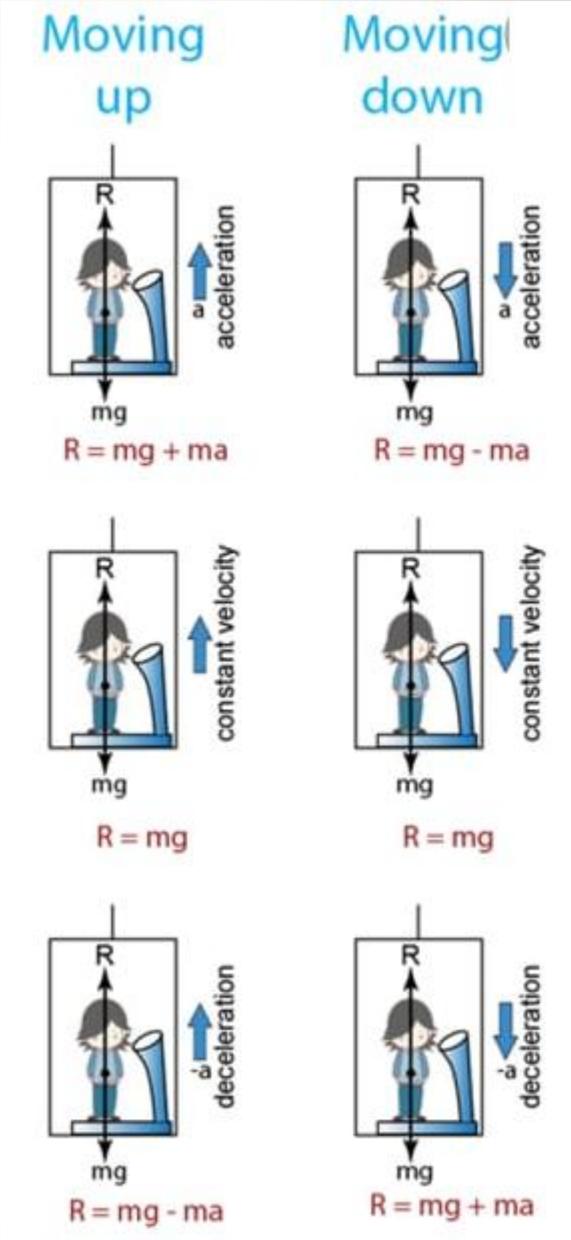
F_3 = 2 N to the left in *both* cases

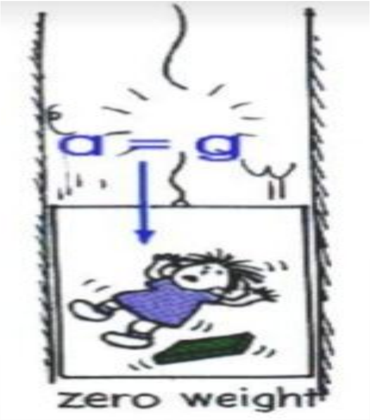
5-2 Some Particular Forces:

1. Gravitational force: A pull that acts on a body, directed toward a second body, normally the Eart. $\vec{F}_g = m\,\vec{g}$ $(down\ toward\ the\ ground)$
   This force still acts on a body at rest!

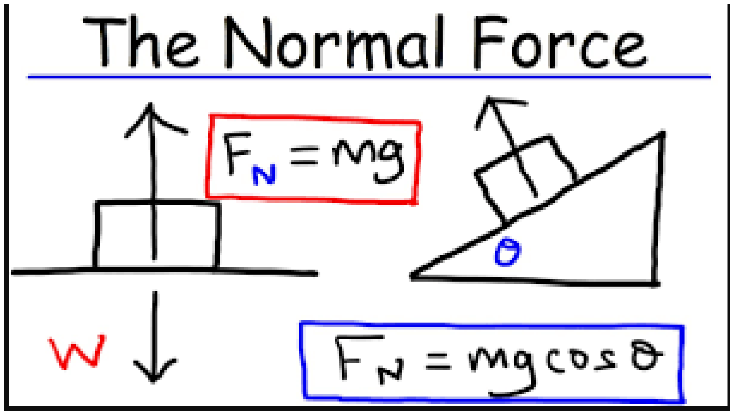
2. Weight: The magnitude of the upward force needed to balance the gravitational force on the body $W = mg$

Weight must be measured when the body is not accelerating vertically. For example, in your bathroom, or on a train, but not in an elevator

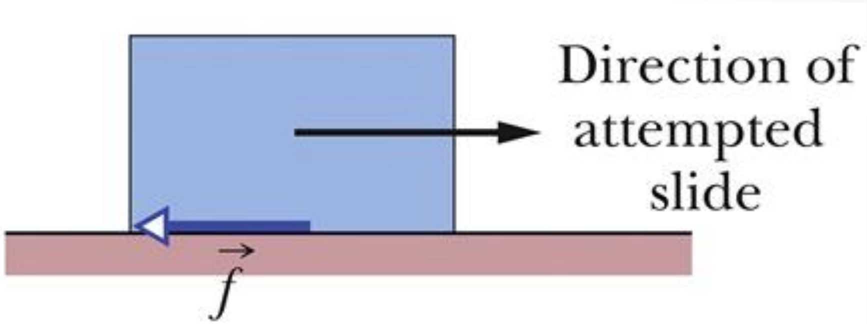




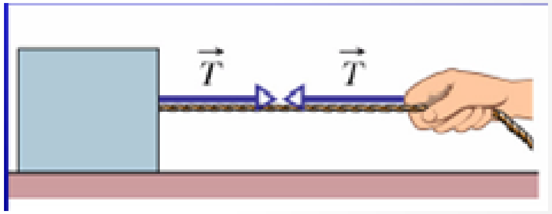
3. Normal force $\vec{F}_N$: perpendicular force on a body from a surface against which the body presses.

