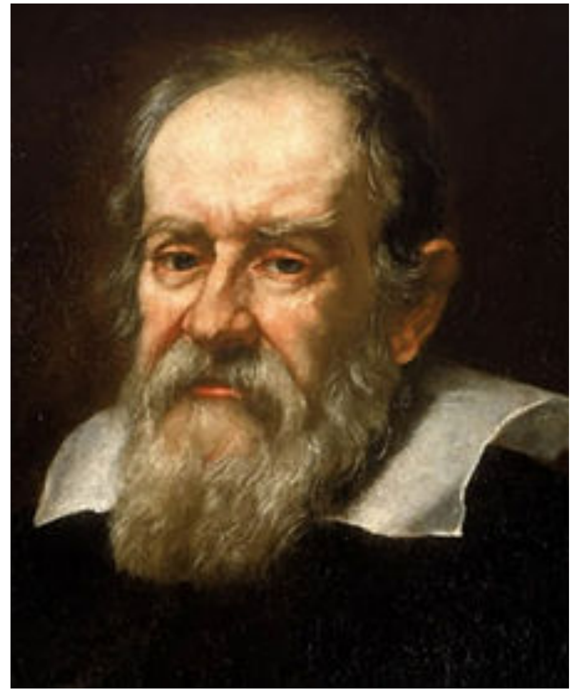
Announcements

- CAPA homework #1 and #2 due on Thursday Sept. 13 at 10 AM
- Please register your iclicker through LON-CAPA
  - only about 1/2 of you have
  - you will not get credit for the iclicker points unless you have registered it on LON-CAPA (instructions given in first and second lecture)

Motion

Aristotle vs Galileo

384-322 BC
Tutor of Alexander the Great
Aristotle's aim was to systematize existing knowledge, just as Euclid had systematized geometry. His systematic approach became the method from which Western science arose.



1564-1642
Born the same year as Shakespeare
Became an advocate of the new theory of the solar system advocated by Copernicus. Ran afoul of the church and was warned not to teach and not to hold Copernican views. Found guilty in a trial and forced to recount his views.

Aristotle on motion

- Three types of motion
  - **natural motion**
  - violent motion
  - celestial motion
- Natural motion
  - solid objects (or liquids) fall because they seek their natural resting place (center of the Earth)
  - air likes to rise upwards, as do flames, since that is their natural resting place
  - so natural motion is either straight up or straight down

Aristotle on motion

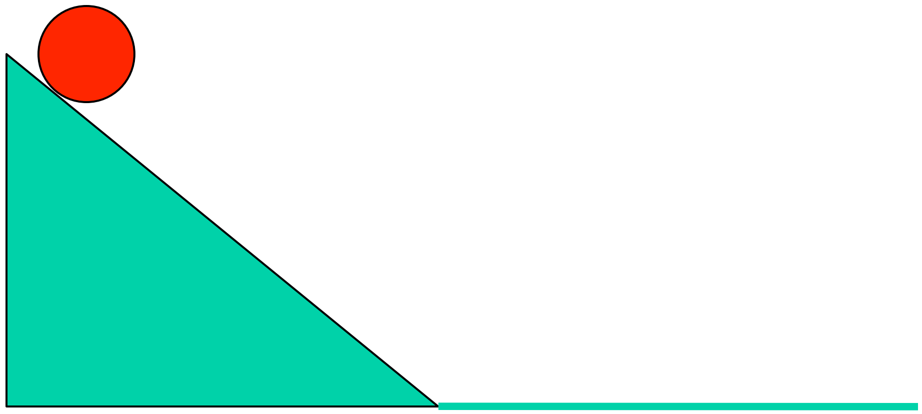
- Three types of motion
  - natural motion
  - **violent motion**
  - celestial motion
- Violent motion
  - horizontal motion
  - imposed by pushes or pulls; objects move not by their nature, but because of impressed forces
  - example: arrow shot from bow; bowstring imparts force to make arrow move horizontally
  - what's the problem with this?

Aristotle on motion

- Three types of motion
  - natural motion
  - violent motion
  - **celestial motion**
- Celestial motion
  - motion of the sun, moon and stars; perfect circles
  - sun, moon and stars formed of perfect, incorruptible substance called ether (or quintessence)
  - this motion is different from anything on the Earth

Inclined plane

- Galileo performed a series of measurements rolling a ball on an inclined plane
  - those of you in ISP209L will do something similar
- Why an inclined plane?
- Vertical motions under the influence of gravity were too fast for him to accurately measure; he needed to slow them down
- After conducting the measurements, he then performed a gedanken
  - what would happen if there were no friction and no air resistance?
  - the ball would keep rolling forever at a constant velocity



Law of inertia: a body that is subject to no external forces will stay at rest if it was at rest to begin with and will keep moving if it was moving to begin with; in the latter case, the motion will be in a straight line at a constant speed

video

- According to Aristotelian physics, which (if any) outside influences act on a stone as it falls?
  - air resistance
  - inertia
  - gravity
  - there are no outside influences

- According to Galilean/Newtonian physics, which (if any) outside influences act on a stone as it falls?
  - air resistance
  - inertia
  - gravity
  - there are no outside influences

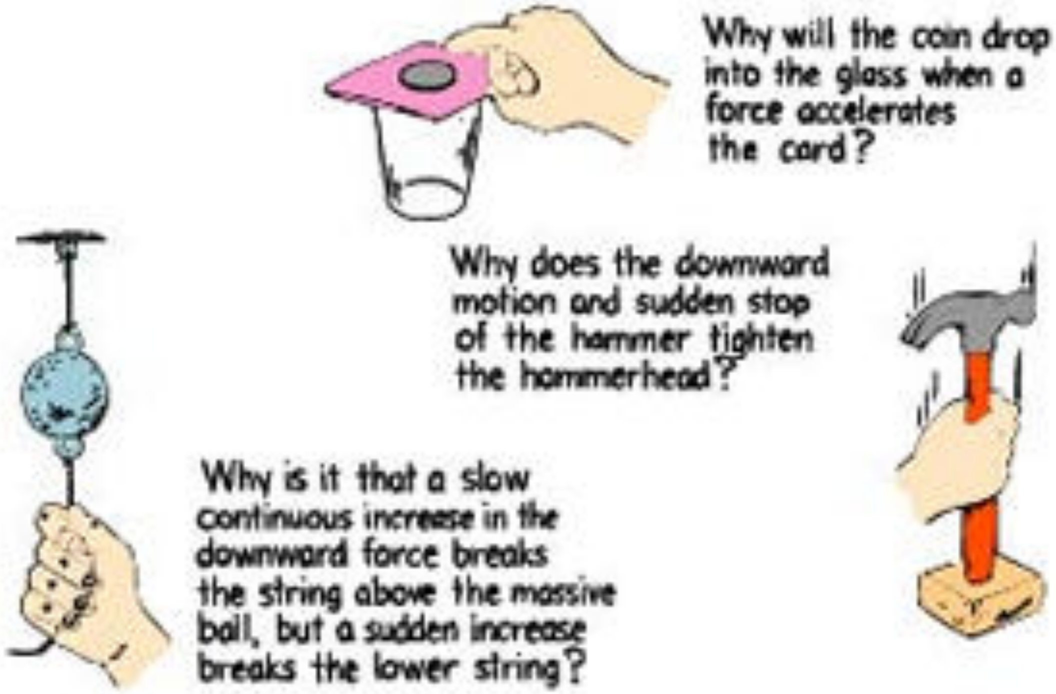
Galileo’s methods

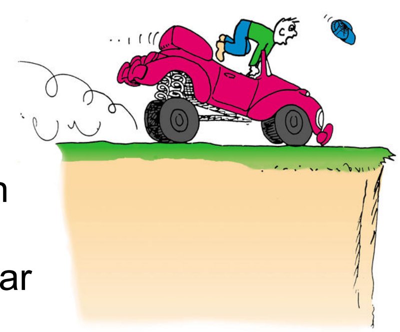
- Experiments, designed to test specific hypotheses
- Idealizations of real world conditions, to eliminate any side effects that may obscure the main effects
- Limiting the scope of the inquiry, by considering only one question at a time
- Quantitative methods, Galileo went to great lengths to precisely measure the motion of bodies
- Scientific process

