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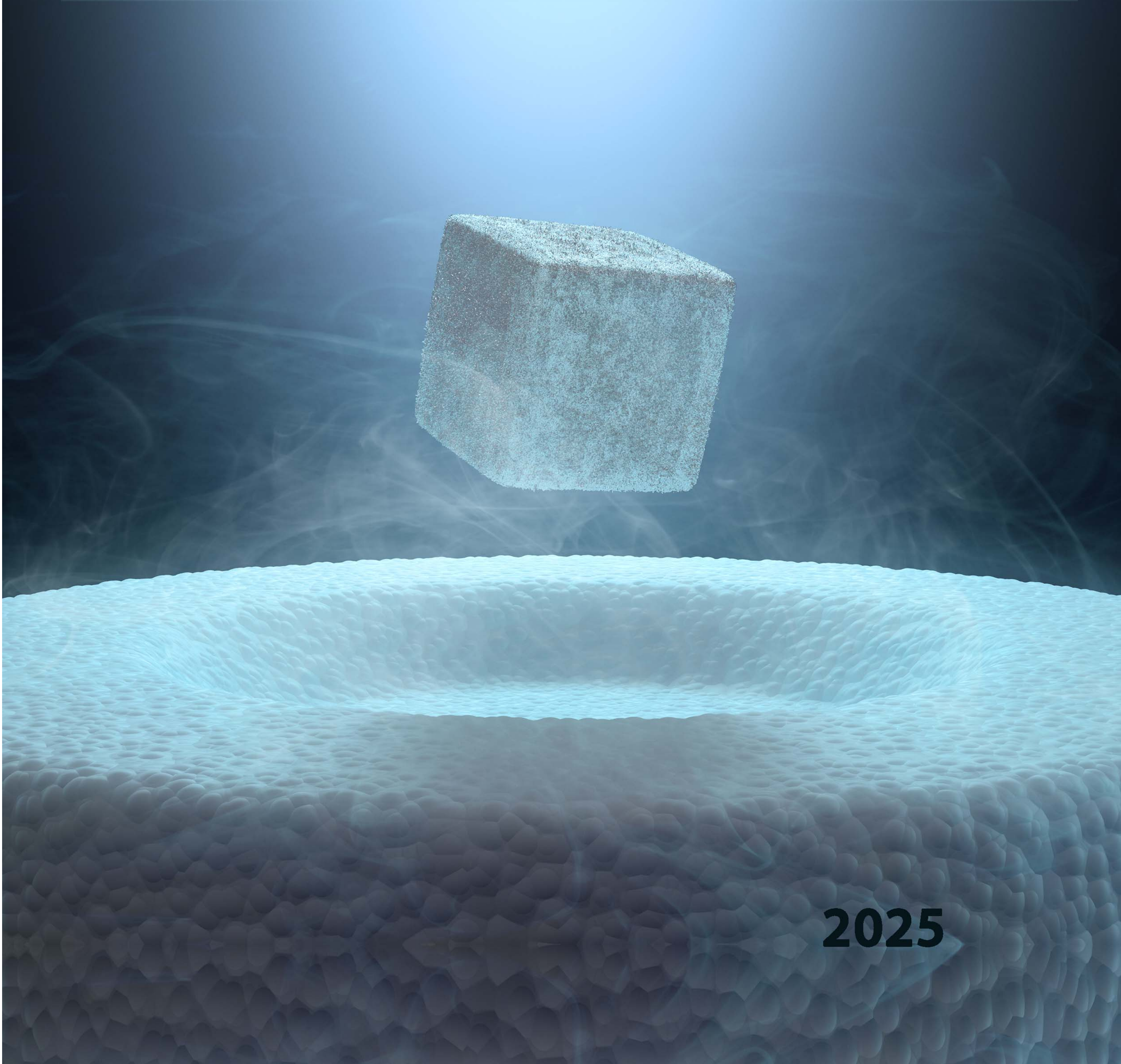
Physics 12



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edvantage interactive

BC SCIENCE

PHYSICS 12

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Contents

1 Vectors and Static Equilibrium

By the end of this chapter, you should be able to do the following:

