Chapter 3

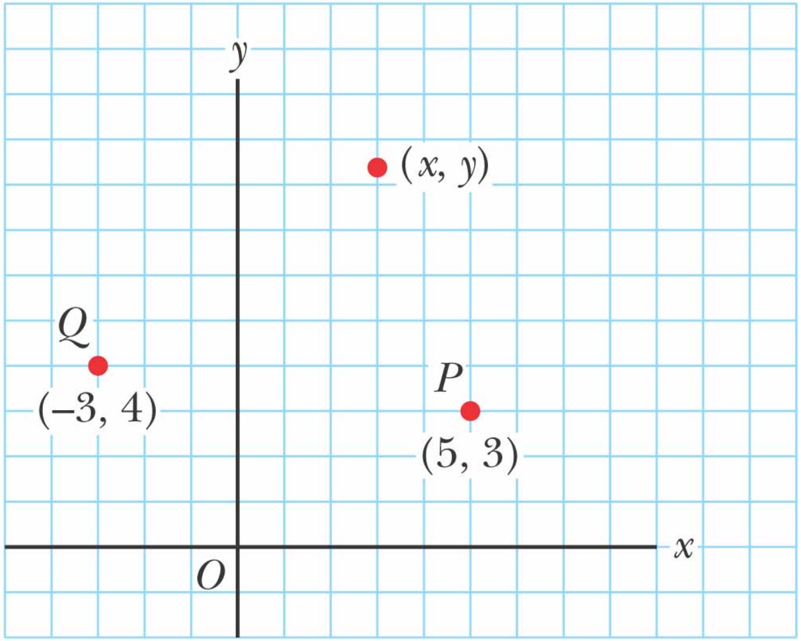
Vectors

Coordinate Systems

- Used to describe the position of a point in space
- Coordinate system consists of
  - a fixed reference point called the origin
  - specific axes with scales and labels
  - instructions on how to label a point relative to the origin and the axes

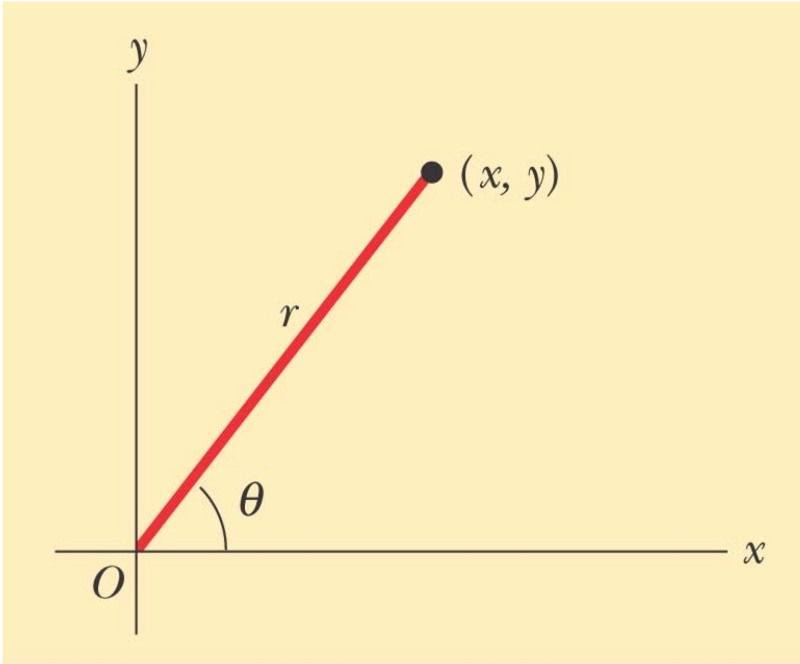
Cartesian Coordinate System

- Also called rectangular coordinate system
- *x*- and *y*- axes intersect at the origin
- Points are labeled (*x*,*y*)



Polar Coordinate System

- Origin and reference line are noted
- Point is distance *r* from the origin in the direction of angle θ, ccw from reference line
- Points are labeled (r,θ)



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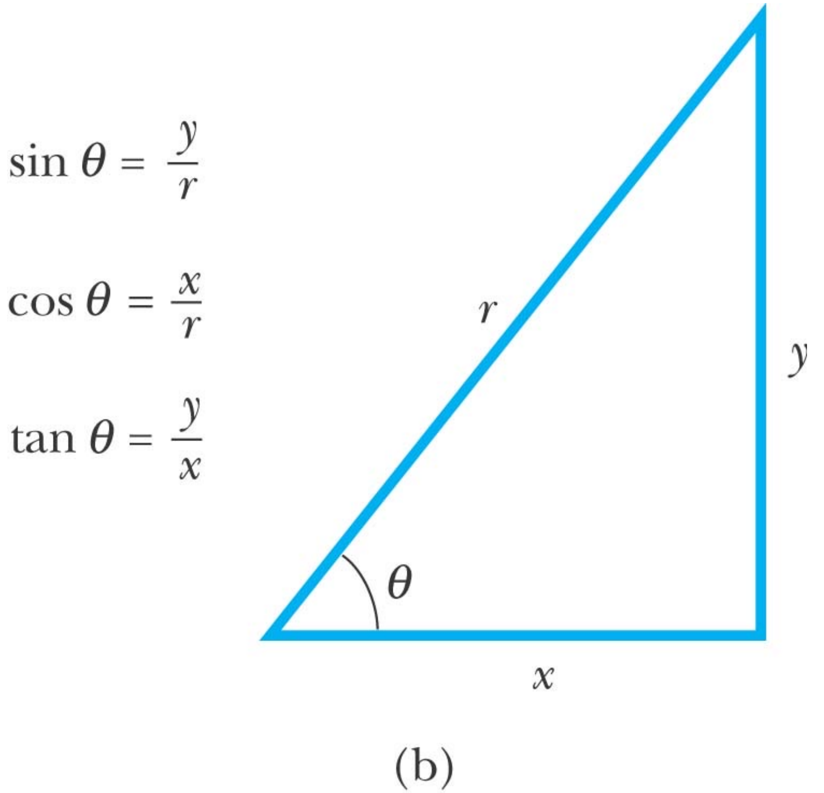
Polar to Cartesian Coordinates

- Based on forming a right triangle from r and θ
- $x = r\cos\theta$
- $y = r\sin\theta$