Mass

- When an object changes its state of motion, slowing down or speeding up, we say it undergoes acceleration
- The amount of acceleration depends on the forces involved and on the inertia of the object
  - how much it resists the change in motion
- The amount of inertia of an object depends on the amount of matter inside an object, or its mass
  - mass=a measure of the inertia of a material object
- Mass is not the same thing as weight
  - weight=the force upon an object due to gravity
- But mass and weight are proportional to each other
  - weight α mass

Inertia



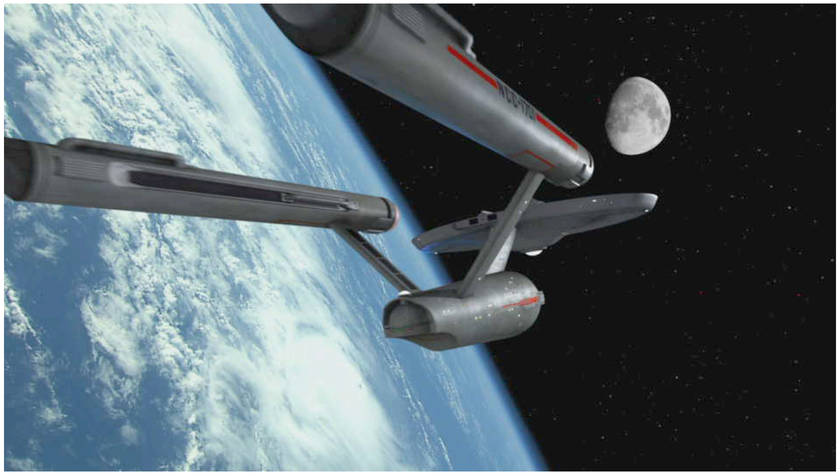


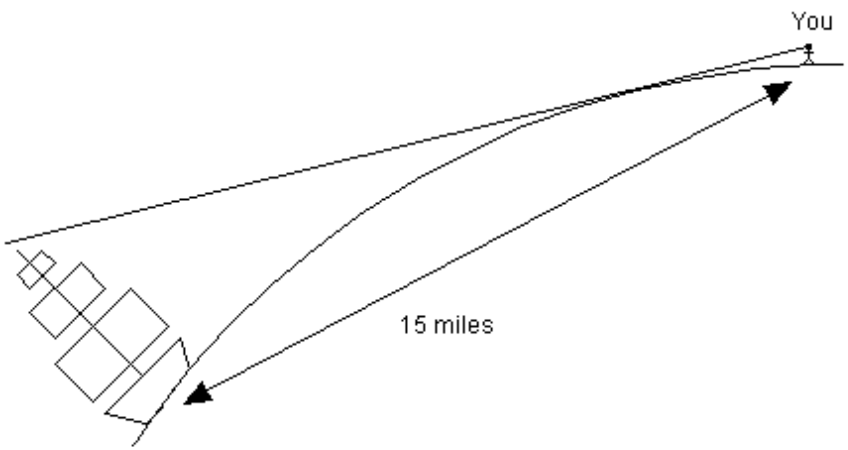
Why does the man continue to move forward after the car stops?

Earth orbit

- What keeps a spaceship in motion around the Earth?
- It's falling under the influence of gravity, but the Earth's surface is *falling away* at the same rate
  - the Earth curves approximately 13 cm every kilometer (8 inches per mile)
- How strong is gravity in outer space (say 200 km above the surface of the Earth)?

http://www.youtube.com/watch?v=VDu9z4SCTmc



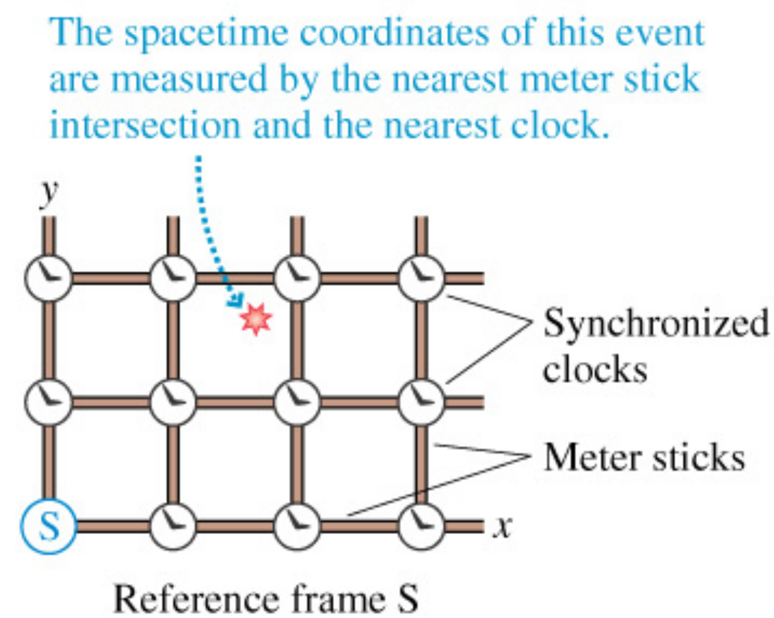


Motion

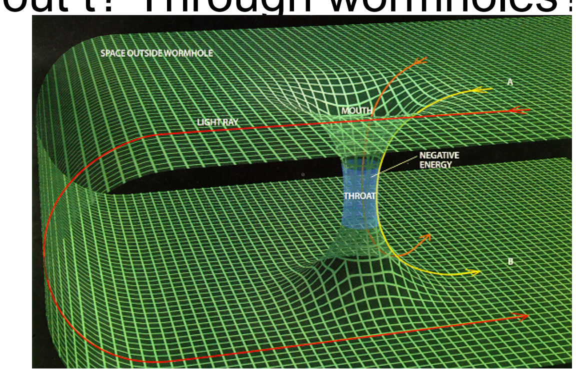
- If we want to talk quantitatively about motion, then we are going to have to deal quantitatively with time and distance
- Start off with time
- What is time?
- According to Woody Allen
  - "Time is nature's way of keeping everything from happening at once"
- An operational definition of time is that it is the thing measured by clocks

Reference systems

- Can imagine a coordinate system with a system of clocks and meter sticks such that it is possible to describe an event with the spacetime coordinates (x,y,z,t)
- Question: is time the same in every reference frame?
- For the moment, yes
- Once we discuss special relativity, we'll find the answer is no
- The clocks for separate observers may run differently, depending on their frames of reference
  - moving clocks tick more slowly than stationary clocks



We can move in either direction along the x, y and z directions
What about t? Through wormholes?

