Chapter 5

Force and Newton's laws

Units of Chapter 5: Force And Newton's Laws

- Newton's First Law.
- Force.
- Mass.
- Newton's Second Law.
- Newton's Third Law.
- Applications of Newton's Laws.

Learning goals of this chapter

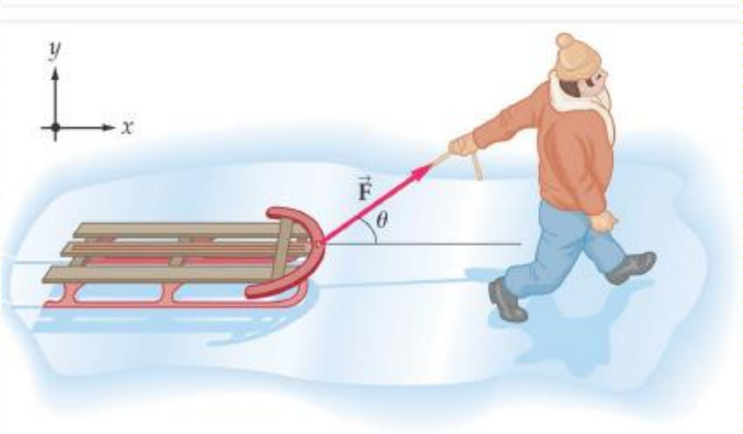
- **On completing this chapter, the student will be able to :**
- Define the force.
- Define the relation between the force, mass, and acceleration.
- Define Newton's First Law.
- Define Newton's Second Law.
- Define Newton's Third Law.
- Apply Newton's law to solve the problems.

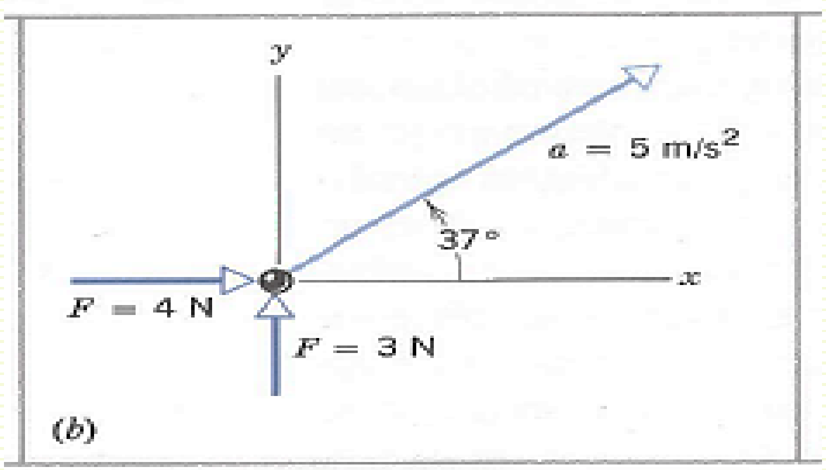
Newton's First Law

- Newton's first law: An object at rest will remain at rest and an object in motion will remain in motion with a constant velocity unless acted on by a net external force.
- The tendency of a body to remain at rest or in uniform linear motion is called *inertia*, and Newton's first law is often called *the law of Inertia*.
- In order to change the velocity of an object – magnitude or direction – a net force is required.
- If the net force acting on a body is zero, then the body has no acceleration.

Force

- Force: push or pull
- Force is a vector – it has a magnitude and direction.
- Force = Mass x acceleration.
- SI unit : kgm/s^2 = 1 Newton (N).
- Let a force of 4 N along the x axis and a force of 3 N along the y axis.
- Then, the net force will be 5 N in the direction make an angle 37^o with x axis.