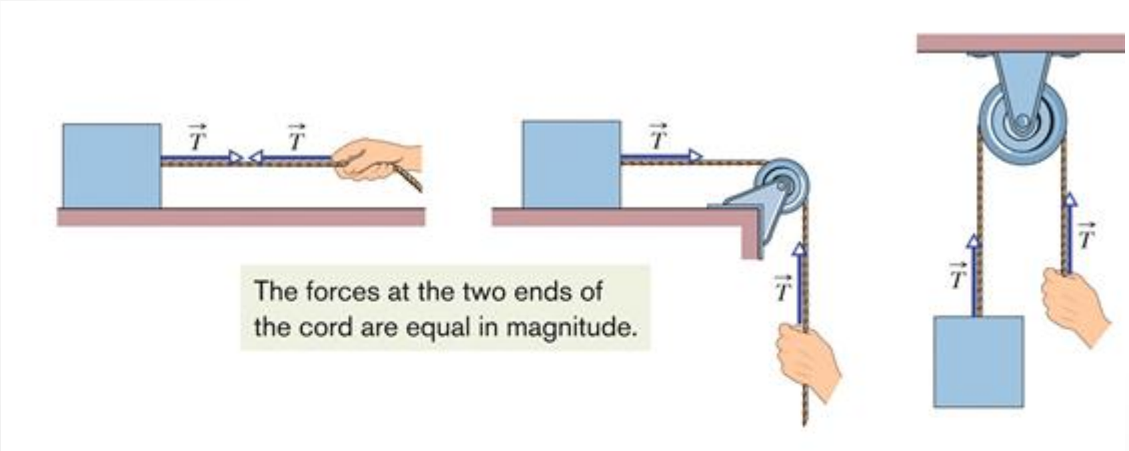


4. Friction force: The force on a body when the body slides or attempts to slide along a surface. The force is always parallel to the surface and directed so as to oppose the sliding.



5. Tension: pull on a body directed away from the body along a massless cord.





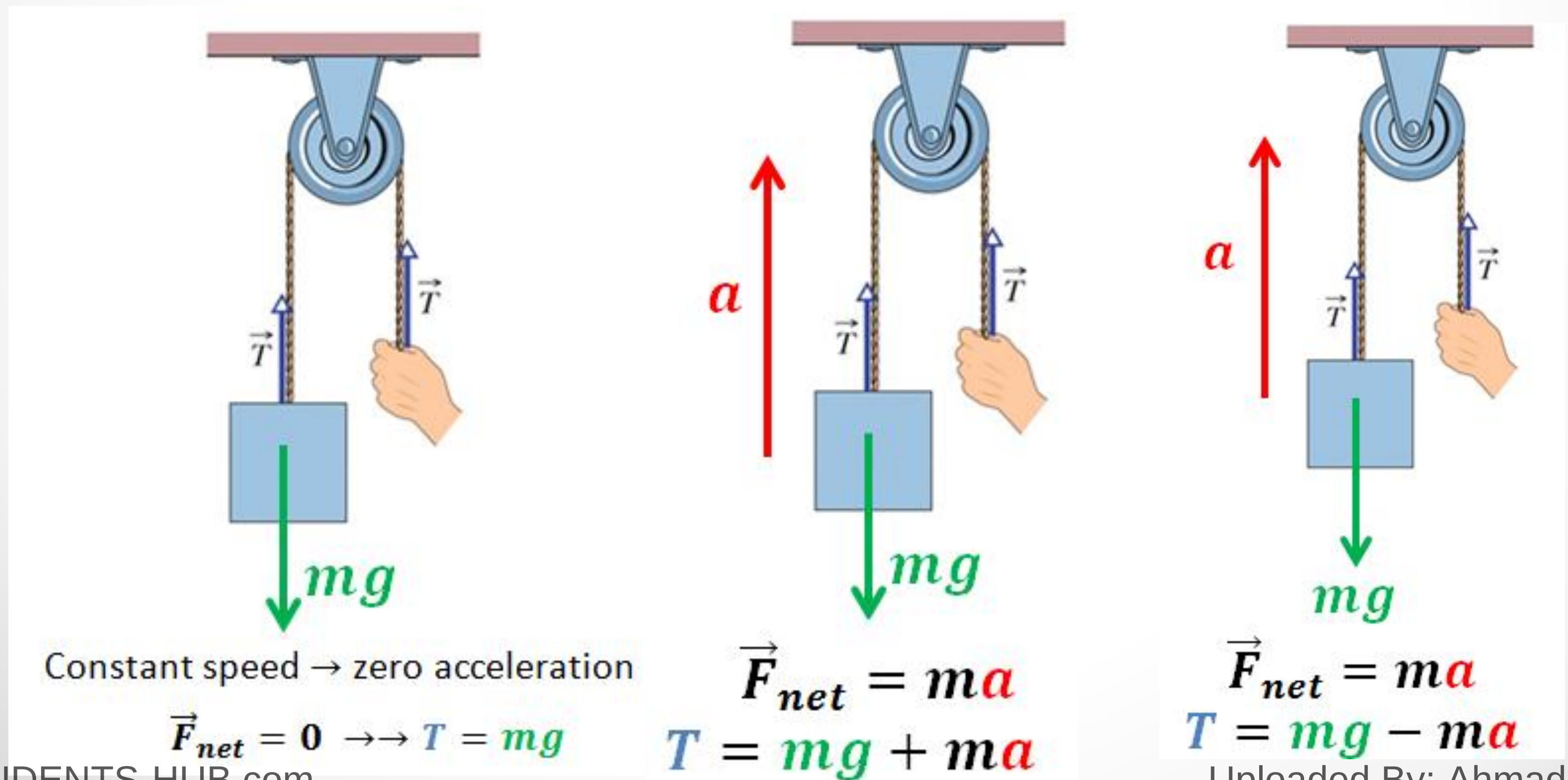
Notes:

- A **system** consists of one or more bodies
- Any force on the bodies inside a system exerted by bodies outside the system is an **external force**
- Net force on a system = sum of external forces
- **Free-body diagram** represents the forces on one object
- Forces between bodies in a system: **internal forces**
  - Not included in a FBD of the system since internal forces cannot accelerate the system

Checkpoint 4

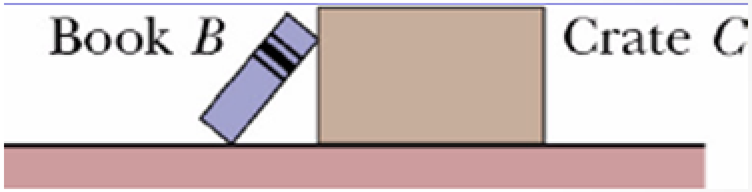
The suspended body in Fig. 5-9*c* weighs 75 N. Is *T* equal to, greater than, or less than 75 N when the body is moving upward (a) at constant speed, (b) at increasing speed, and (c) at decreasing speed?

Answer: (a) equal to 75 N (b) greater than 75 N (c) less than 75 N

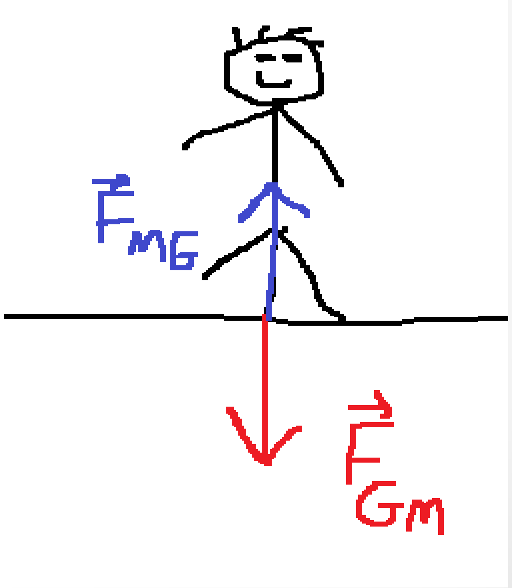


Newton's third law:

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



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



- We call these two forces a **Third-law force pair (Action and Reaction pair)**
- Any time any two objects interact, there is a third-law force pair

•3 If the 1 kg standard body has an acceleration of 2.00 m/s^2 at 20.0° 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?

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

$$\vec{a} = (a\cos\theta)\hat{i} + (a\sin\theta)\hat{j}$$

$$\vec{a} = (2\cos 20^\circ)\frac{m}{s^2}\hat{i} + (2\sin 20^\circ)\frac{m}{s^2}\hat{j}$$

$$\vec{a} = 1.88\frac{m}{s^2}\hat{i} + 0.68\frac{m}{s^2}\hat{j}$$

$$\vec{F}_{net} = m(a_x\hat{i} + a_y\hat{j})$$

$$\vec{F}_{net} = 1\,kg\left(1.88\frac{m}{s^2}\hat{i} + 0.68\frac{m}{s^2}\hat{j}\right)$$

$$\vec{F}_{net} = (1.88\,N)\hat{i} + (0.68\,N)\hat{j}$$

••9 A 0.340 kg particle moves in an xy plane according to $x(t) = -15.00 + 2.00t - 4.00t^3$ and $y(t) = 25.00 + 7.00t - 9.00t^2$, with x and y in meters and t in seconds. At $t = 0.700$ s, what are (a) the magnitude and (b) the angle (relative to the positive direction of the x axis) of the net force on the particle, and (c) what is the angle of the particle's direction of travel?

- $X(t) = -15 + 2t - 4t^3$

$$a_x = \frac{d^2x}{dt^2} = -24t$$

- $Y(t) = 25 + 7t - 9t^2$

$$a_y = \frac{d^2Y}{dt^2} = -18$$

$$\vec{a} = (-24t)\hat{i} + (-18)\hat{j}$$

$$\vec{a}(t = 0.7\,s) = (-24(0.7))\hat{i} + (-18\hat{j})$$

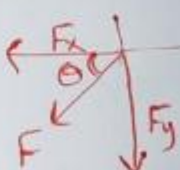
$$\vec{a}(t = 0.7\,s) = (-16.8\,\tfrac{m}{s^2}\,\hat{i}) + (-18\,\tfrac{m}{s^2})\hat{j}$$

$$\vec{F}_{net} = m\vec{a} = 0.34\,kg\left((-16.8\,\tfrac{m}{s^2})\hat{i} + (-18\,\tfrac{m}{s^2})\hat{j}\right)$$

$$\vec{F}_{net} = (-5.71\,N)\hat{i} + (-6.12\,N\hat{j})$$

a) $$F_{net} = \sqrt{(-5.71)^2 + (-6.12)^2} = 8.37\,N$$

b) $$\theta = \tan^{-1}\left(\frac{F_y}{F_x}\right) = \tan^{-1}\left(\frac{6.12}{5.71}\right)$$



$\theta = 47°$ take $\boxed{\theta = 227°}$

$\vec{F}$ is in 3rd quadrant

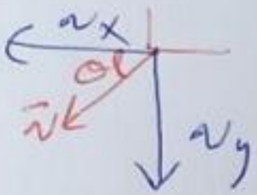
The angle of the particle's direction of travel = ?

