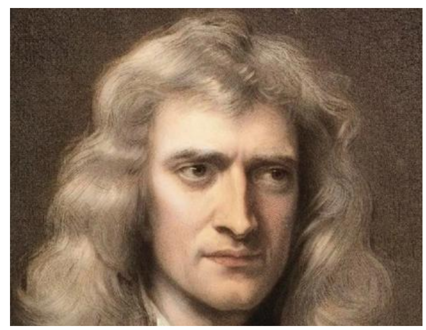
Newton's Laws of Motion

1) **INTRODUCTION:** distinguish concepts:

Kinematics: describes the motion of bodies (objects) without considering the forces that cause them to move.

- We have seen in the last chapters how to use **kinematics** to describe motion in one, two dimension. However, what ***causes*** bodies to move the way that they do?
- For example, why does a dropped ***feather*** fall more slowly than a dropped ***baseball***? The answers to such question take us into the subject of **Dynamics**, the relationship of ***motion to the forces*** that cause it.

The principles of **dynamics** were clearly stated for the first time by Sir **Isaac Newton** (1642–1727);



- The first law states that when the net force on a body is zero, its motion does not change.
- The second law tells us that a body accelerates when the net force is not zero.
- The third law relates the forces that two interacting bodies exert on each other.

Newton's laws are the foundation of **classical mechanics** (also called Newtonian mechanics); using them, we can understand most familiar kinds of motion. However, Newton's laws need ***modification*** only for situations involving extremely high speeds (near the speed of light) or very small sizes (such as within the atom size).

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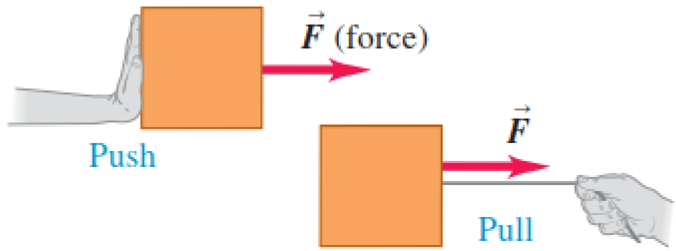
Force & Interactions

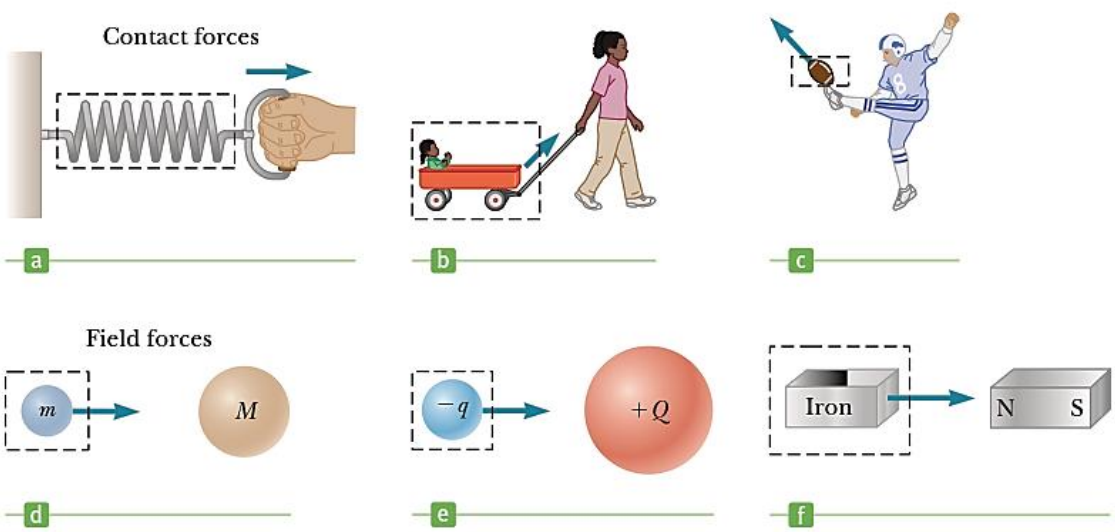
- Force is an interaction between two bodies or between a body and its environment.



- Force is a vector quantity which means direction and magnitude are required to represented force $\vec{F}$.