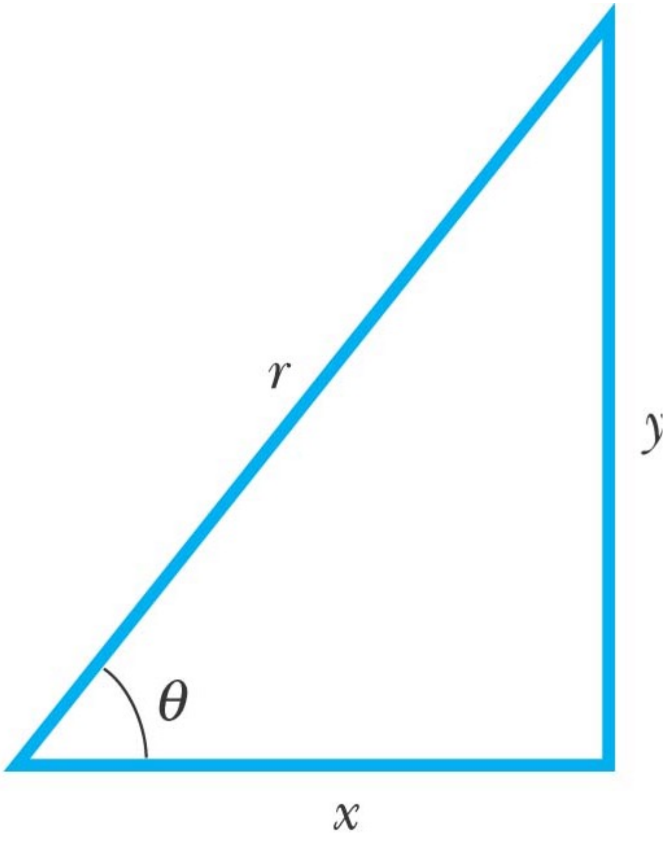
Cartesian to Polar Coordinates

- *r* is the hypotenuse and θ an angle

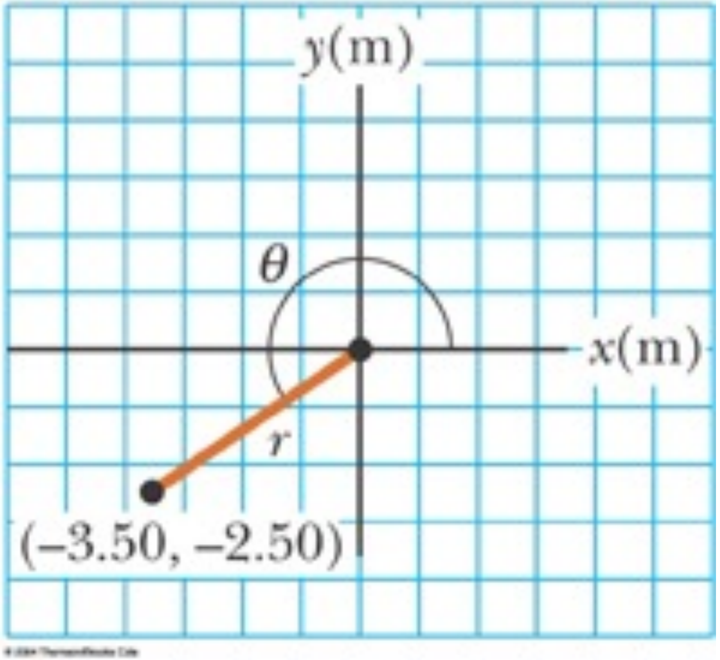
$$\tan\theta = \frac{y}{x}$$

$$r = \sqrt{x^2 + y^2}$$

- θ must be ccw from positive *x* axis for these equations to be valid



Example 3.1



- The Cartesian coordinates of a point in the *xy* plane are (*x,y*) = (-3.50, -2.50) m, as shown in the figure. Find the polar coordinates of this point.

- **Solution:** From Equation 3.4,

$$r = \sqrt{x^2 + y^2} = \sqrt{(-3.50\text{ m})^2 + (-2.50\text{ m})^2} = 4.30\text{ m}$$

and from Equation 3.3,

$$\tan\theta = \frac{y}{x} = \frac{-2.50\text{ m}}{-3.50\text{ m}} = 0.714$$

$$\theta = 216°$$

Vectors and Scalars

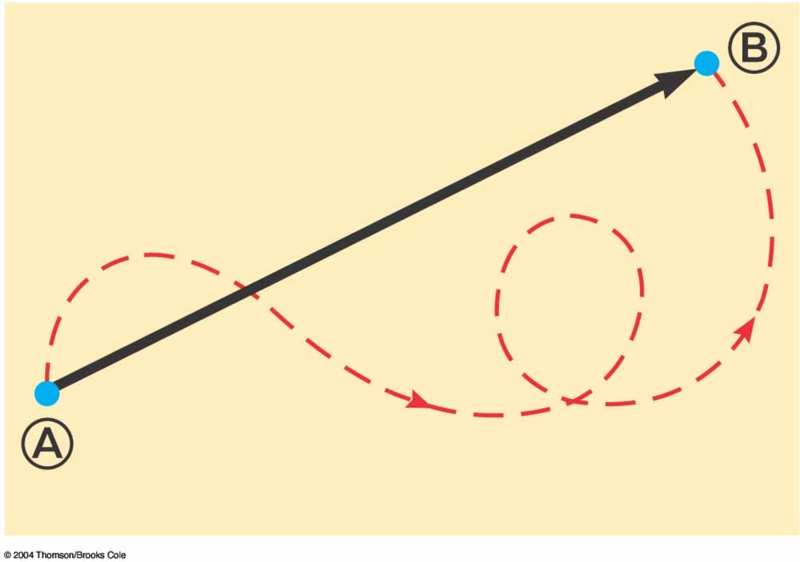
- A ***scalar quantity*** is completely specified by a single value with an appropriate unit and has no direction.
- A ***vector quantity*** is completely described by a number and appropriate units plus a direction.

Vector Notation

- When handwritten, use an arrow: $\vec{A}$
- When printed, will be in bold print: **A**
- When dealing with just the magnitude of a vector in print, an italic letter will be used: *A* or |**A**|
- The magnitude of the vector has physical units
- The magnitude of a vector is always a positive number