⇒ The direction of travel is the direction of a tangent to the path, which is the direction of the velocity vector.

$$\vec{v}(t) = \frac{dx}{dt}\hat{i} + \frac{dy}{dt}\hat{j} = (2-12t^2)\hat{i} + (7-18t)\hat{j}$$

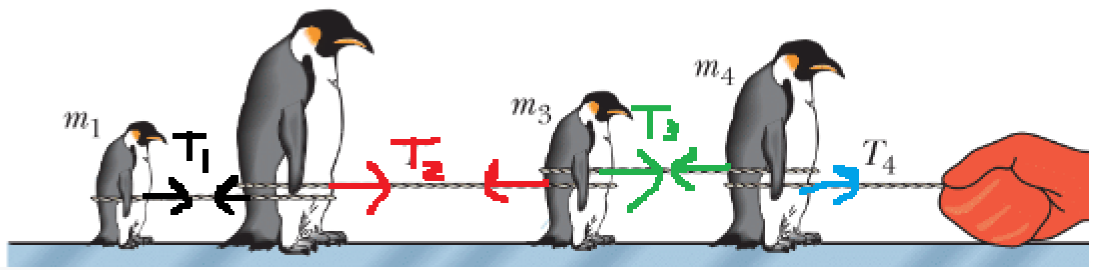
$$\vec{v}(t = 0.7s) = \left(-3.88\,\frac{m}{s}\,\hat{i}\right) + \left(-5.6\,\frac{m}{s}\,\hat{j}\right)$$

$$\theta = \tan^{-1}\left(\frac{v_y}{v_x}\right), \quad \theta = 55.3^\circ$$



We take (235°)

••54 GO Figure 5-49 shows four penguins that are being playfully pulled along very slippery (frictionless) ice by a curator. The masses of three penguins and the tension in two of the cords are $m_1 = 12$ kg, $m_3 = 15$ kg, $m_4 = 20$ kg, $T_2 = 111$ N, and $T_4 = 222$ N. Find the penguin mass m_2 that is not given.



$$T_1 = m_1 a$$

$$T_2 - T_1 = m_1 a$$

$$T_3 - T_2 = m_3 a$$

$$T_4 - T_3 = m_4 a$$

$$T_4 = (m_1 + m_2 + m_3 + m_4)\, a = 222\,N$$

$$T_2 = (m_1 + m_2)\, a = 111\,N$$

$$T_4 - T_2 = (222 - 111) = 111\,N$$

$$111\,N = (m_3 + m_4)\, a$$

$$111\,N = (15 + 20)\,kg\ a$$

$$\boxed{a = 3.17\ m/s^2}$$

$$T_2 = (m_1 + m_2)\, a = 111\,N$$

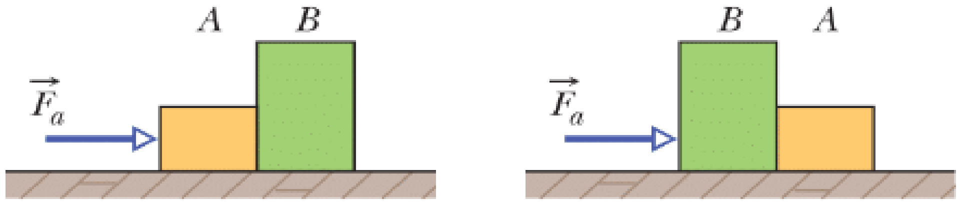
$$(12\,kg + m_2)(3.17\,\tfrac{m}{s^2}) = 111\,N$$

$$\boxed{m_2 = 23\,kg}$$

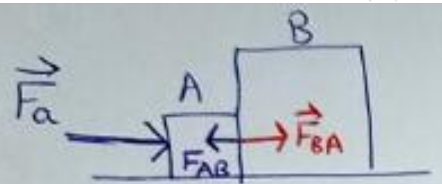
All penguins accelerate with the same rate and direction.

••56 GO In Fig. 5-51*a*, a constant horizontal force $\vec{F}_a$ is applied to block *A*, which pushes against block *B* with a 20.0 N force directed horizontally to the right. In Fig. 5-51*b*, the same force $\vec{F}_a$ is applied to block *B*; now block *A* pushes on block *B* with a 10.0 N force directed horizontally to the left. The blocks have a combined mass of 12.0 kg. What are the magnitudes of (a) their acceleration in Fig. 5-51*a* and (b) force $\vec{F}_a$?

$$\boxed{F_a = (m_A + m_B)a}$$



(*a*) (*b*)