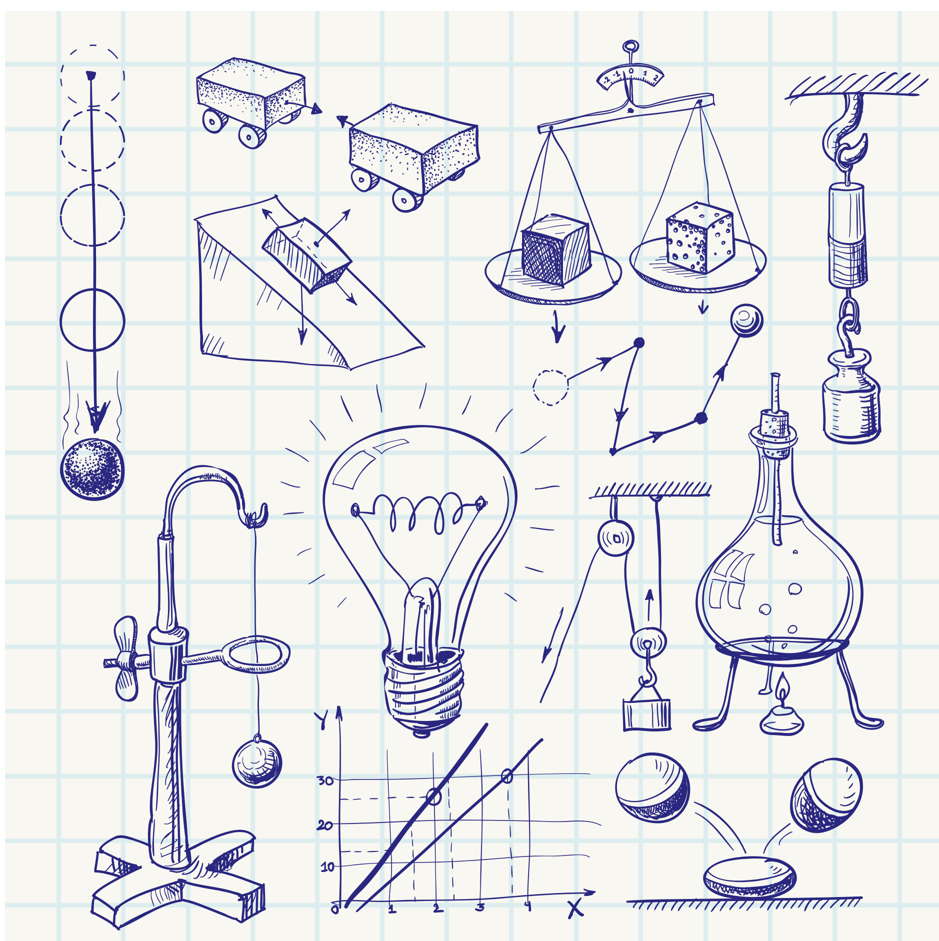
- Perform vector analysis in one or two dimensions
- Apply vector analysis to solve practical navigation problems
- Use knowledge of force, torque and equilibrium to analyse various situations

By the end of this chapter, you should know the meaning of these **key terms**:

- centre of gravity
- centre of mass
- components
- equilibrium
- fulcrum
- horizontal component
- net force
- resultant force
- scalar quantities
- static equilibrium
- torque
- vector quantities
- vertical component

By the end of this chapter, you should be able to use and know when to use the following formulae:

$\tau = F \cdot \ell_{\perp}$ or $\tau = F \cdot \ell_{\perp} \sin\theta$



Welcome to Physics 12. In this course, you will study a variety of concepts that will help you better understand the world around you. From vector motion to dynamics to gravitational and electromagnetic fields, you will be able to use what you learn throughout your life.

1.1 Vectors in Two Dimensions

Warm Up

An airplane is flying north at 200 km/h. A 25 km/h wind is blowing from the east. Will this crosswind speed up, slow down, or have no effect on the plane? Defend your answer.

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Review of Vectors

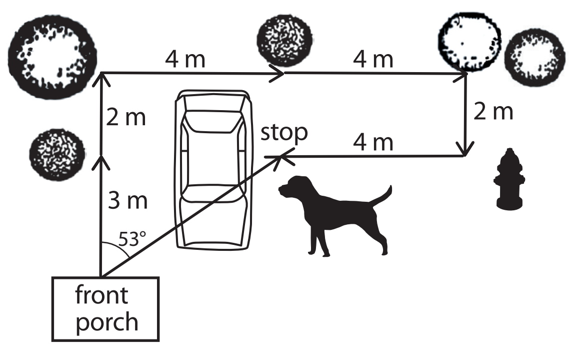


Figure 1.1.1 *Buddy's trip around the front yard*

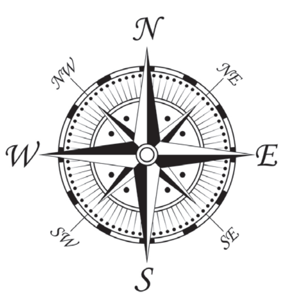


Figure 1.1.2 *The cardinal directions are north, east, south, and west, as shown on this compass.*

In Figure 1.1.1, notice a series of arrows drawn on the map of a physics teacher's front lawn. Each arrow shows the *magnitude* (size) and *direction* of a series of successive trips made by Buddy, the teacher's dog. Buddy was "doing his thing" before getting into the car for a trip to school. These arrows, showing both magnitude and direction of each of Buddy's displacements, are called **vectors**.

To identify the direction of vectors, two common conventions are used: numerical and compass. Sometimes compass directions are also called cardinal directions.

Numerical directions use a positive and negative sign to indicate direction. If you think of a graph, the "up" direction on the *y*-axis and the "right" direction on the *x*-axis are positive. "Down" on the *y*-axis and "left" on the *x*-axis is negative. For example, a person walking 2 km right is walking +2 km and a person walking 2 km left is walking –2 km. The sign indicates direction. Compass or cardinal directions are another way of indicating vector directions. As Figure 1.1.2 shows, there are four main directions on the compass: north, east, south, and west. North and west are usually positive, and east and south are negative. For example, if a person walking north encounters a person walking south, the two people are walking in opposite directions.

Trigonometric Ratios

To determine the angle θ, you use trigonometric ratios. The summary below reviews the key points related to using trigonometric ratios when solving vector related situations.

Trigonometric Ratios Used in Vector Problems

In many problems, the most useful way of resolving a vector into components is to choose components that are perpendicular to each other. Let's review trigonometric ratios so you can recall how to do this.