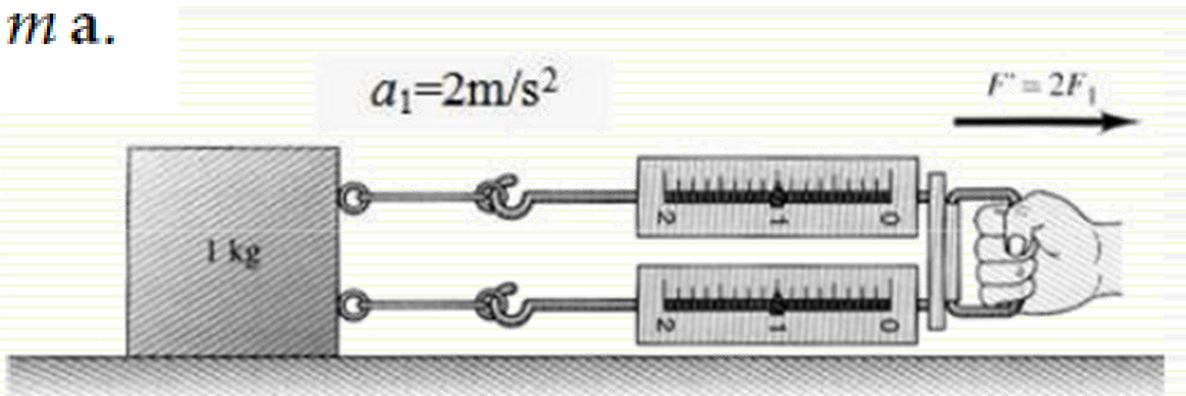
Mass

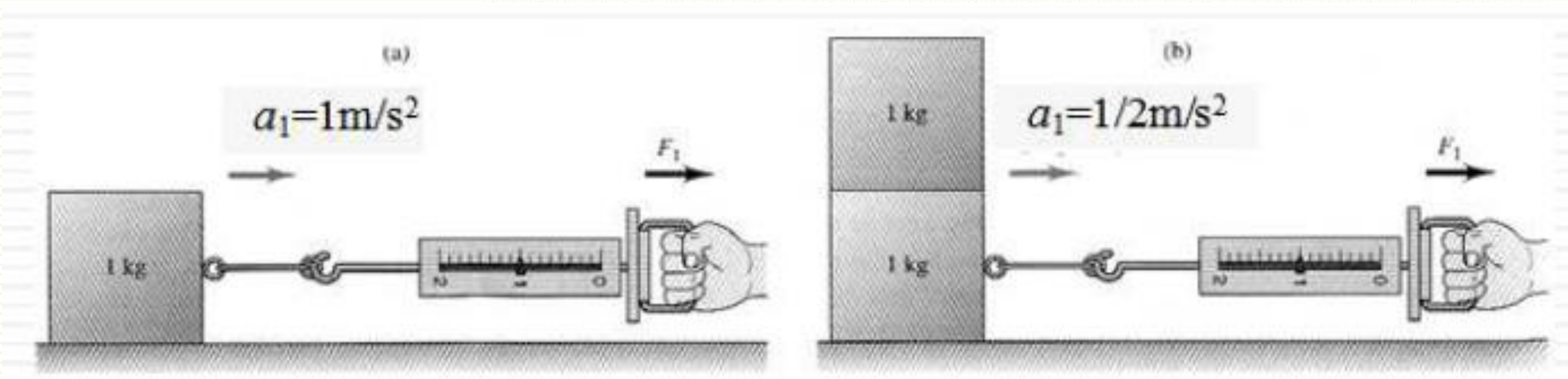
- The force F = Mass x acceleration,
- If we apply a constant force on an object, then as the mass of the object is increased, the acceleration of the object will be lowered.
- Since the acceleration is the rate of change of the velocity of the body, then
- The mass of an object is the measure of how hard it is to change an object's velocity.

Newton’s Second Law

- Newton’s second law: The acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass.

$$\sum F = ma.$$





Newton's Second Law

- As in the case of all vector equations, we can write this single vector equation as three scalar equations

$$\sum F_x = m\,a_x, \quad \sum F_y = m\,a_y, \quad \text{and} \quad \sum F_z = m\,a_z,$$

- The *x*, *y*, and *z* components of the resultant force (F_x, F_y, and F_z) to the *x*, *y*, and *z* components of acceleration (a_x, a_y, and a_z) for the mass *m*.

TABLE 5–2 Units of Mass, Acceleration, and Force

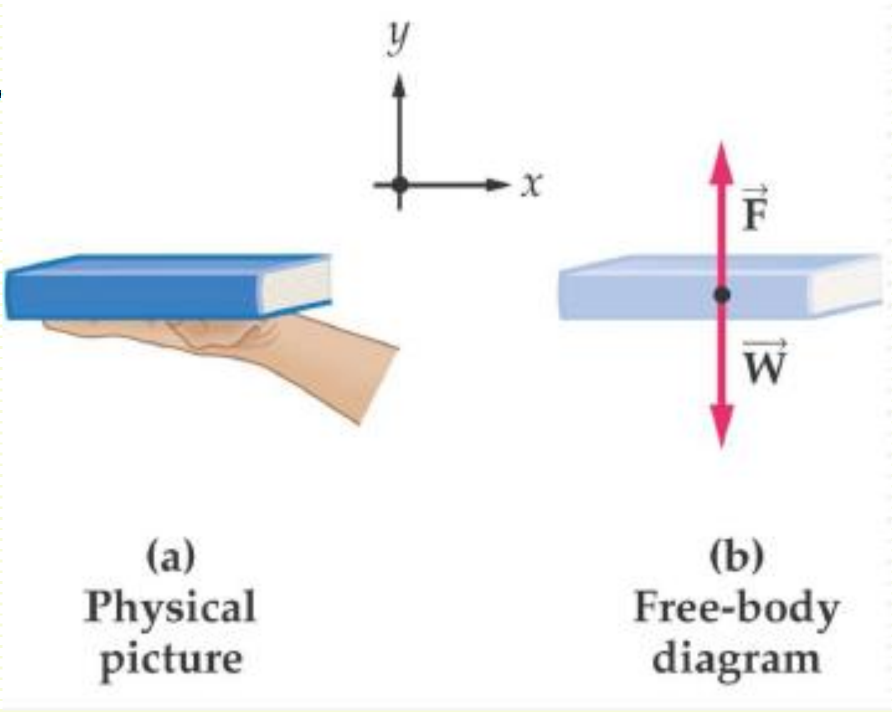
System of units	Mass	Acceleration	Force
SI	kilogram (kg)	m/s^2	newton (N)
cgs	gram (g)	cm/s^2	dyne (dyn)
British	slug	ft/s^2	pound (lb)

(*Note:* $1\ N = 10^5$ dyne $= 0.225$ lb.)