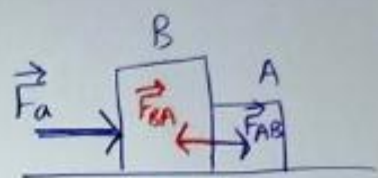


$F_{BA} = 20N$

Block A ⇒ $F_a - F_{AB} = m_A a$

Block B ⇒ $F_{BA} = m_B a$

$F_a = 20N + m_A a$ — ①



$F_{BA} = 10N$

$F_{AB} = m_A a$

$F_a - F_{BA} = m_B a$

$F_a - 10N = m_B a$

$F_a = 10N + m_B a$ — ②

① + ② ⇒ $2F_a = 30N + (m_A + m_B)a$

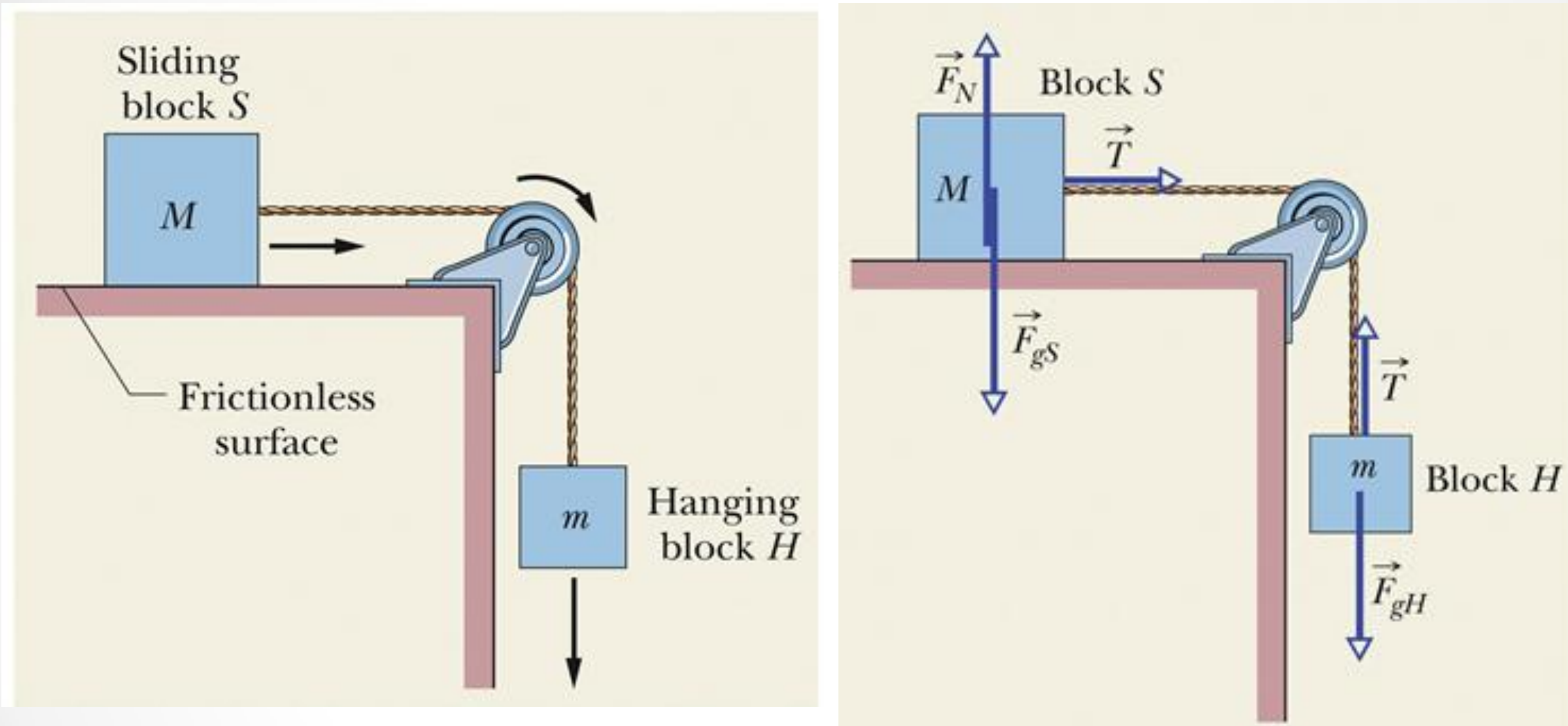
$2F_a = 30N + F_a$

$$\boxed{F_a = 30N}$$

$F_a = (m_A + m_B)a$

$a = \frac{F_a}{m_A + m_B} = \frac{30}{12} = 2.5\ m/s^2$

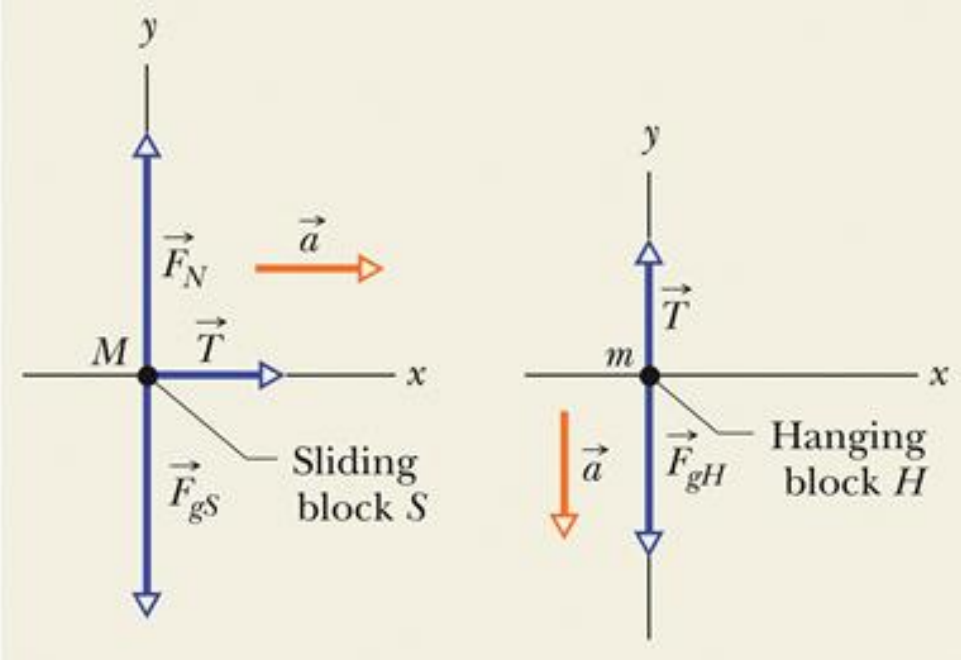
Sample Problem A block of mass M = 3.3 kg, connected by a cord and pulley to a hanging block of mass m = 2.1 kg, slides across a frictionless surface



