Course Notes and Workbook for INTRODUCTION TO SOUND: Acoustics for the Hearing and Speech Sciences

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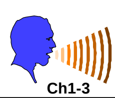
A Comment About the Printed Slides

All figures and tables in this Course Notes and Workbook also appear in larger, more readable form in the textbook, “Introduction to Sound: Acoustics for the Hearing and Speech Sciences.” In the interest of cost and convenience to students, the figures were organized and reproduced in a condensed format in this workbook.

Chapter 1

THE NATURE OF SOUND WAVES



What is Sound?

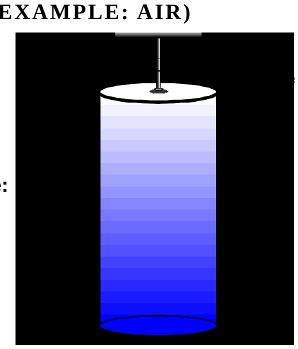
- We will emphasize the <u>physical</u>, not <u>psychological</u>, perspective
- A <u>source</u> of sound must be able to <u>vibrate</u>
- To vibrate, a source must have two properties
  - mass (m)
  - elasticity (E)

What is Sound?

- To transmit sound, a medium must be capable of being set into vibration
- To do so, it must have the same two properties
  - mass (m)
  - elasticity (E)

PROPERTIES OF THE TRANSMITTING MEDIUM (EXAMPLE: AIR)

- 400 billion, billion (4×10^{20}) molecules / in.^{3}
- Random molecular motion: 1,500 kph (940 mph)
- Atmospheric pressure:
  - 14.7 lb / in.^{2}
  - 100,000 N / m^2
  - 1,000,000 dynes / cm^2



Two Physical Properties are Essential

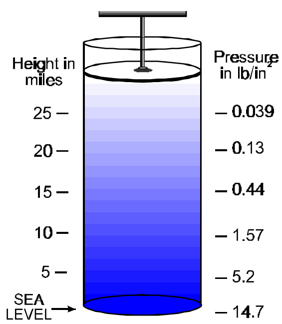
- What are they?
  - ☑ Mass (m)
  - ☑ Elasticity (E)
- 1. Mass (m)
  - ♦ The amount of matter present
  - ♦ Applies to gases, liquids, & solids

Mass Contrasted with Weight

- Weight is an attractive gravitational <u>force</u>; mass is the quantity of matter present
- 160 lb on earth = 27 lb on the moon because force of gravity is 6:1
- Weight ∝ to mass, but they are different concepts
  - ♦ weight is a force
  - ♦ mass is the quantity of matter present
  - ♦ air has mass and weight

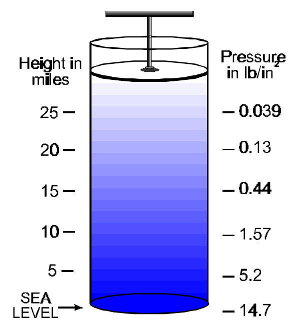
Mass (m) and Density (ρ)

- Density (ρ) is the mass per unit volume ($\rho = m / v$)
- Density is a quantity <u>derived</u> from another quantity (mass)
- Note how density varies with height above sea level



Two Physical Properties

- 2. Elasticity (E)
  - ♦ Property that enables <u>recovery</u> from <u>distortion</u> of shape or volume
  - ♦ Concept of "Elastic Limit"
  - ♦ Air: "Tendency of air volume to return to its former volume after compression" i.e., density is restored

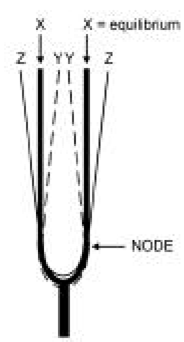


PROPERTIES OF THE SOUND SOURCE

- Same two properties: What are they?
  - ☑ Mass (m)
  - ☑ Elasticity (E)

Vibratory Motion of a Tuning Fork

- Animation F1-2
- Strike the fork: Vibration occurs
- Tines displaced from equilibrium
- Amplitude of displacement is proportional to force applied

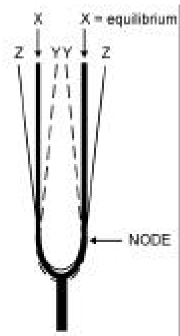


Newton's First Law of Motion: Inertia

- The property addressed by Newton's first law is called <u>inertia</u>
- Newton's Inertial Law: All bodies remain at rest or in a state of uniform motion unless another force acts in opposition
- Magnitude of inertia is directly proportional to the <u>mass</u>: thus mass is a <u>measure of inertia</u>

Vibratory Motion: Why does it occur?