Three trigonometric ratios are particularly useful for solving vector problems. In the right-angled triangle ABC in Figure 1.1.3, consider the angle labeled with the Greek symbol θ (theta). With reference to θ, AC is the **opposite side**, BC is the **adjacent side**, and AB is the **hypotenuse**. In any right-angled triangle, the hypotenuse is always the side opposite to the right angle.

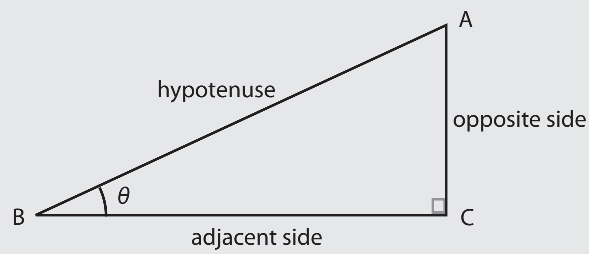


Figure 1.1.3 *A right-angled triangle with the labels you need to know for the trigonometric ratios you'll be using in vector problems*

The three most commonly used trigonometric ratios are defined as follows:

$$\textbf{sin}\ \theta = \frac{\text{opposite side}}{\text{hypotenuse}} = \frac{\text{o}}{\text{h}}$$

$$\textbf{cosine}\ \theta = \frac{\text{adjacent side}}{\text{hypotenuse}} = \frac{\text{a}}{\text{h}}$$

$$\textbf{tangent}\ \theta = \frac{\text{opposite side}}{\text{adjacent side}} = \frac{\text{o}}{\text{a}}$$

Trigonometric ratios, available with the push of a button from your calculator, can help you solve vector problems quickly. Following is a sample vector question involving velocities. The rules for adding velocity vectors are the same as those for displacement and force vectors or any other vector quantities.

Now, back to Figure 1.1.1. When Buddy reaches his final spot near the car door, how far has he walked since he left the front porch? This question has two answers, depending on what "How far?" means. The distance Buddy has travelled is the arithmetic sum of all the short distances he has travelled between the shrubs, trees, and fire hydrant while he visited them. This is simple to calculate.

$$\text{total distance} = 3.0 \text{ m} + 2.0 \text{ m} + 4.0 \text{ m} + 4.0 \text{ m} + 2.0 \text{ m} + 4.0 \text{ m} = 19.0 \text{ m}$$

If, however, you want to know how far Buddy has travelled from the porch, the bold line in Figure 1.1.1, then you want to know Buddy's **displacement**. It turns out that Buddy's displacement from the front porch is 5.0 m. The bold arrow represents the magnitude (5.0 m) and the direction (53° to the right of his starting direction) of Buddy's displacement, and is called the **resultant displacement**. The resultant displacement is not the arithmetic sum, but the vector sum of the individual displacement vectors shown on the diagram.

There are two ways to indicate that a quantity is a vector quantity. The best way is to include a small arrow above the symbol for the vector quantity. For example, $\Delta\vec{d}$ symbolizes a displacement **vector**. If it's not possible to include the arrow when typing, a vector quantity may be typed in ***bold italics***. For example, $\boldsymbol{\Delta d}$ also symbolizes a displacement **vector**. If only the magnitude of the vector is of importance, the symbol Δd (no arrow or not bold) is used.

Adding Vectors

Draw the first vector to scale and in the proper direction. Draw the second vector to scale, beginning at the tip of the first vector, and in the proper direction. Add the third vector (if there is one), beginning at the tip of the second vector. Repeat this procedure until all the vectors have been added. The vector sum or resultant of all the vectors is the vector that starts at the tail of the first vector and ends at the tip of the last vector.

This is what was done in Figure 1.1.1. The resultant displacement of Buddy is correctly written as 5.0 m, 53° to the right of his starting direction.

Scalars and Vectors

If you add 3 kg of sugar to 2 kg of sugar, you will have 5 kg of sugar. If you add 3 L of water to 2 L of water, you will have 5 L of water. Masses and volumes are added together by the rules of ordinary arithmetic. Mass and volume are **scalar quantities**. Scalar quantities have magnitude but no direction. Other scalar quantities include: distance, speed, time, energy, and density.

If you add a 3 m displacement to a 2 m displacement, the two displacements together may add up to 5 m, but they may also add up to 1 m or any magnitude between 1 m and 5 m! Figure 1.1.4 shows some of the ways these displacements might add up. In Figure 1.1.4, the two displacement vectors are added by the rule for vector addition. As you can see, the resultant displacement depends on the directions of the two vectors as well as their magnitudes. In addition to displacements, other vector quantities include force, velocity, acceleration, and momentum.

When you describe displacement, force, velocity, acceleration, or momentum, you must specify not only the magnitude of the quantity but also its direction.