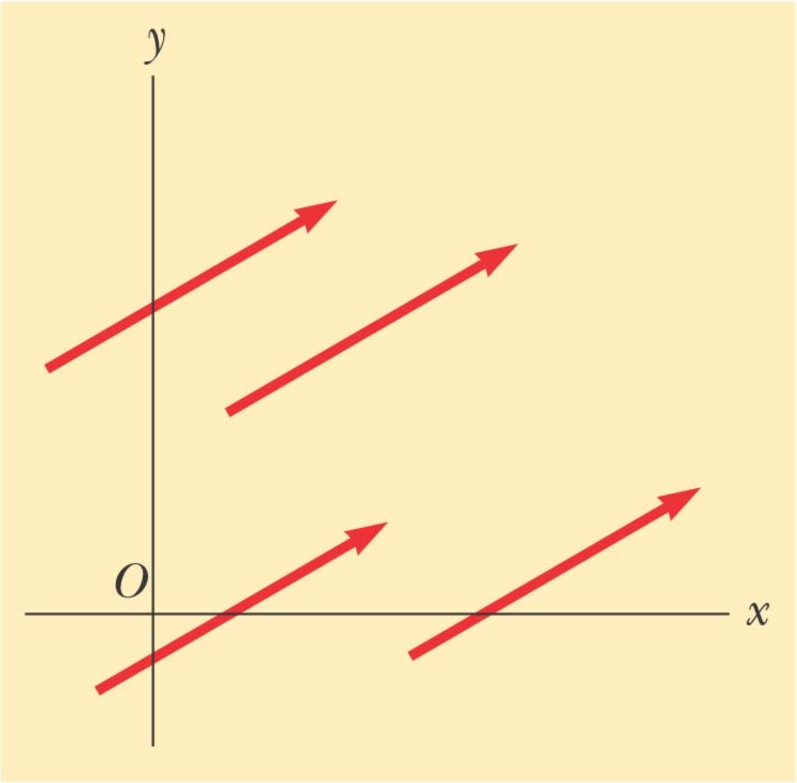
Vector Example

- A particle travels from A to B along the path shown by the dotted red line
  - This is the ***distance*** traveled and is a scalar
- The ***displacement*** is the solid line from A to B
  - The displacement is independent of the path taken between the two points
  - Displacement is a vector



Equality of Two Vectors

- Two vectors are ***equal*** if they have the same magnitude and the same direction
- **A** = **B** if $A = B$ and they point along parallel lines
- All of the vectors shown are equal



Adding Vectors

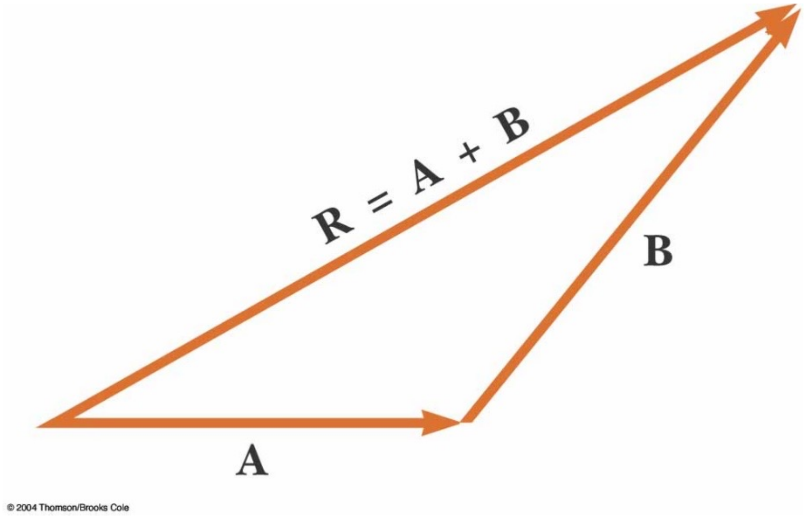
- When adding vectors, their directions must be taken into account
- Units must be the same
- Graphical Methods
  - Use scale drawings
- Algebraic Methods
  - More convenient

Adding Vectors Graphically

- Choose a scale
- Draw the first vector with the appropriate length and in the direction specified, with respect to a coordinate system
- Draw the next vector with the appropriate length and in the direction specified, with respect to a coordinate system whose origin is the end of vector **A** and parallel to the coordinate system used for **A**

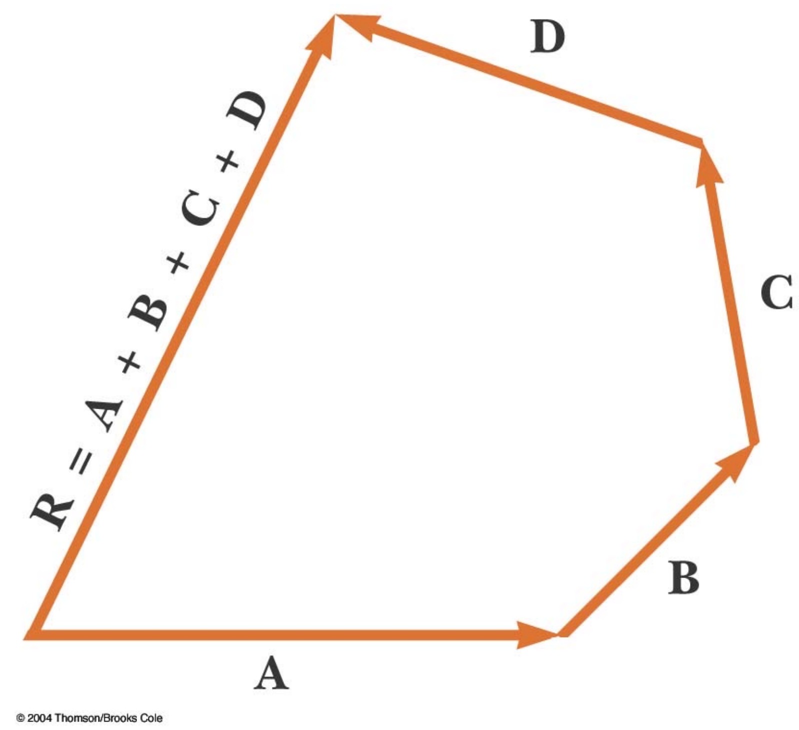
Adding Vectors Graphically, cont.

- Continue drawing the vectors "tip-to-tail"
- The resultant is drawn from the origin of **A** to the end of the last vector
- Measure the length of **R** and its angle
  - Use the scale factor to convert length to actual magnitude



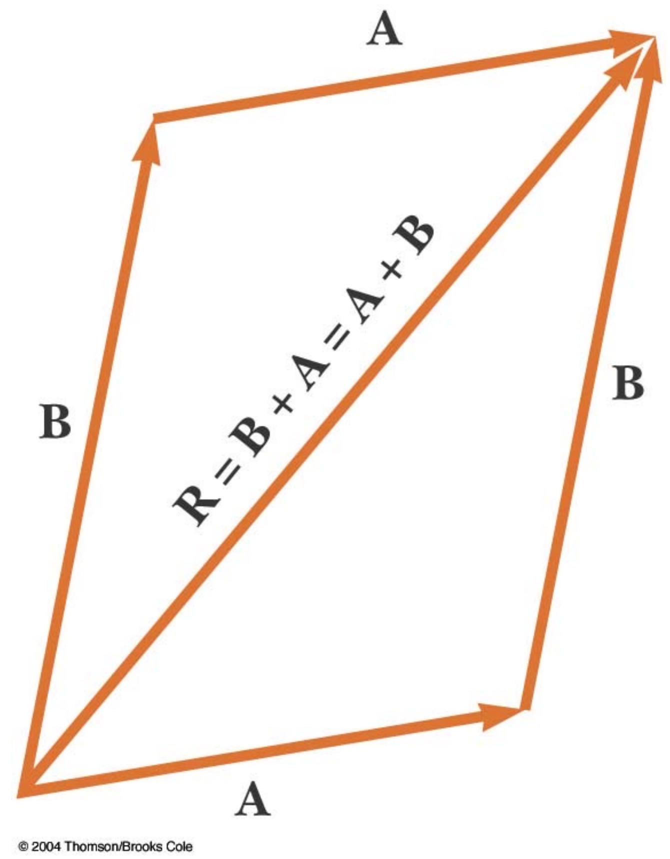
Adding Vectors Graphically, final

- When you have many vectors, just keep repeating the process until all are included
- The resultant is still drawn from the origin of the first vector to the end of the last vector