- The interaction of two opposing forces: inertia and elasticity
- Back and forth, to and fro, movement
- The opposition of two forces is consistent with Newton's third law

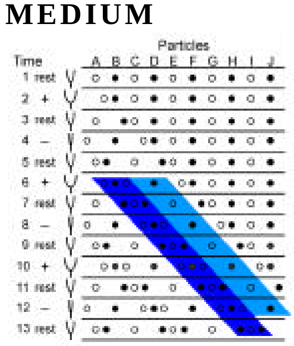


Newton's Third Law of Motion: Reaction Forces

- Newton's Third Law: With every force there <u>must</u> be an <u>equal</u> and opposite reaction force
  - Hammer- nail: Bat- ball
  - Force cannot exist alone
- Vibration: elasticity is the <u>reaction force</u> to inertia
  - Vibration continues without reapplication of external force: vibration sustained by opposing forces
  - One <u>cycle of vibration</u> (return to #14)

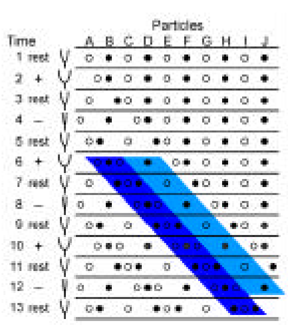
SOUND SOURCE ACTING ON A MEDIUM

- Animation F1-3
- Place tuning fork in medium: observe effect on medium
- Before force is applied, particles are, on average, equidistant from one another



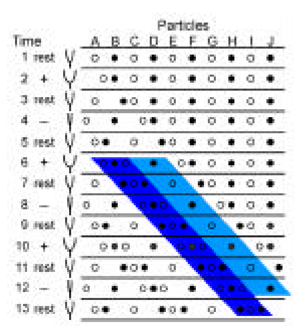
Movement of Air Particles

- Particles move about positions of equilibrium because of two opposing forces: What are they?
  - ☑ Inertia
  - ☑ Elasticity



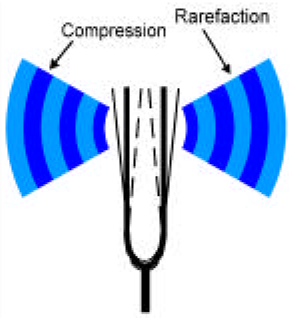
Movement of Air Particles

- Force from A to B to..........n
  - Across rows: particles move to and fro <u>over a small distance</u>
  - Note <u>crowding</u> (compression) and <u>thinning</u> (rarefaction)



Movement of Air Mass

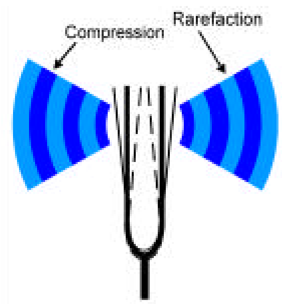
- Animation F1-4
- Density increases: compression
- Density decreases: rarefaction
- Alternate regions of compression and rarefaction move through medium



Ch1-19

Displacement of Air Medium & Wave Motion

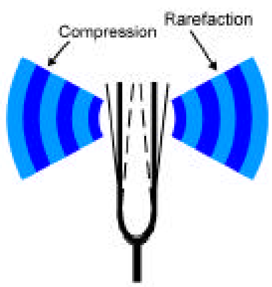
- Medium is not displaced over a great distance!
- A wave of disturbance moves through the medium
  - Sporting events (the “wave”)
  - Synchronized flashing of light bulbs on theater marquees



Ch1-20

Displacement of Air Medium & Wave Motion

- SOUND: characterized by propagation of density changes through elastic medium
- Need to consider selected physical quantities such as
  - mass
  - density
  - force
  - pressure
  - displacement



Ch1-21

FUNDAMENTAL PHYSICAL QUANTITIES

- There are three: What are they?
  - ☑ Length
  - ☑ Mass
  - ☑ Time
- All other physical quantities are derived

Ch1-22

Systems of Measure

- Metric: MKS & cgs
- English: fps

	MKS	cgs	fps
♦ length	(m)	(cm)	(ft)
♦ mass	(kg)	(g)	(lb)
♦ time	(s)	(s)	(s)

Ch1-23

1. Length

- A measure of distance: the amount of spatial separation between two points
  - How many times a unit (meter, cm, ft, etc.) is contained in a given distance.
  - 1 m = distance traveled by light in a vacuum during 3×10^{-9} ms.

