Conceptual Physics

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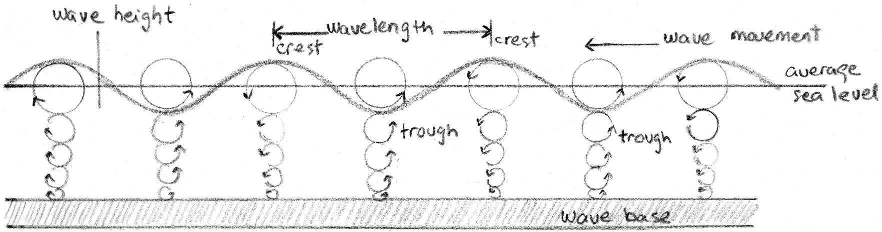
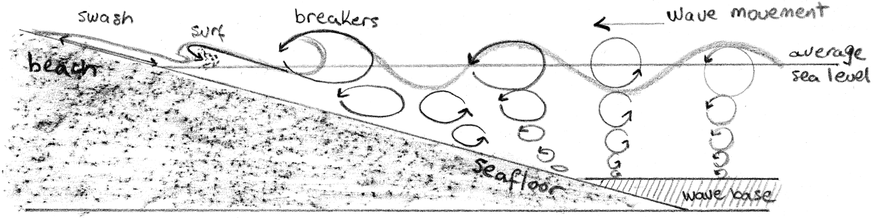
1. Waves as Energy Transfer
   - Wave basics
   - Periodic motion
   - What is sound?
   - Doppler effect

- Wave ☞ type of energy transmission
  that results from periodic disturbance ☞ vibration
- Waves transfer energy from one place to another
  without transferring matter
- They are composed of series of repeating patterns
- Two classes of waves ☞ $\begin{cases} \text{transverse} \\ \text{longitudinal} \end{cases}$
  - traverse ☞ vibration is perpendicular to direction of motion of wave
  - longitudinal ☞ vibration is in same direction as direction of wave

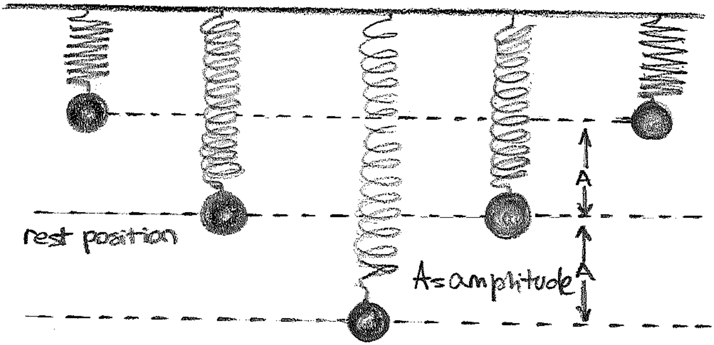
- Everyone has seen waves on surface water
- Water wave can travel hundreds of kilometers over ocean
  but water just moves up and down as waves passes
- Energy is transferred from one water molecule to next
  by forces that hold molecules together
- In open ocean ☞ water waves are transverse
- Near shore ☞ water waves becomes also longitudinal
- We live surrounded by waves
- Some are visible ☞ others are not
- By observing visible waves (e.g. ☞ in water)
  we can describe some characteristics that all waves
  (including invisibles ones) have in common

Water waves


wave height
wavelength
crest
crest
wave movement
average sea level
trough
trough
wave base


swash
surf
breakers
wave movement
beach
average sea level
seafloor
wave base

- Most waves originate from objects that are vibrating so rapidly that they are difficult to observed with our unaided senses
- For purposes of describing properties of vibrating objects we need slowly moving device ☞ mass bouncing on spring

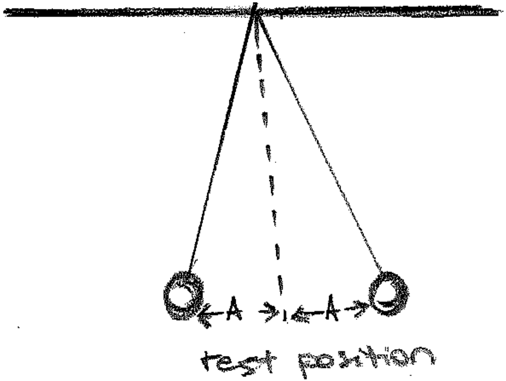


- When object repeat pattern of motion ☞ e.g. bouncing springs
  we say object exhibits periodic motion
- Vibration or oscillation of object is repeated over and over
  with same time interval each time
- When we describe the motion of vibrating object
  we call one complete oscillation a *cycle*
- Frequency ν ☞ number of cycles per second
- Unit used to measure frequency ☞ hertz (Hz)
- Period $\mathcal{T}$ ☞ time required for one cycle
- Period is usually measured in seconds
- Frequency and period are reciprocals

$$\nu = \frac{1}{\mathcal{T}} \quad \text{and} \quad \mathcal{T} = \frac{1}{\nu}$$