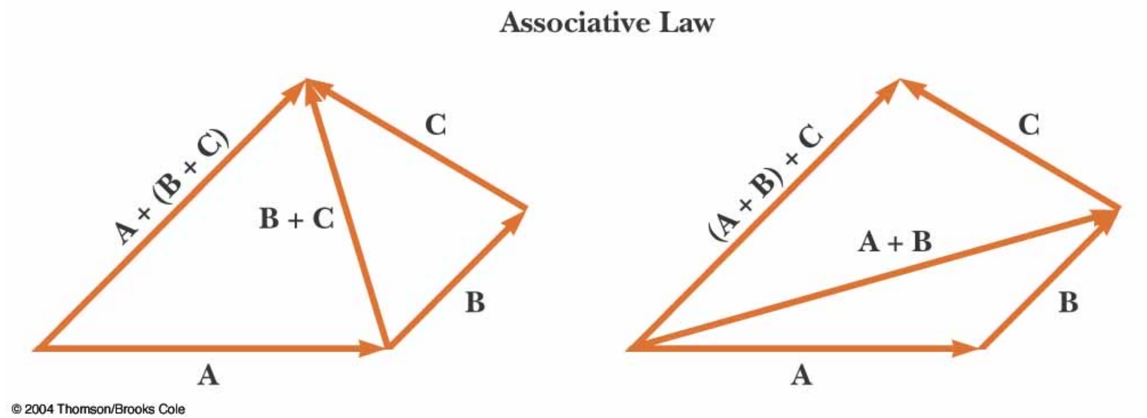
Adding Vectors, Rules

- When two vectors are added, the sum is independent of the order of the addition.
  - This is the ***commutative law of addition***
  - **A** + **B** = **B** + **A**



Adding Vectors, Rules cont.

- When adding three or more vectors, their sum is independent of the way in which the individual vectors are grouped
  - This is called the ***Associative Property of Addition***
  - **(A** + **B)** + **C = A** + (**B** + **C)**



Adding Vectors, Rules final

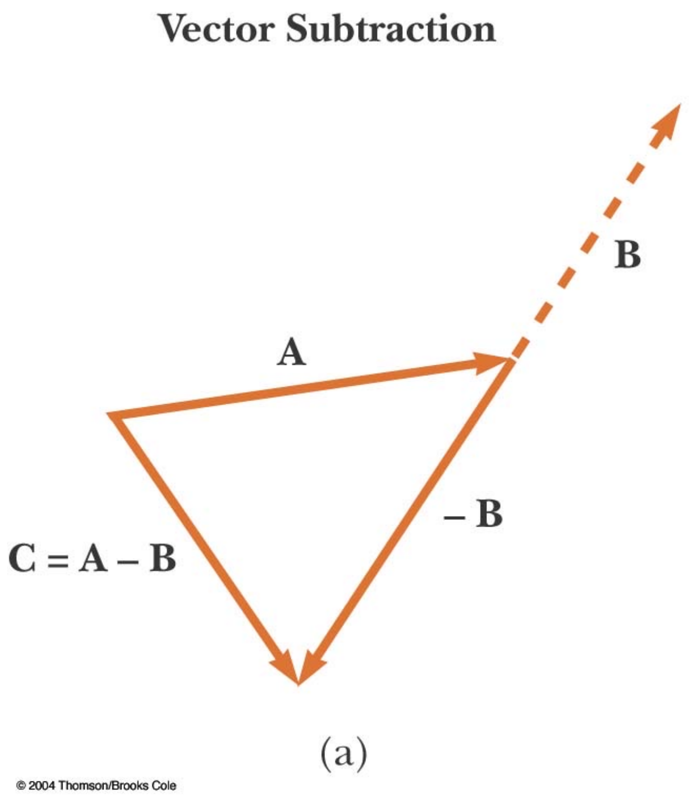
- When adding vectors, all of the vectors must have the same units
- All of the vectors must be of the same type of quantity
  - For example, you cannot add a displacement to a velocity

Negative of a Vector

- The negative of a vector is defined as the vector that, when added to the original vector, gives a resultant of zero
  - Represented as –**A**
  - **A** + (-**A**) = 0
- The negative of the vector will have the same magnitude, but point in the opposite direction

Subtracting Vectors

- Special case of vector addition
- If **A** – **B**, then use **A**+(**-B**)
- Continue with standard vector addition procedure

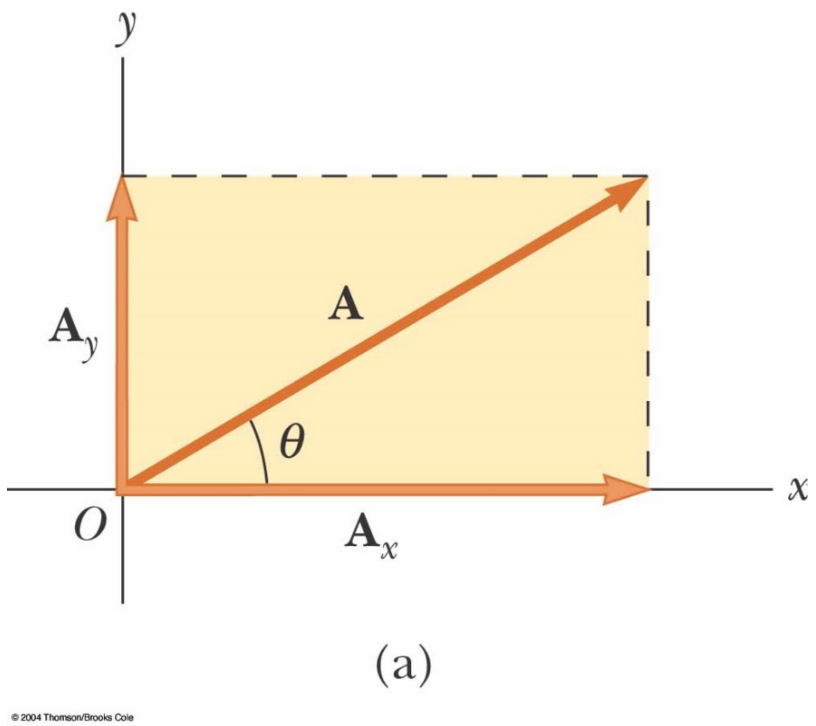


Multiplying or Dividing a Vector by a Scalar

- The result of the multiplication or division is a vector
- The magnitude of the vector is multiplied or divided by the scalar
- If the scalar is positive, the direction of the result is the same as of the original vector
- If the scalar is negative, the direction of the result is opposite that of the original vector