Ch1-24

Units of Measure: Length

- Units of Measure

  MKS -- meter (m)

  cgs -- centimeter (cm)

  fps -- foot (ft)

- Sample Conversions

  1 in. = 2.54 cm

  1 ft = .3048 m

  1 m = 100 cm

  1 cm = .01 m

  1 mm = .001 m

2. Mass

- The quantity of matter present
- Defines the magnitude of inertia
- Inertia ∝ mass
  - A steel ball and ping-pong ball are the same size: Which has greater mass, hence greater inertia?
    - ☑ steel ball

Units of Measure: Mass

- MKS ----- kilogram (kg)
- cgs ----- gram (g)
- fps ----- pound (lb)
- The quantity of mass defines the amount of inertia

3. Time

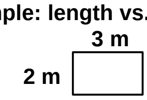
- A quantity expressed in seconds (s), minutes (min), hours (hr), etc.
- 1 s = 1/86,400 of a solar day
  - 24 hrs × 60 min × 60 s = 86,400

Units of Measure: Time

- MKS ---- second (s)
- cgs ---- second (s)
- fps ---- second (s)

DERIVED PHYSICAL QUANTITIES

- A derived quantity is a quotient or product of fundamental, or of fundamental and derived, physical quantities
- Example: length vs. area



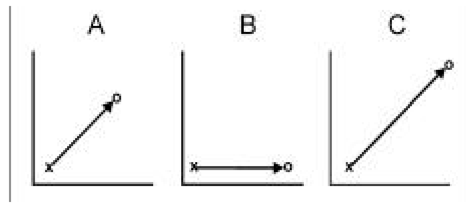
  - L_l = 3 m fundamental quantity
  - L_w = 2 m fundamental quantity
  - A = 6 m^2 derived quantity

Derived Quantities of Interest

- Displacement (x)
- Velocity (c)
- Acceleration (a)
- Force (F)
- Pressure (p)

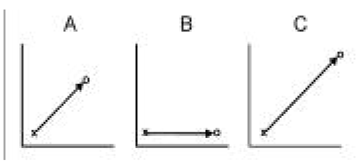
1. Displacement (x)

- A change in position (re: equilibrium, e.g.)



1. Displacement (x)

- A <u>vector</u> quantity: incorporates both
  - <u>Magnitude</u>
  - <u>Direction</u>
    - >> A vs. B
    - >> A vs. C
    - >> B vs. C



- Contrast with a <u>scalar</u> quantity: has only <u>magnitude</u> (e.g., mass, time, energy, etc.)

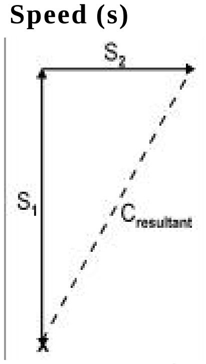
2. Velocity (c)

- The <u>amount of displacement per unit time</u>

  Or
- The <u>time-rate of displacement</u>
- Also a vector quantity
- Average velocity
  - c = x / t
  - c = derived (x) / fundamental (t)

Velocity (c) vs. Speed (s)

- Speed is a scalar quantity (only <u>magnitude</u>)
- s = d / t
- $c_{resultant} = \sqrt{s_1^2 + s_2^2}$
- Average vs. Instantaneous Velocity



Summary of Velocity: Displacement Per Unit Time

- MKS --- m / s
- cgs --- cm / s
- fps --- ft / s, mph, etc.

3. Acceleration (a)

- The time-rate change in velocity
- Also a vector quantity
- Positive vs. Negative Acceleration (Deceleration)

Ch1-37

3. Acceleration (a)

- $a = \Delta c / t = (c_2 - c_1) / t$
  - $c_1 = 20$ m / s
  - $c_2 = 40$ m / s
  - t = 5 s
  - What is a?
    - ☑ $a = \frac{(40 - 20)}{5} = 4$ m / s / s
      $= 4$ m / s^2

Ch1-38

3. Acceleration (a)

- A car moves around a circular tract at a constant speed. Is it accelerating?
  - ☑ YES: Direction is changing, hence velocity is changing. Velocity cannot change without acceleration.