Newton's Second Law

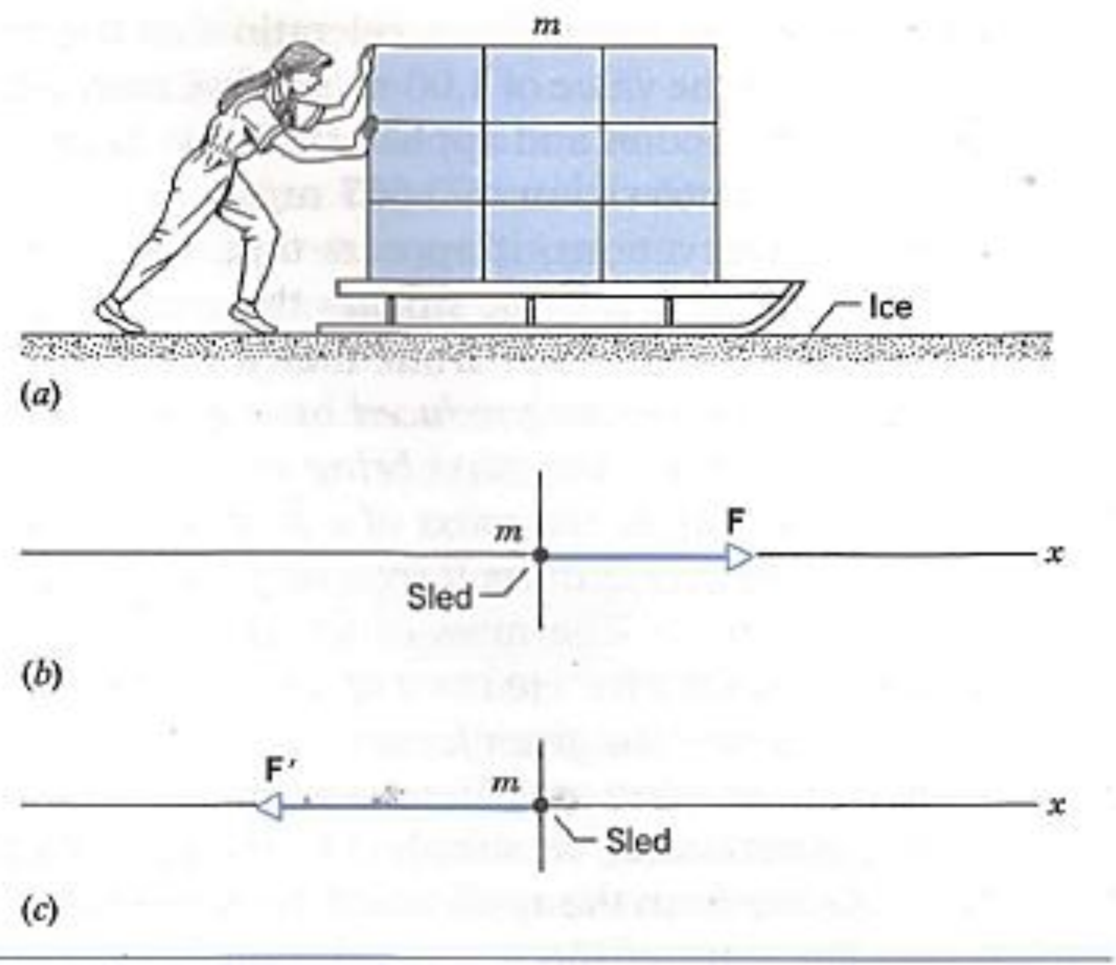
- A free-body diagram shows every force acting on an object.
- Example of a free-body diagram

$$\sum F_x = m a_x, \quad \sum F_y = m a_y,$$



Problem 1

- A student pushes a loaded sled whose mass m is 240 kg for a distance d of 2.3 m over the frictionless surface of a frozen lake. He exerts a constant horizontal force F of 130 N (=29 lb) as he does so; see the figure. If the sled starts from rest, what is its final velocity?



Problem 1

- **Solution:** In drawing free-body diagrams, it is important always to include all forces that act on the particle

- We can then find the acceleration of the sled from Newton's second law, or

$$a = \frac{F}{m} = \frac{130\,\mathrm{N}}{240\,\mathrm{kg}} = 0.54\,\mathrm{m/s^2}.$$

The final velocity $v^2 = v_0^2 + 2a(x - x_0)$

Putting $v_0 = 0$ and $x - x_0 = d$ and solving for v, we obtain

$$v = \sqrt{2ad} = \sqrt{(2)(0.54\,\mathrm{m/s^2})(2.3\,\mathrm{m})} = 1.6\,\mathrm{m/s}.$$

Problem 2

- The student in problem 1 wants to reverse the direction of the velocity of the sled in 4.5 s. with what constant force must he push on the sled to do so?

