Physics for Scientists and Engineers

Chapter 1
Concepts of Motion

Spring, 2008

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Physics

- Fundamental science
  - concerned with the basic principles of the Universe
  - foundation of other physical sciences
- Divided into six major areas
  - Classical Mechanics
  - Thermodynamics
  - Electromagnetism
  - Optics
  - Relativity
  - Quantum Mechanics

Classical Physics

- Mechanics and Electromagnetism are basic to all other branches of classical physics
- Classical physics were developed before 1900
  - Our study will start with Classical Mechanics.
    - Also called Newtonian Mechanics

Classical Physics, cont

- Includes Mechanics
  - Major developments by Newton, and continuing through the latter part of the 19^{th} century
- Thermodynamics
- Optics
- Electromagnetism
  - All of these were not developed until the latter part of the 19^{th} century

Modern Physics

- Began near the end of the 19th century
- Phenomena that could not be explained by classical physics
- Includes
  - Theories of Relativity
  - Quantum Mechanics

Classical Mechanics Today

- Still important in many disciplines
- Wide range of phenomena can be explained with classical mechanics
- Many basic principles carry over into other phenomena
  - Conservation Laws apply directly to other areas

Objective of Physics

- To find the fundamental laws that govern natural phenomena
- To express the laws in the language of mathematics
- To use these laws to develop theories that can predict the results of future experiments

Theory and Experiments

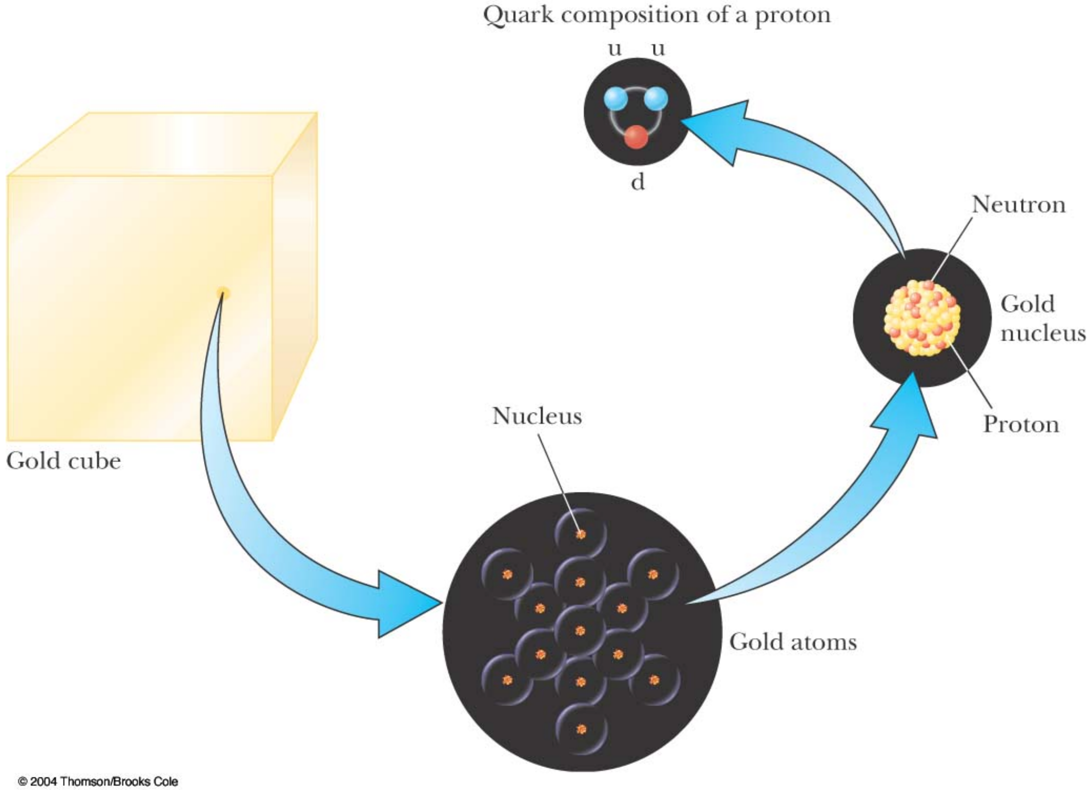
- Should complement each other
- When a discrepancy occurs, *theory* may be modified
  - Theory may apply to limited conditions
    - e.g. Newtonian Mechanics confined to objects
      - 1) traveling slowly with respect to the speed of light
      - 2) larger than atoms
  - Try to develop a more general theory

Model Building

- A *model* is often a simplified system of physical components
  - Identify the components
- Make predictions about the behavior of the system
  - The predictions will be based on interactions among the components and/or
  - Based on the interactions between the components and the environment

Models of Matter

- Atoms has a central *nucleus* surrounded by *electrons*
- Nucleus contains *protons* and *neutrons*
  - Protons and neutrons are made up of *quarks*



“Particle” Model

- The fundamental constituents of matter are considered to be *particles* that have zero size
  - e.g. electrons, quarks, photon, etc.
- An extended object can be *modeled* as a mass at a single point in space and time
  - when its internal motions can be ignored
- More complex objects can often be modeled as a collection of particles

Quantities Used

- In Mechanics, three *basic quantities* are used
  - Length
  - Mass
  - Time
- Will also use *derived quantities*
  - These are other quantities that can be expressed in terms of basic quantities

Systems of Measurements

- US System of measurement
  - Length in feet (ft)
  - Time in seconds (s)
  - Mass in slugs
    - Commonly, in pounds (lb)
- SI – Systéme Internationale
  - Agreed to in 1960 by an international committee
  - Main system used in this text