Ch1-39

4. Force (F)

- A push or pull
- The product of mass (m) and acceleration (a)
- F = ma (Newton's 2nd Law: a = F / m)
- Object has mass (inertia), which opposes change in motion: force is applied to overcome inertia
  - a = F / m
  - ∴ F = ma

Ch1-40

Consequences of Force

- Distortion of matter

  and / or
- Acceleration of matter
- A push or pull OR that which imparts acceleration to a mass

Ch1-41

Force as a Vector

- Magnitude and Direction
- Vector addition necessary
  - If two forces are at right angles to one another, resultant forces solved by the Pythagorean theorem
  - $F_{resultant} = \sqrt{F_1^2 + F_2^2}$

Ch1-42

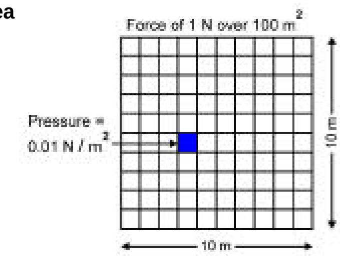
Units of Measure of Force

- MKS — newton (N)
  - Force required to accelerate a mass of 1 kg from c = 0 m / s to c = 1 m / s in 1 s
- cgs — dyne
  - Force required to accelerate mass of 1g from c = 0 cm / s to c = 1 cm / s in 1 s
- 1 N = 100,000 dynes

Ch1-43

5. Pressure (p)

- Force per unit area
- p = F / A
- p = 1 N / 100 m^2 = .01 N / m^2



Ch1-44

Units of Measure of Pressure

- What are they in MKS and cgs systems?
  - ☑ MKS — N / m^2
  - ☑ cgs — dyne / cm^2
- 1 N / m^2 = how many dynes / cm^2?
  - 1 N / m^2 = 10 dynes / cm^2

Ch1-45

Derivation

1 N = 100,000 dynes
1 m = 100 cm
Thus,
1 N / m^2 = 100,000 dynes / m^2
$m^2 = m \times m$
1 N / m^2 = 100,000 dynes / 10,000 cm^2
Thus,
1 N / m^2 = 10 dynes / cm^2

Ch1-46

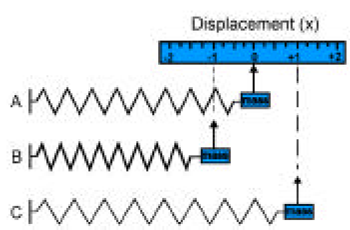
An Alternative Unit of Measure for Pressure

- The pascal (Pa)
- 1 pascal (Pa) = 1 N / m^2
- 1 Pa = how many dynes / cm^2?
  - ☑ 1 Pa = 10 dynes / cm^2

Ch1-47

VIBRATORY MOTION OF A SPRING - MASS SYSTEM

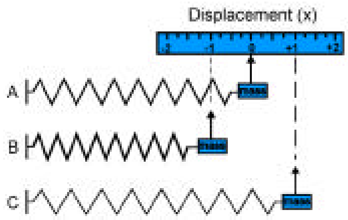
- Animation F1-8
- Panel A: spring at equilibrium
- Panel B: spring compressed
- Panel C: spring stretched



Ch1-48

Characteristics of a Spring

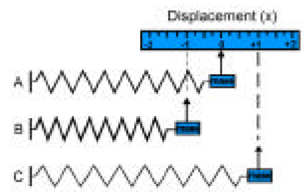
- Spring can be <u>compressed</u>
- Elasticity (<u>restoring force</u>) opposes deformation force



Ch1-49

Characteristics of a Spring

- Hooke's Law: Magnitude of restoring force (F_r) is directly proportional to magnitude of displacement (x)
- $F_r = - kx$
- As spring is compressed, greater force required for additional compression



Ch1-50

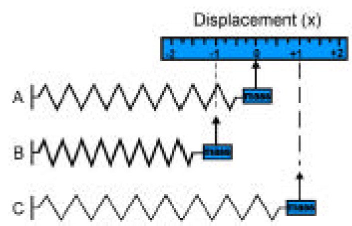
Stiffness and Compliance

- Stiffness is the spring constant (k)
- Compliance is the inverse of stiffness

Ch1-51

VIBRATORY MOTION OF A SPRING - MASS SYSTEM

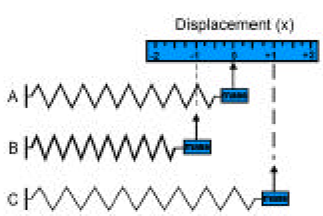
- Displace mass
- Spring is compressed
- System is set into vibration