Solution

- Let us find the (constant) acceleration, using Eq. $v = v_0 + at$

Solving for a gives

$$a = \frac{v - v_0}{t} = \frac{(-1.6\ \mathrm{m/s}) - (1.6\ \mathrm{m/s})}{4.5\ \mathrm{s}} = -0.71\ \mathrm{m/s^2}.$$

This is larger in magnitude than the acceleration in Sample Problem 1 ($0.54\ \mathrm{m/s^2}$) so it stands to reason that the student must push harder this time. We find this (constant) force F' from

$$F' = ma = (240\ \mathrm{kg})(-0.71\ \mathrm{m/s^2})$$
$$= -170\ \mathrm{N}\ (= -38\ \mathrm{lb}).$$

The negative sign shows that the student is pushing the sled in the direction of decreasing *x*.

Problem 3

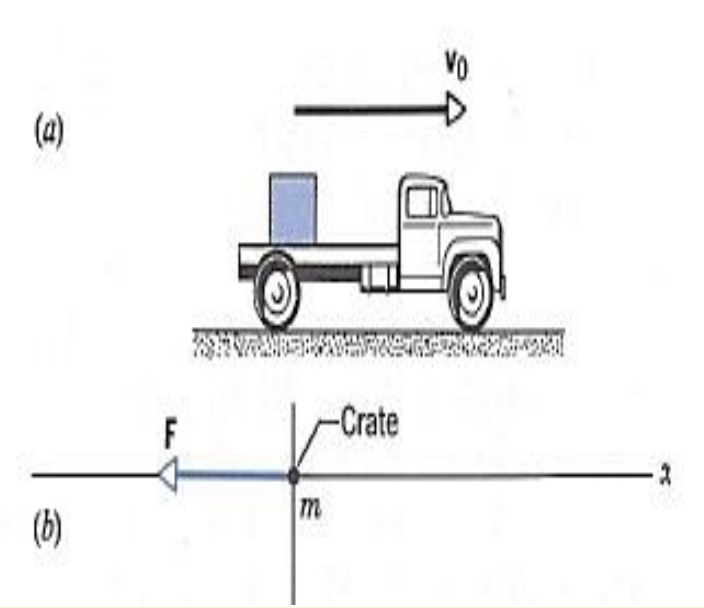
- A crate whose mass m is 360 kg rests on the bed of a truck that is moving at a speed v_o of $120\ km/h$, as in Fig. a. The driver applies the brakes and slows to a speed v of $62 km/h$ in 17 s. What force (assumed constant) acts on the crate during this time? Assume that the crate does not slide on the truck bed.

Solution

We first find the (constant) acceleration of the crate. Solving Eq. $v = v_0 + at$,

$$a = \frac{v - v_0}{t} = \frac{(62\text{ km/h}) - (120\text{ km/h})}{17\text{ s}}$$

$$= \left(-3.41 \frac{\text{km}}{\text{h}\cdot\text{s}}\right)\left(\frac{1\text{ h}}{3600\text{ s}}\right)\left(\frac{1000\text{ m}}{1\text{ km}}\right) = -0.95\text{ m/s}^2$$



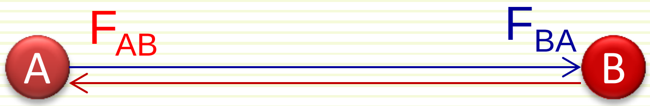
- The force on the crate follows from Newton's second law:

$$F = ma = (360\text{ kg})(-0.95\text{ m/s}^2) = -340\text{ N}.$$

Newton's Third law

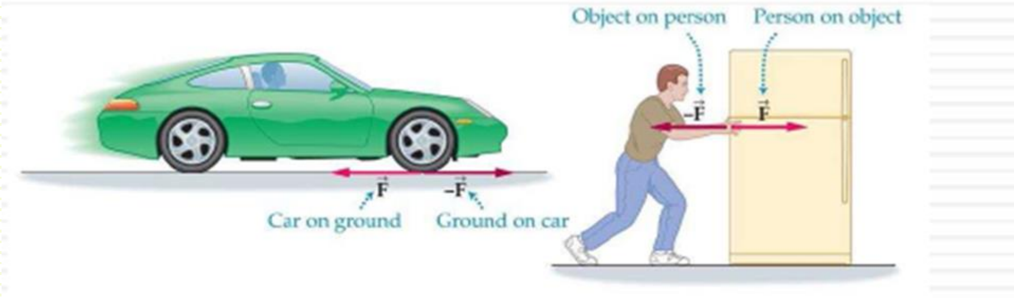
The law of action-reaction

- **Newton's third law**
- To every action there is an equal and opposite reaction
- When two bodies interact, the force "$\boldsymbol{F_{BA}}$" which body A exerts on body B (the action force) is equal in magnitude and opposite in direction to the force "$\boldsymbol{F_{AB}}$" which body B exerts on body A (the reaction force).



$$\boldsymbol{F_{AB} = -\ FBA}$$

- The action force and the reaction force act on different objects.



