

Introductory Physics I: Topics to be covered

Linear motion:

Kinematics

Ch. 1-3, quiz 1

Dynamics

Forces, Newton's laws

Ch. 4-5, quiz 2

Conservation of energy, conservation of linear momentum

Ch. 6-7, quiz 3

Rotational motion:

Kinematics

Dynamics

Torques, Newton's laws, Conservation of angular momentum, Statics

Ch. 9-11, quiz 4

Oscillatory motion

Kinematics

Dynamics

Ch. 13

Final exam on all chapters

Chapter 1: TOOLING UP

- Scientific method
- Scientific notation
- Physical quantities and units
- Dimensional analysis and estimates
- Accuracy and significant figures
- Scalars and vectors

Welcome to PHYSICS

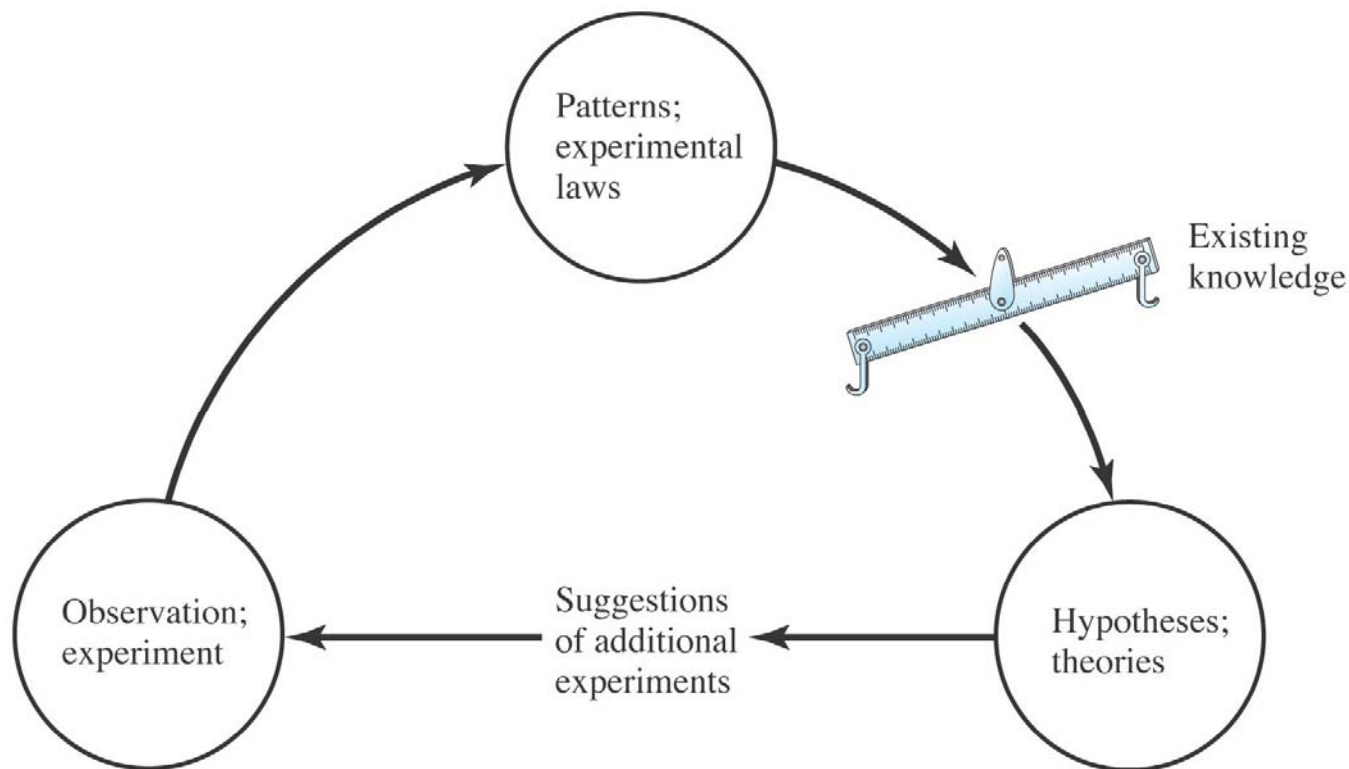
- Physics studies the physical world around us
 - Everything from atoms to astronomical objects
- Physics is the most fundamental science, which serves other fields
 - chemistry, life sciences, etc.
- Physics generates knowledge necessary to make technological advances which affect our everyday life
 - Lasers, transistors, etc. are widely used in consumer products
 - Global Positioning Systems (GPS) rely on general relativity
 - Modern electronics will soon rely on quantum mechanics

Scientific method

- Scientific method:

- interplay between observation and theory

- Observations suggest new theories, which lead to further observations, and so on.



Classical mechanics

● Mechanics studies motion of objects

➤ Kinematics describes how the object moves

- ❑ Concepts: position, displacement, velocity, acceleration.

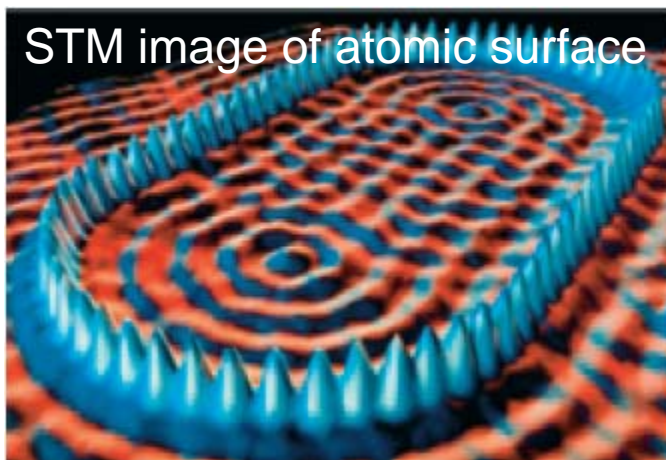
➤ Dynamics studies why the object moves

- ❑ Concepts: force, energy, momentum, angular momentum, ..

● Only a few fundamental laws are needed to describe motion of everyday objects!