Types of Forces

- There are two main types of forces: ***Contact*** and ***Field***.



The Contact Force: exists when an object from the external world touches a system and exerts a force on it (think about a book on a table). If you push it, you are exerting a contact force but if you put it down, no longer interacting… so, no more force from you, But table is touching it- table is now exerting a force.

- The Field Forces: An object can move without something directly touching it. What if the book is dropped? It falls due to gravity. Gravitational force is a field force. They affect movement without being in physical contact.
- You can think of other field forces, for example; Magnetic fields, Electric Forces, and Nuclear Forces.

Newton's First Law:

An object at rest tends to stay at rest and an object in motion tends to stay in motion unless acted upon by an unbalanced force.

Newton's Second Law:

The acceleration $\vec{a}$ of an object is directly proportional to the net force $\sum \vec{F}$ acting on it and inversely proportional to its mass m.

Or, $\boldsymbol{\vec{a} = \frac{\sum \vec{F}}{m}}$, where $\sum \vec{F}$ is the net forces acting on the object.

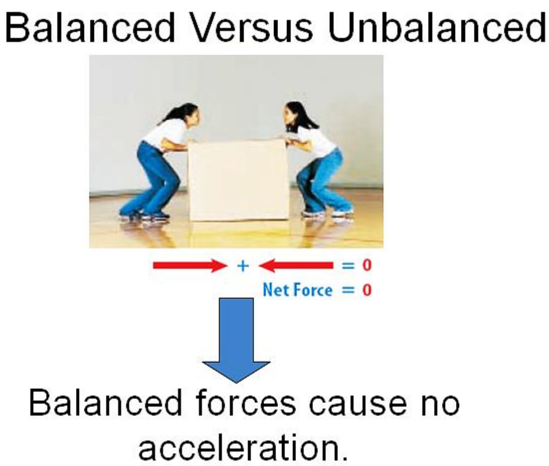
- Units of Force and Mass:

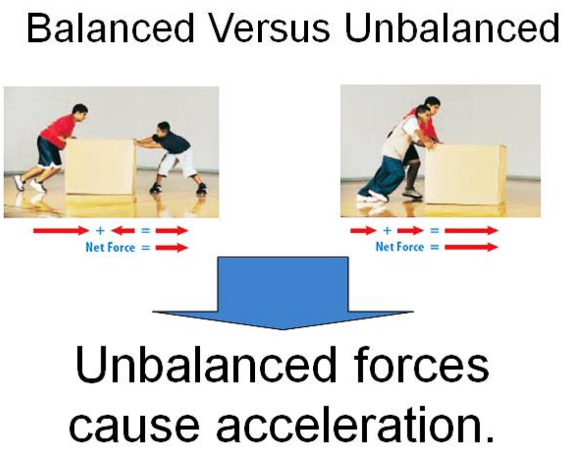
The SI unit of force is the newton. When 1 newton of force acts on an object that has a mass of 1 kg, it produces an acceleration of 1 m/s^2 in the object. From this definition and Newton's second law, we see that the newton can be expressed in terms of the fundamental units of mass, length, and time as

Force unite is $1\ N \equiv 1\ kg \cdot m/s^2$

- Acceleration:
  - An ***unbalanced force*** causes something to accelerate.
  - A force can cause motion only if it is faced with an ***unbalanced force***.
  - Forces can be balanced or unbalanced.
  - Depends on the **net force** acting on the object

- **Net force ($\mathbf{F_{net}} \equiv \sum \vec{F}$):** The sum total and direction of all forces acting on the object.



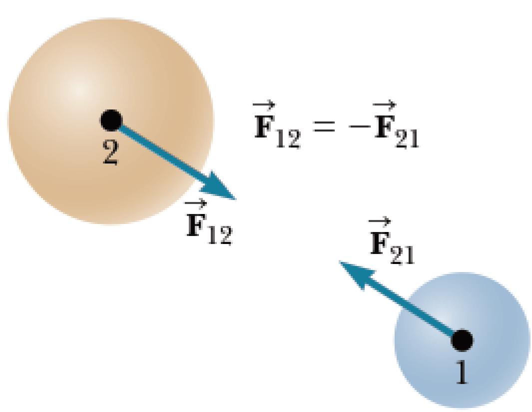


<u>Newton's Third Law:</u>

The ***action force*** is equal in magnitude to the ***reaction force*** and opposite in direction. In all cases, the action and reaction forces act on different objects.