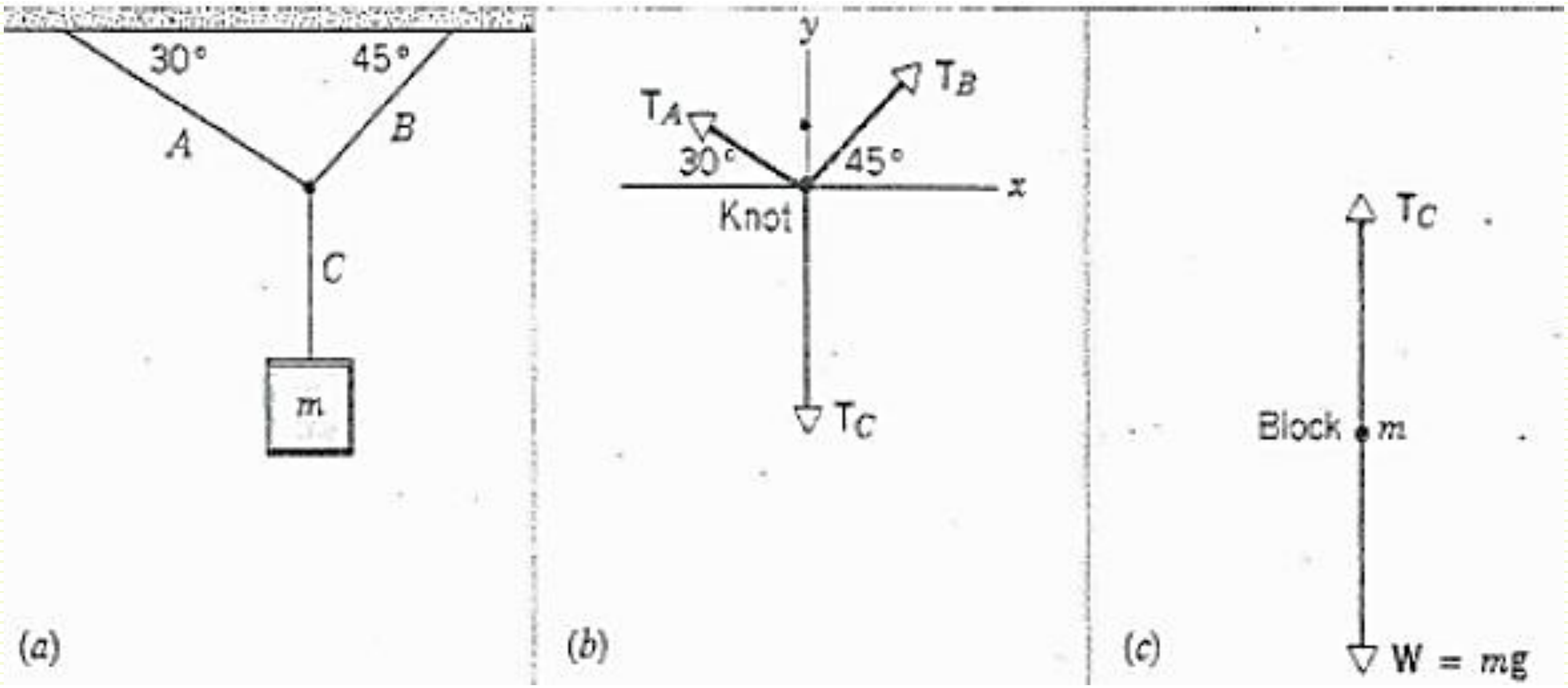
Applications of Newton's laws

The basic steps in applying Newton's laws are these:

1. Clearly identify the body that will be analyzed. Sometimes there will be two or more such bodies; each is usually treated independently.
2. Identify the environment that will be exerting forces on the body-surfaces, other objects, Earth, springs, cords, and so on.
3. Select a suitable inertial (nonaccelerating) reference frame.
4. Pick a convenient coordinate system (in the chosen reference frame), locate the origin, and orient the axes to simplify the problem as much as possible. With suitable care, a different coordinate system can be chosen for each component of a complex problem.
5. Make a free-body diagram, showing each object as a particle and all forces acting on it.
6. Now apply Newton's second law to each component of force and acceleration.

Problem 4

- Figure a shows a block of mass $m = 15.0$ kg hung by three strings. What are the tensions in the three strings?