Ch1-52

VIBRATORY MOTION OF A SPRING - MASS SYSTEM

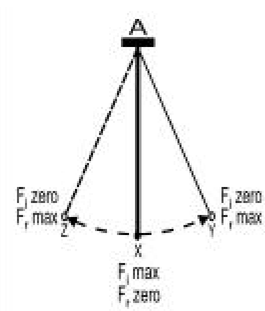
- Vibration sustained by interaction of two opposing forces: What are they?
  - ☑ inertia
  - ☑ elasticity
- System engages in <u>simple harmonic</u>, or <u>sinusoidal</u>, <u>motion</u>



Ch1-53

THE PENDULUM: EXAMPLE OF SLOW MOTION VIBRATION

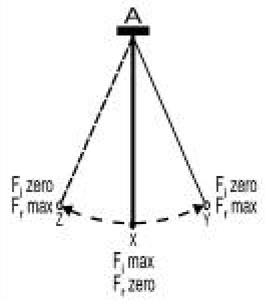
- Animation F1-9
- Restoring force <u>opposes</u> applied force
- Restoring force is gravity, not elasticity
- Sustained vibratory motion has two opposing forces:
  - ♦ Inertia
  - ♦ Gravity



Ch1-54

THE PENDULUM: EXAMPLE OF SLOW MOTION VIBRATION

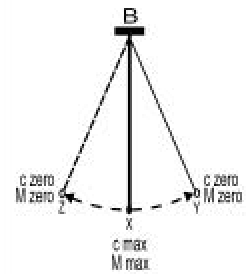
- Inertial force (F_i) is maximal at equilibrium and zero at maximum displacement where motion is momentarily halted
- Restoring force (F_r) is maximal at maximum displacement and zero at equilibrium



Momentum

Effect of momentum replaces force of inertia

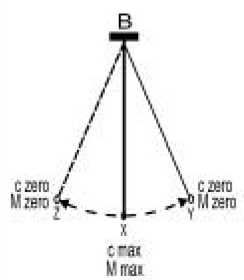
- Momentum given by the product of mass and velocity
- M = mc
- Why does pendulum gain momentum as it approaches equilibrium?
  - ☑ Because c increases



Momentum

Effect of momentum replaces force of inertia

- c is maximal at equilibrium and zero at maximum displacement where motion is momentarily halted
- M is also maximal at equilibrium and zero at maximum displacement where motion is momentarily halted



The Energy Principle

- Used to describe vibratory motion of a pendulum
- System must receive a supply of energy
- Energy is something that can <u>produce a change in matter</u>
  - e.g., Displacement, distortion

The Energy Principle

- If a change in matter occurs, <u>work</u> has been done
- Energy is the <u>capacity to do work</u>

Energy vs. Work

- Energy: Something that a body <u>possesses</u>
- Work: Something that a body <u>does</u>

Work

- A body is moved because a force is applied
- Work is given by product of the force applied and the distance moved

$W = Fd$

Ch1-61

Units of Measure: Work

- MKS — joule
- How would you define it?
  - 1 joule = 1 N × 1 m
- cgs — erg
- How would you define it?
  - 1 erg = 1 dyne × 1 cm

Ch1-62

Units of Measure: Work

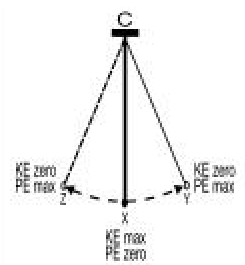
- 1 joule = 10^7 ergs
- Derivation
  - 10^0 N = 10^5 dynes
  - 10^0 m = 10^2 cm
  - 10^5 dynes × 10^2 cm = 10^7 ergs

Ch1-63

Transformation of Energy

The unifying concept that explains SHM and pendular motion, even though RESTORING FORCES are different