Length scales of the world

- Classical mechanics describes motion of everyday objects extremely well.
 - Galilei, Kepler, Newton, XVI-XVII century
- Modifications are needed at:
 - very small length scales
 - ❑ quantum mechanics (Bohr, Heisenberg, Schrödinger, Plank)
 - very large length scales
 - ❑ general relativity (Einstein)
 - very large velocities
 - ❑ special relativity (Einstein)



Fundamental physical quantities and their units

● Fundamental physical quantities:

➤ Length L

➤ Mass M

➤ Time T

● All other quantities in mechanics are combinations of these three quantities.

● Units are needed to communicate the results.

● International System of units (SI):

➤ Length is measured in meters (m)

➤ Mass is measured in kilograms (kg)

➤ Time is measured in seconds (s)

❑ SI is also called “metric” or “mks” system

Other systems of units

● cgs:

- Length is measured in centimeters $1 \text{ cm} \equiv 0.01 \text{ m}$
- Mass is measured in grams $1 \text{ g} \equiv 0.001 \text{ kg}$
- Time is measured in seconds

● British Engineering system:

- Length is measured in inches
- Mass is measured in slugs
- Time is measured in seconds

$$1 \text{ ft} = 12 \text{ in} = 0.3048 \text{ m}$$

$$1 \text{ mi} = 5280 \text{ ft} = 1609.3 \text{ m}$$

❑ used primarily in the U.S.

$$1 \text{ inch} \equiv 0.0254 \text{ m}$$

$$1 \text{ slug} \equiv 14.5939 \text{ kg}$$



Scientific notation

● Physics deals with extreme range of numbers

● Scientific notation

➤ use powers of 10 to express numbers that are not between 1 and 10 (or, often, between 0.1 and 100);

❑ Example: Mass of Earth (in kg):

$$5,980,000,000,000,000,000,000,000 = 5.98 \times 10^{24}$$

❑ Exponents are added when multiplying and subtracted when dividing:

$$\frac{7.5 \times 10^{-3}}{2.5 \times 10^{-4}} = \frac{7.5}{2.5} \times 10^{-3} \times 10^{+4} = 3.0 \times 10 = 30$$

● Unit prefixes $1,000 \text{ m} = 10^3 \text{ m} = 1 \text{ km}$; $0.01 \text{ m} = 10^{-2} \text{ m} = 1 \text{ cm}$

TABLE 1-4 • Unit Prefixes for Powers of 10

Prefix	Symbol	Multiple	Prefix	Symbol	Multiple	Prefix	Symbol	Multiple	Prefix	Symbol	Multiple
Exa [†]	E	10^{18}	Mega	M	10^6	Deci [†]	d	10^{-1}	Nano	n	10^{-9}
Peta [†]	P	10^{15}	Kilo	k	10^3	Centi	c	10^{-2}	Pico	p	10^{-12}
Tera	T	10^{12}	Hecto [†]	h	10^2	Milli	m	10^{-3}	Femto [†]	f	10^{-15}
Giga	G	10^9	Deka [†]	da	10^1	Micro	μ	10^{-6}	Atto [†]	a	10^{-18}

Length: standard meter

- 1791: 10^{-7} (one ten millionth) of the distance along Earth's surface between the equator and the North Pole
- 1889: distance between two marks on a particular Pt-Ir bar
- 1960: based on the wavelength of orange line of ^{86}Kr (Krypton) gas
- 1983: distance that light travels in a vacuum during $1/299,792,458$ s.

TABLE 1-1 • Orders of Magnitude for Length

Parameter	Length (m)	Parameter	Length (m)
Proton	10^{-15}	Earth–Moon distance	10^9
Hydrogen atom	10^{-10}	Earth–Sun distance	10^{11}
Flu virus	10^{-7}	Diameter of solar system	10^{13}
One bit on a DVD	10^{-6}	Distance to nearest star (Proxima Centauri)	10^{17}
Raindrop	10^{-3}	Diameter of our galaxy (Milky Way)	10^{21}
Height of person	10^0	Distance to nearest galaxy	10^{22}
One mile	10^3	Distance to edge of observable universe	10^{26}
Diameter of Earth	10^7		

Mass: standard kilogram

- 1791: mass of 1 liter of water (under certain conditions)
- 1901: mass of a particular Platinum-Iridium cylinder
 - ❑ (IBWM, France, copy in NIST, Maryland)
- Search for a more precise standard continues...

TABLE 1–3 • Orders of Magnitude for Mass

Parameter	Mass (kg)	Parameter	Mass (kg)
Electron	10^{-30}	Battleship	10^8
Hydrogen atom	10^{-27}	Moon	10^{23}
Uranium atom	10^{-24}	Earth	10^{25}
Dust particle	10^{-13}	Sun	10^{30}
Raindrop	10^{-6}	Our galaxy (Milky Way)	10^{41}
Piece of paper	10^{-2}	Observable universe	10^{52}
Human	10^2		

Time: standard second

- Original: 1/86,400 of a mean solar day
- 1956: 1/31,556,925.9747 of the tropical year for 1900 January 0 at 12 hours ephemeris time
- 1967: 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs (Cesium) atom

TABLE 1-2 • Orders of Magnitude for Time

Parameter	Time (s)	Parameter	Time (s)
Time for light to cross proton	10^{-23}	Class lecture	10^3
Time for light to cross atom	10^{-19}	One Earth day	10^5
Period of visible light wave	10^{-15}	One Earth year	10^7
Period of vibration for standard cesium clock	10^{-10}	Age of Greek antiquities	10^{11}
Time required for one operation in a personal computer	10^{-9}	Age of first humanoids	10^{14}
Half-life of muon	10^{-6}	Age of Earth	10^{17}
Period of highest audible sound	10^{-4}	Age of universe	10^{18}
Period of human heartbeat	10^0		

Special units

- Special units are used sometimes for historical reasons or because they are more convenient
- Examples for length:
 - Angstrom: 10^{-10} m
 - Micron: 10^{-6} m
 - Astronomical unit (AU): 1.496×10^{11} m
 - ☐ distance between Earth and the Sun
 - Light year (ly): 9.46×10^{15} m
 - ☐ distance light travels in one year
 - Parsec (pc): $1 \text{ pc} = 3.09 \times 10^{16} \text{ m} = 3.26 \text{ ly} = 2.06 \times 10^5 \text{ AU}$

Unit conversion

- Quantities can be converted to different units using conversion factors.