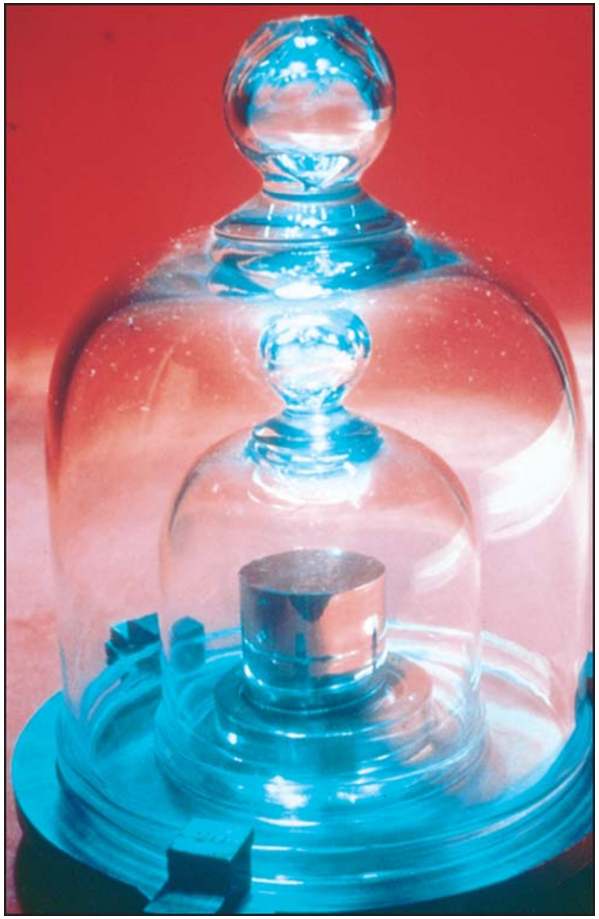
Length

- SI Unit: meter, m
  - 1 in = 2.54 cm $\Rightarrow$ 1 m $\approx$ 3.28 ft
- Previously defined in terms of a standard meter bar
- Now defined by the distance traveled by *light* in a vacuum during a given period of time

Mass

- SI Unit: kilogram, kg
  - 1 lb = 0.45359237 kg

    $\Rightarrow$ 1 kg $\approx$ 2.20 lb
- Based on a *metal cylinder* kept at the International Bureau of Standards, Paris



Time

- SI Unit: second, s
- Previously defined based on a mean solar day
- Now defined in terms of the oscillation of radiation from a *cesium atom*

Prefixes

- Prefixes correspond to powers of 10
- They are multipliers of the base unit
- Examples:
  - 2 mm = 2 x 10^{-3} m
  - 3 g = 3 x 10^{-3} kg

Table 1.4

Prefixes for Powers of Ten

Power	Prefix	Abbreviation
10^{-24}	yocto	y
10^{-21}	zepto	z
10^{-18}	atto	a
10^{-15}	femto	f
10^{-12}	pico	p
10^{-9}	nano	n
10^{-6}	micro	μ
10^{-3}	milli	m
10^{-2}	centi	c
10^{-1}	deci	d
10^{3}	kilo	k
10^{6}	mega	M
10^{9}	giga	G
10^{12}	tera	T
10^{15}	peta	P
10^{18}	exa	E
10^{21}	zetta	Z
10^{24}	yotta	Y

Derived Quantities

- Combinations of the fundamental quantities of length, mass and time
- Example: Density
  - It is defined as mass per unit volume

$$\rho \equiv \frac{m}{V}$$

  - Units are kg/m^3

Densities

Substance	Density ρ (10^3 kg/m^3)
Platinum	21.45
Gold	19.3
Uranium	18.7
Lead	11.3
Copper	8.92
Iron	7.86
Aluminum	2.70
Magnesium	1.75
Water	1.00
Air at atmospheric pressure	0.0012

Average Density of Earth?

- From Earth's radius $R_E = 6.37 \times 10^6$ m,

$$V_E = \tfrac{4}{3}\pi(6.37\times10^6)^3 = 1.08\times10^{21}\,\mathrm{m}^3$$

- Earth's mass is $M_E = 5.98 \times 10^{24}$ kg, therefore

$$\rho_E = \frac{M_E}{V_E} = \frac{5.98\times10^{24}\,\mathrm{kg}}{1.08\times10^{21}\,\mathrm{m}^3} = 5.54\times10^3\,\mathrm{kg/m}^3$$

  - The density of granite is 2.75×10^3 kg/m^3
  - What does this tell us about the *interior* of Earth?

Atomic Mass

- The atomic mass is the total number of protons and neutrons in the element
- Often measured in *atomic mass units*, u (or amu), the mass of a proton
  - 1 u = $1.6605387 \times 10^{-27}$ kg
  - Note electron masses are negligible compared with 1 amu

Dimensions

- By dimensions, we mean how a quantity depends on L,M & T
  - denotes the physical nature of a quantity, not its size
- Dimensions are denoted with square brackets
  - Length [L]
  - Mass [M]
  - Time [T]

Symbols

- The symbol used for a quantity is not necessarily the symbol used for its dimension
- Some quantities have one symbol used consistently
  - e.g. time is t virtually everywhere
- Some quantities have many symbols used, depending upon the situation
  - e.g. lengths may be x, y, z, r, etc.

Dimensional Analysis

- Technique to check the correctness of an equation or to assist in deriving an equation
- Dimensions (length, mass, time) can be treated as algebraic quantities
  - add, subtract, multiply, divide
- Both sides of equation must have *the same dimensions!*

Dimensional Analysis, cont

- Given the equation: $x = 1/2\ at^2$
- Check dimensions on each side to see if it might be correct:

$$L = \frac{L}{T^2} \cdot T^2 = L$$

- The equation is dimensionally correct
  - There are no dimensions for the constant 1/2

Conversion of Units

- When units are not consistent, you may need to convert to appropriate ones
  - e.g. ft to m
- Units can be treated like algebraic quantities that can multiply or cancel each other out
- See the *inside of the front cover* for an extensive list of conversion factors

Conversion of Units, cont

- Multiply original value by a ratio equal to one, e.g., 12 in/1 ft = 1
- Example, 15.0 in = ? cm

  1 in = 2.54 cm,
  $$15.0\,\text{in} \times \frac{2.54\,\text{cm}}{1\,\text{in}} = 38.1\,\text{cm}$$

- *Always include units* for every quantity in your answer

Reasonableness of Results

- When solving a problem, check your answer to see if it seems reasonable
  - e.g. a car going at 10^6 m/s is not reasonable
- Make an *order of magnitude "guess"* to estimate what the answer should be
- Order of magnitude is the closest power of 10
  - Order of magnitude of 20 $\Rightarrow$ 10
  - Order of magnitude of 700 $\Rightarrow$ 10^3

How Many Ping Pong Balls?

