Lectures: Physics 3306

Provides an introduction to a wide variety of topics in classical (pre-quantum) physics as a bridge to prepare students for subsequent upper-level courses in physics. The topics covered include thermodynamics, fluid mechanics, mechanical waves, optics, radiation, electromagnetic phenomena, atoms, and laboratory techniques. Prerequisites: C- or better in PHYS 1106; and in PHYS 1304 or PHYS 1308.

Saptaparna Bhattacharya

February 16th, 2026

Based on Simon Dalley's lectures taught in Spring 2025

Labs

Lectures

Schedule

No class

Month	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
January	19	20	21 ✅	22	23 ✅	24	25
	26 ❄️🌨️❄❄❄	27	28 ❄️🌨️❄❄❄	29	30 ✅	31	1
February	2 ✅	3	4 ✅	5	6 ✅	7	8
	9 ✅	10	11 HWB due	12	13 ✅	14	15
	16 ✅	17	18 HWC due	19	20	21	22
	23	24	25 HWD due	26	27	28	1
March	2	3	4	5	6	7	8
	9	10	11	12	13	14	15
	16	17	18	19	20	21	22
	23	24	25	26	27	28	29
April	30	31	1	2	3	4	5

Labs

Lectures

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No class

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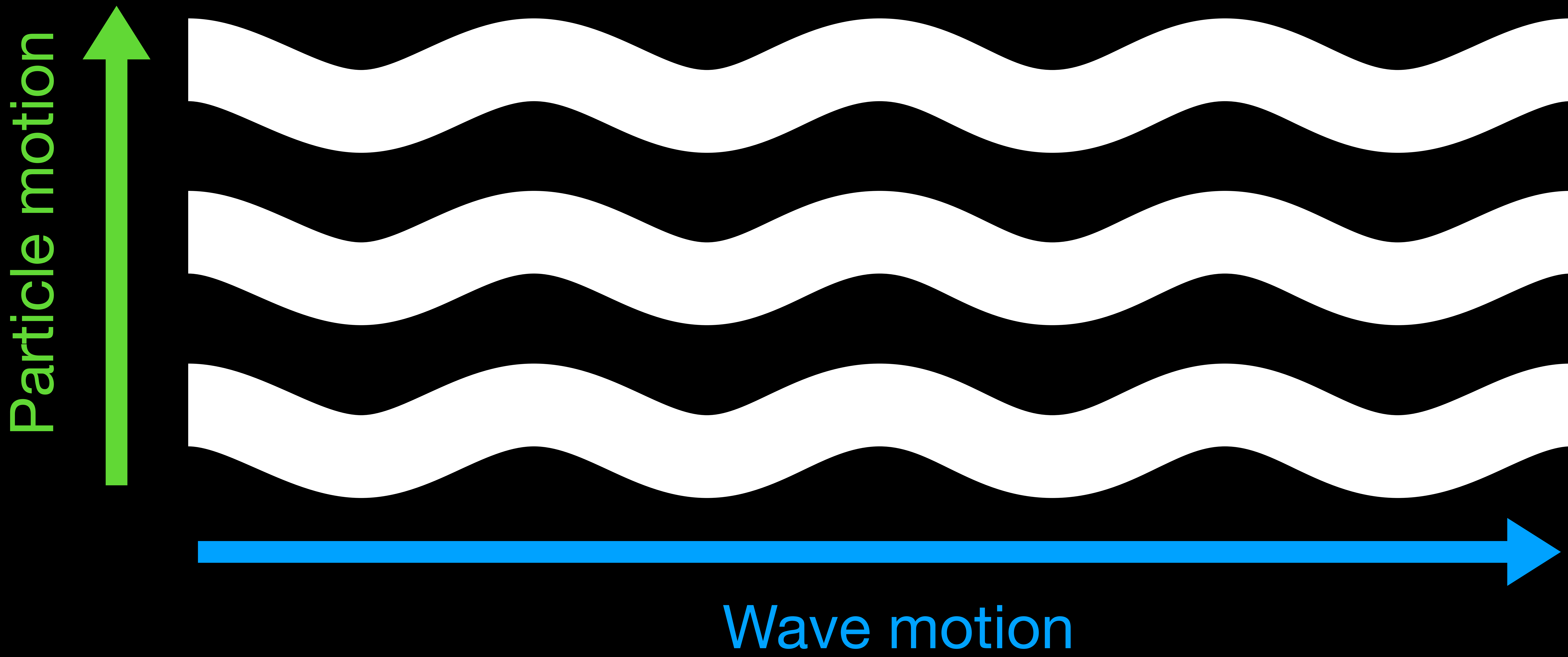
April	6	7	8	9	10	11	12
	13	14	15	16	17	18	19
	20	21	22	23	24	25	26
May	27	28	29	30	1	2	3
	4	5	6	7	8	9	10