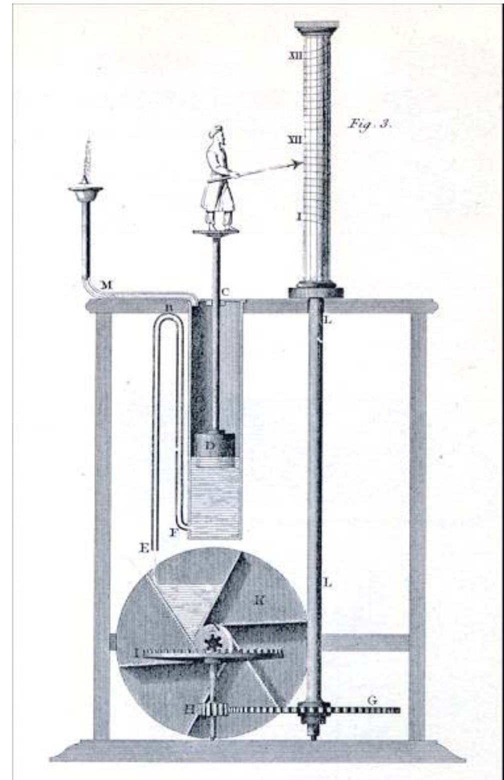


Newton's point-of-view

- A basic premise of Newtonian mechanics is that a universal time scale exists that is the same for all observers
- "Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external"
  - Isaac Newton

Galileo’s experiments

- How did Galileo measure time in his experiments?
- We saw that he used a pendulum in the video
- He also used a water clock, a device that may date back as early as 4000 BC
- Relies on the steady flow of water from a reservoir through a small opening
- Not so accurate, but more so than an hourglass



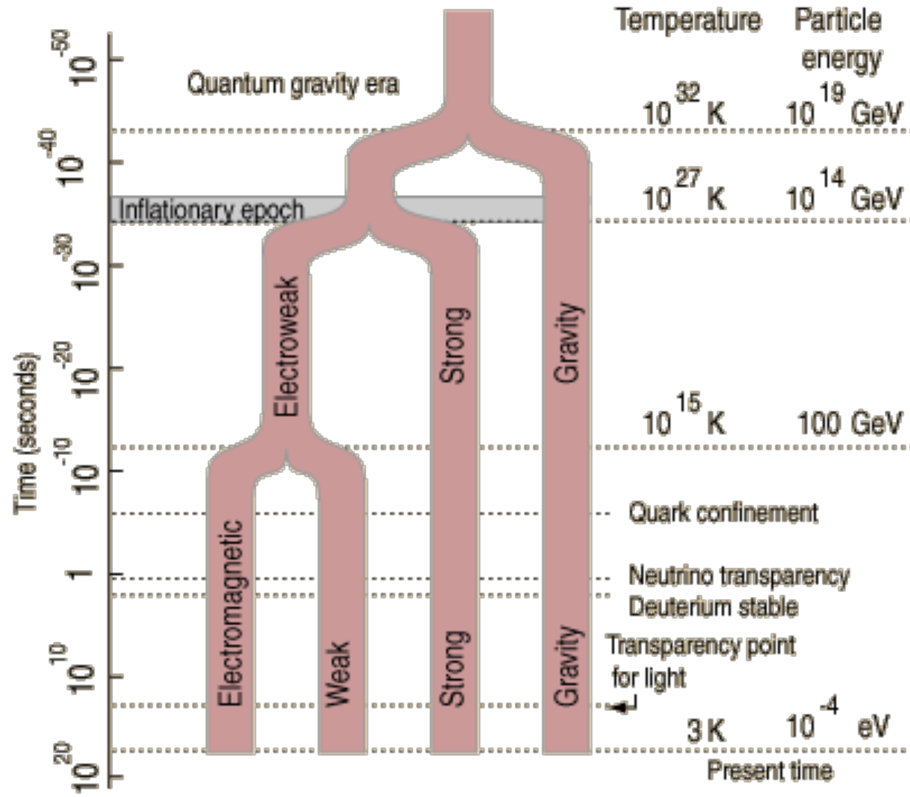
An early 19th-century illustration of Ctesibius’ clepsydra from the 3rd century BC. The hour indicator ascends as water flows in. Also, a series of gears rotate a cylinder to correspond to the temporal hours.

Smallest unit of time

- Planck time

$$t_P = \sqrt{\frac{\hbar G}{c^5}} \approx 5.39124(27) \times 10^{-44}\ \mathrm{s}$$

- Where $\hbar$ is the reduced Planck constant, G is the gravitational constant and c is the speed of light (all constants we'll encounter later in the course)
- At the Planck time after the Big Bang, all forces were the same
- Smallest unit of time that has been physically measured is the attosecond (10^{-18} s ,or 10^{26} Planck's time)



Scalars, vectors and tensors

- Physical quantities can have characteristics
- Scalars-a quantity without direction
  - the mass of an object
  - the magnitude of a vector
- Vectors-a quantity that has both a length and a direction
- Tensors-generalized versions of vectors in multiple directions
  - the number of dimensions of a tensor is called its rank
  - rank 0 tensor is a scalar
  - rank 1 tensor is a vector
  - don’t worry about tensors; the math is beyond the course

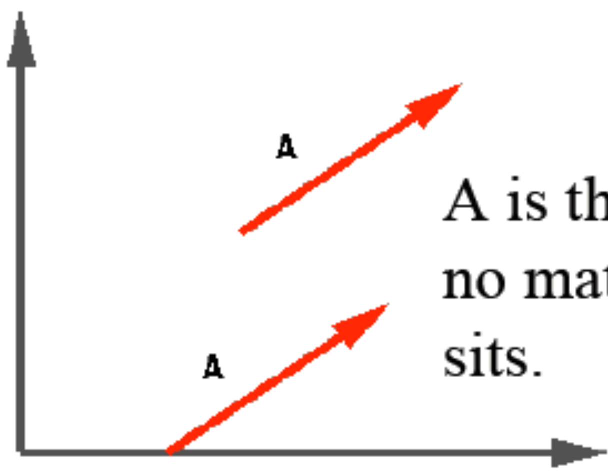
Examples

- Scalars
  - mass, electric charge
  - speed (magnitude of a velocity)
  - amount of money in my wallet (a small scalar)
  - the volume of a container
- Vectors
  - position: 2 miles east of Spartan Stadium
  - velocity: 60 mph towards Detroit
  - acceleration: 9.8 m/s^2 towards the center of the Earth

Vectors

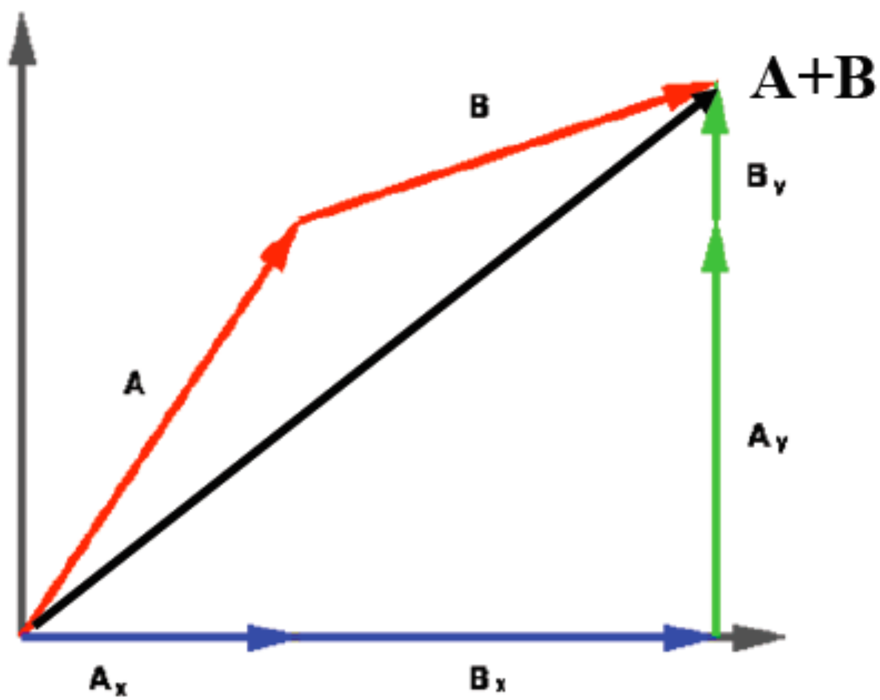
Representation

1 meter East



A is the same vector no matter where it sits.