- The average room size is ~20 ft x 15 ft x 8 ft

  $\Rightarrow V_{room} \approx 10^3 \text{ ft}^3$

- The diameter of a ping pong ball is ~1 inch

  $\Rightarrow V_{ball} \approx (.1 \text{ ft})^3 = 10^{-3} \text{ ft}^3$

- The ballpark estimate for the number *N* of balls that could fit in a room is:

  $N\, V_{ball} \approx V_{room} \Rightarrow N \approx 10^6$

Significant Figures

- A *significant figure* is one that is reliably known
- Zeros may or may not be significant
  - Those used to position the decimal point are not significant
  - To remove ambiguity, use scientific notation
- In a measurement, the significant figures include the first estimated digit

Significant Figures, examples

- 0.0075 m has 2 significant figures
  - The leading zeros are placeholders only
  - Scientific notation: 7.5×10^{-3} m
- 10.0 m has 3 significant figures
  - The decimal point gives information about the reliability of the measurement
- 1500 m is ambiguous
  - Use 1.5×10^{3} m for 2 significant figures
  - Use 1.50×10^{3} m for 3 significant figures

Significant Figures, operations

- Multiplying or dividing:

  The number of significant figures is the same as the lowest number of *significant figures* in any factor

  - e.g. 25.57 m x 2.45 m = 62.6 m^2

- Adding or subtracting:

  The number of decimal places is equal to the smallest number of *decimal places* in any term

  - e.g. 135 cm + 3.25 cm = 138 cm

Rounding Off Numbers

- Last retained digit is increased by 1, if the last digit dropped is ≥ 5
  - e.g. $1.36 \Rightarrow 1.4$
- Last retained digit remains as it is, if the last digit dropped is < 5
  - e.g. $1.34 \Rightarrow 1.3$
- Saving rounding *until the final result* will help eliminate accumulation of errors

Measurement Uncertainty

- When measurements are made, there is *always* an uncertainty
- Example: a rectangular plate is measured to have dimensions
  - L = 5.5 ± .1 m, W = 6.4 ± .1 m
- This can be expressed as percentages
  - L = 5.5 m ± 1.8%, W = 6.4 m ± 1.6%

Propagation of Uncertainty

- Multiplying or dividing:

  The percentage uncertainties are added

  - L x W = (5.5 m ± 1.8%)(6.4 m ± 1.6%)

    = 35 m^2 ± 3.4%

- Adding or subtracting:

  The absolute uncertainties are added

  - W - L = (6.4 m ± 0.1 m) - (5.5 m ± 0.1 m)

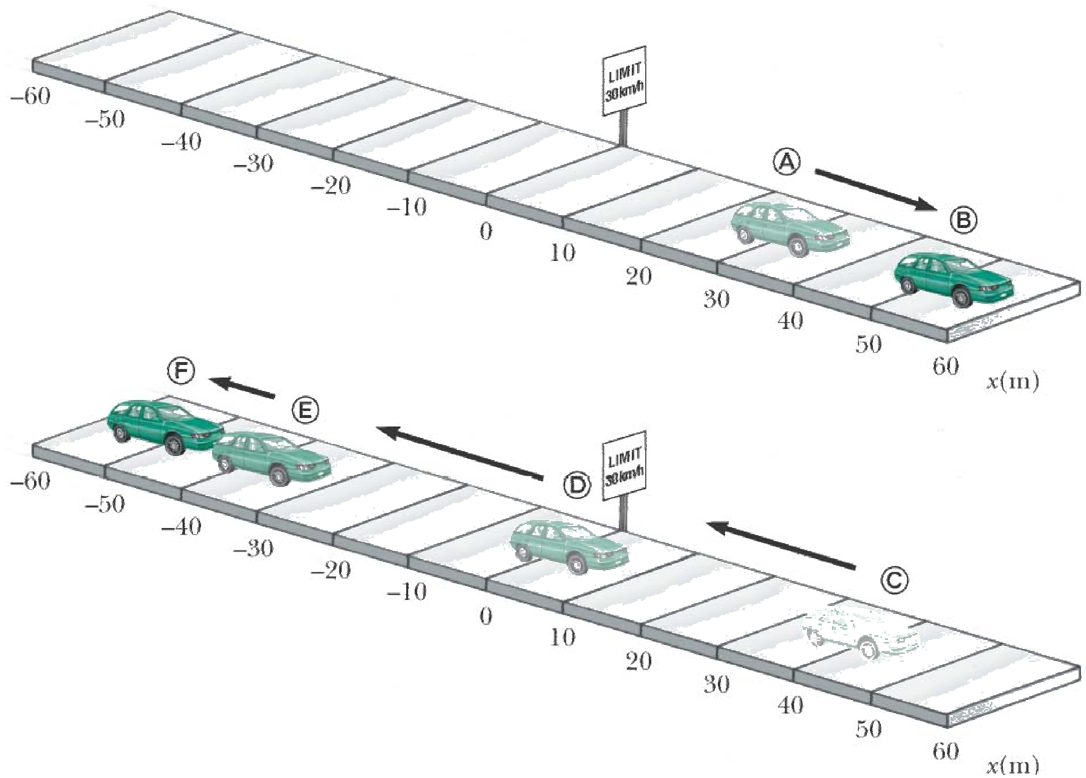
    = 0.9 m ± 0.2 m

Kinematics

- Describes motion while ignoring the agents (forces) that caused the motion
- For now, will consider motion in one dimension
  - Along a straight line
- Will use the particle model
  - Infinitesimal size, but has a finite mass