➤ Examples:

$$1 \text{ mi} = 5280 \text{ ft} = 5280 \cdot 12 \text{ in} = 5280 \cdot 12 \cdot 0.0254 \text{ m} = 1609.3 \text{ m}$$

$$\begin{aligned} 1 \text{ yr} &= 365.25 \text{ d} = 365.25 \cdot 24 \text{ h} = 365.25 \cdot 24 \cdot 60 \text{ min} \\ &= 365.25 \cdot 24 \cdot 60 \cdot 60 \text{ s} \approx 3.156 \cdot 10^7 \text{ s} \end{aligned}$$

$$1 \text{ ly} = \underbrace{2.998 \cdot 10^8 \text{ m/s}}_{\text{speed of light}} \cdot 3.156 \cdot 10^7 \text{ s} \approx 9.461 \cdot 10^{15} \text{ m}$$

- In physics, SI system is preferred

Derived units, Dimensions

- All quantities in mechanics can be derived from fundamental quantities *L, M, and T*.

- ☐ Outside mechanics more fundamental units are needed (Mole, Ampere, Kelvin)

- In SI, all units are combinations of m, kg, and s.

- ☐ Some units have their own names...

- ☐ [..] denotes “dimension”

- Area: $A = \pi R^2 \Rightarrow [A] = [L^2] = \text{m}^2$

- Volume: $V = \pi R^2 h \Rightarrow [V] = [L^3] = \text{m}^3$

- Density: $\rho = m/V \Rightarrow [\rho] = [M/L^3] = \text{kg}/\text{m}^3$

- Force: $F = ma \Rightarrow [F] = [ML/T^2] = \text{kg} \cdot \text{m}/\text{s}^2 \equiv N \text{ (Newton)}$

- Hints:

- ☐ Never add or subtract quantities expressed in different units

- ☐ Always check that your result has the correct units

- ☐ Units have to be the same on both sides of an equation

Accuracy and Significant Figures

● Uncertainty in measurement:

- Almost no measurement can be done with perfect accuracy – there are possible variations that are below the limit of detection
- Measurements are “usually” quoted with a **central value** (X_0) and an **uncertainty** (ΔX), indicating how accurate the measurement is

$$X = X_0 \pm \Delta X$$

- ❑ Example: How accurate can you measure the length of a sheet of paper using a ruler?

$$L = L_0 \pm \Delta L = 27.9 \pm 0.1 \text{ cm}$$

- ❑ Absolute uncertainty: $\Delta L = 0.1 \text{ cm}$

- ❑ Relative uncertainty: $\delta_L \equiv \frac{\Delta L}{L_0} = \frac{0.1 \text{ cm}}{27.9 \text{ cm}} = 3.6 \cdot 10^{-3} = 0.36\%$

Algebra with uncertainties

- If measurements are combined to form some quantity, the effect of the uncertainty of each needs to be taken into account.

- When adding/subtracting numbers, absolute uncertainties are added

$$Z = X \pm Y \Rightarrow \Delta Z = \Delta X + \Delta Y \Rightarrow Z = \underbrace{(X_0 \pm Y_0)}_{Z_0} \pm \underbrace{(\Delta X + \Delta Y)}_{\Delta Z}$$

- When multiplying/dividing numbers, relative uncertainties are added

$$Z = X \cdot Y \Rightarrow \delta_Z = \delta_X + \delta_Y \Rightarrow (Z_0 = X_0 Y_0)$$

$$\Delta Z \equiv \delta_Z Z_0 = (\delta_X + \delta_Y) X_0 Y_0 = (\Delta X / X_0 + \Delta Y / Y_0) X_0 Y_0 \Rightarrow$$

$$Z = \underbrace{(X_0 Y_0)}_{Z_0} \pm \underbrace{(\Delta X / X_0 + \Delta Y / Y_0) X_0 Y_0}_{\Delta Z}$$

Significant figures

● The number of significant figures represents the accuracy with which a number is known

➤ **Terminal zeroes after a decimal point are significant figures:**

❑ 2.0 is between 1.95 and 2.05, whereas 2.00 is between 1.995 and 2.005

➤ **Trailing zeroes with no decimal point are not significant:**

❑ 1200 is between 1150 and 1250, whereas 1200.0 is between 1199.5 and 1200.5

Significant figures and scientific notation

➤ Example:

- ❑ Mass of Earth (in kg) is not known to accuracy of 25 digits – use scientific notation

$$5,980,000,000,000,000,000,000,000 = 5.98 \times 10^{24}$$

● If numbers are written in scientific notation, it is clear how many significant figures there are:

- 6×10^{24} has one
- 6.0×10^{24} has two
- 5.98×10^{24} has three...

- ❑ Note: Calculators typically show many more digits than are significant.
- ❑ It is important to know which are accurate and which are meaningless.
- ❑ Your numerical answer should not contain meaningless figures!

Summary

- Fundamental quantities are length, mass, and time
- Scientific notation is much easier to read than strings of zeroes
- Derived units can be expressed in terms of fundamental units
- Units can be converted from one into another
- Quantities to be added, subtracted, or equated must have the same dimensions (and units when numbers are used)
- Dimensional analysis is useful in checking your result
- Physical quantities are known only to a certain accuracy, indicated by the number of significant figures

Vectors

● Scalar:

- ordinary algebraic quantity, such as mass, time, or temperature

- ☐ Note: represented by a single number = magnitude


● Vector:

- Quantity that needs both magnitude and direction for full description, such as velocity (where and how fast)

- ☐ Represented by several numbers depending on space dimensionality, e.g. in 2D – two #, in 3D – three #s

- ☐ Denoted with bold face or arrow:

- ☐ Can be represented graphically by **B** or \vec{B} (length of an arrow is the magnitude)


$$|\mathbf{B}| = B$$

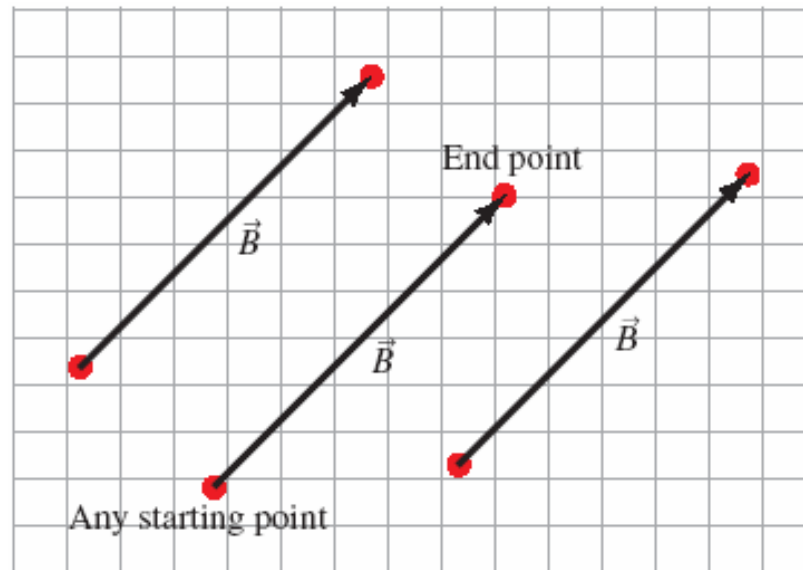
Displacement vector

- Displacement vector:

- points from an object's initial position to its final one

- Starting point is not relevant for the definition of a vector

- All parallel vectors of the same length are equivalent

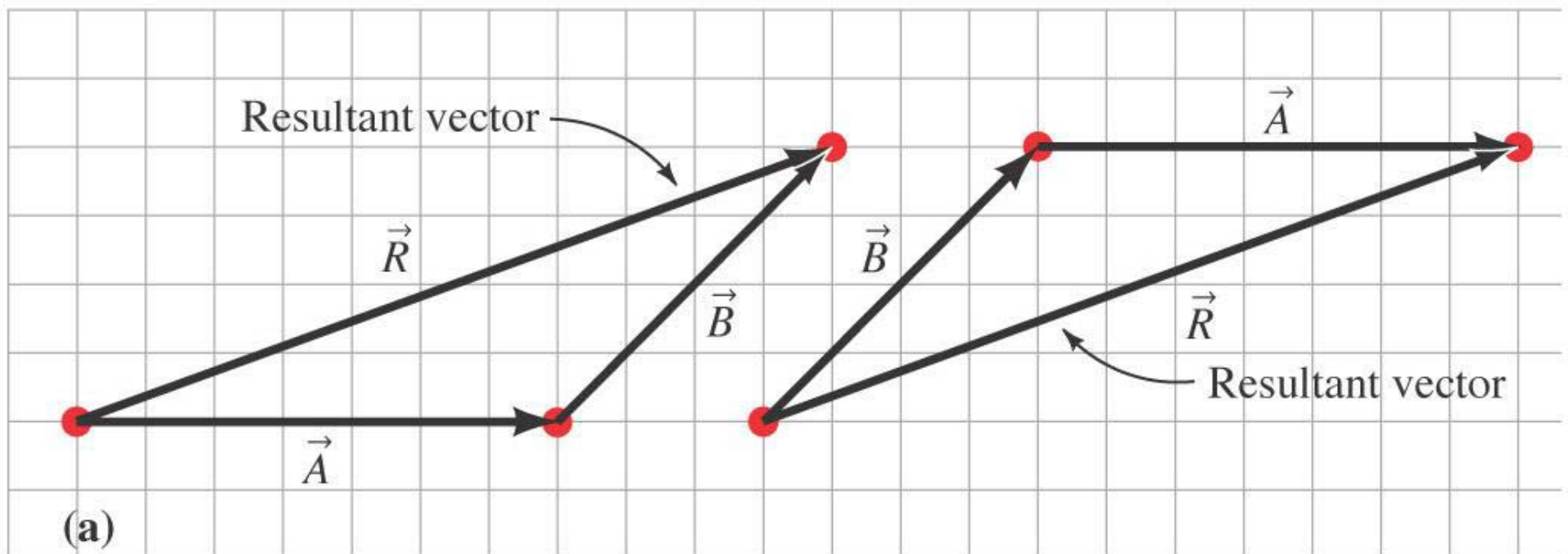


Vector algebra: vector addition

● Vector sum:

- Place vectors so the tail of the second starts at the head of the first, and so on. Vector sum points from tail of the first to head of the second.