Addition



Motion

- Position
  - location in space relative to an origin (x,y,z); often-times we will just quote an x position for simplicity
- Velocity
  - rate of change of position
- Acceleration
  - rate of change of velocity

Units

- Physical quantities always have a unit attached
  - for example, a distance of 2 m
  - quoting a distance of 2 means nothing
- Some quantities are a combination of units
  - for example a speed of 2 m/s
- We use the SI system of units in this course
  - kilogram (kg) for mass
  - meter (m) for length
  - second (s) for time
  - Newton (N) for force
  - Joules (J) for energy
  - moles (mol) for amount of a substance

Velocity

- Velocity is the rate of change of position

$$\vec{v} = \frac{\text{change in position}}{\text{change in time}} = \frac{\Delta x}{\Delta t}$$

- Speed is the magnitude of the velocity

$$v = |\ \vec{v}\ |$$

- What is the speed between 1 and 2 s?

$$v = |\ \vec{v}\ | = \frac{x_{final} - x_{initial}}{t_{final} - t_{initial}} = \frac{\Delta x}{\Delta t}$$

$$= \frac{1.0m - 0.0m}{2.0s - 1.0s} = 1.0m/s$$

- Position vs time for an object

Position (m)	Time (s)
-1.0	0.0
0.0	1.0
1.0	2.0
1.0	3.0
0.5	4.0

Acceleration

- Rate of change of velocity

x (m)	t (s)
0	0
1	1
2	2
2.5	2.5
3.0	3
3.0	4
2.0	5

v (*m/s*)
1
1
1
1
0
-1

What is the average acceleration at 1 s?

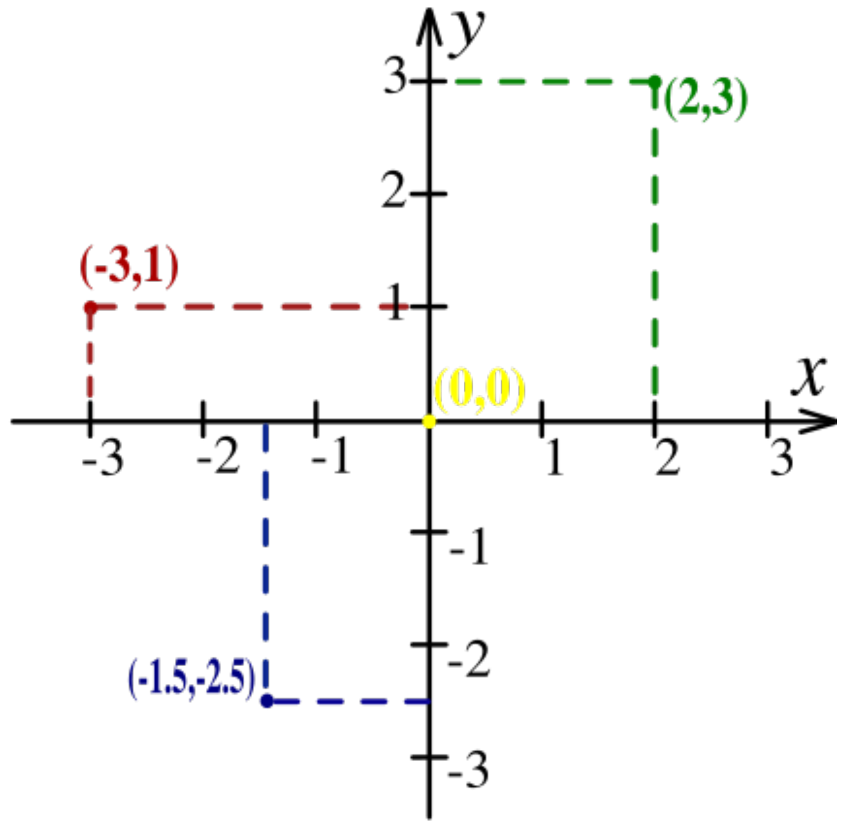
$$a = \frac{\Delta v}{\Delta t} = \frac{1m/s - 1m/s}{1s} = 0\ m/s^2$$

What is the average acceleration at 4 s?

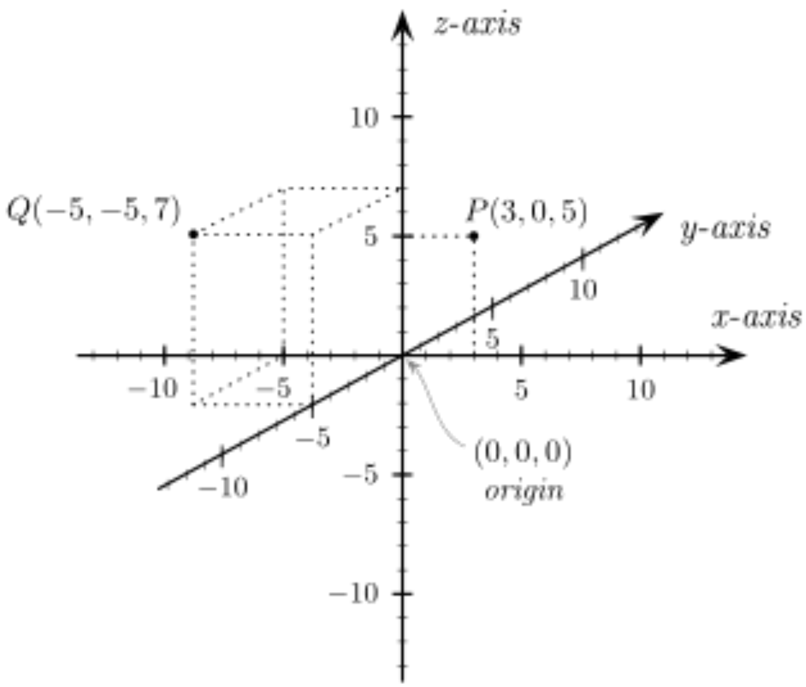
$$a = \frac{\Delta v}{\Delta t} = \frac{-1m/s - 0m/s}{1s} = -1\ m/s^2$$

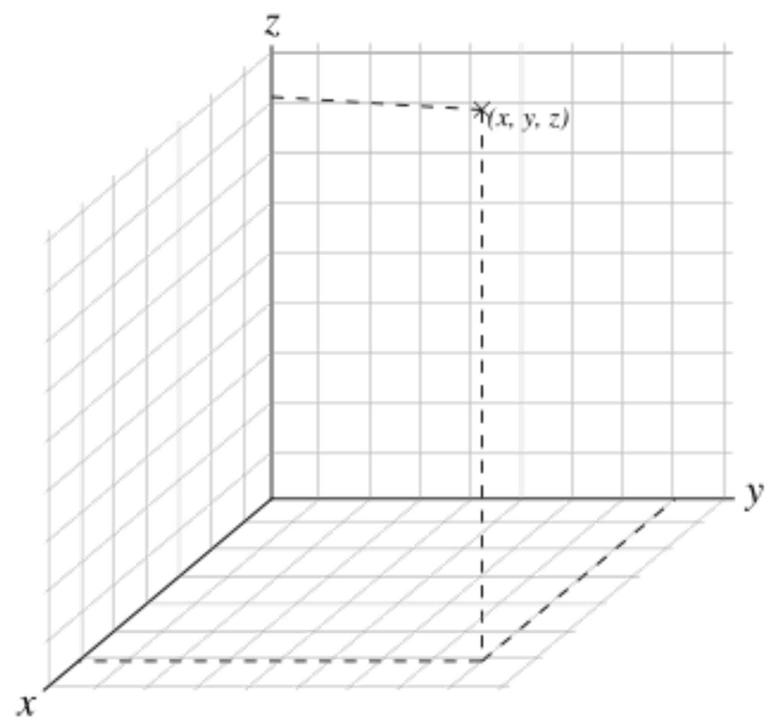
Cartesian coordinate systems

- Rectilinear coordinate axes (axes are perpendicular to each other)