In other words:

If object 1 and object 2 interact, the force: $\vec{F}_{12}$ exerted by object 1 on object 2 is equal in magnitude but opposite in direction to the force: $\vec{F}_{21}$ exerted by object 2 on object 1.



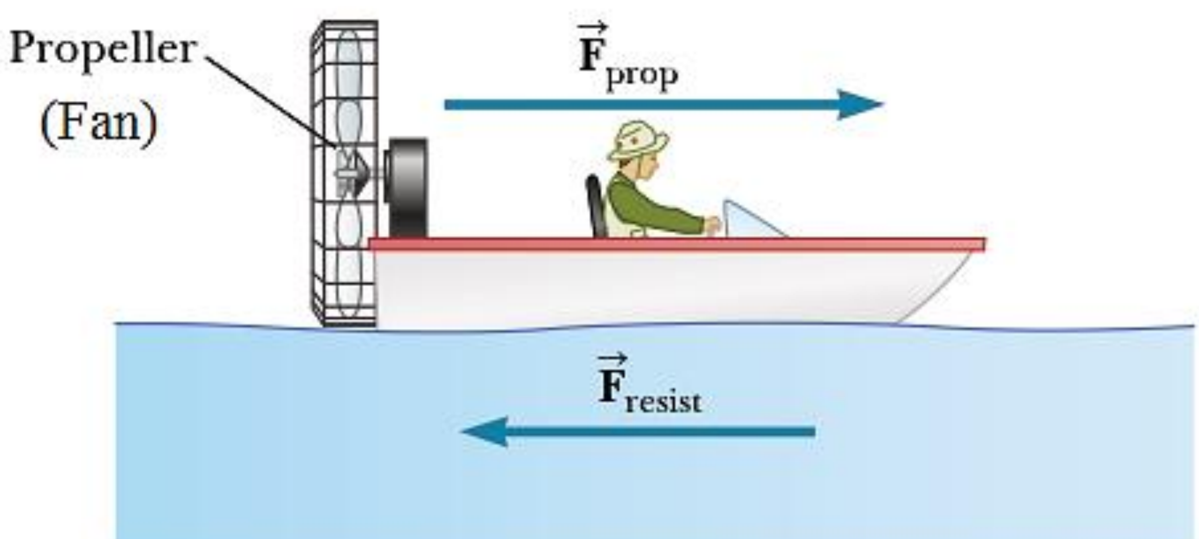
Important Note: In applying Newton's third law, remember that an action and its reaction force always act on different objects. Two external forces acting on the same object, even if they are equal in magnitude and opposite in direction, cannot be an action–reaction pair. Which means the action force does not cancel reaction force.

2) Solved problems

Example 1:

An airboat with mass 3.5×10^2 kg, including the passenger, has an engine that produces a net horizontal force of 7.7×10^2 N, after accounting for forces of resistance (see Fig. below).

(a) Find the acceleration of the airboat
(b) Starting from rest, how long does it take the airboat to reach a speed of 12 m/s?
(c) After reaching that speed, the pilot turns off
(d) The engine and drifts to a stop over a distance of 50 m. Find the resistance force, assuming it's constant.



SOLUTION

(a) Find the acceleration of the airboat.

Apply Newton's second law and solve for the acceleration:

$$ma = F_{\text{net}} \quad \rightarrow \quad a = \frac{F_{\text{net}}}{m} = \frac{7.70 \times 10^2\ \text{N}}{3.50 \times 10^2\ \text{kg}}$$
$$= \boxed{2.20\ \text{m/s}^2}$$

(b) Find the time necessary to reach a speed of 12.0 m/s.

Apply the kinematics velocity equation:

$$v = at + v_0 = (2.20\ \text{m/s}^2)t = 12.0\ \text{m/s} \quad \rightarrow \quad t = \boxed{5.45\ \text{s}}$$

(c) Find the resistance force after the engine is turned off.