Problem 4

solution

- Figure b shows the free-body diagram of the knot, which remains at rest under the action of the three forces T_A, T_B and T_C, which are the tensions in the strings.

$$x \text{ component:}, \quad \sum F_x = T_{Ax} + T_{Bx} = ma_x = 0,$$

$$y \text{ component:}, \quad \sum F_y = T_{Ay} + T_{By} + T_{Cy} = ma_y = 0.$$

$$T_{Ax} = -T_A \cos 30^\circ = -0.866 T_A,$$

$$T_{Ay} = T_A \sin 30^\circ = 0.500 T_A,$$

$$T_{Bx} = T_B \cos 45^\circ = 0.707 T_B,$$

$$T_{By} = T_B \sin 45^\circ = 0.707 T_B,$$

and

$$T_{Cx} = 0,$$

$$T_{Cy} = -T_C.$$

Problem 4

solution

Only the *y* components enter, and again the acceleration is zero:

$$T_{Cy} - mg = ma_y = 0.$$

Because T_C has only a y component, we can write

$$T_{Cy} = mg = (15.0\,\text{kg})(9.80\,\text{m/s}^2) = 147\,\text{N}.$$

We can now rewrite the x and y component equations for the forces on the knot:

$$\text{x component:,} \quad -0.866T_A + 0.707T_B = 0,$$

$$\text{y component:,} \quad 0.500T_A + 0.707T_B - T_C = 0.$$

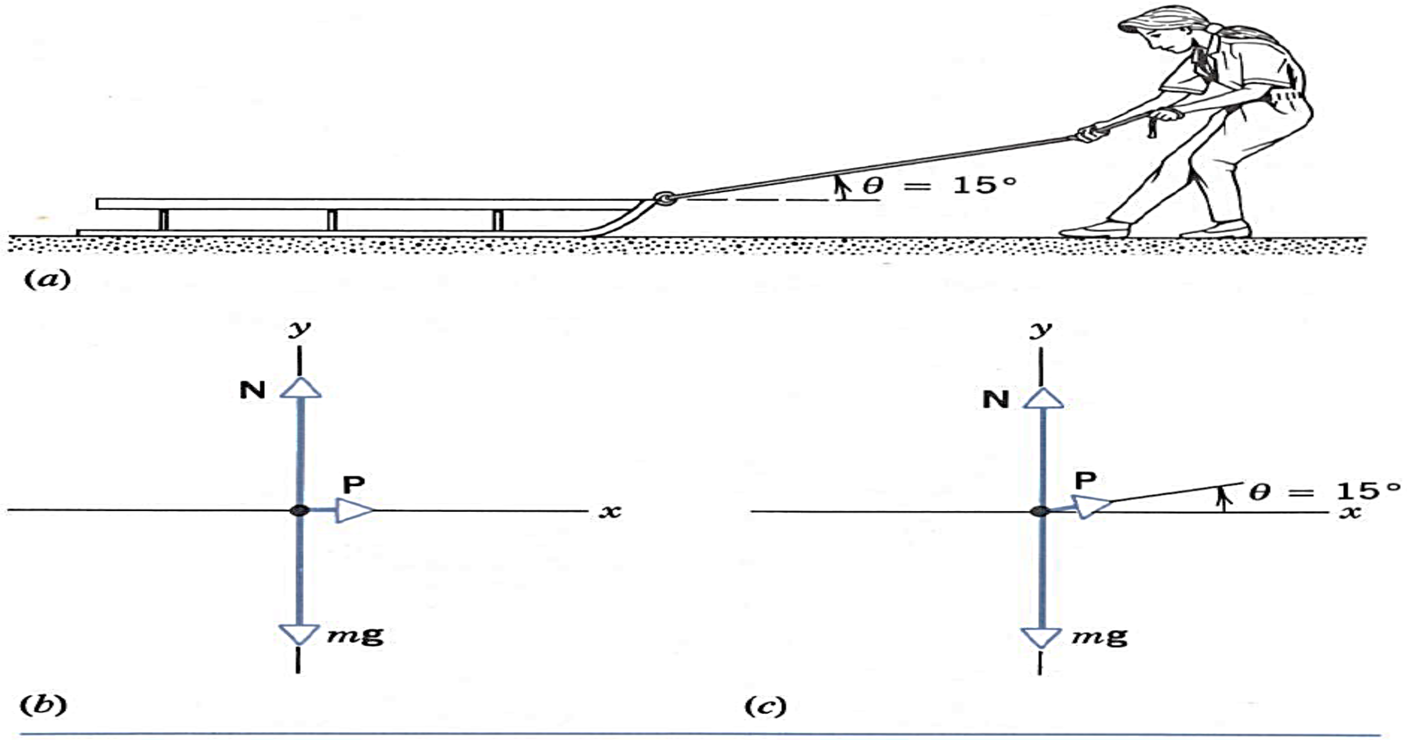
Substituting the value for T_C and solving the two equations simultaneously, we find

$$T_A = 108\,\text{N}$$

$$T_B = 132\,\text{N}$$

Problem 5

- A sled of mass $m = 7.5$ kg is pulled along a frictionless horizontal surface by a cord. A constant force of $P = 21.0$ N is applied to the cord. Analyze the motion if (a) the cord is horizontal and (b) the cord makes an angle of = 15 with the horizontal.