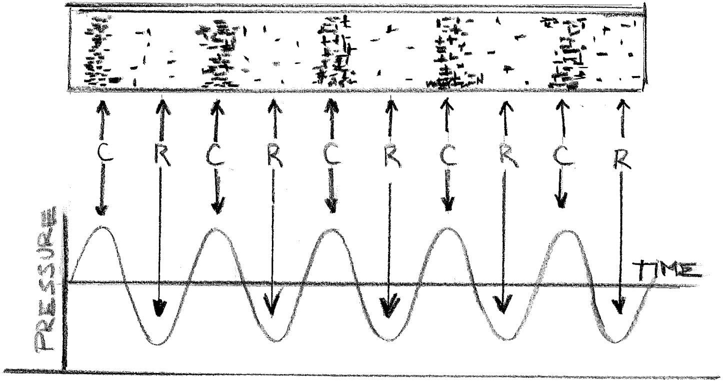
- If frequency is 60 Hz ☞ period is 1/60 s (or 0.017 s)

- As pendulum swings ☞ repeats same motion in = time intervals
- We say it exhibits periodic motion
- Observe successive swings ☞ distances reached by pendulum on either side of rest position are almost equal
- Amplitude A ☞ distance in either direction from rest position to maximum displacement



- We have seen that a wave is a transfer of energy
  in form of disturbance usually through a material
- Sound is a pressure wave which is created by vibrating object
- This vibrations set particles in surrounding medium
  (typical air) in vibrational motion
  thus transporting energy through medium
- Since particles are moving in parallel direction to wave movement sound wave is referred to as a longitudinal wave

Longitudinal waves



Creation of compressions and rarefactions within air

- A sound wave (as any other wave) can be characterized by its:
  1. amplitude A ☞ distance from midpoint of wave to a crest or trough (maximum displacement from equilibrium)
  2. frequency ν ☞ number of repeating patterns (cycles) per unit time
  3. period $\mathcal{T}$ ☞ time for one cycle
  4. wavelength λ ☞ distance from crest (or trough) to another crest (or trough)
  5. speed

$$v = \lambda \, \nu = \lambda / \mathcal{T}$$

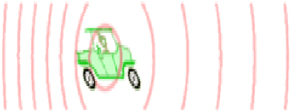
- Speed of sound in dry air

$$v_{\rm sound} = \left[331.5 + 0.6 \left(\frac{T}{{}^\circ{\rm C}}\right)\right] \ {\rm m/s}$$

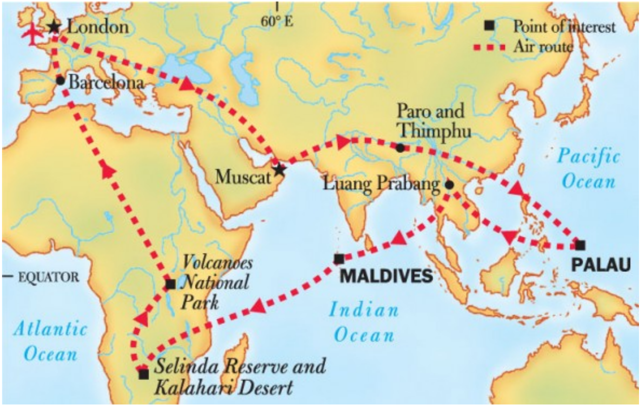
- Human ear can hear from 20 to $20,000~{\rm Hz}$
- Infrasonic is below this frequency and ultrasonic above

- Sound can bounce off of objects
  angle of incidence = angle of *reflection*
- Sound *reflection* gives rise to echoes
- Change of sound speed in different mediums
  can bend wave if it hits different medium at non 90° angle
- This is called *refraction*
- Waves can superimpose
  and constructively and destructively interfere
  increasing each other or destroying each other
- Standing waves are formed when a wave is reflected
  and constructively interferes such that wave appears to stand still

- When we observe sound wave from source at rest
  time between arrival wave crests at our instruments
  is same as time between crests as they leave source
- If source is moving toward us
  time between arrivals of wave crests is decreased
  because each successive crest has shorter distance to go
- Time between crests ☞ wavelength divided by speed of wave
- A wave sent out by source moving towards us
  will appear to have shorter wavelength than if source were at rest

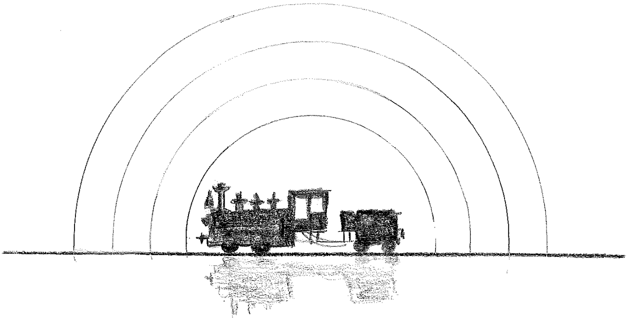


- Weinberg's analogy



- *Doppler effect* ☞ change in observed frequency of source due to relative motion between source and receiver
- Relative motion that affects observed frequency is only motion in line-of-sight between source and receiver