Using kinematics, find the net acceleration due to resistance forces:

$$v^2 - v_0^2 = 2a\,\Delta x$$
$$0 - (12.0\ \text{m/s})^2 = 2a(50.0\ \text{m}) \quad \rightarrow \quad a = -1.44\ \text{m/s}^2$$

Substitute the acceleration into Newton's second law, finding the resistance force:

$$F_{\text{resist}} = ma = (3.50 \times 10^2\ \text{kg})(-1.44\ \text{m/s}^2) = \boxed{-504\ \text{N}}$$

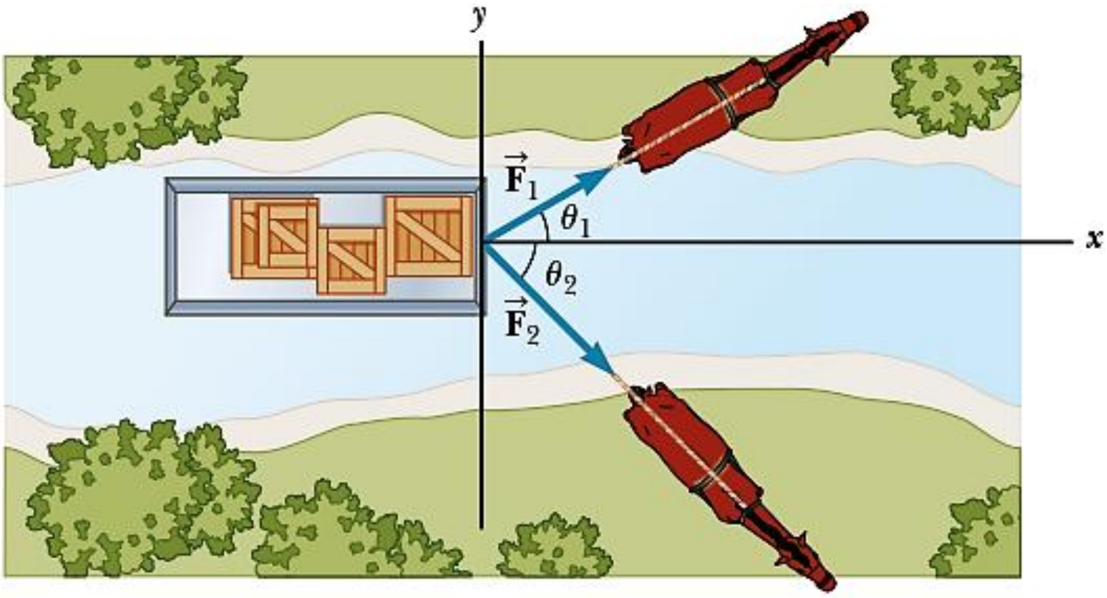
REMARKS: The propeller exerts a force on the air, pushing it backwards behind the boat. At the same time, the air exerts a force on the propellers and consequently on the airboat. Forces always come in pairs of this kind, which are formalized in the next section as Newton's third law of motion. The negative answer for the acceleration in part (c) means that the airboat is slowing down.

Exercise: Suppose the pilot, starting again from rest, opens the throttle partway. At a constant acceleration, the airboat then covers a distance of 60m in 10s. Find the net force acting on the boat.

ANSWER: 4.2×10^2 N

Example 2:

Two horses are pulling a barge with mass 2×10^3 kg along a canal, as shown in Figure. The cable connected to the first horse makes an angle of $\theta_1 = 30°$ with respect to the direction of the canal, while the cable connected to the second horse makes an angle of $\theta_1 = -45°$.Find the initial acceleration of the barge, starting at rest, if each horse exerts a force of magnitude 6×10^2 N on the barge (زورق). Ignore forces of resistance on the barge.