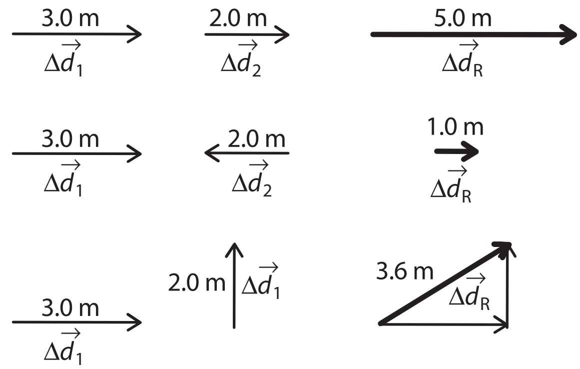


Figure 1.1.4 *Different ways to add up displacements*

Free Body Diagrams

In Figure 1.1.5(a), two basketball players, A and B, are having a tug-of-war for possession of the ball. Neither is winning. What is the resultant of the forces exerted by A and B on the ball? A is pulling with a force of 120.0 N to the left, and B is pulling with a force of 120.0 N to the right. If the two force vectors $\vec{F}_A$ and $\vec{F}_B$ are added by the rule for vector addition, the resultant is zero. (See Figure 1.1.5(b).) This should not surprise anyone, because if there is no acceleration of the ball in either direction, the net force on the ball *should* be zero!

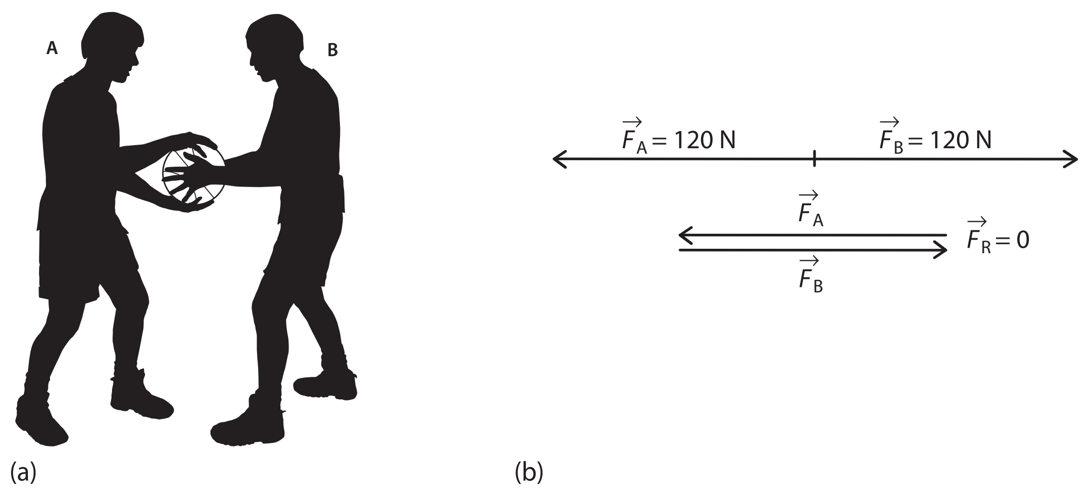


Figure 1.1.5 **(a)** *The basketball players are both exerting forces on the ball.* **(b)** *The free body diagram on the right shows the forces and work and the resultant force.*

For many problems, it helps to draw a diagram that represents the situation being examined. These diagrams do not have to be a work of art, but rather a clear representation of the vectors being examined. When you sketch a diagram and add vector arrows you have created a **free-body diagram**. Figure 1.1.5(b) is an example of a very simple, but effective diagram. A free-body diagram is a representation used to analyze the forces acting on a body of interest. A free body diagram shows all forces of all types acting on this body. All other information in the problem is not included. While all the vectors may not be exerted on the same point in real life, it is customary to place the tails of the vectors at the centre of the object. You should also include directions indicating what direction is positive and what direction is negative.

Defining Vector Components

Figure 1.1.6 shows three ways you could travel from A to B. The vectors are displacement vectors. In each of the three "trips," the resultant displacement is the same.

$$\vec{D}_1 + \vec{D}_2 = \vec{D}_R$$

Any two or more vectors that have a resultant such as $\vec{D}_R$ are called **components** of the resultant vector. A vector such as $\vec{D}_R$ can be **resolved** into an endless number of component combinations. Figure 1.1.6 shows just three possible combinations of components of $\vec{D}_R$.

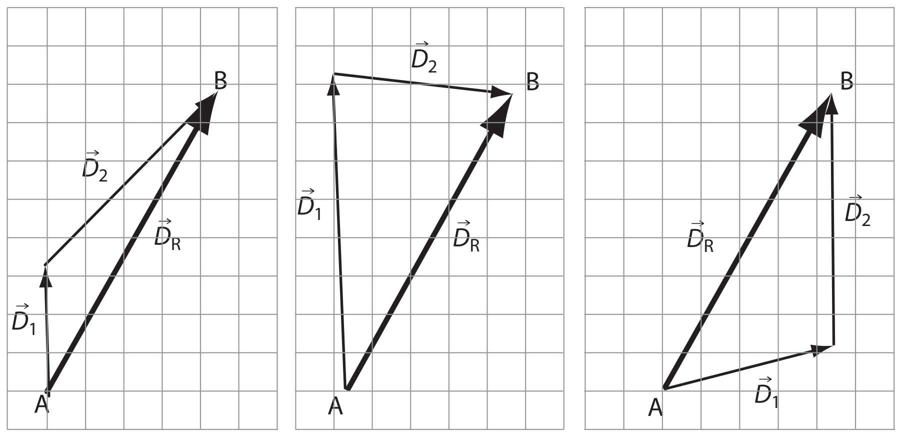
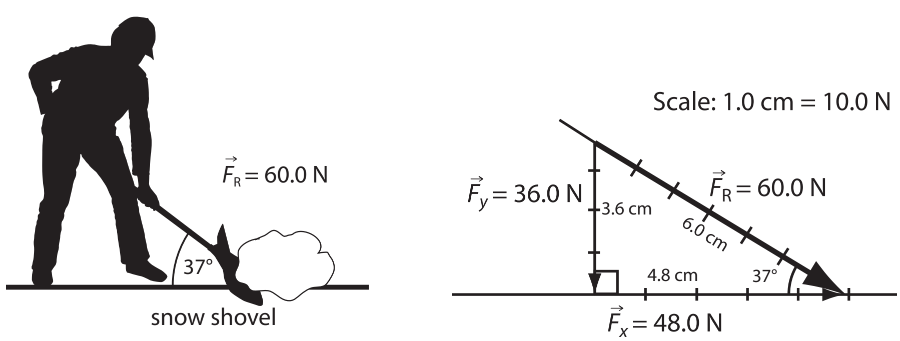