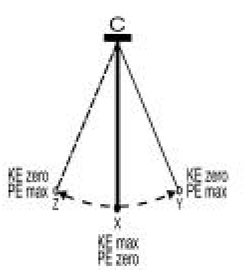
- Energy is not depleted; It is transferred or transformed
- Potential Energy (PE)
  - Stored energy
- Kinetic Energy (KE)
  - Energy of motion
- PE + KE = k



Ch1-64

Transformation of Energy

- KE is
  - maximal at equilibrium where c is maximal, &
  - zero at maximum displacement where motion is momentarily halted and c = 0
- PE is
  - maximal at maximum displacement, &
  - zero at equilibrium



Ch1-65

Frictional Resistance

- Motion ultimately ceases because of frictional resistance
- Frictional resistance is a force that opposes motion and thus limits velocity

Ch1-66

Frictional Resistance

- KE transformed to thermal energy (heat)
- Result is damping, or damped vibration
- Frictional resistance is analogous to electrical resistance to the flow of current in a circuit

Ch1-67

Characteristics of Pendular Motion

- 1. Amplitude of displacement
  - A vector quantity
  - Why a vector?
    - ☑ Displacement (x) is a vector quantity

Ch1-68

Characteristics of Pendular Motion

- 2. Frequency (f)
  - The rate of vibratory motion
  - The number of "cycles per second" (cps)
  - Unit of measure: hertz (Hz)
  - 1 Hz = 1 cps

Ch1-69

Characteristics of Pendular Motion

- What defines "one cycle?"
  - ☑ Movement from equilibrium to maximum displacement in one direction, back to equilibrium, on to maximum displacement in the opposite direction, and then back to equilibrium.

Ch1-70

Characteristics of Pendular Motion

- 3. Period (T)
  - The time required to complete one cycle
  - (seconds per cycle)
  - Equations !

>> $T = 1/f$

>> $f = 1/T$

Reciprocal relations

Ch1-71

Determinants of Frequency: Pendulum

- $T = 2\pi\sqrt{L/G}$
  - $T \propto \sqrt{L}$
  - $T \propto 1/\sqrt{G}$
  - $G = 9.8\ m/s^2$ (on earth)

Ch1-72

Determinants of Frequency: Pendulum

- f = ?
  - $f = \dfrac{1}{2\pi\sqrt{L/G}}$
- What are the proportional relations of f with L and G?
  - $f \propto 1/\sqrt{L}$
  - $f \propto \sqrt{G}$

PROPORTIONALITY

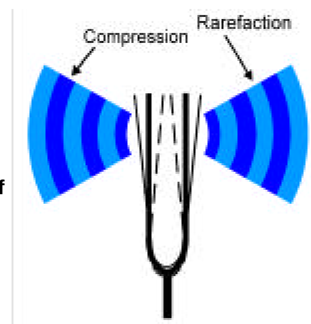
- Inversely proportional
  - $A \propto 1/B$
- Directly Proportional
  - $A \propto B$

Examples

- $T = 2\pi\sqrt{L/G}$: What are the proportional relations of T with L and G?
  - $T \propto \sqrt{L}$ (direct)
  - $T \propto 1/\sqrt{G}$ (inverse)
- W = Fd: What are the proportional relations of W with F and d?
  - $W \propto F$ (direct)
  - $W \propto d$ (direct)

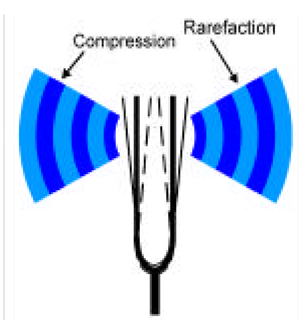
SOUND WAVE PROPAGATION

- Air particles move over a very small distance
  - 7.68×10^{-8} m
  - Equal to 1/300 of the diameter of a hydrogen molecule



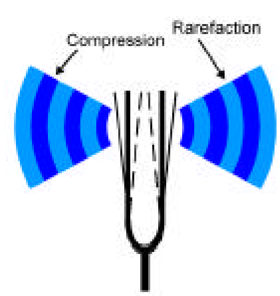
SOUND WAVE PROPAGATION

- See alternate regions of compression (increased density) and rarefaction (decreased density)
- That disturbance is propagated through the medium



SOUND WAVE PROPAGATION

- Consider water analogy
  - Place cork on water surface and initiate a wave
  - wave (crests and troughs) move by the cork
  - cork bobs (approximately) upward and downward



Two Events That Occur at Some Rate

- Rate (frequency) of vibratory movement
- Rate (speed) of wave propagation

Frequency of Vibratory Motion (f)

- Frequency of vibration of the source is determined by characteristics of source!
  - Tuning fork: density of metal & length of bar
  - String or wire: length, cross-sectional mass, & tension
- Frequency of vibration of air particles is the same as frequency of the source!