Position

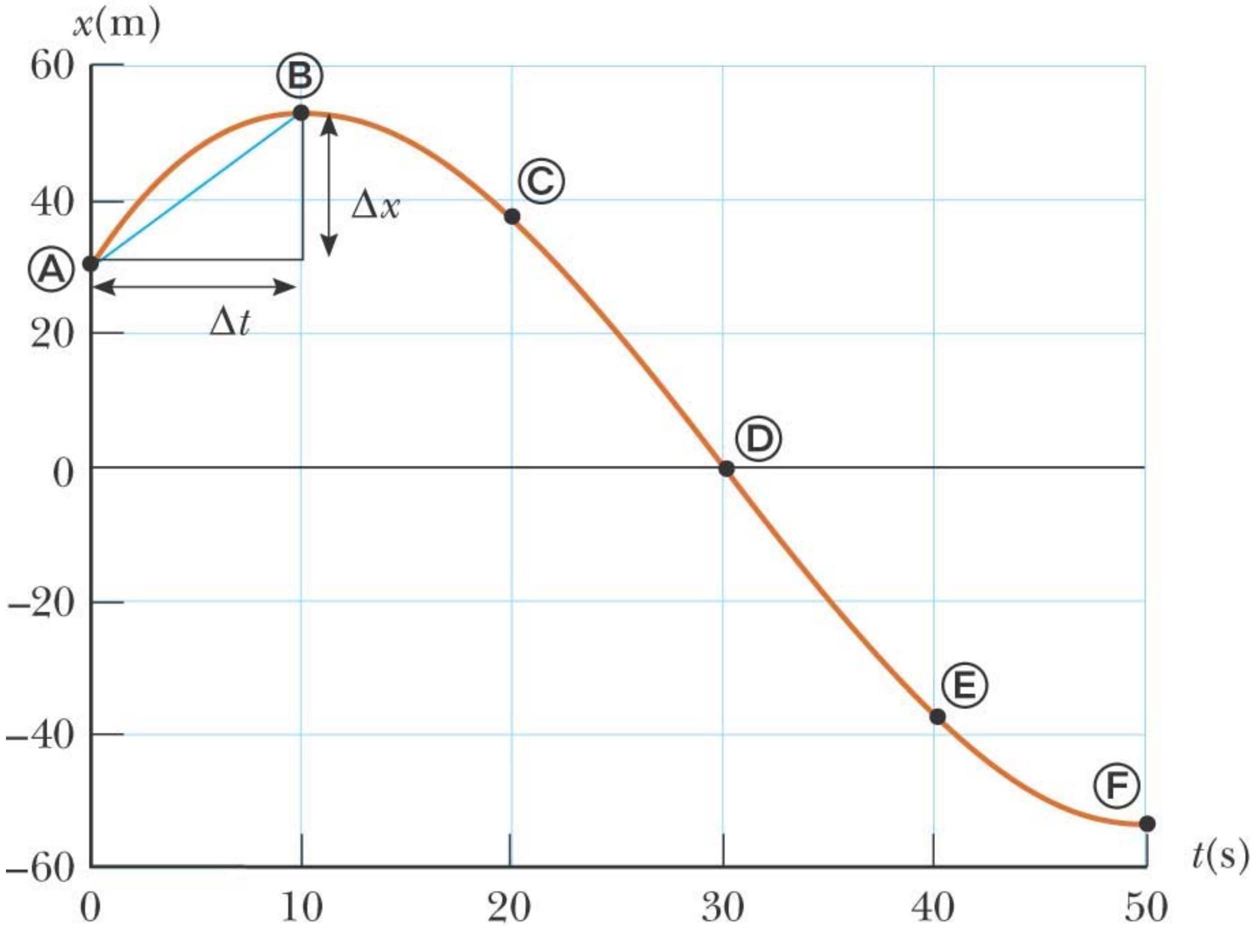
- Defined in terms of a *frame of reference* (coordinate system)
- The object's position is its location with respect to the frame of reference



A = 28 m, B = 50 m
C = 36 m, D = 0 m, E = –40 m, F = –55 m

Position-Time Graph

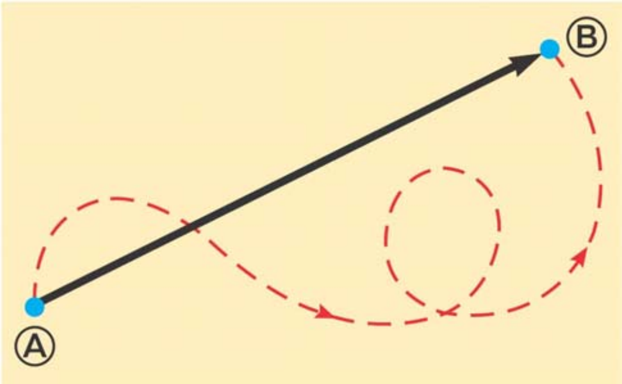
- Shows the motion of the particle (car)
- The smooth curve is a guess as to what happened between the data points



1-D Displacement

- Defined as the *change* in position during some time interval
- Represented as Δx; $\Delta x = x_f - x_i$
  - SI units are meters (m)
  - Δx can be positive or negative
- Is independent of the frame of reference