Components of a Vector

- A **component** is a part
- It is useful to use **rectangular components**
  - These are the projections of the vector along the x- and y-axes



Vector Component Terminology

- $\mathbf{A}_x$ and $\mathbf{A}_y$ are the ***component vectors*** of $\mathbf{A}$
  - They are vectors and follow all the rules for vectors
- A_x and A_y are scalars, and will be referred to as the ***components*** of $\mathbf{A}$

Components of a Vector, 2

- The x-component of a vector is the projection along the x-axis

$$A_x = A\cos\theta$$

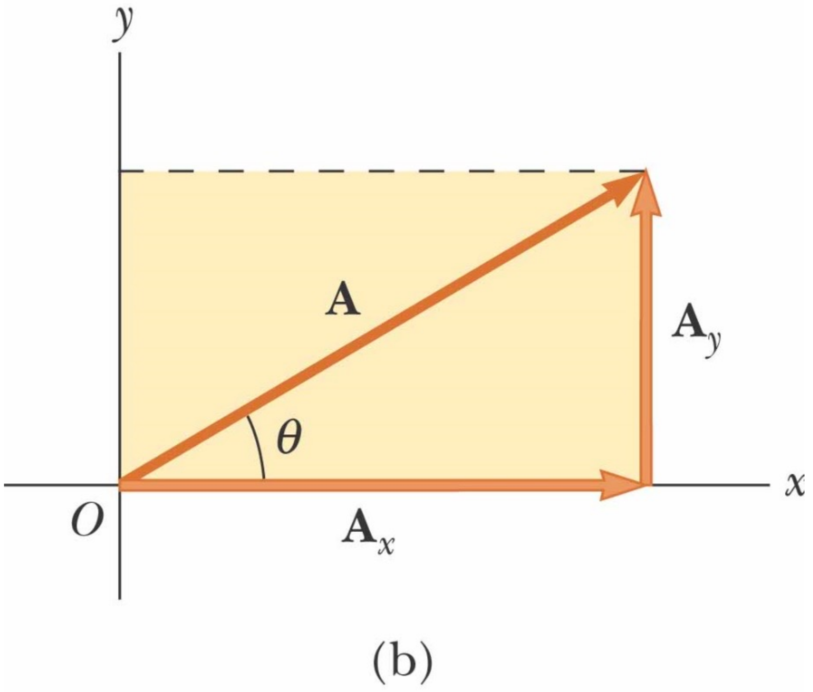
- The y-component of a vector is the projection along the y-axis

$$A_y = A\sin\theta$$

- Then, $\mathbf{A} = A_x + A_y$

Components of a Vector, 3

- The *y*-component is moved to the end of the *x*-component
- This is due to the fact that any vector can be moved parallel to itself without being affected
  - This completes the triangle



Components of a Vector, 4

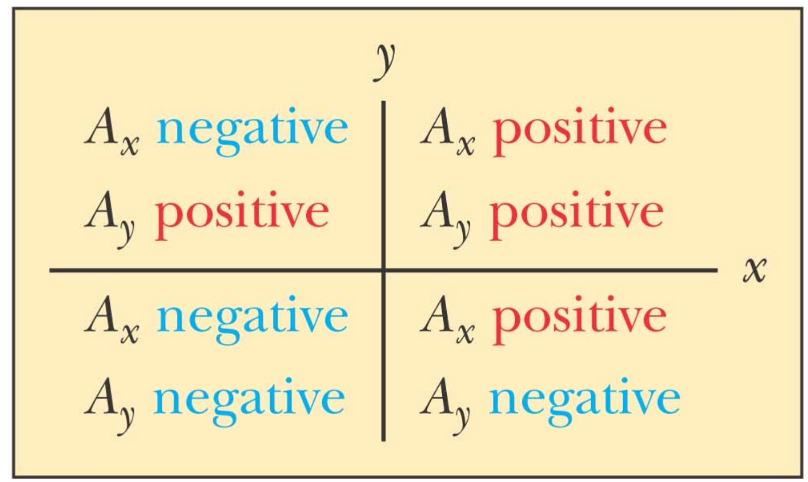
- The previous equations are valid ***only if θ is measured with respect to the x-axis***
- The components are the legs of the right triangle whose hypotenuse is **A**

$$A = \sqrt{A_x^2 + A_y^2} \quad \text{and} \quad \theta = \tan^{-1}\frac{A_y}{A_x}$$

  - May still have to find *θ* with respect to the positive *x*-axis

Components of a Vector, final

- The components can be positive or negative and will have the same units as the original vector
- The signs of the components will depend on the angle



Unit Vectors

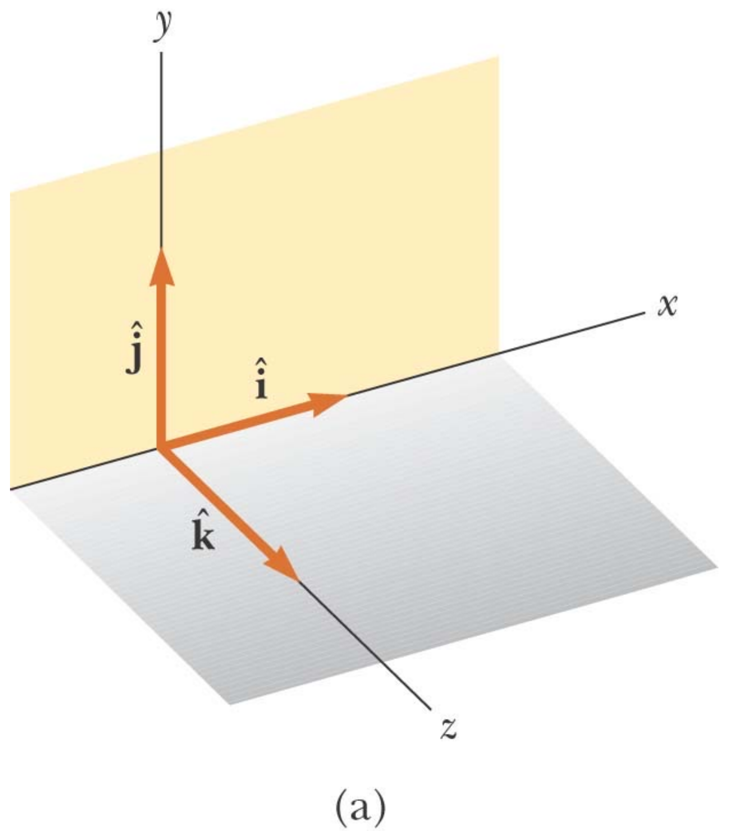
- A ***unit vector*** is a dimensionless vector with a magnitude of exactly 1.
- Unit vectors are used to specify a direction and have no other physical significance

Unit Vectors, cont.