- Draw the forces involved
- Treat the string as unstretchable, the pulley as massless and frictionless, and each block as a particle

- Draw a free-body diagram for each mass
- Apply Newton's 2nd law

  ($\vec{F} = m\vec{a}$) to each block



- For the sliding block:

$$T = Ma.$$

- For the hanging block:

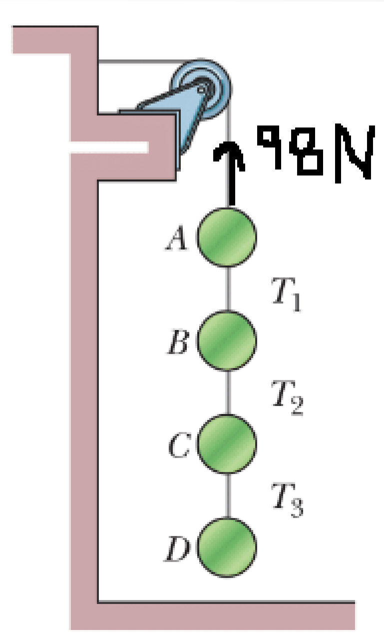
$$T - mg = -ma.$$

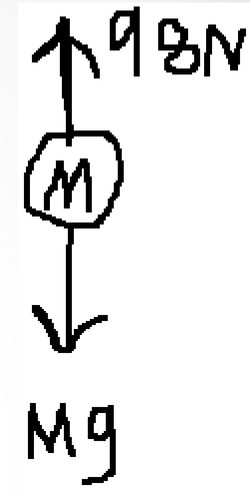
- Subtract two equations:

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

$a = 3.8\ \mathrm{m/s^2}$ $\qquad$ $T = 13\ \mathrm{N}$

•**13** Figure 5-33 shows an arrangement in which four disks are suspended by cords. The longer, top cord loops over a frictionless pulley and pulls with a force of magnitude 98 N on the wall to which it is attached. The tensions in the three shorter cords are $T_1 = 58.8$ N, $T_2 = 49.0$ N, and $T_3 = 9.8$ N. What are the masses of (a) disk *A*, (b) disk *B*, (c) disk *C*, and (d) disk *D*?