- We first consider relative motion of receiver with $V_{\rm receiver}$
- Stationary source emitting sound waves



- If receiver moves towards the source with velocity $V_{\rm receiver}$
  each successive sound wave will be detected earlier
  than it would have if receiver were stationary
  due to motion of receiver along line-of-sight

- Detected frequency of each successive wave front will be changed by this relative motion ☞ $\Delta\nu = V_{\rm receiver}/\lambda_{\rm emitted}$

  $\Delta\nu = \nu_{\rm received} - \nu_{\rm emitted}$ ☞ change in the observed frequency

  $\lambda_{\rm emitted}$ ☞ original wavelength of source

- Since $\nu_{\rm emitted} = v_{\rm sound}/\lambda_{\rm emitted}$ and $\nu_{\rm received} = \nu_{\rm emitted} + \Delta\nu$

$$\nu_{\rm received} = \frac{v_{\rm sound} + V_{\rm receiver}}{\lambda_{\rm emitted}} = \nu_{\rm emitted}\left(\frac{v_{\rm sound} + V_{\rm receiver}}{v_{\rm sound}}\right)$$

- If motion is away from source

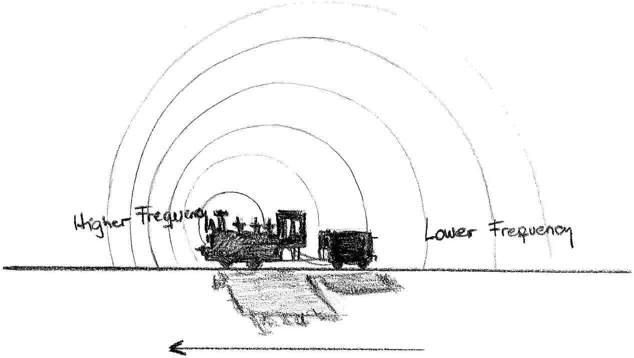
  relative velocity would be in opposite direction

$$\nu_{\rm received} = \nu_{\rm emitted}\left(\frac{v_{\rm sound} - V_{\rm receiver}}{v_{\rm sound}}\right)$$

- Two equations are usually combined and expressed as

$$\nu_{\rm received} = \nu_{\rm emitted}\left(\frac{v_{\rm sound} \pm V_{\rm receiver}}{v_{\rm sound}}\right)$$

- If source is moving towards receiver with $V_{\rm source}$ spacing between successive wave fronts would be less



- This would be expressed as ☞ $\Delta\lambda = V_{\rm source}/\nu_{\rm emitted}$
- To calculate the observed frequency

$$\nu_{\rm received} = \frac{v_{\rm sound}}{\lambda_{\rm emitted} + \Delta\lambda} = \nu_{\rm emitted}\left(\frac{v_{\rm sound}}{v_{\rm sound} - V_{\rm source}}\right)$$

- If source is moving away

$$\nu_{\rm received} = \nu_{\rm emitted} \left(\frac{v_{\rm sound}}{v_{\rm sound} + V_{\rm source}} \right)$$

- When combined with previous result

$$\nu_{\rm received} = \nu_{\rm emitted} \left(\frac{v_{\rm sound}}{v_{\rm sound} \mp V_{\rm source}} \right)$$

- By combining all previous results

$$\nu_{\rm received} = \nu_{\rm emitted} \left(\frac{v_{\rm sound} \pm V_{\rm receiver}}{v_{\rm sound} \mp V_{\rm source}} \right)$$

- One interesting application of Doppler effect ☞ active sonar
- We must carefully define *source* and *receiver*
- For outgoing active pulse ☞ reciver is target

$$\nu_{\rm received}^{\rm target} = \nu_{\rm emitted} \left(\frac{v_{\rm sound} \pm V_{\rm target}}{v_{\rm sound} \mp V_{\rm source}} \right)$$

- For return pulse (echo) ☞ receiver is ship sending original pulse

$$\nu_{\rm echo} = \nu_{\rm received}^{\rm target} \left(\frac{v_{\rm sound} \pm V_{\rm source}}{v_{\rm sound} \mp V_{\rm target}} \right)$$

- Substituting for $\nu_{\rm received}^{\rm target}$

$$\nu_{\rm echo} = \nu_{\rm emitted} \left(\frac{v_{\rm sound} \pm V_{\rm target}}{v_{\rm sound} \mp V_{\rm source}} \right) \left(\frac{v_{\rm sound} \pm V_{\rm source}}{v_{\rm sound} \mp V_{\rm target}} \right)$$