- The symbols

  $$\hat{\mathrm{i}}, \hat{\mathrm{j}}, \text{and } \hat{\mathrm{k}}$$

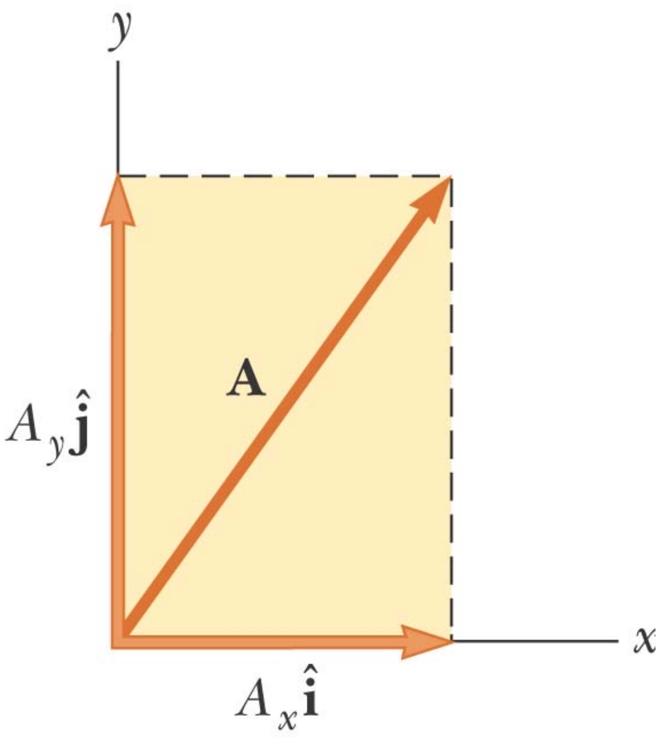
  represent unit vectors
- They form a set of mutually perpendicular vectors



Unit Vectors in Vector Notation

- $\mathbf{A_x}$ is the same as $A_x\hat{\mathbf{i}}$ and $\mathbf{A_y}$ is the same as $A_y\hat{\mathbf{j}}$ etc.
- The complete vector can be expressed as

$$\mathbf{A} = A_x\hat{\mathbf{i}} + A_y\hat{\mathbf{j}} + A_z\hat{\mathbf{k}}$$



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Adding Vectors Using Unit Vectors

- Using **R** = **A** + **B**
- Then

$$\mathbf{R} = \left(A_x\hat{\mathbf{i}} + A_y\hat{\mathbf{j}}\right) + \left(B_x\hat{\mathbf{i}} + B_y\hat{\mathbf{j}}\right)$$

$$\mathbf{R} = \left(A_x + B_x\right)\hat{\mathbf{i}} + \left(A_y + B_y\right)\hat{\mathbf{j}}$$

$$\mathbf{R} = R_x + R_y$$

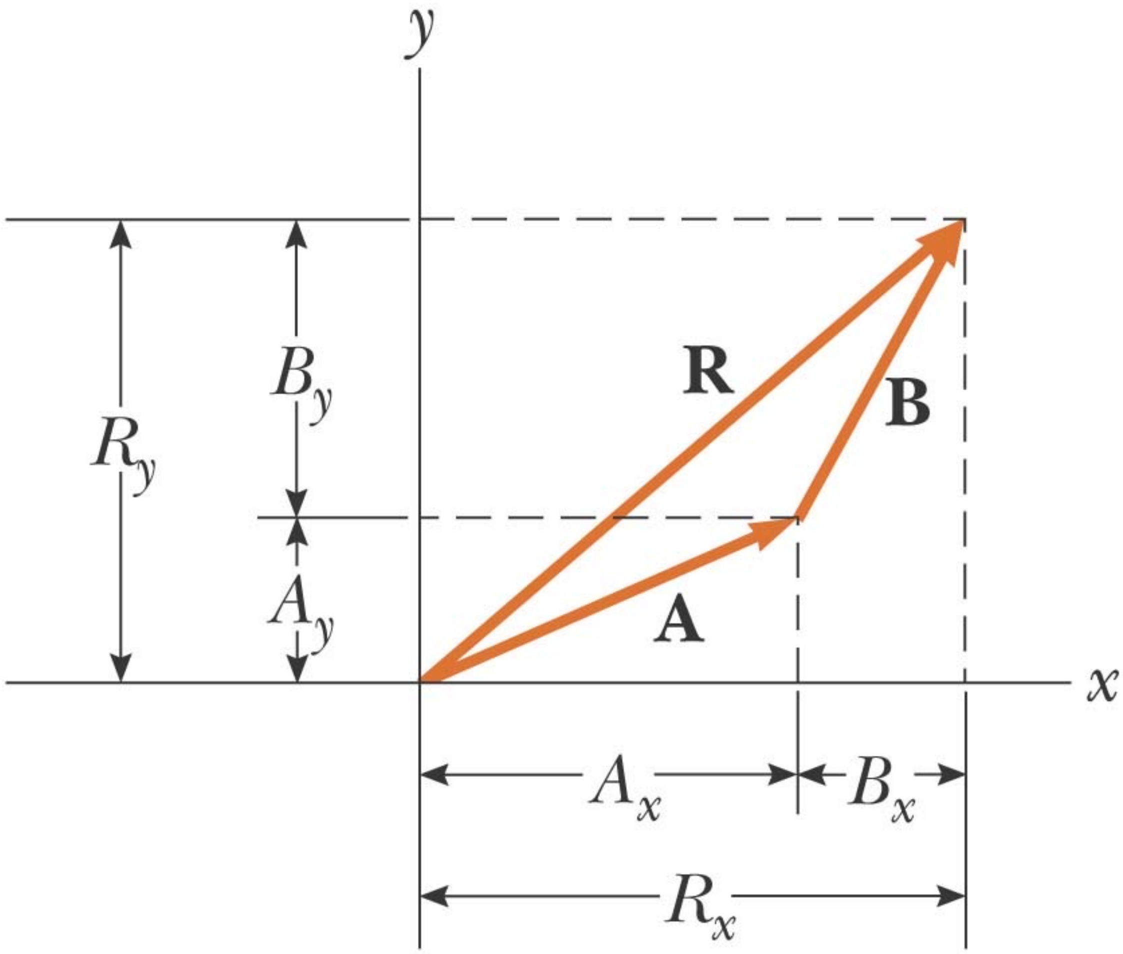
- and so $R_x = A_x + B_x$ and $R_y = A_y + B_y$

$$R = \sqrt{R_x^2 + R_y^2} \qquad \theta = \tan^{-1}\frac{R_y}{R_x}$$

Trig Function Warning

- The component equations ($A_x = A \cos \theta$ and $A_y = A \sin \theta$) apply only when the angle is measured with respect to the *x*-axis (preferably ccw from the positive *x*-axis).
- The resultant angle ($\tan \theta = A_y / A_x$) gives the angle with respect to the *x*-axis.
  - You can always think about the actual triangle being formed and what angle you know and apply the appropriate trig functions