Key concepts: directionality



Key concepts: transverse waves

- First picture:
  - Pulse is sent
- Second picture:
  - Continuous simple harmonic motion (traveling to velocity $\vec{v}$)
- Example of a transverse wave

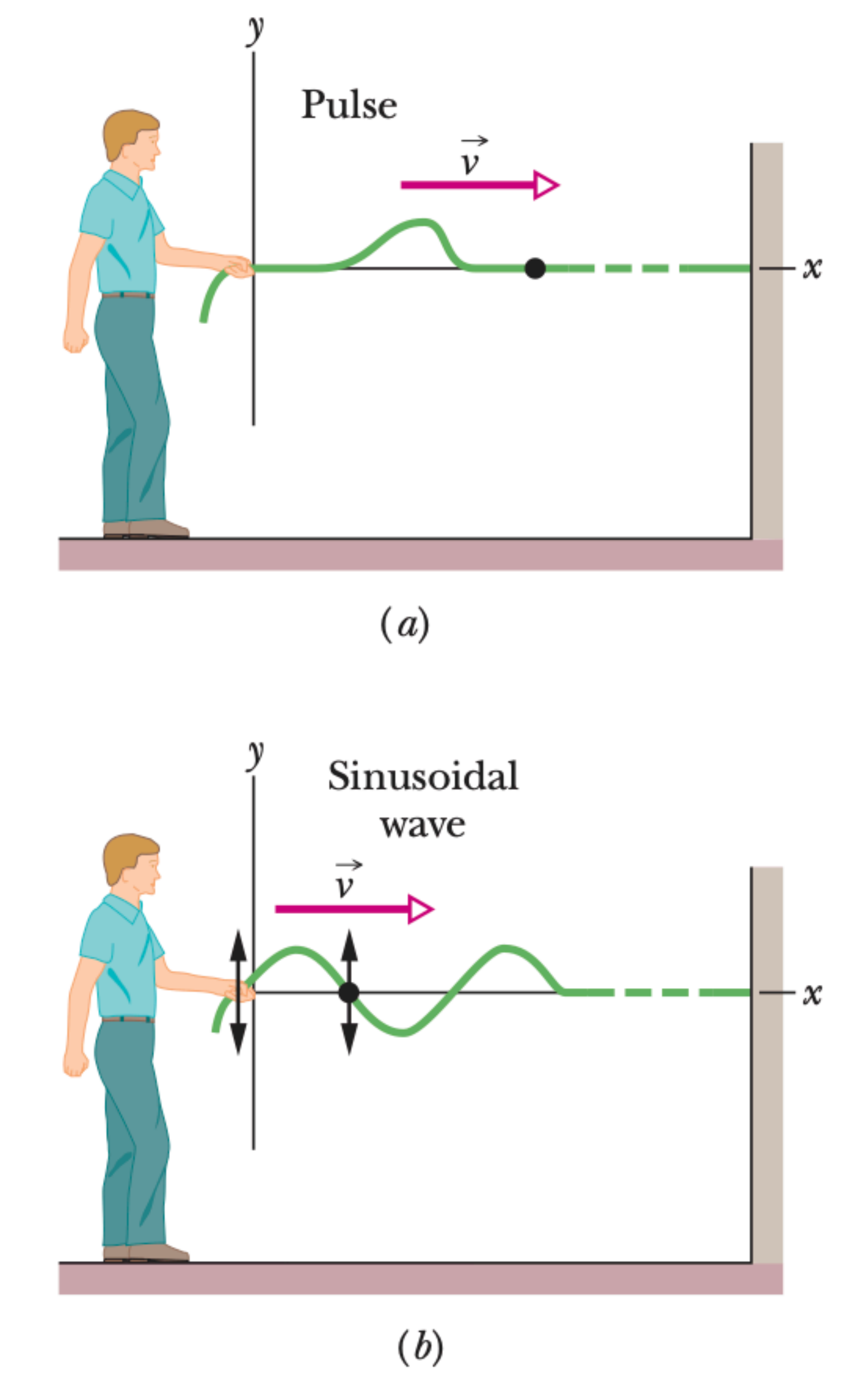


Figure 16-1 (*a*) A single pulse is sent along a stretched string. A typical string element (marked with a dot) moves up once and then down as the pulse passes. The element's motion is perpendicular to the wave's direction of travel, so the pulse is a *transverse wave*. (*b*) A sinusoidal wave is sent along the string. A typical string element moves up and down continuously as the wave passes. This too is a transverse wave.

Key concepts: longitudinal waves

- Produce a sound wave by moving the piston right to left
- Motion of the air and change in air pressure travel rightward along the pipe as a pulse