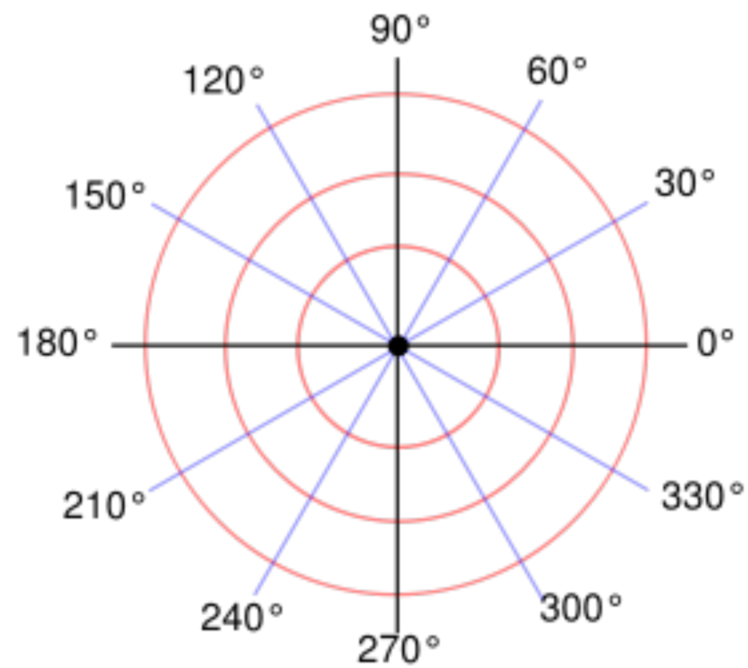
Can expand to 3 dimensions





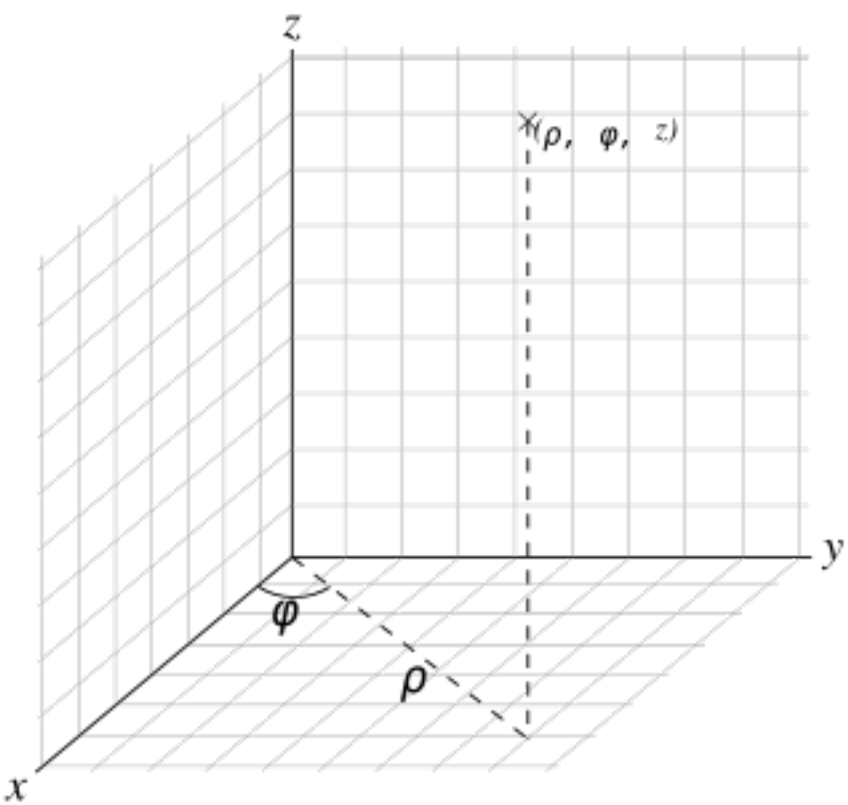
What other kind of coordinate systems are there?

- Polar coordinate system where you can represent a 2D position by the coordinates r and θ

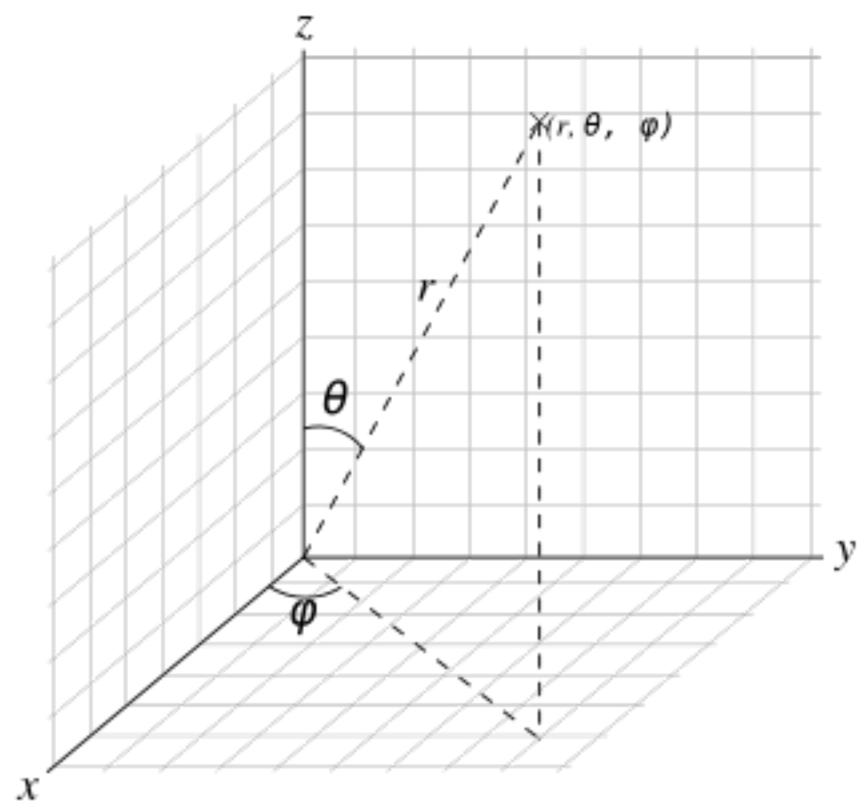


Other coordinate systems

- Cylindrical (ρ,ϕ,z)



- Spherical (r,θ,ϕ)

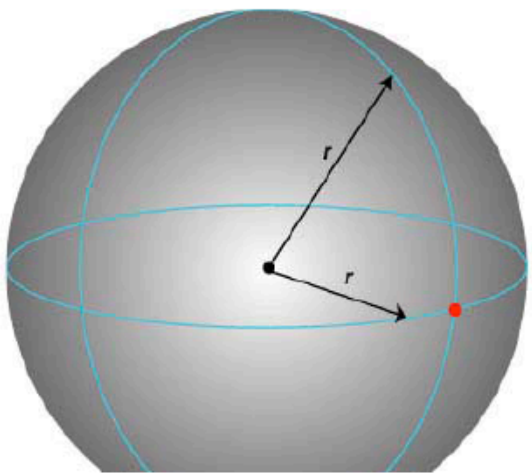


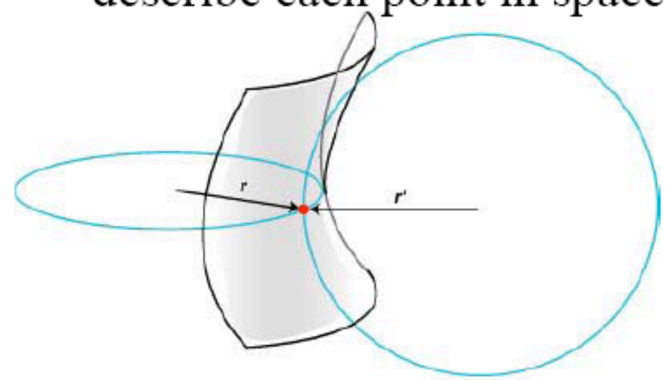
Tensors

Tensors are objects that have more than one value at each point in space.