Figure 1.1.6 *Examples of possible components of* $\vec{D}_R$

Resolving Vectors into Vertical and Horizontal Components

Figure 1.1.6 shows one situation where it is wise to use perpendicular components.

In Figure 1.1.7(a), a 60.0 N force is exerted down the handle of a snow shovel. The force that actually pushes the snow along the driveway is the **horizontal component** $\vec{F}_x$. The **vertical component** $\vec{F}_y$ is directed perpendicular to the road (Figure 1.1.7(b)).



(a   (b)

Figure 1.1.7 *The force the man exerts on the snow shovel can be resolved into horizontal and vertical components.*

Method 1: Solving By Scale Diagram

To find out what the horizontal component $\vec{F}_x$ is, you can use a scale diagram like Figure 1.1.7(b). First, draw a horizontal reference line. Then draw a line forming an angle of 37° with the horizontal reference line, because this is the angle formed by the snow shovel handle with the road.

Using a scale of 1.0 cm for each 10.0 N, draw a force vector to represent $\vec{F}_R$, where $\vec{F}_R = 60.0$ N. Next, drop a line down from the tail of $\vec{F}_R$ meeting the horizontal reference line at an angle of 90°. This gives you both the vertical and the horizontal component forces. Label these $\vec{F}_y$ and $\vec{F}_x$, and place arrows on them to show their directions.

Since the horizontal component vector has a length of 4.8 cm, and each 1.0 cm represents 10.0 N, then $\vec{F}_x = 48.0$ N. The vertical component vector is 3.6 cm long, therefore $\vec{F}_y = 36.0$ N.

Method 2: Resolve into Components

Figure 1.1.7(b) shows the force vector $\vec{F}_R = 60$ N at an angle of 37° to the surface or horizontal. This vector is then resolved into its vertical component $\vec{F}_y$ and horizontal component $\vec{F}_x$. How do we find the magnitude of these component vectors without the aid of a scale diagram?

Recall from your math class that the three angles in a triangle add up to 180°. (See, you would use that fact one day!) So, the unknown angle in Figure 1.1.7 is 53°. Remember that a right angle is 90°. So the unknown angle is equal to 180 – (90° + 37°), which is 53°.

Then to find $\vec{F}_y$, we know $\vec{F}_R$ and the angle between $\vec{F}_R$ and $\vec{F}_y$. Using cos θ, we can calculate $\vec{F}_y$:

$$\cos 53° = \frac{\vec{F}_y}{60}$$
$$\vec{F}_y = \cos 53° \times 60$$
$$\vec{F}_y = 36 \text{ N}$$

To find $\vec{F}_x$, we use sin θ to calculate the horizontal component:

$$\sin 53° = \frac{\vec{F}_x}{60}$$
$$\vec{F}_x = \sin 53° \times 60$$
$$\vec{F}_x = 48 \text{ N}$$

To check that we have the right answers, we use the Pythagorean theorem as the three vectors form a right angle triangle:

$$F_R = \sqrt{F_x^2 + F_y^2}$$
$$F_R = \sqrt{(36)^2 + (48)^2}$$
$$F_R = 60 \text{ N}$$

More than One Vector: Using a Vector Diagram

Figure 1.1.8 shows a typical force vector situation, where there are three forces acting, but no motion resulting. Two strings support a 36.0 N object. One string makes an angle of 30° with the vertical, and the other string is horizontal. The question is, "What is the tension in each string?" The tension in a string is simply the force exerted along the string. To find the answer to this question, we must first represent the forces in a vector diagram.

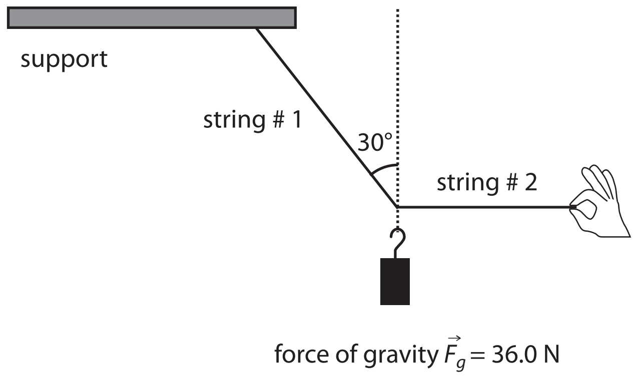


Figure 1.1.8 *Two strings support an object. You want to find the tension in each string.*

Figure 1.1.9 shows one way to look at this problem. The 36.0 N object is not moving, so the three forces acting on it must have a resultant of zero. That means the vector sum of the three forces acting on the object is zero.