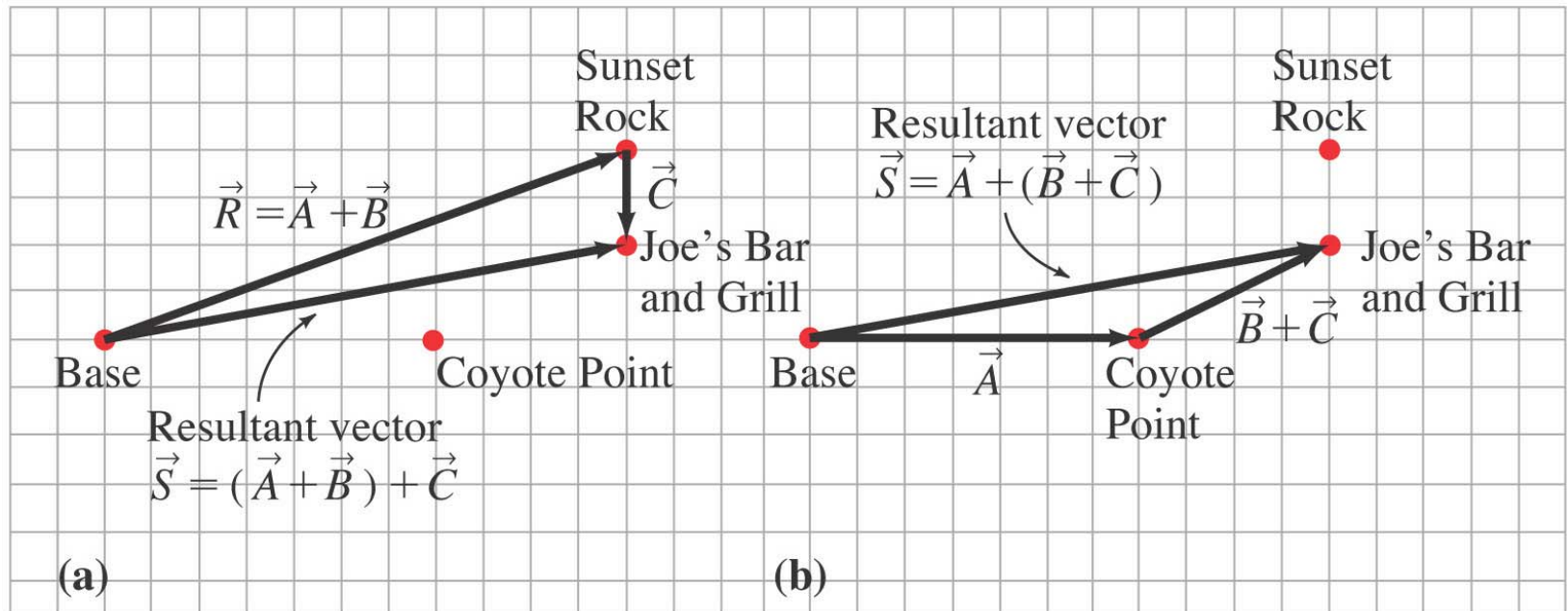
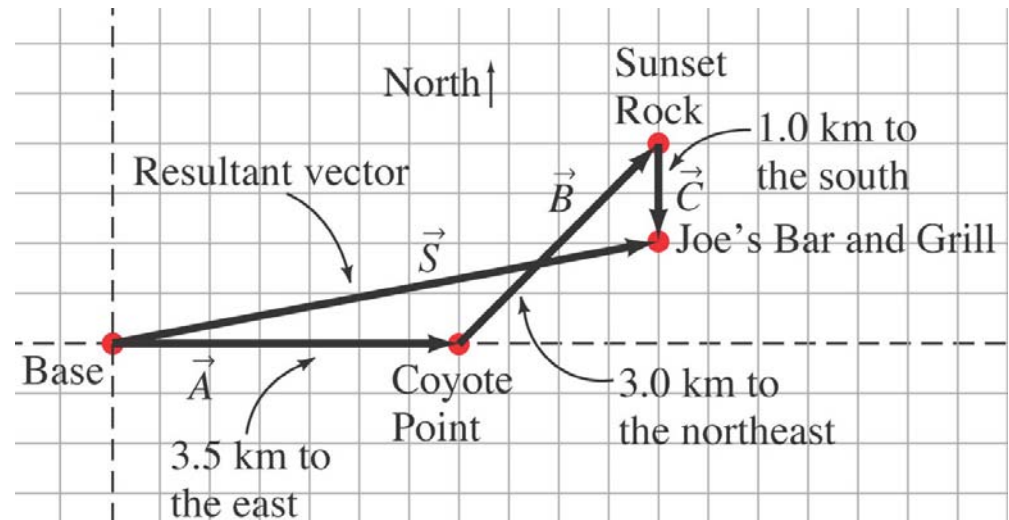
● Commutativity: $\mathbf{A} + \mathbf{B} = \mathbf{B} + \mathbf{A}$



Sum of three vectors: Associativity

● Associativity:

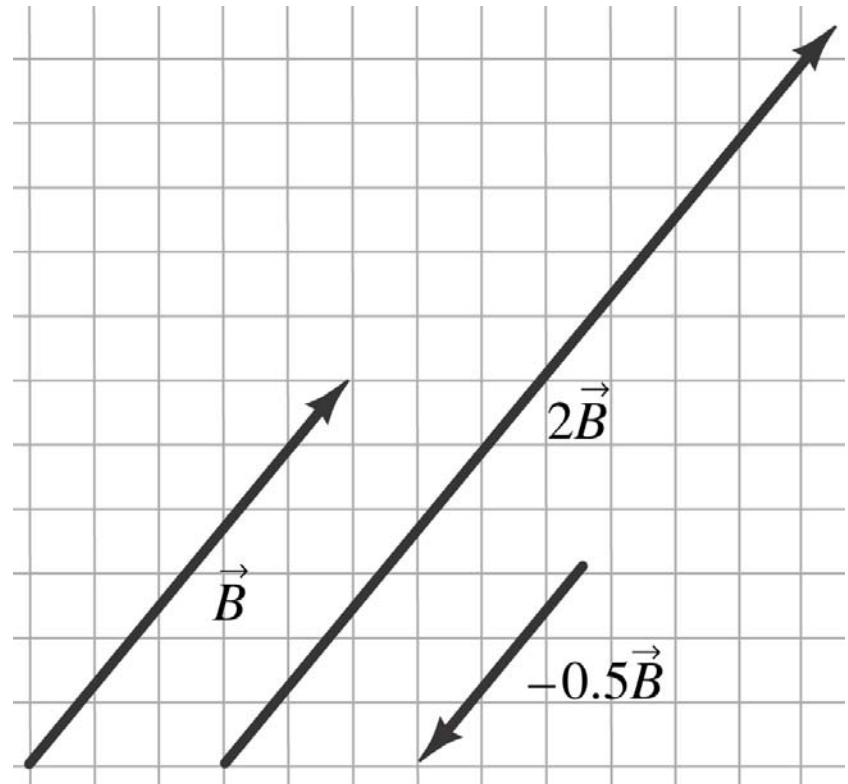
$$(\mathbf{A} + \mathbf{B}) + \mathbf{C} = \mathbf{A} + (\mathbf{B} + \mathbf{C})$$



Vector algebra: Scalar multiplication of vector

● Scalar multiplication of vector:

- Direction is the same if multiplication factor is positive and opposite, if multiplication factor is negative.
- Magnitude is scaled by multiplication factor.