- Example: Curvature of space-time: $R_{\mu\upsilon}$ $(=T_{\mu\nu})$
  Riemann curvature tensor

One number is not sufficient to describe each point in space.





Einstein's field equations (from General Theory of Relativity)

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

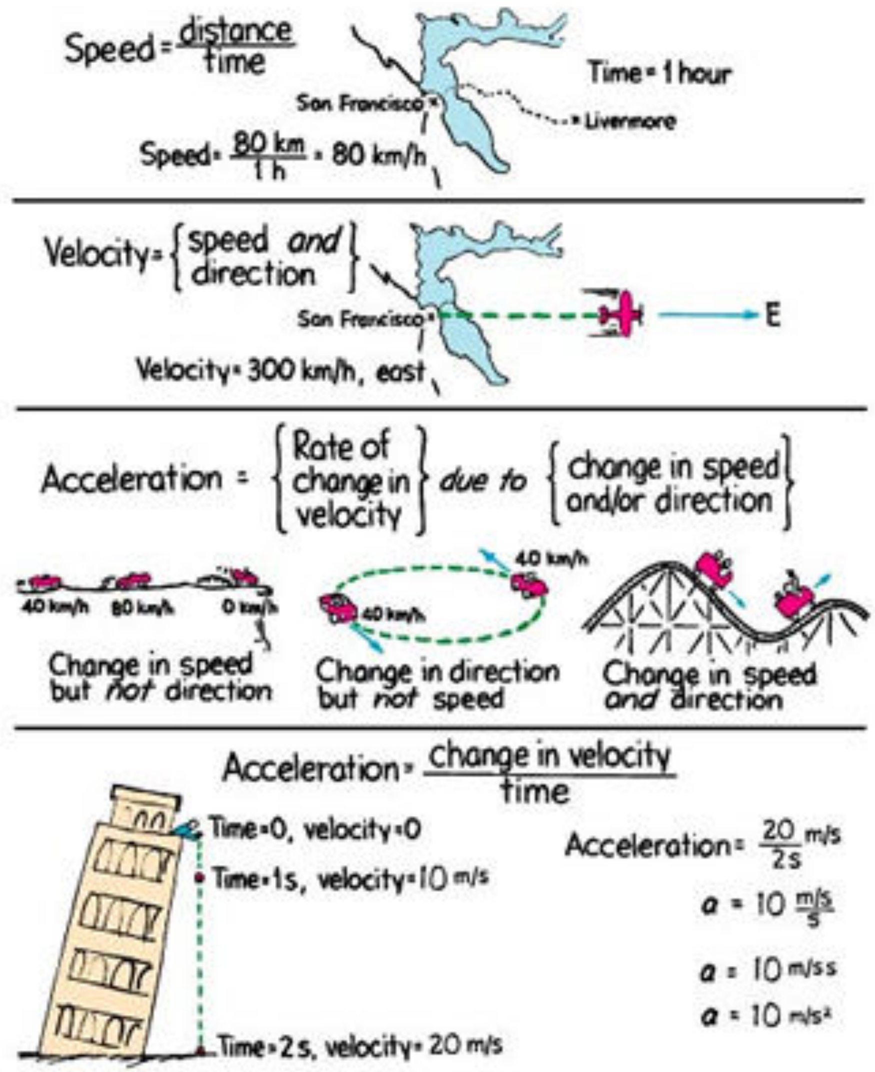
Einstein tensor (describes how space is curved)

energy-momentum tensor

cosmological constant ("my biggest blunder")

Motion

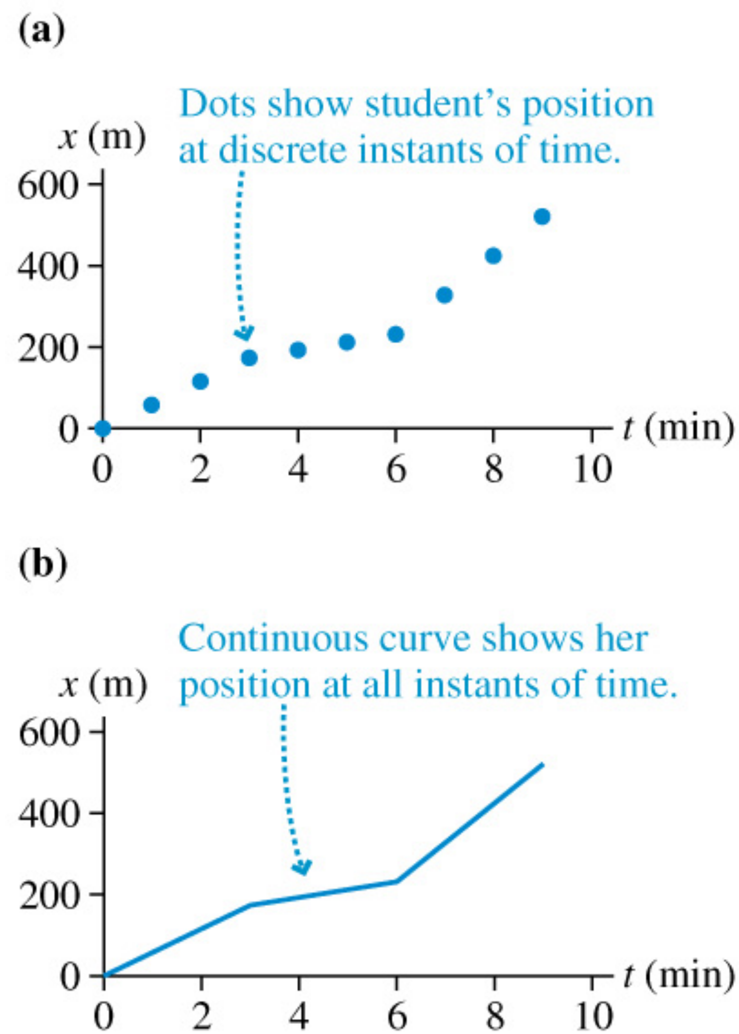
- Position
  - location in space relative to an origin (x,y,z); often-times we will just quote an x position for simplicity
- Velocity
  - rate of change of position (vector quantity)
  - note that since velocity is a vector, it will change as
    - the magnitude changes
    - the direction changes
- Speed
  - magnitude (scalar) of velocity
- Acceleration
  - rate of change of velocity
  - we'll often deal with the acceleration due to gravity, g, equal to 9.8 m/s^2