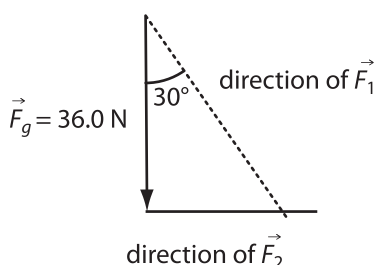


Figure 1.1.9 *Vector diagram representing the three forces acting on the object in Figure 1.1.8*

The vector to draw first is the one for which you have the most complete information. You know that the force of gravity $\vec{F}_g$ has a magnitude of 36.0 N and is directed down.

You do *not* know the *magnitude* of the tension along string #1 ($\vec{F}_1$) but you know its *direction,* which is 30° to the vertical. You do *not* know the *magnitude* of the tension in string #2 ($\vec{F}_2$), but you know that it acts in a direction *perpendicular to* $\vec{F}_g$. You also know that vectors $\vec{F}_1$, $\vec{F}_2$, and $\vec{F}_g$ form a closed triangle since their resultant is zero.

In Figure 1.1.9, dashed lines show the directions of $\vec{F}_1$ and $\vec{F}_2$. To complete the vector triangle of forces, arrows must be added to show that $\vec{F}_1$ ends at the tail of $\vec{F}_g$, and $\vec{F}_2$ starts at the tip of $\vec{F}_g$. If $\vec{F}_g$ has been drawn to scale, then both $\vec{F}_1$ and $\vec{F}_2$ will have the same scale.

Figure 1.1.10 shows what the completed vector diagram looks like. To solve for tension forces $\vec{F}_1$ and $\vec{F}_2$, you must know to what scale $\vec{F}_g$ was drawn. In the next sample problem, the tension will be found using this diagram and components.

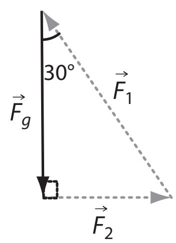


Figure 1.1.10 *Completed vector diagram from Figure 1.1.8*

Sample Problem — Using a Vector Diagram

Use components to find the tension in the two strings shown in Figure 1.1.10.

What to Think About

1. Draw a vector diagram to identify all the forces in the problem.
2. Identify what to solve.
3. For $\vec{F}_1$, find the horizontal and vertical components and use the Pythagorean theorem to solve for $\vec{F}_1$.

How to Do It

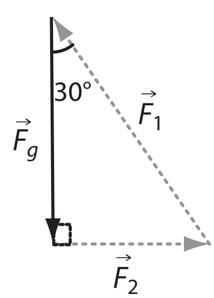


Figure 1.1.11

Find $\vec{F}_1$ and $\vec{F}_2$

$$\cos 30° = \frac{\vec{F}_g}{\vec{F}_1} = \frac{36.0\text{ N}}{\vec{F}_1}$$

$$\vec{F}_1 = \frac{36.0\text{ N}}{\cos 30°} = 41.6\text{ N}$$

Sample Problem continued

Sample Problem — Using a Vector Diagram (Continued)

What to Think About	How to Do It
4. Repeat for $\vec{F}_2$.	$\tan 30° = \dfrac{\vec{F}_2}{36.0\ \text{N}}$ $F_2 = (\tan 30°)(36.0\ \text{N})$ $F_2 = 20.8\ \text{N}$
5. Check that $\vec{F}_g = \vec{F}_1 + \vec{F}_2$.	$\vec{F}_g = \vec{F}_1 + \vec{F}_2$ $F_g = \sqrt{(41.6\ \text{N})^2 - (20.8\ \text{N})^2}$ $F_g = 36.0\ \text{N}$

Practice Problems — Using a Vector Diagram

1. Figure 1.1.12 shows three force vectors.

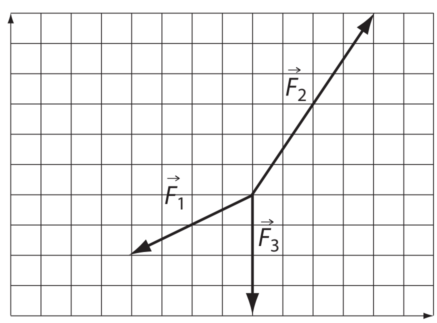


Figure 1.1.12

(a) What is the resultant of the three force vectors, added "head-to-tail"?

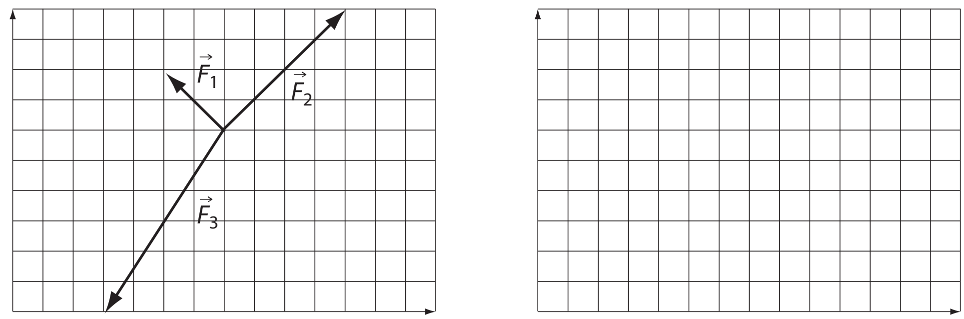
(b) What is the resultant of the three horizontal components?