Adding Vectors with Unit Vectors



Adding Vectors Using Unit Vectors – Three Directions

- Using **R** = **A** + **B**

$$\mathbf{R} = \left(A_x\hat{\mathbf{i}} + A_y\hat{\mathbf{j}} + A_z\hat{\mathbf{k}}\right) + \left(B_x\hat{\mathbf{i}} + B_y\hat{\mathbf{j}} + B_z\hat{\mathbf{k}}\right)$$

$$\mathbf{R} = \left(A_x + B_x\right)\hat{\mathbf{i}} + \left(A_y + B_y\right)\hat{\mathbf{j}} + \left(A_z + B_z\right)\hat{\mathbf{k}}$$

$$\mathbf{R} = R_x + R_y + R_z$$

- $R_x = A_x + B_x$, $R_y = A_y + B_y$ and $R_z = A_z + B_z$

$$R = \sqrt{R_x^2 + R_y^2 + R_z^2} \qquad \theta_x = \tan^{-1}\frac{R_x}{R}$$

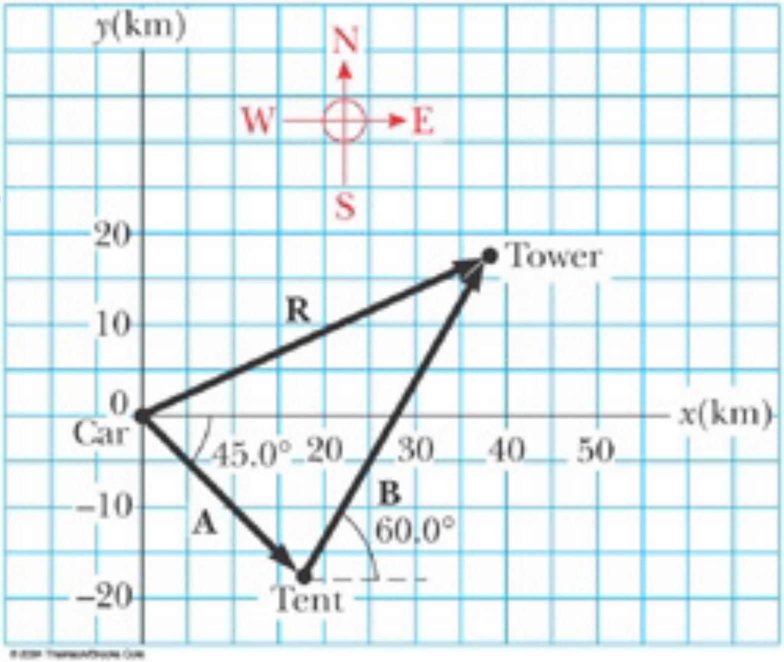
etc.

Example 3.5: Taking a Hike

- A hiker begins a trip by first walking 25.0 km southeast from her car. She stops and sets up her tent for the night. On the second day, she walks 40.0 km in a direction 60.0° north of east, at which point she discovers a forest ranger's tower.

Example 3.5

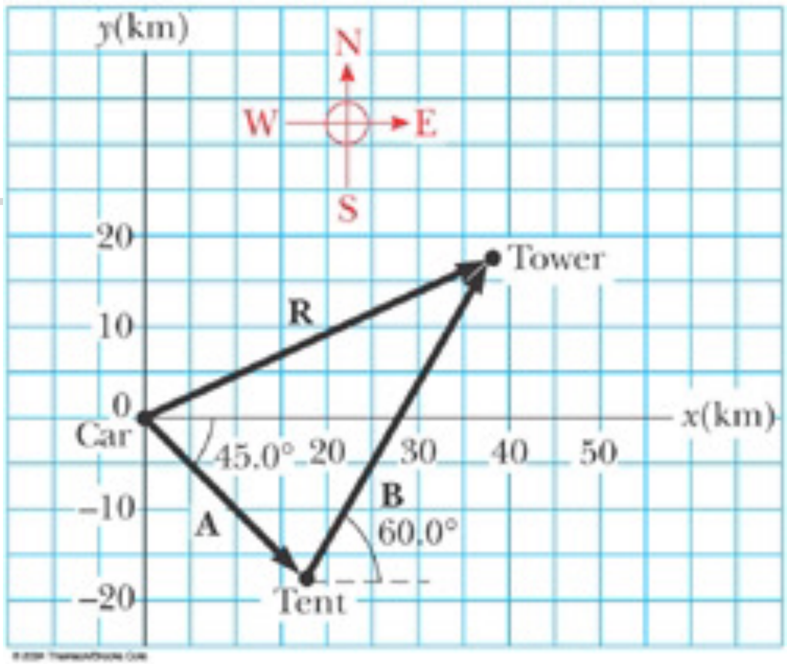
- (A) Determine the components of the hiker's displacement for each day.



Solution: We *conceptualize* the problem by drawing a sketch as in the figure above. If we denote the displacement vectors on the first and second days by **A** and **B** respectively, and use the car as the origin of coordinates, we obtain the vectors shown in the figure. Drawing the resultant **R**, we can now *categorize* this problem as an addition of two vectors.

Example 3.5

- We will analyze this problem by using our new knowledge of vector components. Displacement **A** has a magnitude of 25.0 km and is directed 45.0° below the positive *x* axis.