SOLUTION

Compute the x-components of the forces exerted by the horses.

$$F_{1x} = F_1 \cos\theta_1 = (6.00 \times 10^2\text{ N})\cos(30.0°) = 5.20 \times 10^2\text{ N}$$

$$F_{2x} = F_2 \cos\theta_2 = (6.00 \times 10^2\text{ N})\cos(-45.0°) = 4.24 \times 10^2\text{ N}$$

Find the total force in the x-direction by adding the x-components:

$$F_x = F_{1x} + F_{2x} = 5.20 \times 10^2\text{ N} + 4.24 \times 10^2\text{ N} = 9.44 \times 10^2\text{ N}$$

Compute the y-components of the forces exerted by the horses:

$$F_{1y} = F_1 \sin\theta_1 = (6.00 \times 10^2\text{ N})\sin 30.0° = 3.00 \times 10^2\text{ N}$$

$$F_{2y} = F_2 \sin\theta_2 = (6.00 \times 10^2\text{ N})\sin(-45.0°) = -4.24 \times 10^2\text{ N}$$

Find the total force in the y-direction by adding the y-components:

$$F_y = F_{1y} + F_{2y} = 3.00 \times 10^2\text{ N} - 4.24 \times 10^2\text{ N} = -1.24 \times 10^2\text{ N}$$

Obtain the components of the acceleration by dividing each of the force components by the mass:

$$a_x = \frac{F_x}{m} = \frac{9.44 \times 10^2\text{ N}}{2.00 \times 10^3\text{ kg}} = 0.472\text{ m/s}^2$$

$$a_y = \frac{F_y}{m} = \frac{-1.24 \times 10^2\text{ N}}{2.00 \times 10^3\text{ kg}} = -0.062\,0\text{ m/s}^2$$

Calculate the magnitude of the acceleration:

$$a = \sqrt{a_x^2 + a_y^2} = \sqrt{(0.472\text{ m/s}^2)^2 + (-0.062\,0\text{ m/s}^2)^2} = \boxed{0.476\text{ m/s}^2}$$

Calculate the direction of the acceleration using the tangent function:

$$\tan\theta = \frac{a_y}{a_x} = \frac{-0.062\,0\text{ m/s}^2}{0.472\text{ m/s}^2} = -0.131$$

$$\theta = \tan^{-1}(-0.131) = \boxed{-7.46°}$$

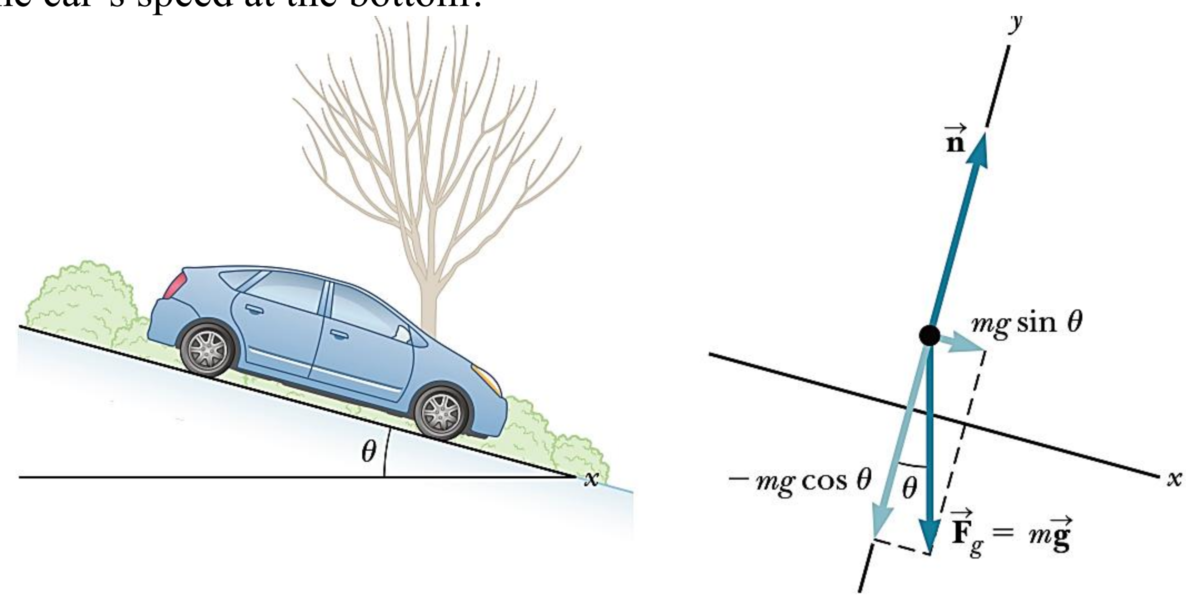
REMARKS: Notice that the angle is in fourth quadrant (الربع الرابع), in the range of the inverse tangent function, so it is not necessary to add 180° to the answer. The horses exert a force on the barge through the tension in the cables, while the barge exerts an equal and opposite force on the horses, again through the cables. If that were not true, the horses would easily move forward, as if unburdened. This example is another illustration of forces acting in pairs.