Practice Problems continued

Practice Problems — Using a Vector Diagram (Continued)

(c) What is the resultant of the three vertical components?

2. Using the empty graph in Figure 1.1.13(b) and by any logical method, find the force F_4 that must be added to F_1, F_2, and F_3 (shown in (a)) to obtain a resultant of zero.



(a) (b)

Figure 1.1.13

3. A dedicated physics student pulls his brand new shiny red wagon along a level road such that the handle makes an angle of 50° with the horizontal road. If he pulls on the handle with a force of 85 N, what is the horizontal component of the force he exerts along the handle? Draw a neat, labeled vector diagram. Use a scale of 1.0 cm for every 10.0 N. Why is the horizontal component more useful information than the force he exerts along the handle?

A Velocity Vector Problem — Vectors in Action!

It might not seem at first glance to be a vector problem, but a boat crossing a river or a plane flying into a strong wind are both examples of more than one vector acting on an object. Commonly called boat or airplane vector problems in physics, these situations involve the object moving through a medium that is also moving. For a boat, this medium is the river that has a current and, for an airplane, it is the air.

Both water and air are mediums that have a velocity and can be represented with a vector. This motion is usually compared to a reference point like the ground. For example, a person watching a boat cross a river observes the boat's motion as a combination of boat speed and river speed. A person in the boat experiences only the boat's speed. This is an example of relative motion. The motion observed is relative to where the person is located.

Let's first look at a motorboat crossing a river. In Figure 1.1.14 an observer sees the boat crossing the river at an angle. This is the boat's speed relative to the ground. But a person in the boat measures the speed of the boat relative to the water. This is the boat's speed relative the water. And the current, which is pushing the boat, is the speed of the water relative to the ground. This is summarized in Figure 1.1.15. Now we can apply this to a boat vector problem.

Problem: A motorboat operator is trying to travel across a fast-moving river, as shown in Figure 1.1.14. Although he aims his boat directly across the stream, the water carries the boat to the right. If the boat's resultant velocity, as seen by an observer on the bank, is 15.0 m/s in the direction shown, how fast is the boat moving
(a) in a direction downstream?
(b) in a direction across the river?

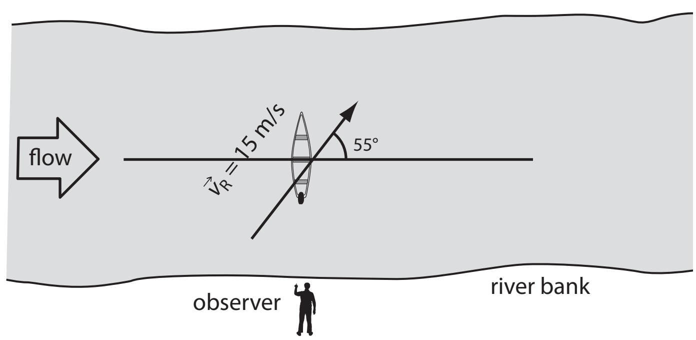


Figure 1.1.14 *The boat is aiming straight across for the shore but is moving diagonally because of the river's current.*

Solution: Consider the resultant velocity to have two component velocities: $\vec{v}_y$**,** the boat's velocity relative to the water, and $\vec{v}_x$**,** the water's velocity relative to the bank.

Component $\vec{v}_y$ is directed across the river, perpendicular to the bank, while component $\vec{v}_x$ is directed down the stream. For your vector diagram, only a neat sketch is needed, since you will be using trigonometric ratios rather than a scale diagram. See Figure 1.1.15.

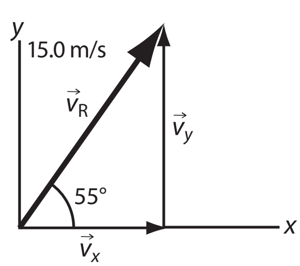


Figure 1.1.15 *Vector diagram showing the direction of the boat*

To solve for $\vec{v}_y$, use

$$\sin 55° = \frac{v_y}{15 \text{ m/s}}$$

$$\vec{v}_y = (15.0 \text{ m/s})(\sin 55°) = (15.0 \text{ m/s})(0.8192) = 12.3 \text{ m/s}$$

To solve for $\vec{v}_x$, use

$$\cos 55° = \frac{v_y}{15 \text{ m/s}}$$

$$\vec{v}_x = (15.0 \text{ m/s})(\cos 55°) = (15.0 \text{ m/s})(0.5736) = 8.60 \text{ m/s}$$

To summarize:

Velocity of the boat relative to the ground	$\vec{v}_R$	15.0 m/s
Velocity of the boat relative to the water	$\vec{v}_B$ or $\vec{v}_y$	12.3 m/s
Velocity of the water relative to the ground	$\vec{v}_C$ or $\vec{v}_x$	8.60 m/s

An airplane vector problem is similar except, instead of water flowing down a river, you must consider wind speed that can come from any direction. The simplest situation is a plane flying with the wind in the same direction (tail wind) or in the opposite direction (head wind). While the plane will have an air speed, which is the speed of the plane relative to the air around it, a person from the ground would see the ground speed being a combination of air speed and wind speed. Figure 1.1.16 demonstrates both of these situations.