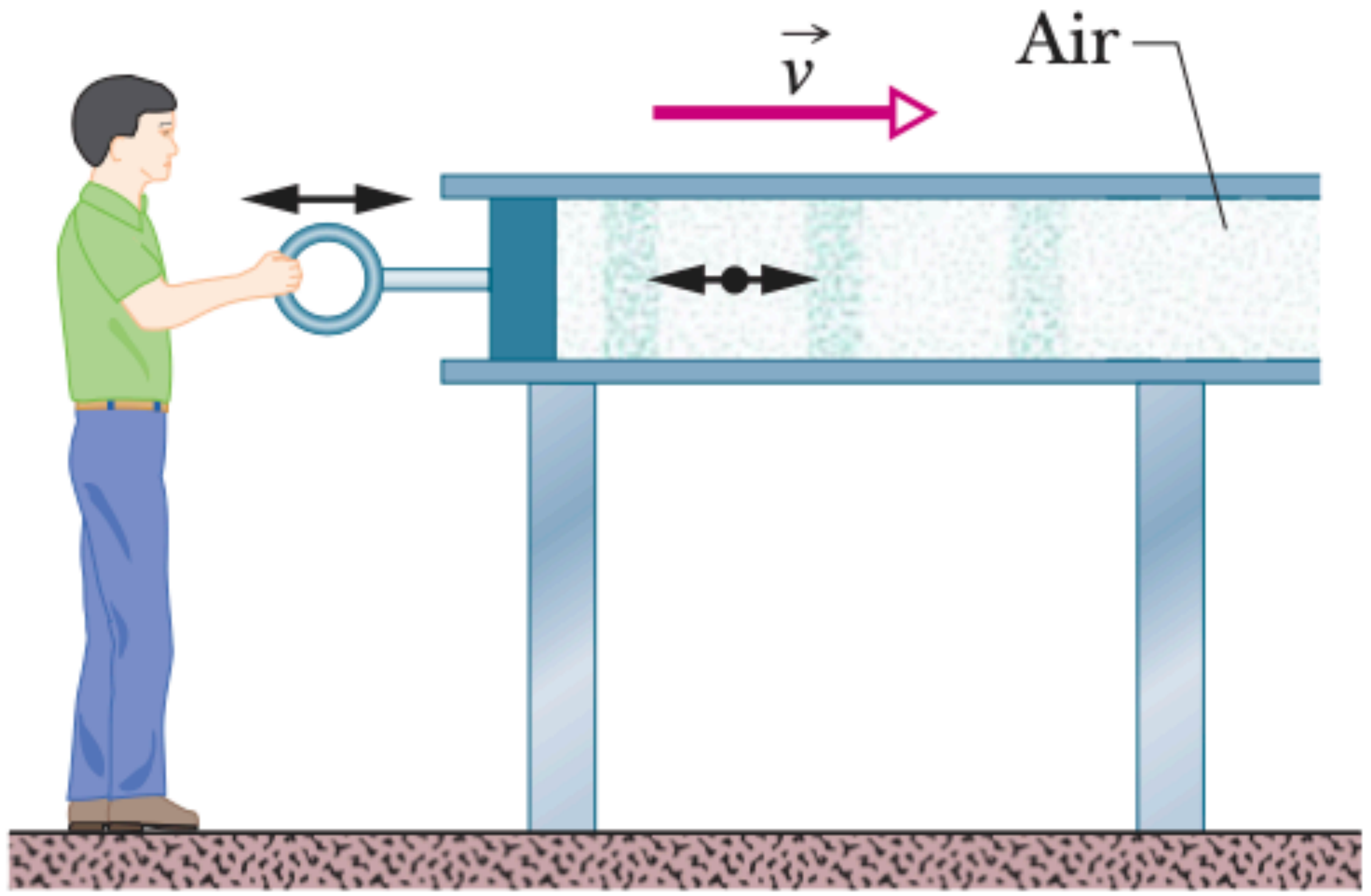