2-D Displacement

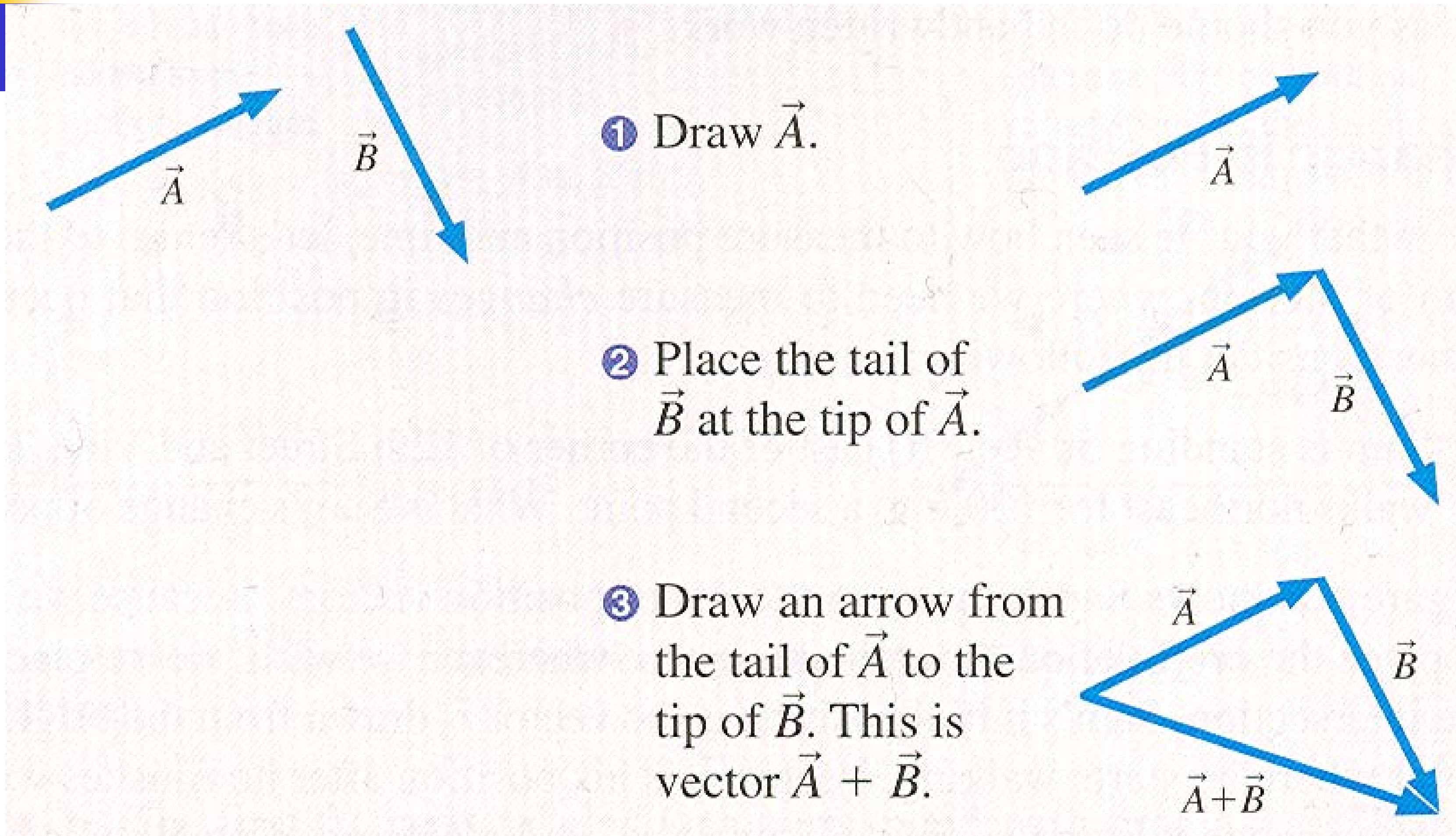


- Example: A particle travels from A to B along the path shown
- The *distance* traveled is the total length of the curve and is a scalar
- The *displacement* is the solid line from A to B and is a vector
  - Independent of the path taken between the two points

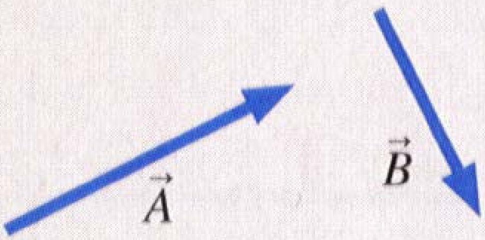
Scalars and Vectors

- Scalar quantities are completely described by magnitude only
  - e.g. distance, speed, mass, temperature
- Vectors quantities need both magnitude (numerical value) *and* direction to completely describe them
  - e.g. displacement, velocity, acceleration, force