Exercise: Repeat last example, but assume the first horse pulls at a 40° angle, the second horse at 20°.

ANSWER: 0.520 m/s^2, 10°

Example 3:

(a) A car of mass m is on an icy driveway inclined at an angle Ө=20°, as in Figure below. Determine the acceleration of the car, assuming the incline is frictionless. (b) If the length of the driveway is 25m and the car starts from rest at the top, how long (*t*) does it take to travel to the bottom? (c) What is the car's speed at the bottom?



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SOLUTION

(a) Find the acceleration of the car.

Apply Newton's second law to the car: $m\vec{\mathbf{a}} = \sum \vec{\mathbf{F}} = \vec{\mathbf{F}}_g + \vec{\mathbf{n}}$

Extract the x- and y-components from the second law:

(1) $ma_x = \sum F_x = mg\sin\theta$

(2) $0 = \sum F_y = -mg\cos\theta + n$

Divide Equation (1) by m and substitute the given values: $a_x = g\sin\theta = (9.80\text{ m/s}^2)\sin 20.0° = \boxed{3.35\text{ m/s}^2}$

(b) Find the time taken for the car to reach the bottom.

Use Equation 3.11b for displacement, with $v_{0x} = 0$: $\Delta x = \frac{1}{2}a_x t^2 \quad \rightarrow \quad \frac{1}{2}(3.35\text{ m/s}^2)t^2 = 25.0\text{ m}$

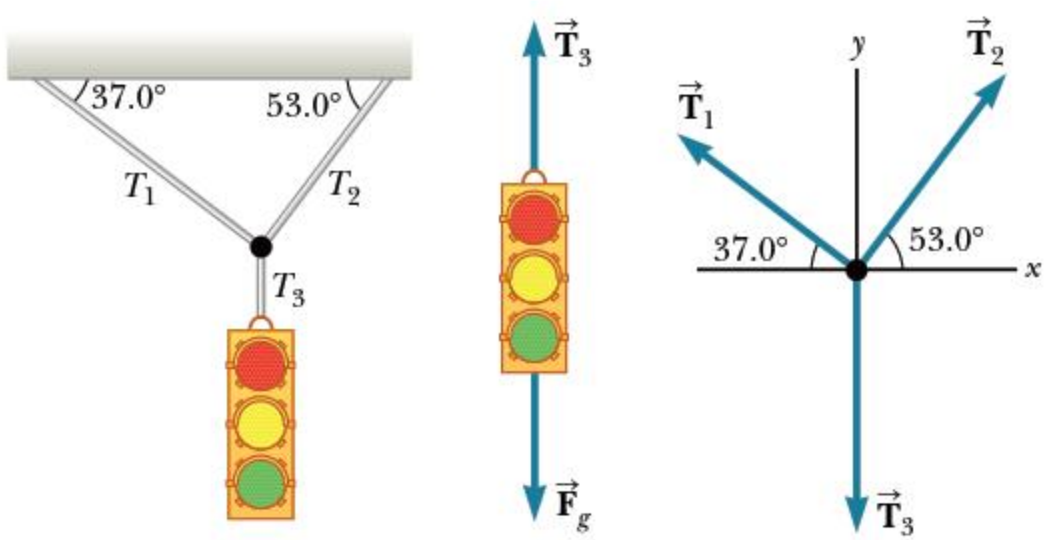
$t = \boxed{3.86\text{ s}}$

(c) Find the speed of the car at the bottom of the driveway.