Problem 5

solution

(a) The free-body diagram with the cord horizontal is shown in Fig. 4.11b. The surface exerts a force N, the normal force, on the sled. The forces are analyzed into components and Newton's second law is used as follows:

$$\text{x component:,} \quad \sum F_x = P = ma_x,$$

$$\text{y component:,} \quad \sum F_y = N - mg = ma_y.$$

If there is to be no vertical motion, the sled remains on the surface and $a_y = 0$. Thus

$$N = mg = (7.5\,\text{kg})(9.80\,\text{m/s}^2) = 74\,\text{N}.$$

The horizontal acceleration is

$$a_x = \frac{P}{m} = \frac{21.0\,\text{N}}{7.5\,\text{kg}} = 2.80\,\text{m/s}^2.$$

Problem 5

solution

(b) When the pulling force is not horizontal, the free-body diagram is shown in Fig. 4.11c and the component equations take the following forms:

$$\text{x component:,} \quad \sum F_x = P\cos\theta = ma_x,$$

$$\text{y component:,} \quad \sum F_y = N + P\sin\theta - mg = ma_y.$$

Let us assume for the moment that the sled stays on the surface; that is, $a_y = 0$. Then

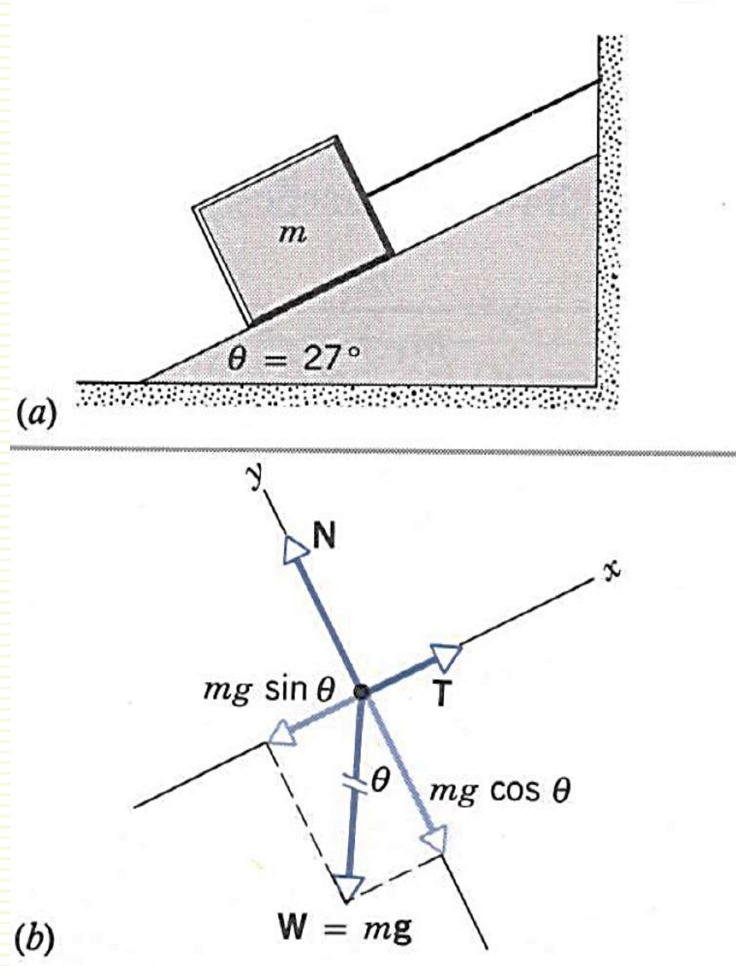
$$N = mg - P\sin\theta = 74\,\text{N} - (21.0\,\text{N})(\sin 15^\circ) = 69\,\text{N},$$

$$a_x = \frac{P\cos\theta}{m} = \frac{(21.0\,\text{N})(\cos 15^\circ)}{7.5\,\text{kg}} = 2.70\,\text{m/s}^2.$$

Problem 6

- A block of mass $m = 18.0$ kg is held in place by a string on a frictionless plane inclined at an angle of 27^o (see a).
- (a) Find the tension in the string and the normal force extended on the block
- by the plane.
- (b) Analyze the subsequent motion after the string is cut.

- Solution:
- In the static case there is no acceleration and the forces must sum to zero. The weight is resolved into its x $(-mg \sin)$ and y $(-mg \cos)$ components, and the force equations are as follows



Problem 6

solution

x component:, $\sum F_x = T - mg \sin\theta = ma_x = 0,$

y component:, $\sum F_y = N - mg \cos\theta = ma_y = 0.$

Solving the equations,

$$T = mg \sin\theta = (18\,\text{kg})(9.80\,\text{m/s}^2)(\sin 27^\circ) = 80\,\text{N},$$

$$N = mg \cos\theta = (18\,\text{kg})(9.80\,\text{m/s}^2)(\cos 27^\circ) = 157\,\text{N}.$$

(b) When the string is cut, the tension disappears from the equations and the block is no longer in equilibrium. Newton's second law now gives the following:

x component:, $\sum F_x = -mg \sin\theta = ma_x,$

y component:, $\sum F_y = N - mg \cos\theta = ma_y.$

Cutting the string doesn't change the motion in the *y* direction (then block doesn't jump off the plane!), so $a_y = 0$ as before and the normal force still equals *mg* cos , or 157 N. In the *x* direction

$$a_x = -g \sin\theta = -(9.80\,\text{m/s}^2)(\sin 27^\circ) = -4.45\,\text{m/s}^2$$

The minus sign shows that the block accelerates in the negative *x* direction, that is, down the plane

Problem 7

- A passenger of mass 72.2 kg is riding in an elevator while standing on a platform scale (Fig. a). What does the scale read when the elevator cab is
- (a) descending with constant velocity and (b) ascending with acceleration 3.2 m/s²?