$$\mathbf{R} = \alpha \mathbf{B} \Rightarrow R = \alpha B$$

$$\mathbf{R} \uparrow \uparrow \mathbf{B} \text{ if } \alpha > 0, \mathbf{R} \uparrow \downarrow \mathbf{B} \text{ if } \alpha < 0$$

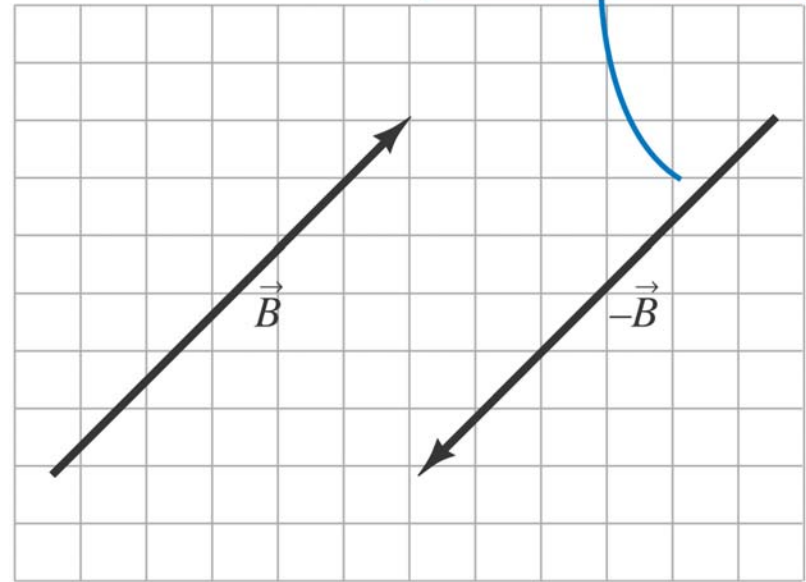
Vector subtraction

$-\vec{B}$ is simply the reverse vector of \vec{B} .

● Negative vector:

- same magnitude as the original, and points in the opposite direction.

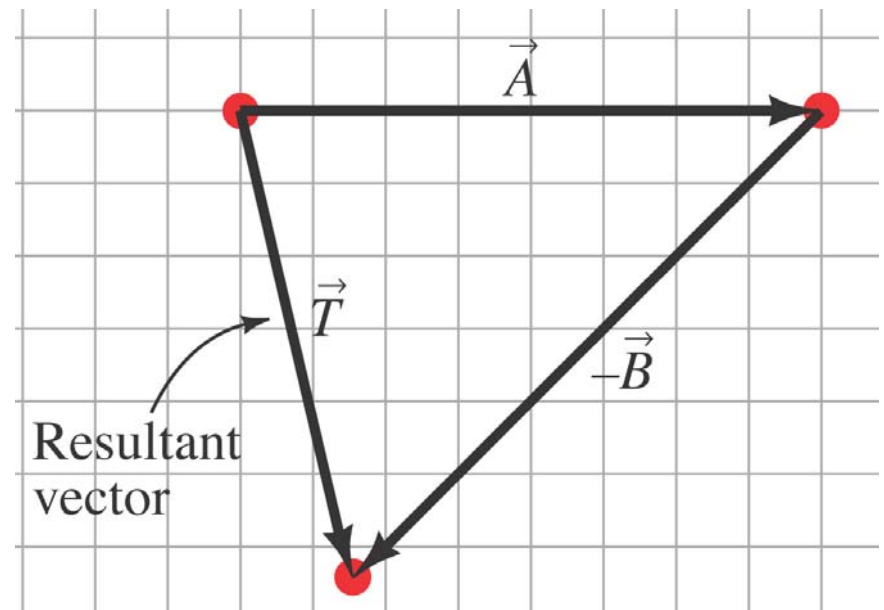
$$|-\mathbf{B}| = |\mathbf{B}| = B, \quad \mathbf{B} \uparrow \downarrow -\mathbf{B}$$



● Subtracting vectors:

- Draw the vector appropriately and proceed as for addition.

$$\mathbf{T} = \mathbf{A} - \mathbf{B} = \mathbf{A} + (-\mathbf{B})$$



Unit vector

● Unit vector:

- has the same direction and unit magnitude.

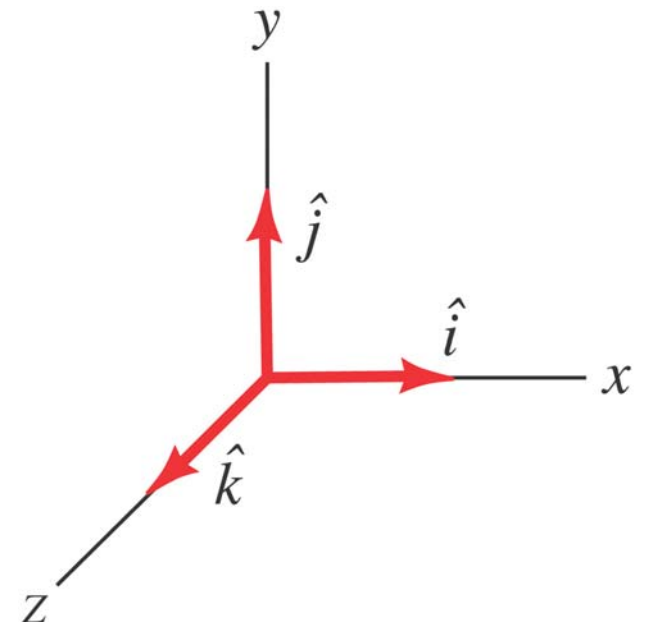
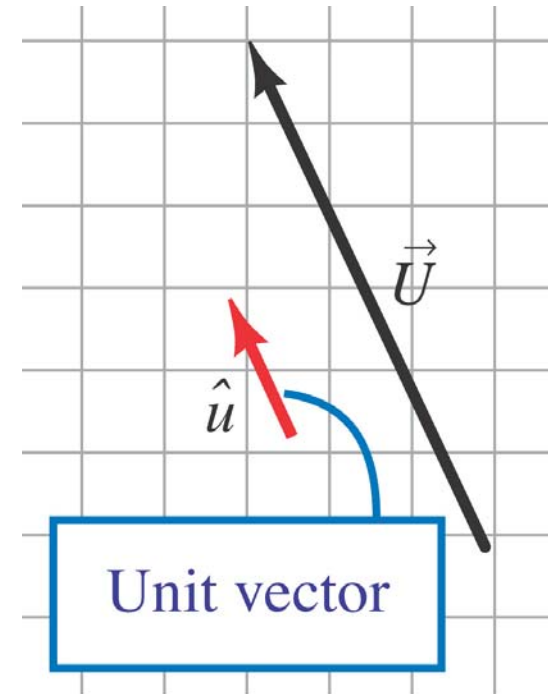
$$\hat{\mathbf{u}} \parallel \mathbf{U}, |\hat{\mathbf{u}}| = 1$$