Use Equation 3.11a for velocity, again with $v_{0x} = 0$: $v_x = a_x t = (3.35\text{ m/s}^2)(3.86\text{ s}) = \boxed{12.9\text{ m/s}}$

Example 4:

A traffic light weighing 1×10^2 N hangs from a vertical cable tied to two other cables that are fastened to a support, as in coming Figure. The upper cables make angles of 37° and 53° with the horizontal. **Find the tension (T) in each of the three cables.**



SOLUTION:

Find T_3 from the Figure , using the condition of **equilibrium**:

$$\sum F_y = 0 \rightarrow T_3 - F_g = 0$$

$$\boldsymbol{T_3 = F_g = 1 \times 10^2\ \mathrm{N}}$$

Using component's Figure, resolve all three tension forces into components and construct a table for convenience:

Force	***x*-Component**	***y*-Component**
$\overrightarrow{T_1}$	$-T_1 \cos 37°$	$T_1 \sin 37°$
$\overrightarrow{T_2}$	$T_2 \cos 53°$	$T_2 \sin 53°$
$\overrightarrow{T_3}$	0	$-1 \times 10^2\ \mathrm{N}$

Apply the conditions for **equilibrium** to the knot, using the components in the table:

$$\boldsymbol{\sum F_x = -T_1 \cos 37° + T_2 \cos 53° = 0}$$

$$\boldsymbol{\sum F_y = T_1 \sin 37° + T_2 \sin 53° - 1 \times 10^2 = 0}$$

For solving the last two equation's we get;

$$T_2 = T_1\left(\frac{\cos 37.0°}{\cos 53.0°}\right) = T_1\left(\frac{0.799}{0.602}\right) = 1.33T_1$$

$$T_1 \sin 37.0° + (1.33T_1)(\sin 53.0°) - 1.00 \times 10^2\ \mathrm{N} = 0$$

$$T_1 = \boxed{60.1\ \mathrm{N}}$$

$$T_2 = 1.33T_1 = 1.33(60.1\ \mathrm{N}) = \boxed{79.9\ \mathrm{N}}$$

REMARKS: It is very easy to make sign errors in this kind of problem. One way to avoid them is to always measure the angle of a vector from the positive x-direction. The trigonometric functions of the angle will then automatically give the correct signs for the components. For example, $\overrightarrow{T_1}$ makes an angle of 180° - 37° = 143° with respect to the positive x -axis, and its x -component, $\overrightarrow{T_1}\cos 143°$, is negative, as it should be.

Accelerating Objects and Newton's Second Law:

Apply the second law of motion for a system not in equilibrium, together with a kinematics equation.

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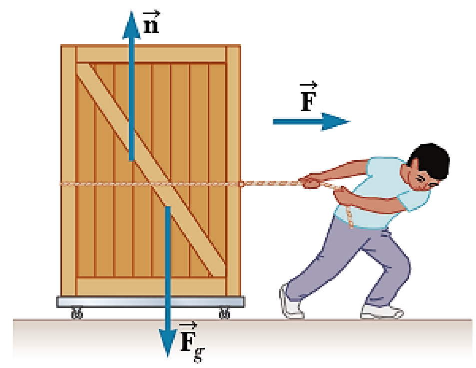
Example 5:

The combined weight of the crate and box in coming Figure is 3×10^2 N. If the man pulls on the rope with a constant force of 20 N, what is the **acceleration** of the system (crate plus box), and how far will it move in 2 s? Assume the system starts from **rest** and that there are no friction forces opposing the motion.



SOLUTION

Find the mass of the system from the definition of weight, $w = mg$:

$$m = \frac{w}{g} = \frac{3.00 \times 10^2\ \text{N}}{9.80\ \text{m/s}^2} = 30.6\ \text{kg}$$

Find the acceleration of the system from the second law:

$$a_x = \frac{F_x}{m} = \frac{20.0\ \text{N}}{30.6\ \text{kg}} = \boxed{0.654\ \text{m/s}^2}$$

Use kinematics to find the distance moved in 2.00 s, with $v_0 = 0$:

$$\Delta x = \tfrac{1}{2} a_x t^2 = \tfrac{1}{2}(0.654\ \text{m/s}^2)(2.00\ \text{s})^2 = \boxed{1.31\ \text{m}}$$