Speed of Sound (s)

- Speed of wave propagation is governed by properties of the medium!
- Examples
  - Light 299,728,458 m / s
    186,282.397 mi / s
  - Sound 331 m / s
    1085.96 ft / s
    >> At sea level, and
    >> If temperature = 0^{o} C

Speed of Sound in Air

- $s = \sqrt{E / \rho}$
- What are the proportional relations of s with E and ρ?
  - ☑ $s \propto \sqrt{E}$
  - ☑ $s \propto 1/\sqrt{\rho}$

Speed of Sound in Air

- Elasticity: Units of measure
  - MKS: N / m^2
  - cgs: $dynes / cm^2$
- Density (mass / volume): Units of measure
  - MKS: kg / m^3
  - cgs: g / cm^3

Effects of "Temperature"

- Speed increases by 0.61 m / s (2 ft / s) for each 1^{o} C increase in temperature
- At sea level, at 0^{o} C, s = 331 m / s
- What is s if temperature = 20^{o} C?
  - ☑ $s = 331 + [(20 - 0) \times .61]$
    $= 343$ m / s

Speed of Sound for Different Transmitting Media

- Air: 331 m / s or 1,086 ft / s
- Water: about 4 times that of air (1,433 m / s)
- Steel: about 14 times that of air (4,704 m / s)

Ch1-85

Steel Compared to Air

- Steel is 6,000 times more dense than air
  - $s \propto 1/\sqrt{\rho}$, but
- Steel is 1,230,000 times more elastic than air
  - $s \propto \sqrt{E}$

Ch1-86

Steel Compared to Air

- $\sqrt{1{,}230{,}000 / 6{,}000} = 14.3$
  - $\sqrt{(1.23 \times 10^6) / (6 \times 10^3)} = 1.43 \times 10^1$
- Elasticity: Best defined as the ability to <u>resist</u> deformation!

Ch1-87

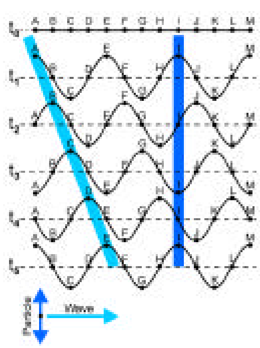
TYPES OF WAVE MOTION

- Classified by direction of <u>vibration of medium</u> re: direction of <u>wave propagation</u>
- Two types of wave motion
  - Transverse
  - Longitudinal

Ch1-88

Transverse Wave Motion

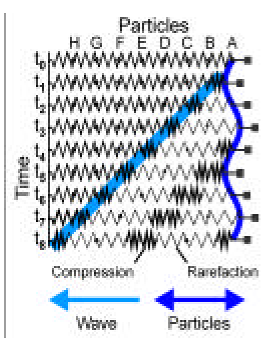
- Stretched rope or string
- Animation F1-10
- Vibration of medium is 90º re: direction of wave propagation
  - Elements of rope move up & down
  - Wave moves at right angles
  - Note peaks and valleys



Ch1-89

Longitudinal Wave Motion

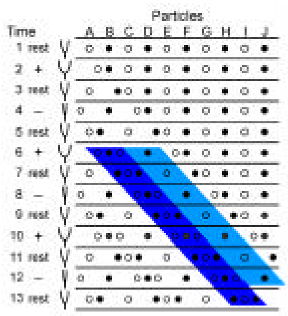
- Spring-mass system
- Animation F1-11
- Direction of particle movement is parallel to wave movement
  - Elements of spring move back & forth
  - Wave moves in same plane
  - Note compressions and rarefactions



Ch1-90

SOUND WAVES

- They are longitudinal waves
- Particles oscillate about their equilibrium positions
- Wave is propagated in same plane as particle displacement



TRANSFER OF ENERGY

- Sound is characterized as propagation of density changes through an elastic medium
- Sound is defined as transfer of energy through an elastic medium
  - Energy is transferred in direction wave is propagated
  - Air mass offers resistance
  - Kinetic energy is transformed to thermal energy