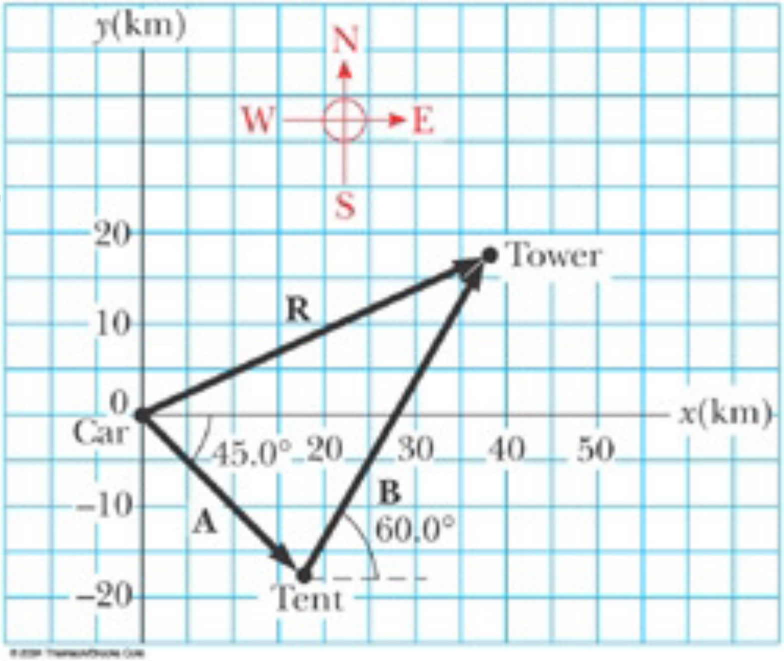
From Equations 3.8 and 3.9, its components are:

$$A_x = A\cos(-45.0°) = (25.0 \text{ km})(0.707) = 17.7 \text{ km}$$

$$A_y = A\sin(-45.0°) = (25.0 \text{ km})(-0.707) = -17.7 \text{ km}$$

The negative value of A_y indicates that the hiker walks in the negative y direction on the first day. The signs of A_x and A_y also are evident from the figure above.

Example 3.5



- The second displacement **B** has a magnitude of 40.0 km and is 60.0° north of east.

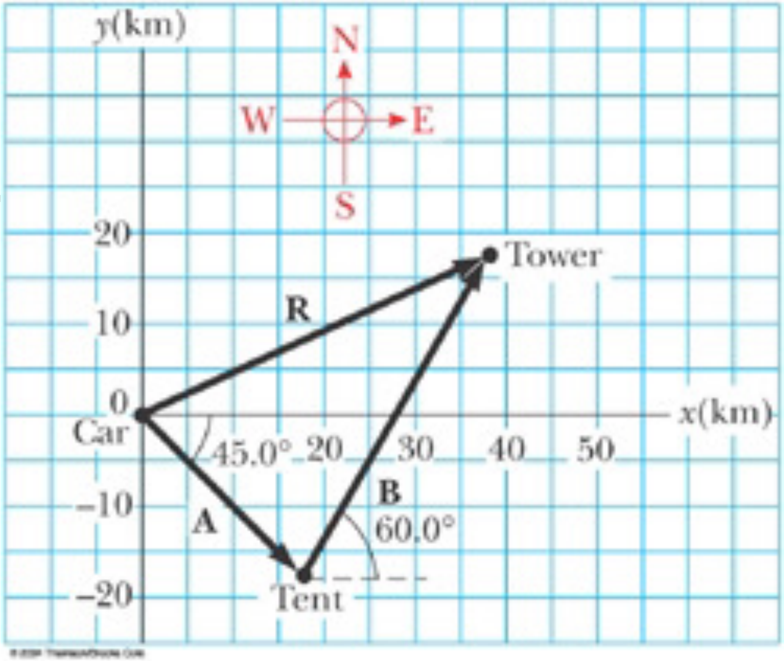
Its components are:

$$B_x = B\cos 60.0° = (40.0\text{ km})(0.500) = 20.0\text{ km}$$

$$B_y = B\sin 60.0° = (40.0\text{ km})(0.866) = 34.6\text{ km}$$

Example 3.5

- (B) Determine the components of the hiker's resultant displacement **R** for the trip. Find an expression for **R** in terms of unit vectors.



Solution: The resultant displacement for the trip **R** = **A** + **B** has components given by Equation 3.15:

$$R_x = A_x + B_x = 17.7 \text{ km} + 20.0 \text{ km} = 37.7 \text{ km}$$

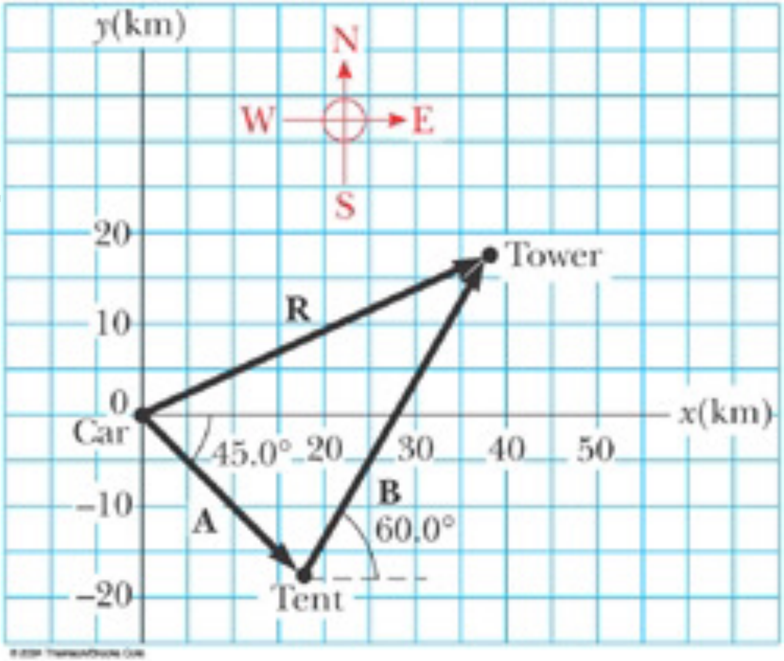
$$R_y = A_y + B_y = -17.7 \text{ km} + 34.6 \text{ km} = 16.9 \text{ km}$$

In unit-vector form, we can write the total displacement as

$$\mathbf{R} = (37.7\,\hat{\mathbf{i}} + 16.9\,\hat{\mathbf{j}}) \text{ km}$$

Example 3.5

- Using Equations 3.16 and 3.17, we find that the vector **R** has a magnitude of 41.3 km and is directed 24.1° north of east.



Let us *finalize*. The units of **R** are km, which is reasonable for a displacement. Looking at the graphical representation in the figure above, we estimate that the final position of the hiker is at about (38 km, 17 km) which is consistent with the components of **R** in our final result. Also, both components of **R** are positive, putting the final position in the first quadrant of the coordinate system, which is also consistent with the figure.

Problem Solving Strategy – Adding Vectors

- Select a coordinate system
  - Try to select a system that minimizes the number of components you need to deal with
- Draw a sketch of the vectors
  - Label each vector

Problem Solving Strategy – Adding Vectors, 2

- Find the *x* and *y* components of each vector and the *x* and *y* components of the resultant vector
  - Find *z* components if necessary
- Use the Pythagorean theorem to find the magnitude of the resultant and the tangent function to find the direction
  - Other appropriate trig functions may be used