Suspended $\Rightarrow$ $\vec{F}_{net} = zero$

- Disk (D): $\uparrow T_3 = 9.8N$, $m_D g \downarrow$

  $9.8N = m_D g$

  $m_D = 1kg$

- Disk (C): $T_2 - T_3 = m_C g$

  $49 - 9.8 = m_C g$

  $m_C = 4 kg$

- Disk (B): $T_1 - T_2 = m_B g$

  $58.8 - 49 = m_B g$

  $m_B = 1 kg$

- Disk (A): $98N - T_1 = m_A g$

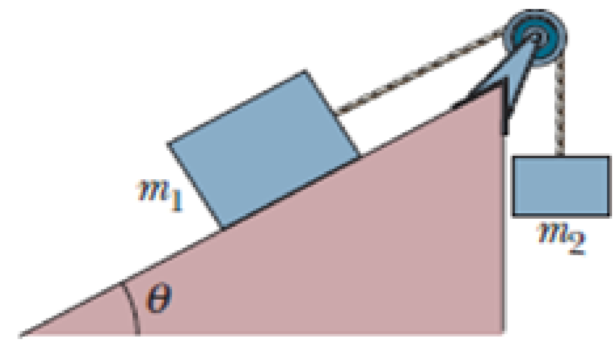
  $98 - 58.8 = m_A g$

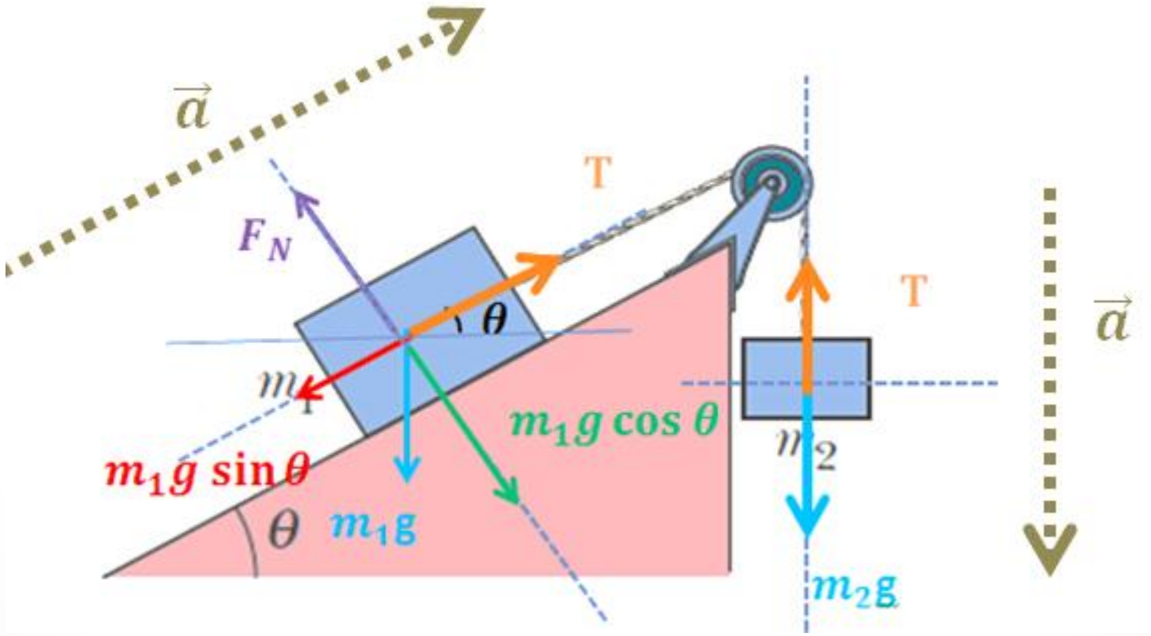
  $m_A = 4 kg$

$M = m_A + m_B + m_C + m_D$

$M = 10 Kg$

p-57) A block of mass m_1 = 3.70 Kg on a frictionless plane inclined at angle $\theta = 30.0^{\circ}$ is connected by a cord over a massless, frictionless pulley to a second block of mass m_2 = 2.3 Kg. What are (a) the magnitude of the acceleration of each block, (b) the direction of the acceleration of the hanging block, and (c) the tension in the cord?





Direction of motion:

m_1 moves UPWARD on the inclined plane and m_2 moves downward

$(m_1 g \sin\theta = 18.13\ N) < (m_2 g = 22.54\ N)$

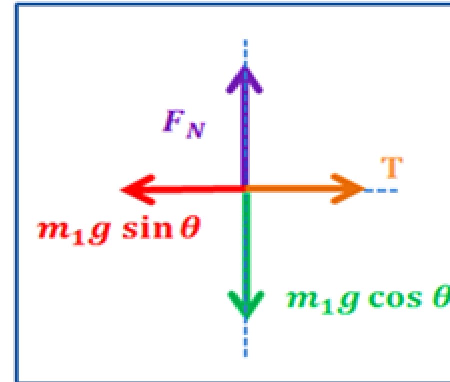
Newton's 2nd law of mass 1:

$$F_{net,x} = T - m_1 g \sin\theta = m_1 a$$

$$F_{net,y} = F_N - m_1 g \cos\theta = zero \text{ , (No motion in y-direction)}$$

Newton's 2nd law of mass 2:

$$F_{net,y} = m_2 g - T = m_2 a$$

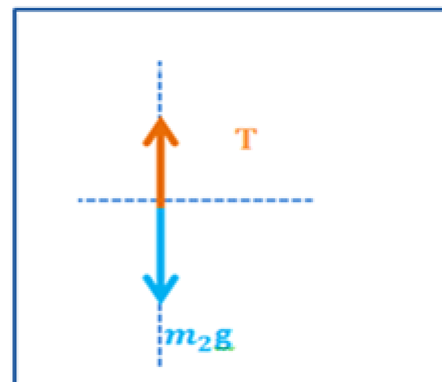


Free Body diagram for m_1

$$T - m_1 g \sin\theta = m_1 a \text{ .... (1)}$$

$$F_N = m_1 g \cos\theta \text{ .... (2)}$$

$$m_2 g - T = m_2 a \text{ .... (3)}$$



Free Body diagram for m_2

Equation (1) + Equation (3):

$$m_2 g - m_1 g \sin\theta = (m_1 + m_2) a$$

$$a = \frac{-m_1 g \sin\theta + m_2 g}{m_1 + m_2} = \frac{(2.3 \times 9.8) - (3.70 \times 9.8 \times \sin 30.0^\circ)}{3.7 + 2.3} = 0.74\, m/s^2$$

(b) The acceleration of block 1 is indeed up the incline and that the acceleration of block 2 is vertically down.

(c) From equation (2):

$$T = m_2 g - m_2 a = m_2 (g - a) = 2.3(9.8 - 0.74) = 20.84\, N$$

71 **SSM** Figure 5-60 shows a box of dirty money (mass $m_1 = 3.0$ kg) on a frictionless plane inclined at angle $\theta_1 = 30°$. The box is connected via a cord of negligible mass to a box of laundered money (mass $m_2 = 2.0$ kg) on a frictionless plane inclined at angle $\theta_2 = 60°$. The pulley is frictionless and has negligible mass. What is the tension in the cord?

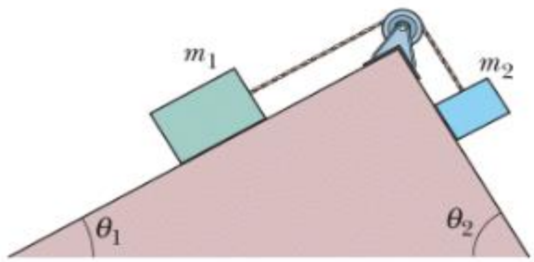
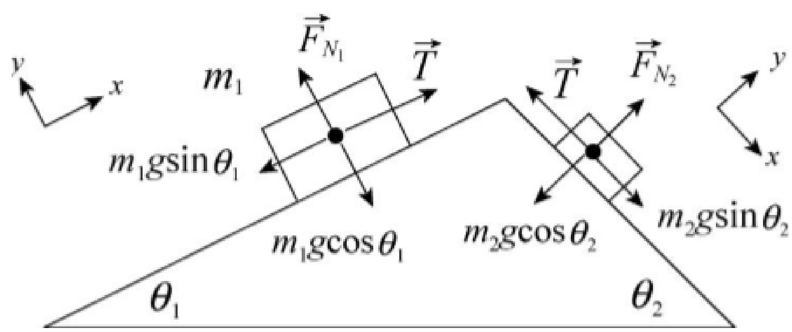


Figure 5-60 Problem 71.