Note the book rounds g off to 10 m/s^2

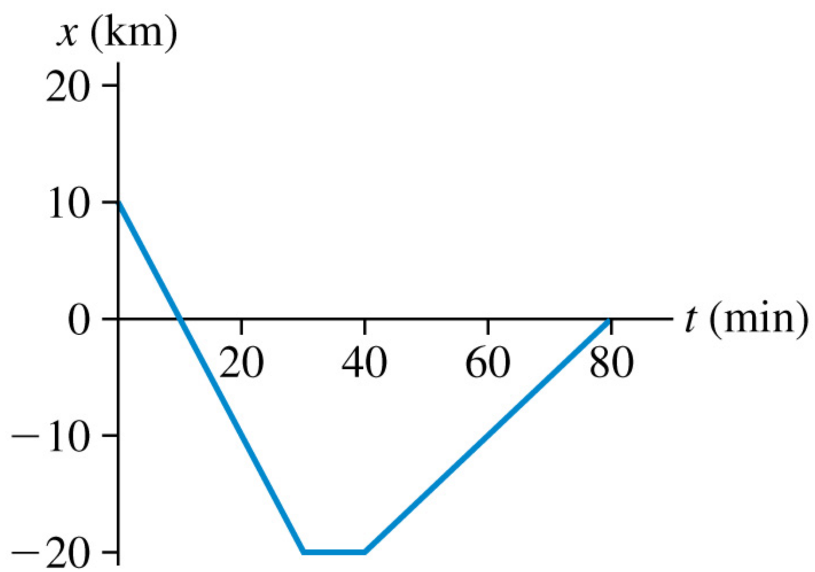
Motion in one dimension

- …or, to be more precise, one space dimension (x) and one time dimension (t)
- We want to characterize the position along the x axis as a function of time
- Note that we plot x on the vertical axis as it is the dependent variable and t on the horizontal axis as it is the independent variable

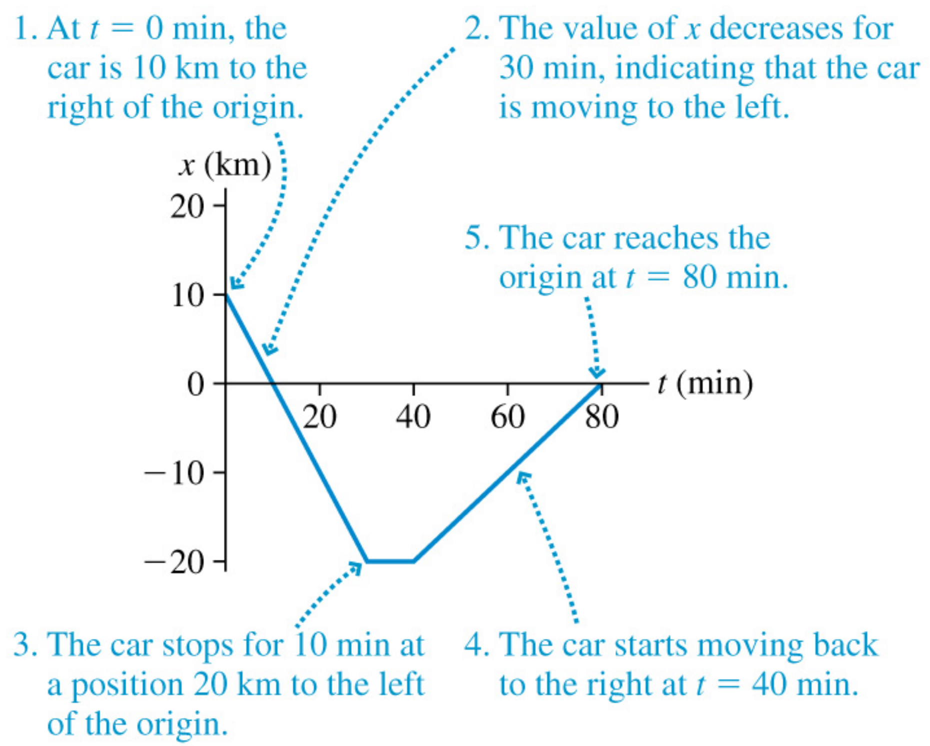


Example

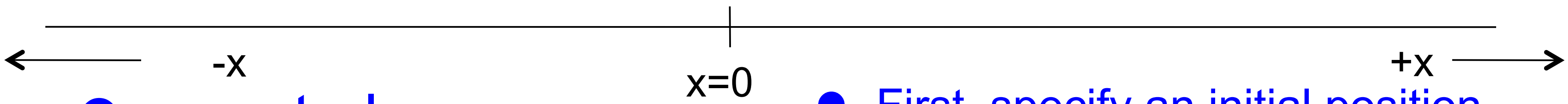
(a)


x (km)
20
10
0
−10
−20
20
40
60
80
t (min)

(b)


1. At t = 0 min, the car is 10 km to the right of the origin.
2. The value of x decreases for 30 min, indicating that the car is moving to the left.
x (km)
20
10
0
−10
−20
20
40
60
80
t (min)
5. The car reaches the origin at t = 80 min.
3. The car stops for 10 min at a position 20 km to the left of the origin.
4. The car starts moving back to the right at t = 40 min.

Motion in one dimension

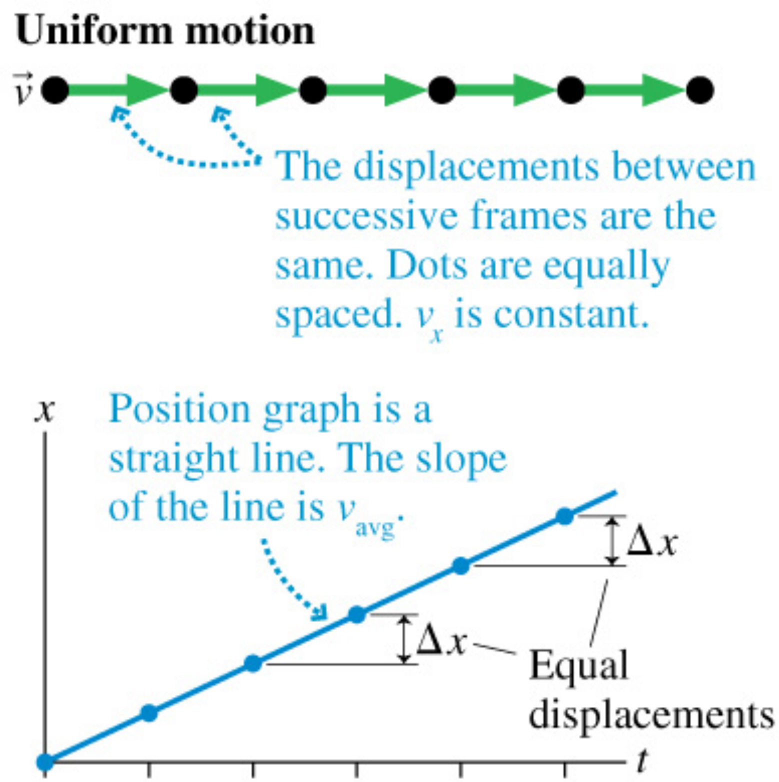


- …or, to be more precise, one space dimension (x) and one time dimension (t)
- We want to characterize the position along the x axis as a function of time