- Any vector can then be written as:

$$\mathbf{U} = U\hat{\mathbf{u}}$$

- In 3D we can define three orthogonal unit vectors parallel to x, y, and z

$$\begin{aligned}\mathbf{i} &\perp \mathbf{j} \perp \mathbf{k} \perp \mathbf{i} \\ i &= j = k = 1\end{aligned}$$



Vector components

● Position vector

- If the coordinate system is given vectors can describe position

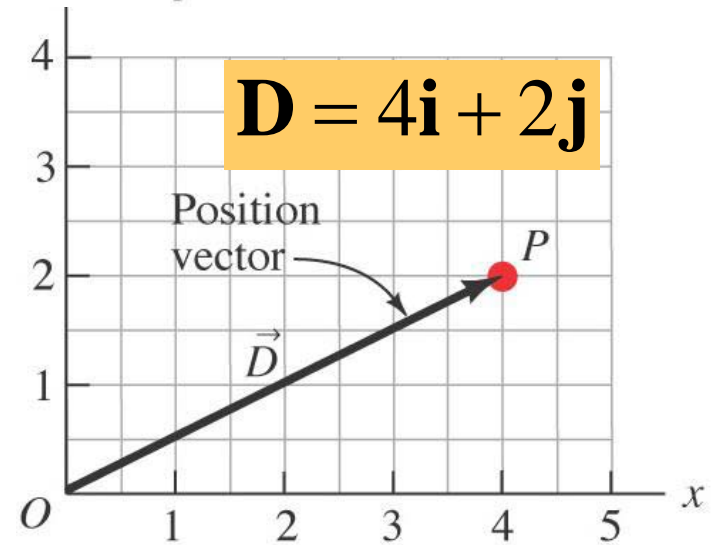
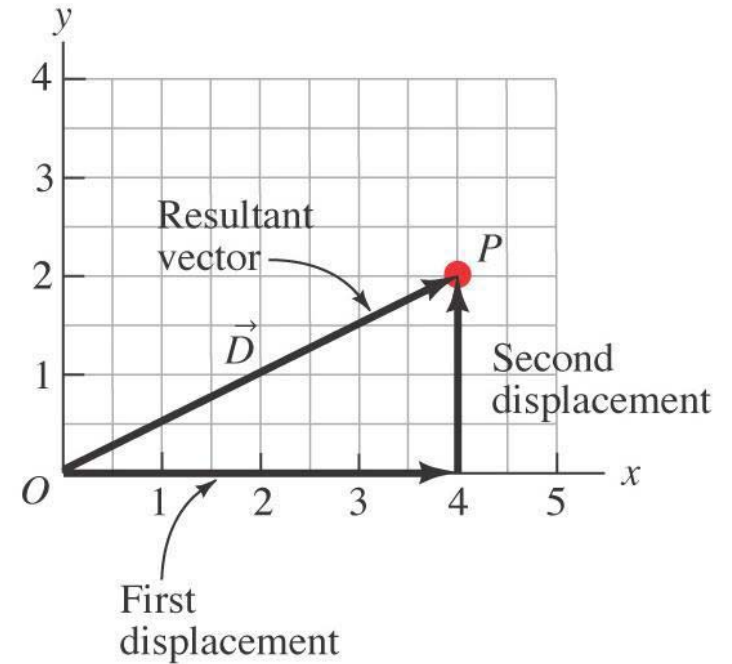
- ☐ Position vector is the displacement vector from the origin

● Components:

- Any vector not lying along the x- or y-axis can be represented by a sum of two vectors, one along x and the other along y.

● Component representation of a vector in 3D:

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



Vector algebra in component form

● Column notation:

$$\mathbf{A} = A_x \mathbf{i} + A_y \mathbf{j} + A_z \mathbf{k} \equiv \begin{pmatrix} A_x \\ A_y \\ A_z \end{pmatrix}$$

● Addition

$$\mathbf{A} \pm \mathbf{B} = (A_x \pm B_x) \mathbf{i} + (A_y \pm B_y) \mathbf{j} + (A_z \pm B_z) \mathbf{k}$$

● Multiplication by a scalar:

$$\alpha \mathbf{A} = (\alpha A_x) \mathbf{i} + (\alpha A_y) \mathbf{j} + (\alpha A_z) \mathbf{k}$$

Polar coordinates in 2D

- Vector can then be described by x and y components....

$$\mathbf{V} = V_x \hat{\mathbf{i}} + V_y \hat{\mathbf{j}}$$

or by a length (magnitude)