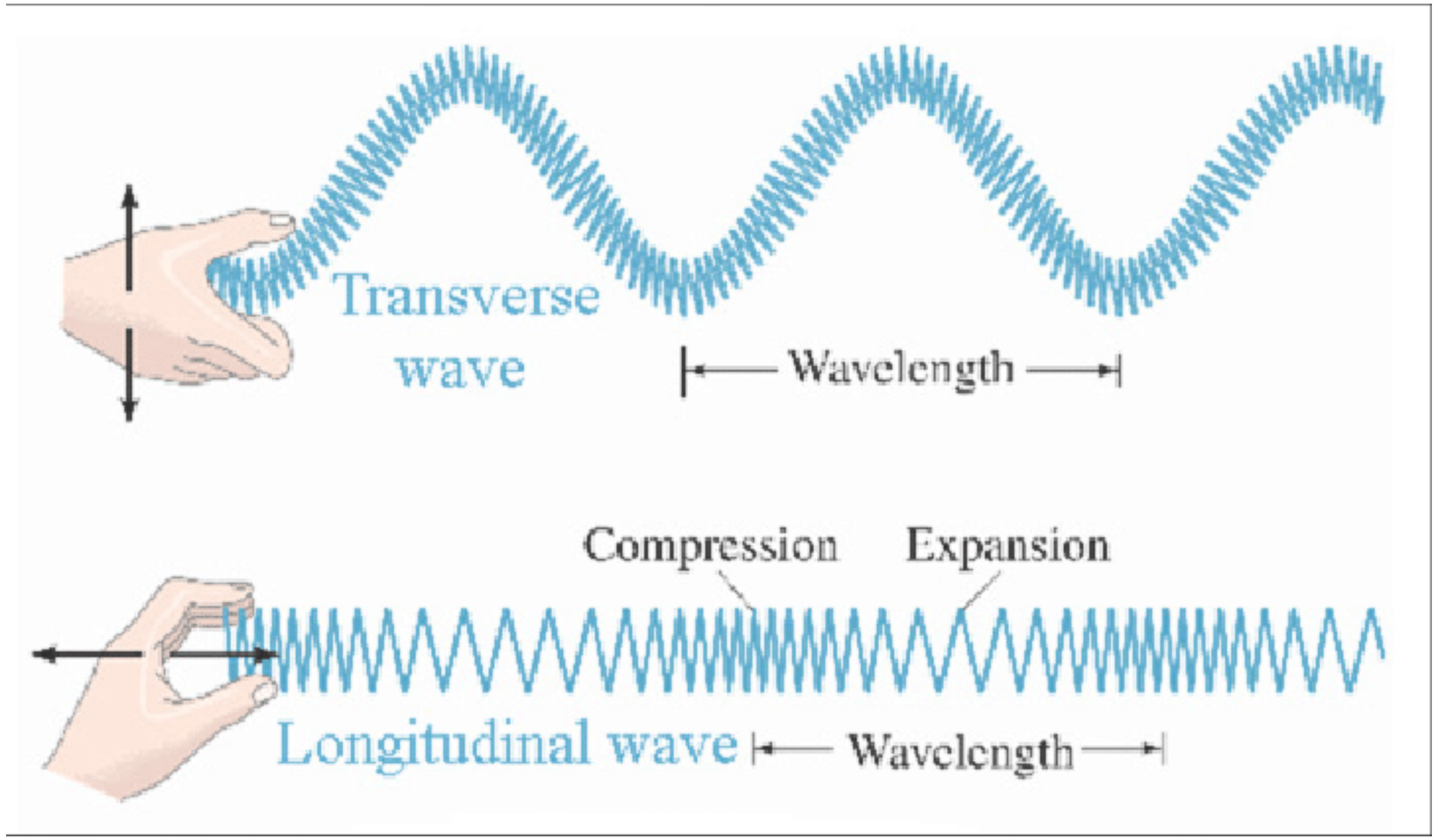