Adding Vectors



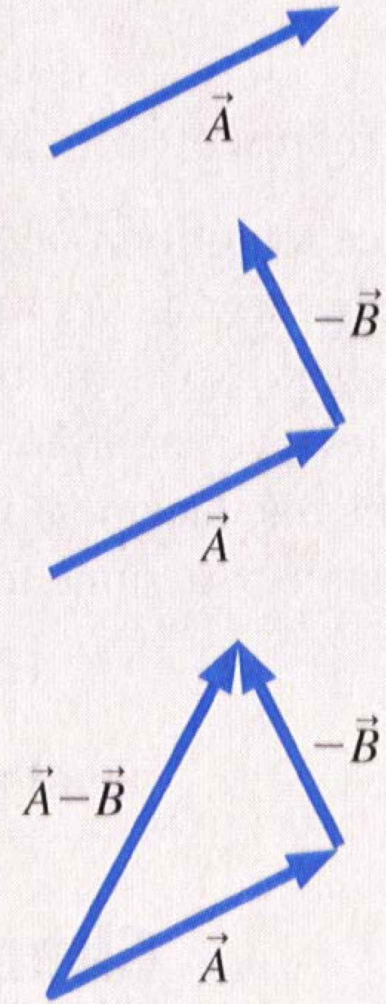
Subtracting Vectors



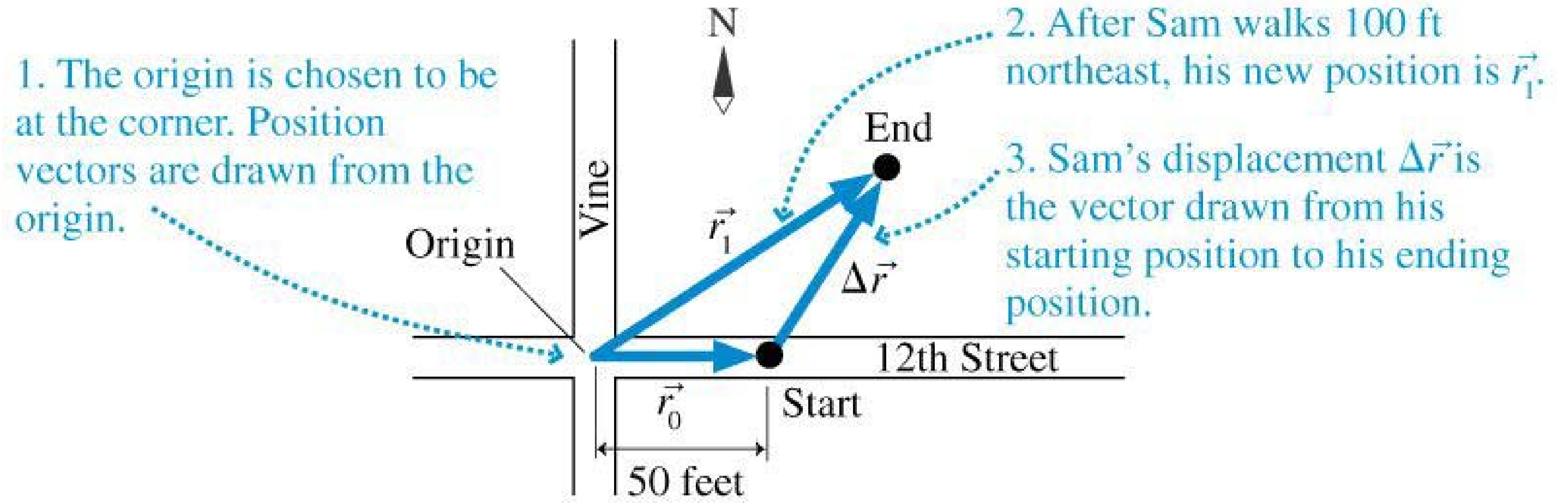
❶ Draw $\vec{A}$.

❷ Place the tail of $-\vec{B}$ at the tip of $\vec{A}$.

❸ Draw an arrow from the tail of $\vec{A}$ to the tip of $-\vec{B}$. This is vector $\vec{A} - \vec{B}$.



2-D Displacement, cont



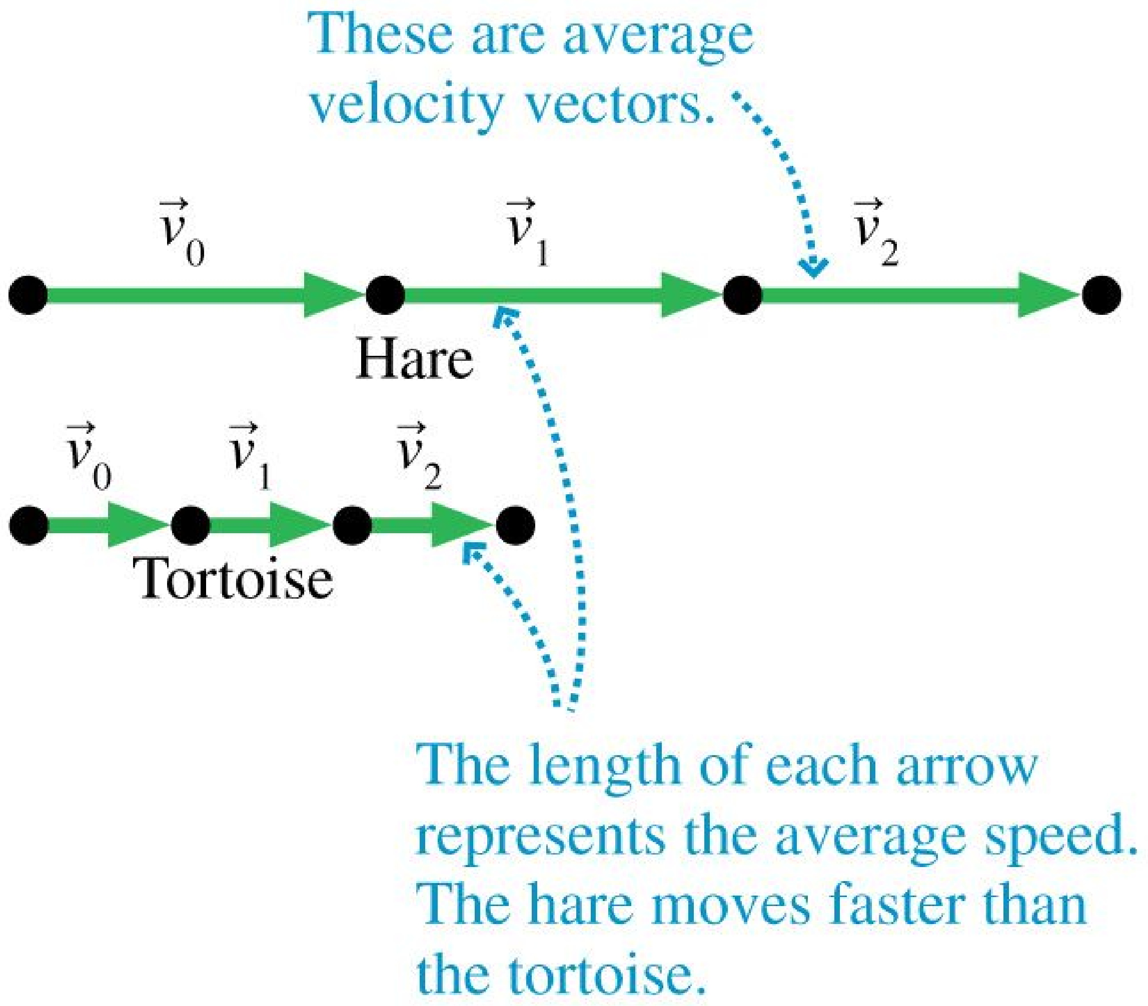
$$\vec{r}_1 = \vec{r}_0 + \Delta\vec{r}$$