- Solution:

From the free-body diagram we have

$$\sum F_y = N - mg = ma$$

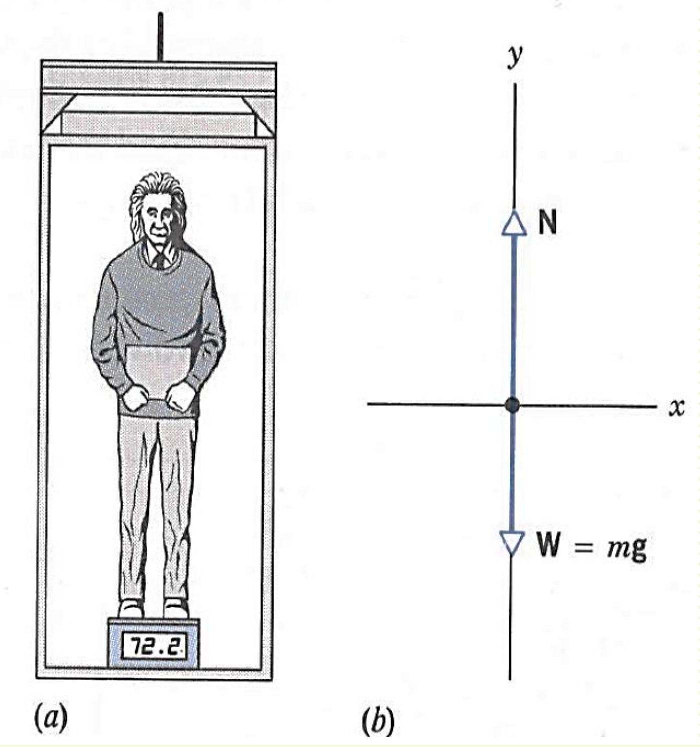
or $$N = m(g + a).$$

When $a = 0$, such that the elevator is at rest or moving with constant velocity, as in part (a), then

$$N = mg = (72.2\,\text{kg})(9.80\,\text{m/s}^2) = 708\,\text{N}(= 159\,\text{lb}).$$

When $a = 3.20\,\text{m/s}^2$, as in pan (b), we have

$$N = m(g + a) = (72.2\,\text{kg})(9.80\,\text{m/s}^2 + 2.30\,\text{m/s}^2)$$
$$= 939\,\text{N}(= 211\,\text{lb}).$$



Summary of Chapter 5

- Force: a push or pull
- Mass: measures the difficulty in accelerating an object
- Newton's first law: if the net force on an object is zero, its velocity is constant
- Inertial frame of reference: one in which the first law holds
- Newton's second law: $\sum F = ma$
- Free-body diagram: a sketch showing all the forces on an object
- Newton's third law: If object 1 exerts a force on object 2, then object 2 exerts a force – on object 1.
- Contact forces: an action-reaction pair of forces produced by two objects in physical contact
- Forces are vectors
- Newton's laws can be applied to each component of the forces independently
- Weight: gravitational force exerted by the Earth on an object

Summary of Chapter 5

- On the surface of the Earth, $W = mg$
- Apparent weight: force felt from contact with a floor or scale
- Normal force: force exerted perpendicular to a surface by that surface
- Normal force may be equal to, lesser than, or greater than the object's weight

Homework

1- A hockey puck having a mass of 0.30 kg slides on the horizontal, frictionless surface of an ice rink. Two forces act on the puck, as shown in Figure 5.5. The force F_1 has a magnitude of 5.0 N, and the force F_2 has a magnitude of 8.0 N. Determine both the magnitude and the direction of the puck's acceleration?

2- A traffic light weighing 125 N hangs from a cable tied to two other cables fastened to a support. The upper cables make angles of 37.0° and 53.0° with the horizontal. Find the tension in the three cables?

3- A crate of mass *m* is placed on a frictionless inclined plane of angle. (a) Determine the acceleration of the crate after it is released?

(b) Suppose the crate is released from rest at the top of the incline, and the distance from the front edge of the crate to the bottom is *d*. How long does it take the front edge to reach the bottom, and what is its speed just as it gets there?

Homework

- 4- A person weighs a fish of mass *m* on a spring scale attached to the ceiling of an elevator, as illustrated in the Figure. Show that if the elevator accelerates either upward or downward, the spring scale gives a reading that is different from the weight of the fish?