EXPRESS The +*x* axis is "uphill" for $m_1 = 3.0$ kg and "downhill" for $m_2 = 2.0$ kg (so they both accelerate with the same sign). The *x* components of the two masses along the *x* axis are given by $m_1 g \sin\theta_1$ and $m_2 g \sin\theta_2$, respectively. The free-body diagram is shown below. Applying Newton's second law, we obtain

$$T - m_1 g \sin\theta_1 = m_1 a$$
$$m_2 g \sin\theta_2 - T = m_2 a$$



Adding the two equations allows us to solve for the acceleration:

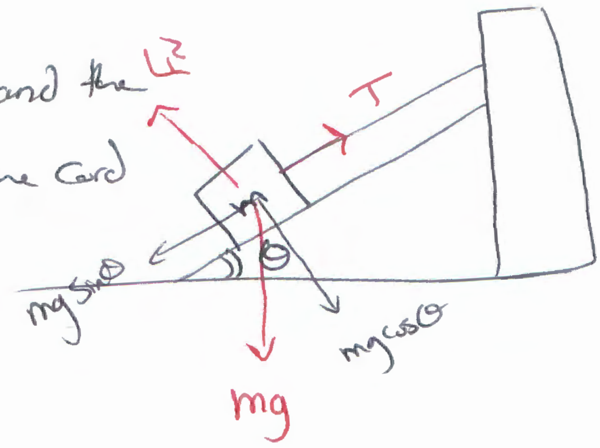
$$a = \left(\frac{m_2 \sin\theta_2 - m_1 \sin\theta_1}{m_2 + m_1}\right) g$$

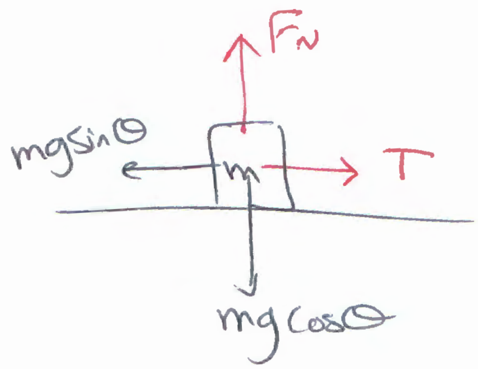
ANALYZE With $\theta_1 = 30°$ and $\theta_2 = 60°$, we have $a = 0.45$ m/s^2. This value is plugged back into either of the two equations to yield the tension

$$T = \frac{m_1 m_2 g}{m_2 + m_1}(\sin\theta_2 + \sin\theta_1) = 16.1\,\text{N}$$

Example

t the mass of the block be 8.5 kg, and the ngle θ be 30°. Find the tension in the cord nd the normal force acting on the block?





No motion

$F_{net,x} = F_{net,y} = 0$

$T = mg\sin\theta$

$= (8.5)(10)\sin(30°)$

$T = 42.5\ N$

$F_N = mg\cos\theta$

$= (8.5)(10)(\cos 30°)$

$F_N = 73.6\ N$

If the cord is cut, find the acceleration of the block?

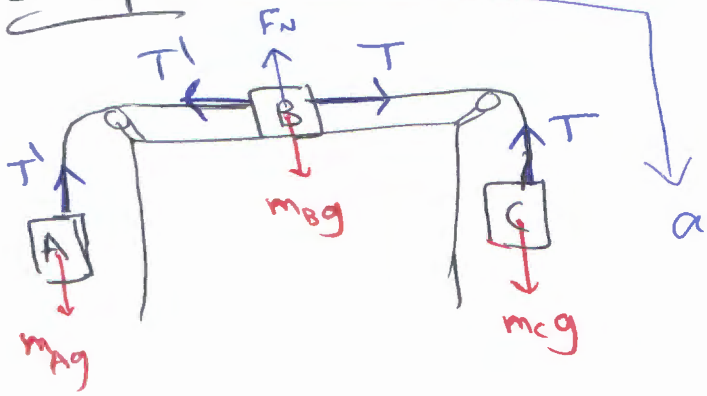
قطع الحبل

$F_{net,y} = 0 \Rightarrow F_N = mg\cos\theta$

$F_{net,x} = ma_x \Rightarrow mg\sin\theta = ma_x$

$a_x = g\sin\theta = 5\ m/s^2$ down

Example



$m_A = 6\ kg$

$m_B = 8\ kg$

$m_c = 10\ kg$

T in the rope at the right ??

⇒ Determine the direction of the motion

$m_cg = 100\ N$

$m_Ag = 60\ N$

$m_cg > m_Ag$

So block C moves down

block B to the right

block A moves up.

$$\begin{cases} m_cg - T = m_c a & \text{——— (1)} \\ T - T' = m_B a & \text{——— (2)} \\ T' - m_Ag = m_A a & \text{——— (3)} \end{cases}$$

Add

$$m_cg - m_Ag = (m_A + m_B + m_c)\, a$$

$$100 - 60 = 24\, a$$

$$\boxed{a = 1.67\ m/s^2}$$

(1) ⇒ $100 - T = 10(1.67)$

$$\boxed{T = 83.3\ N}$$