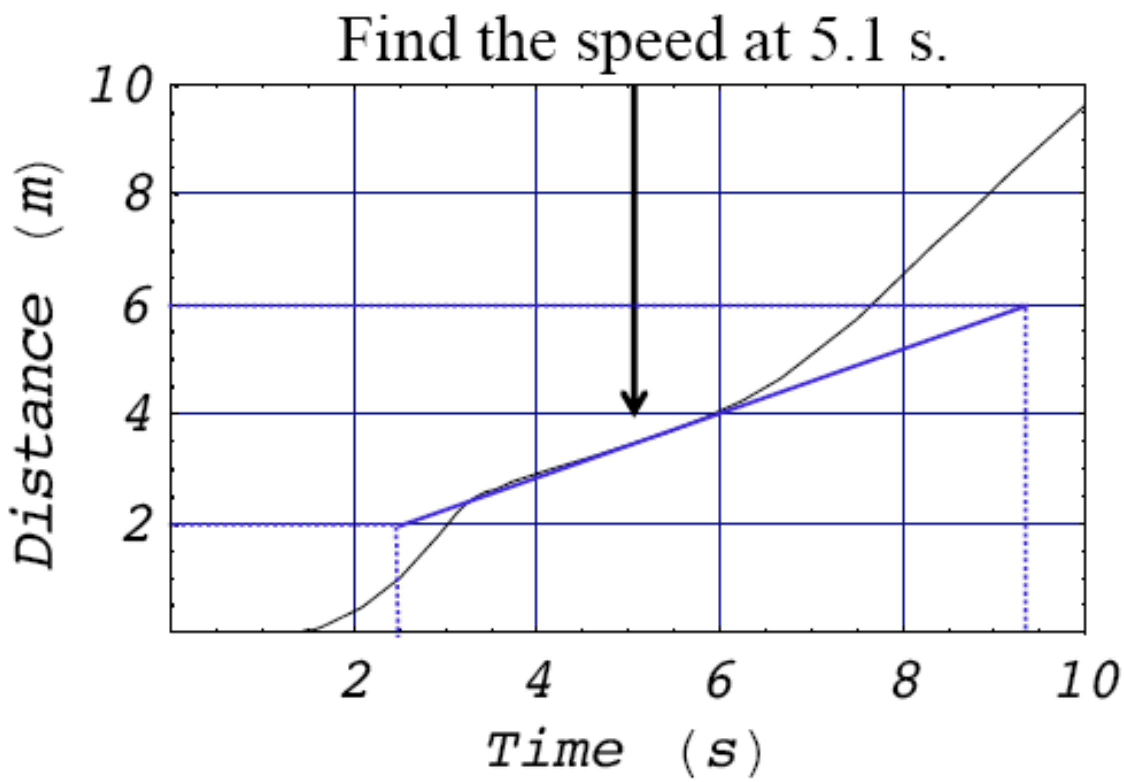
- First, specify an initial position
  - $x=x_o$
  - this is boring since the object just stands still
- And then an initial velocity
  - $x=x_o +v_o t$ now the position x changes with time
  - x increases (to the right) with t if v_o is +, decreases (to the left) if v_o is –
  - with only 1 dimension to work with, we can specify a direction just by saying "+" or "-"
  - if we were working in 2 or more dimensions, this wouldn't be enough

Motion in one dimension

- x increases uniformly with time
- In each time increment Δt, there is an equal displacement Δx
- Note that the velocity is given by the slope of the x vs t graph
  - v=Δx/Δt



I can find the speed at any moment in time



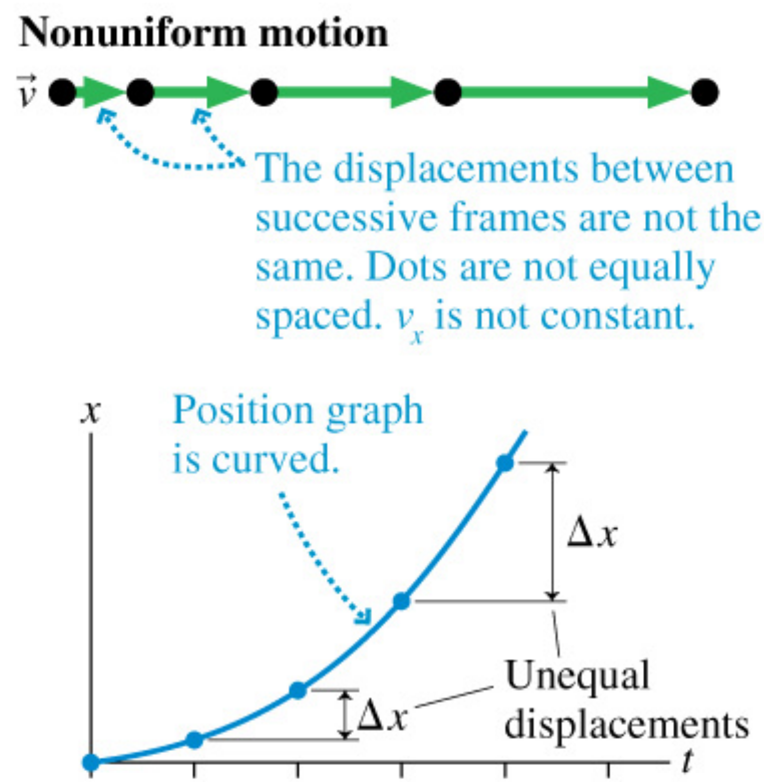
Steps in calculating rates of change:

- Draw a line tangent to the curve at the time you want. The line can be any length.
- Mark two points on the line and record the values.
- Calculate the slope

$$m = speed = \frac{d_2 - d_1}{t_2 - t_1} = \frac{6-2}{9.3-2.5} = 0.59\, {}^{m}\!/_{s}$$

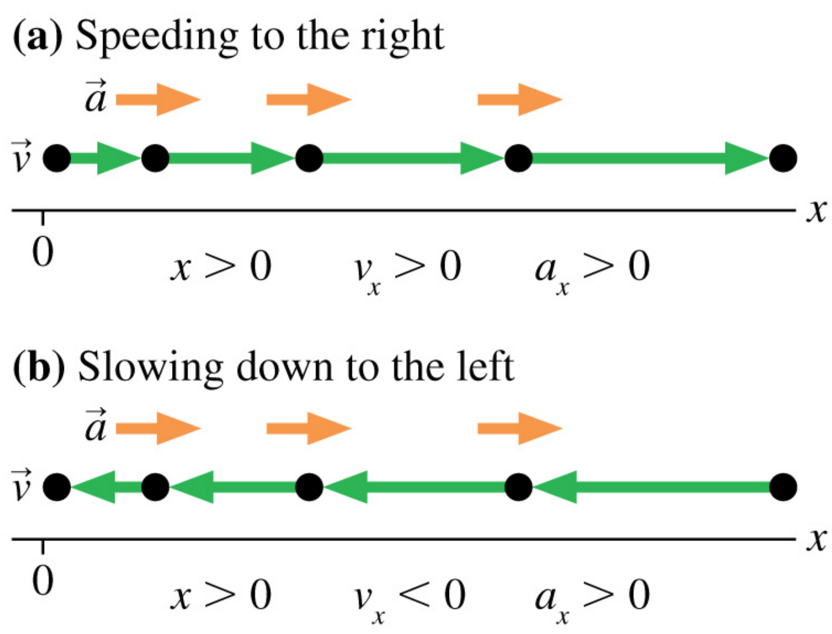
Non-uniform motion

- What if I have an acceleration?
- Then the motion is non-uniform
  - the displacements are not uniform for equal time periods
- The equations are easiest if the acceleration is constant
  - and this is the only case we will consider on a quantitative basis
- The displacements grow in magnitude as t increases; x vs t now has a (positive) curvature
  - $x=x_o+v_ot+1/2at^2$
- The velocity ($\Delta x/\Delta t$) increases with time
  - $v=v_o + at$



Acceleration

- Acceleration can be positive or negative
- In the figure shown to the right, the acceleration is positive (to the right)
- For case a, where the acceleration is in the same direction as the velocity, the speed increases
- For case b, where the acceleration is in the opposite direction to the velocity, the speed decreases



Falling bodies

- Remember, Galileo found that the distance travelled by a falling body increased with the square of the amount of time it fell
  - $y \alpha t^2$
  - so if a body is falling for twice the length of time, it falls four times as far
  - …and so on

Acceleration

- An example of an accelerated object is an object falling under the influence of gravity
  - $y = y_o + 1/2at^2$
  - here I've used y instead of x for the axis (from convention)
  - I can also write this as $y = y_o - 1/2gt^2$
  - where a=-g (the acceleration is in the –y direction
  - and $g = 9.8 \text{ m/s}^2$

$\vec{g}$