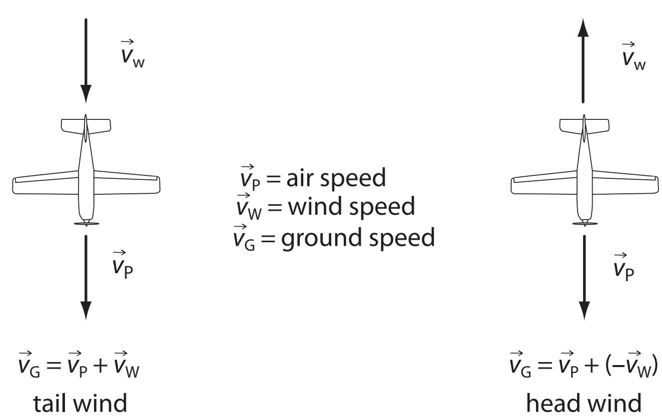
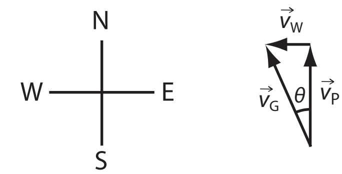


Figure 1.1.16 *The effects of a tail wind and a head wind on an airplane's velocity*

Now, what happens if the wind is moving at an angle to the plane?

Sample Problem — Relative Motion

What is the ground speed of a plane flying 200 km/h north if the wind is blowing from the east at 40.0 km/h?

What to Think About	How to Do It
1. Identify what you know and what you are solving.	$\vec{v}_P = 200$ km/h [N] $\vec{v}_W = 40.0$ km/h [W] $\vec{v}_G = ?$
2. Represent the problem with a diagram.	 **Figure 1.2.17**
3. Solve using the Pythagorean theorem.	$\vec{v}_G = \vec{v}_P + \vec{v}_W$ $v_G = \sqrt{(200 \text{ km/h})^2 + (40 \text{ km/h})^2}$ $v_G = 204$ km/h $\tan\theta = \frac{40}{200}$ $\theta = 11°$ W of N

Practice Problems — Relative Motion

1. What is the tailwind a plane experiences if the groundspeed is 350 km/h and the air speed is 320 km/h?

2. A plane flying 275 km/h [W] experiences a 25 km/h [N] wind. At what angle does an observer see the plane flying?

3. What airspeed would a plane have to travel to have a groundspeed of 320 km/h [S] if there is a 50.0 km/h wind coming from the northwest?

1.1 Review Questions

1. It is 256 m across the river in Figure 1.1.14, measured directly from bank to bank.
   (a) If you wished to know how much time it would take to cross the river, which of the three velocity vectors would you use to obtain the answer most directly?

   (b) What is the magnitude of this vector?

   (c) How long would it take to cross the river?

2. You wish to calculate how far down the bank the boat in Figure 1.1.14 will land when it reaches the other side.
   (a) Which velocity vector will give you the answer most directly?

   (b) What is the magnitude of this vector?

   (c) How far down the bank will the boat travel?

3. You absolutely *must* land your boat directly across from your starting point. This time, your resultant velocity will be 15.0 m/s, but in a direction straight across the river. In what direction will you have to aim the boat to end up straight across from your starting point?

4. A girl is mowing her lawn. She pushes down on the handle of the mower with a force of 78 N. If the handle makes an angle of 40° with the horizontal, what is the horizontal component of the force she exerts down the handle?

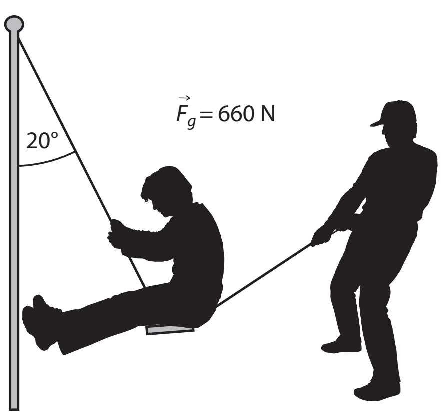
5. A hunter walks 225 m toward the north, then 125 m toward the east. What is his resultant displacement?

6. An airborne seed falls to the ground with a steady terminal velocity of 0.48 m/s. The wind causes it to drift to the right at 0.10 m/s. What is the magnitude and direction of the resultant velocity?

7. A helium balloon is released and rises with a steady vertical velocity of 12 km/h. A wind from the east blows the balloon toward the west at 18 km/h.
(a) What is the resultant velocity of the balloon?

(b) How far west will the balloon drift in five minutes?

8. (a) In the diagram below, what horizontal force must the boy exert to hold his friend on the swing still?



(b) What is the tension in each of the two ropes of the motionless swing, if the two ropes share the load equally?

9. A hockey player is moving north at 15 km/h. A body check changes her velocity to 12 km/h toward the west. Calculate the change in velocity of the hockey player.