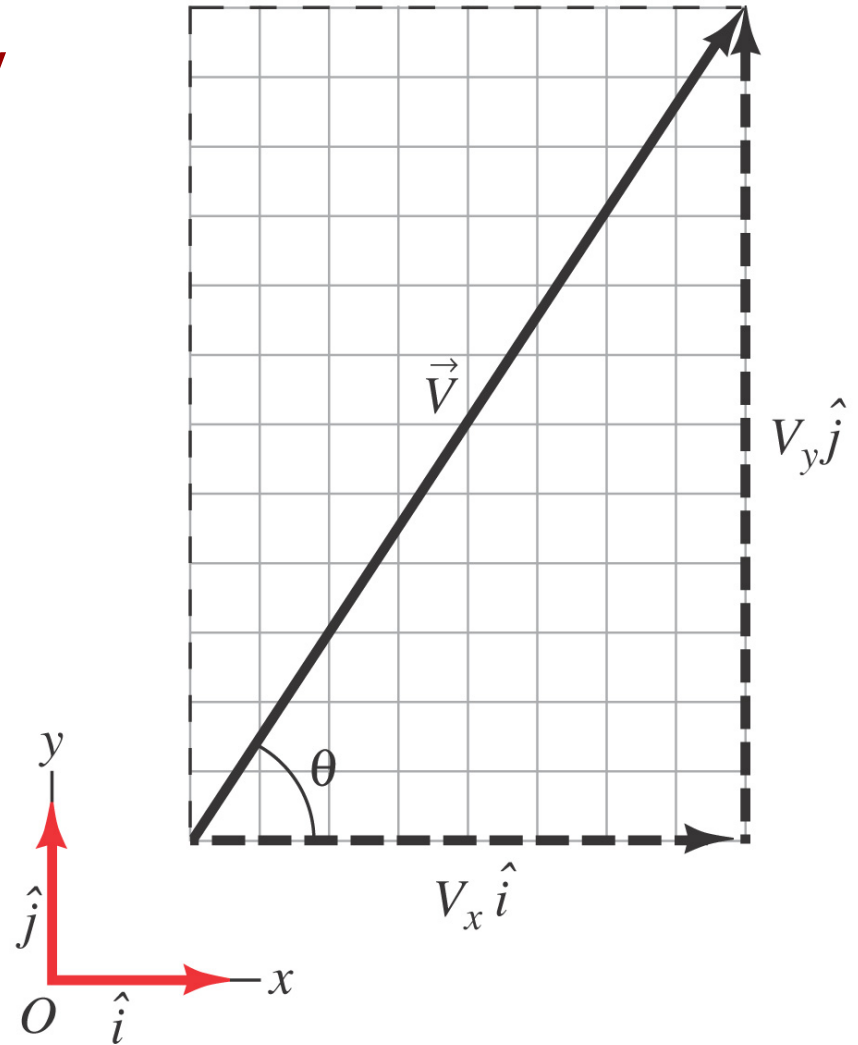
$$V = \sqrt{V_x^2 + V_y^2}$$

and an angle (direction)

$$\tan \theta = \frac{V_y}{V_x}$$

- In polar coordinates vector is represented by length and angle:

$$V, \theta$$



Relation between polar and cartesian coordinates

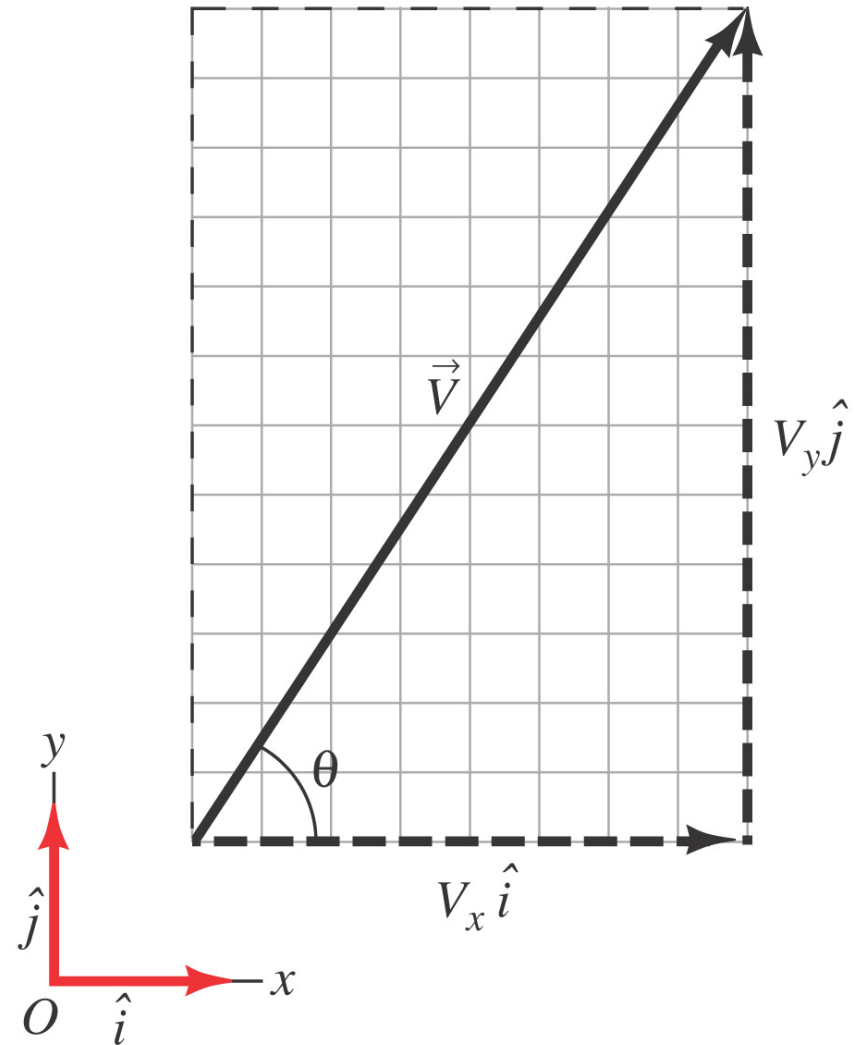
$$\begin{pmatrix} V_x \\ V_y \end{pmatrix} \text{ vs. } \begin{pmatrix} V \\ \theta \end{pmatrix}$$

● From cartesian to polar:

$$V = \sqrt{V_x^2 + V_y^2}$$
$$\tan \theta = \frac{V_y}{V_x}$$

● From polar to cartesian:

$$V_x = V \cos \theta$$
$$V_y = V \sin \theta$$



Summary for Chapter 1

- Fundamental quantities are length, mass, and time
- Scientific notation is much easier to read than strings of zeroes
- Derived units can be expressed in terms of fundamental units
- Units can be converted from one into another
- Quantities to be added, subtracted, or equated must have the same dimensions
- Dimensional analysis is useful in checking your result
- Physical quantities can be measured only to a certain accuracy, indicated by the number of significant figures
- Vectors have both magnitude and direction
- Vectors can be added, subtracted, and multiplied by scalars