Final position   Initial position   Displacement

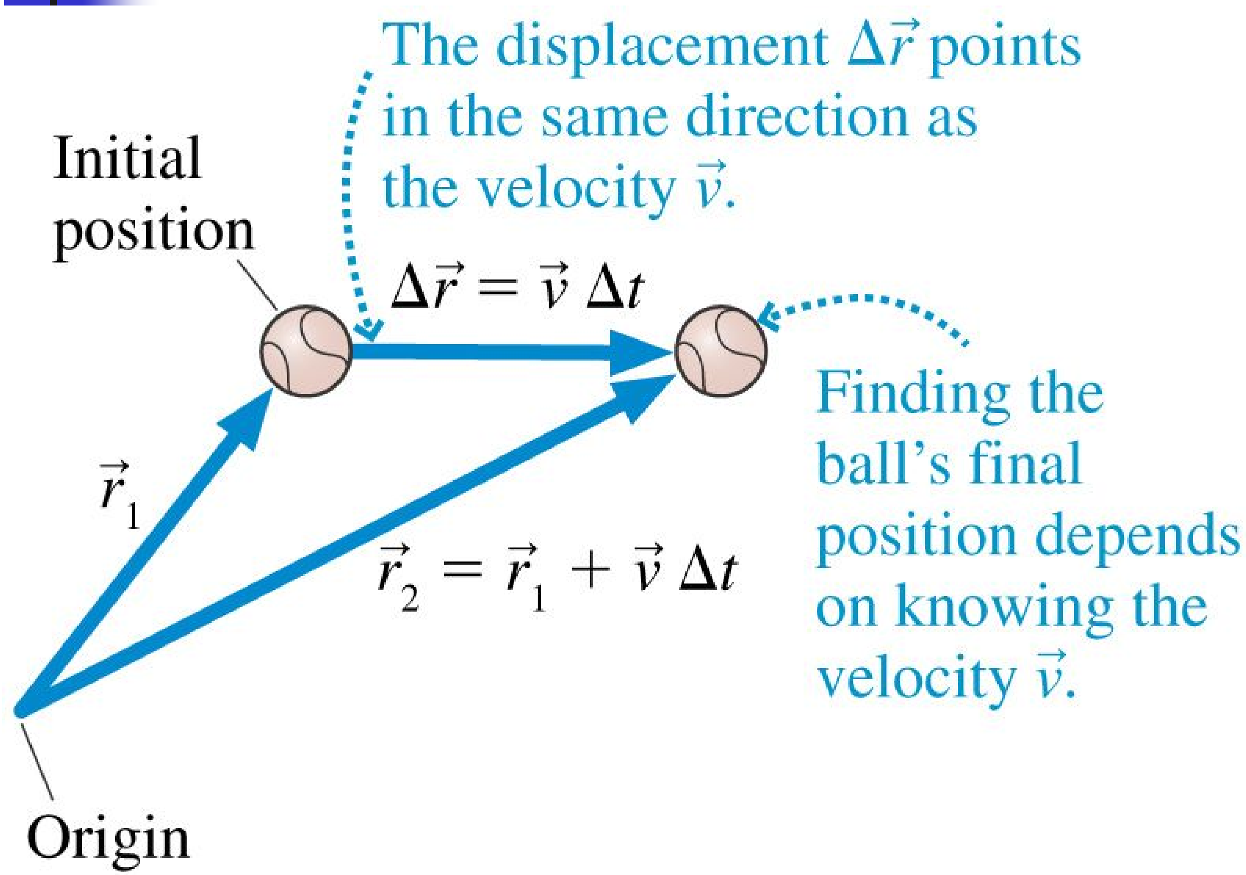
Speed and Velocity

- Speed is the distance traveled (scalar) divided by the time interval spent
  - $v_{avg} = \dfrac{\Delta \ell}{\Delta t}$, has no direction
- Velocity is the displacement (vector) divided by the time interval spent
  - $\vec{v}_{avg} = \dfrac{\Delta \vec{r}}{\Delta t}$, has a direction

Velocity Vectors



Relating Position to Velocity



$$\Delta\vec{r} = \vec{r}_2 - \vec{r}_1$$

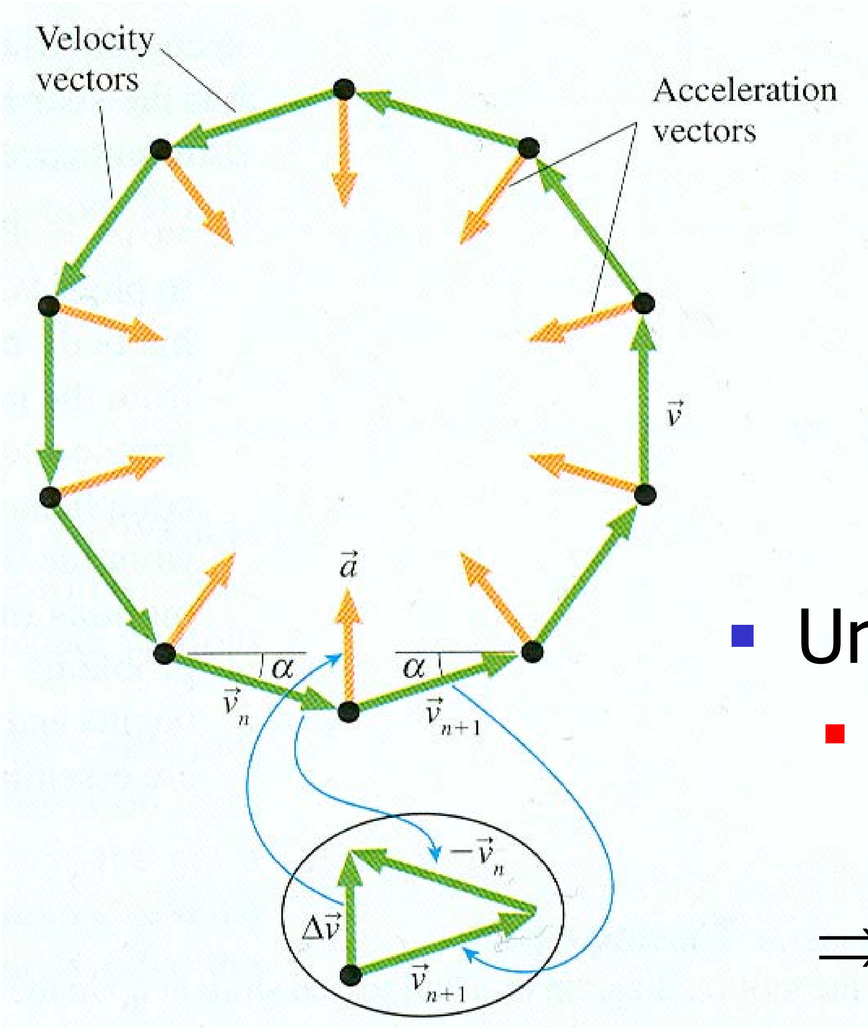
$$\vec{v} = \frac{\Delta\vec{r}}{\Delta t}$$

$$\vec{r}_2 = \vec{r}_1 + \vec{v}\Delta t$$

Acceleration

- Acceleration is the velocity change (vector) divided by the time interval spent
  - $\vec{a}_{\text{avg}} = \dfrac{\Delta\vec{v}}{\Delta t}$, has a direction
- Acceleration occurs when
  - the magnitude of velocity (speed) changes,
  - the direction of the velocity changes, or
  - both the speed and direction change

Acceleration in Circular Motion



$$\vec{a} = \frac{\Delta\vec{v}}{\Delta t}$$

$$\Delta\vec{v} = \vec{v}_f - \vec{v}_i$$

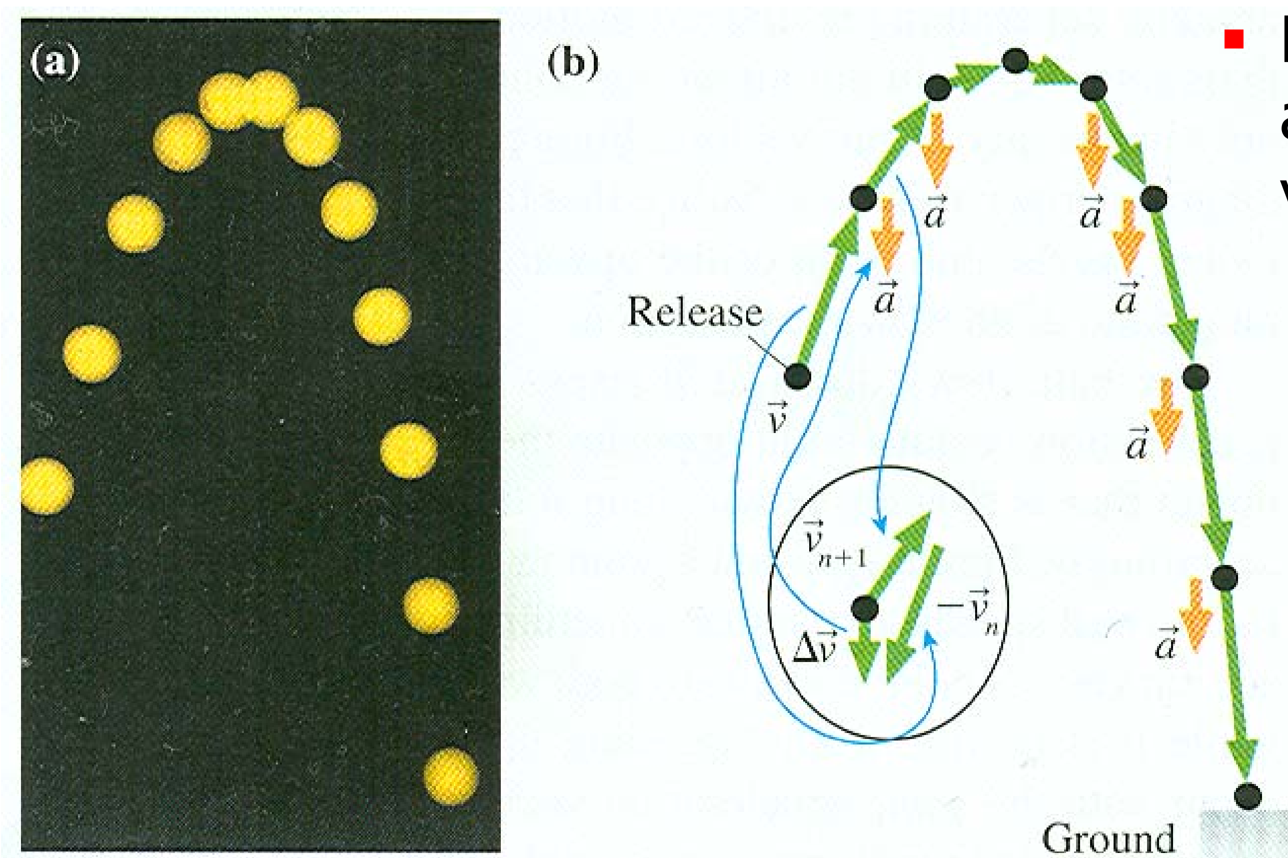
$$\vec{v}_f = \vec{v}_i + \vec{a}\Delta t$$

- Uniform circular motion
  - Only the *direction* of velocity changes

$\Rightarrow$ Centripetal acceleration

Acceleration due to Gravity

- Projectile motion
  - Both the *direction* and *magnitude* of velocity changes



$$\vec{a} = \frac{\Delta\vec{v}}{\Delta t}$$

$$\Delta\vec{v} = \vec{v}_f - \vec{v}_i$$

$$\vec{v}_f = \vec{v}_i + \vec{a}\Delta t$$