Figure 16-2 A sound wave is set up in an air-filled pipe by moving a piston back and forth. Because the oscillations of an element of the air (represented by the dot) are parallel to the direction in which the wave travels, the wave is a *longitudinal wave.*

Longitudinal vs. Transverse (17.1-17.3)



Longitudinal waves: Key concepts

- A sound wave is defined as a longitudinal wave
- Key ideas:
  - Point S represents a tiny source, called a point source S
    - Emits sound in all directions
    - Wavefronts and rays indicate the direction of travel and the spread of sound waves
    - Wavefront: surface over which oscillation due to sound has the same value
      - Such surfaces are represented by whole or partial circles in a two-dimensional drawing for a point source

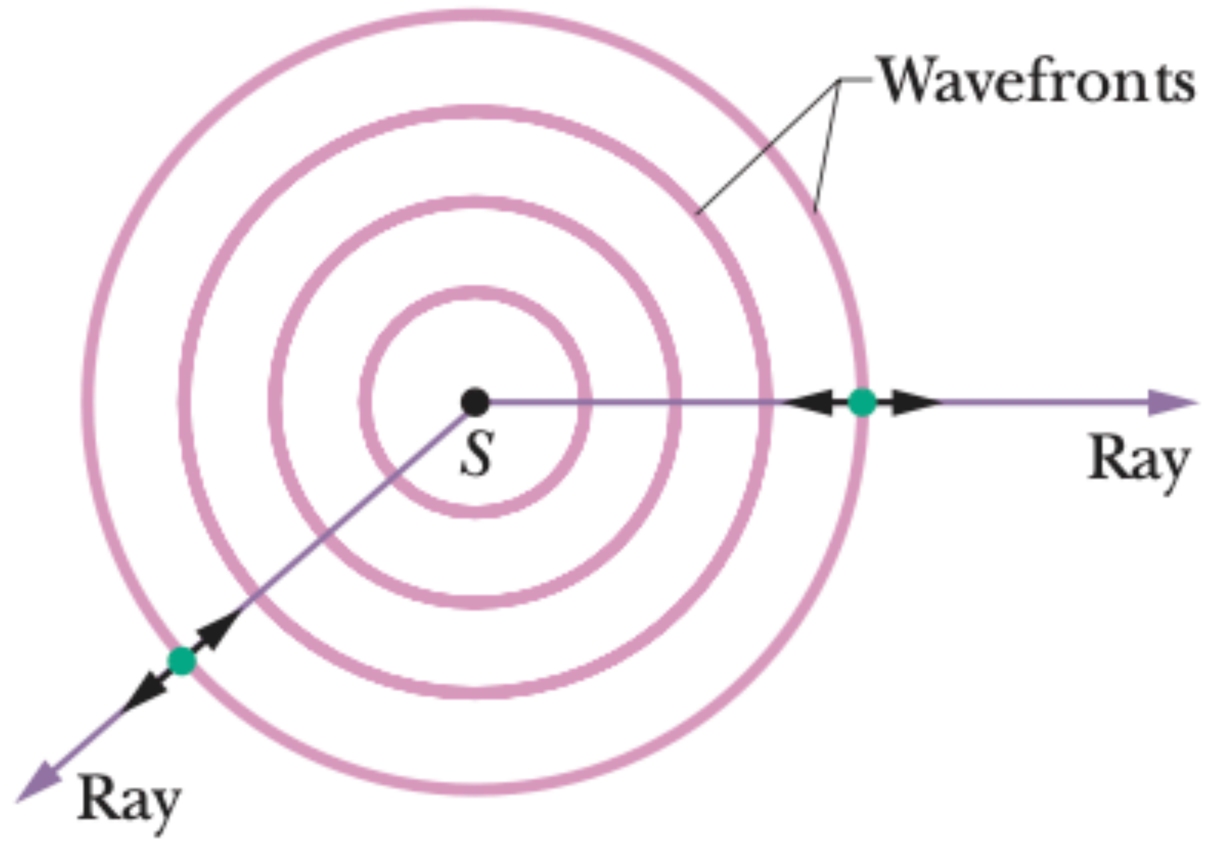
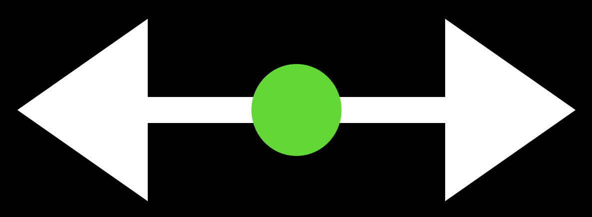
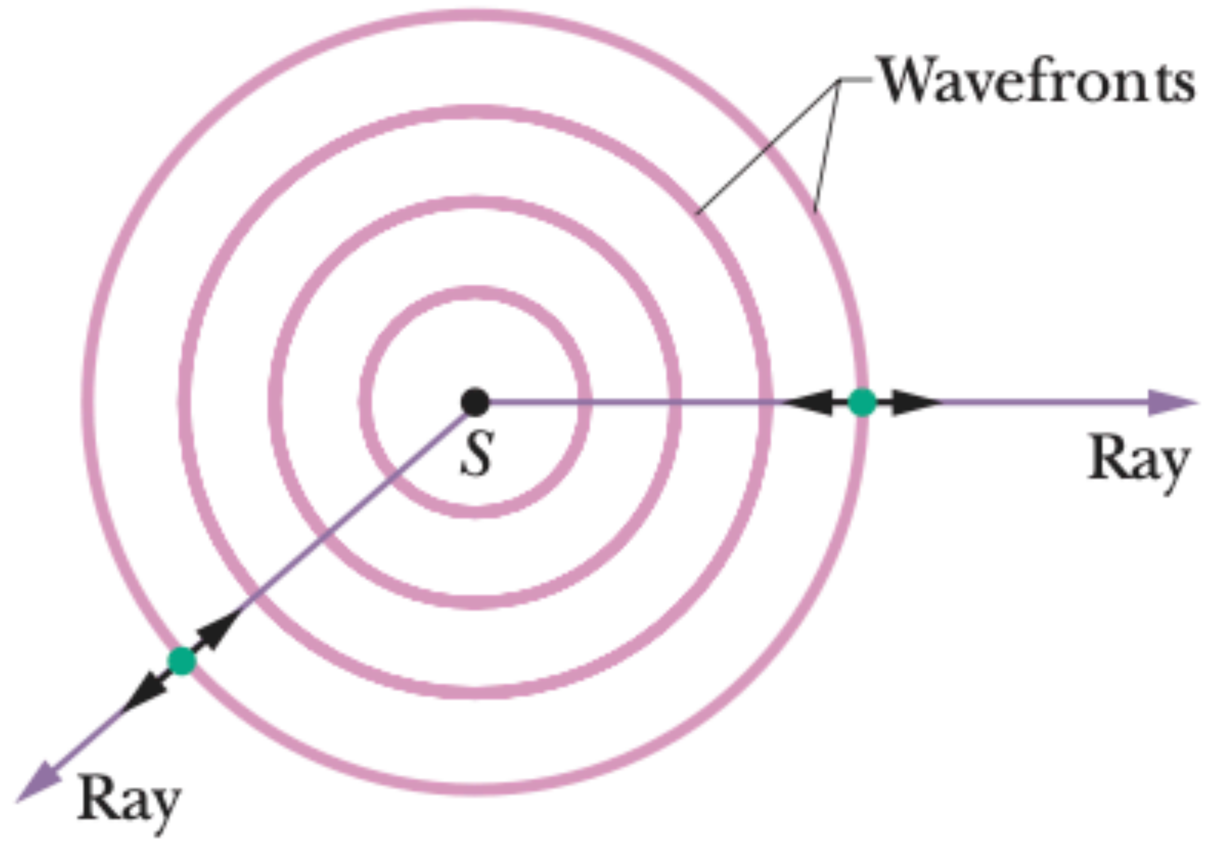


Figure 17-2 A sound wave travels from a point source S through a three-dimensional medium. The wavefronts form spheres centered on S; the rays are radial to S. The short, double-headed arrows indicate that elements of the medium oscillate parallel to the rays.

Longitudinal waves: Key concepts

- A sound wave is defined as a longitudinal wave
- Key ideas:
  - Ray: Directed lines perpendicular to the wavefront
    - The short double arrows superimposed on the rays indicate that the longitudinal oscillations of the air are parallel to the rays
    - 



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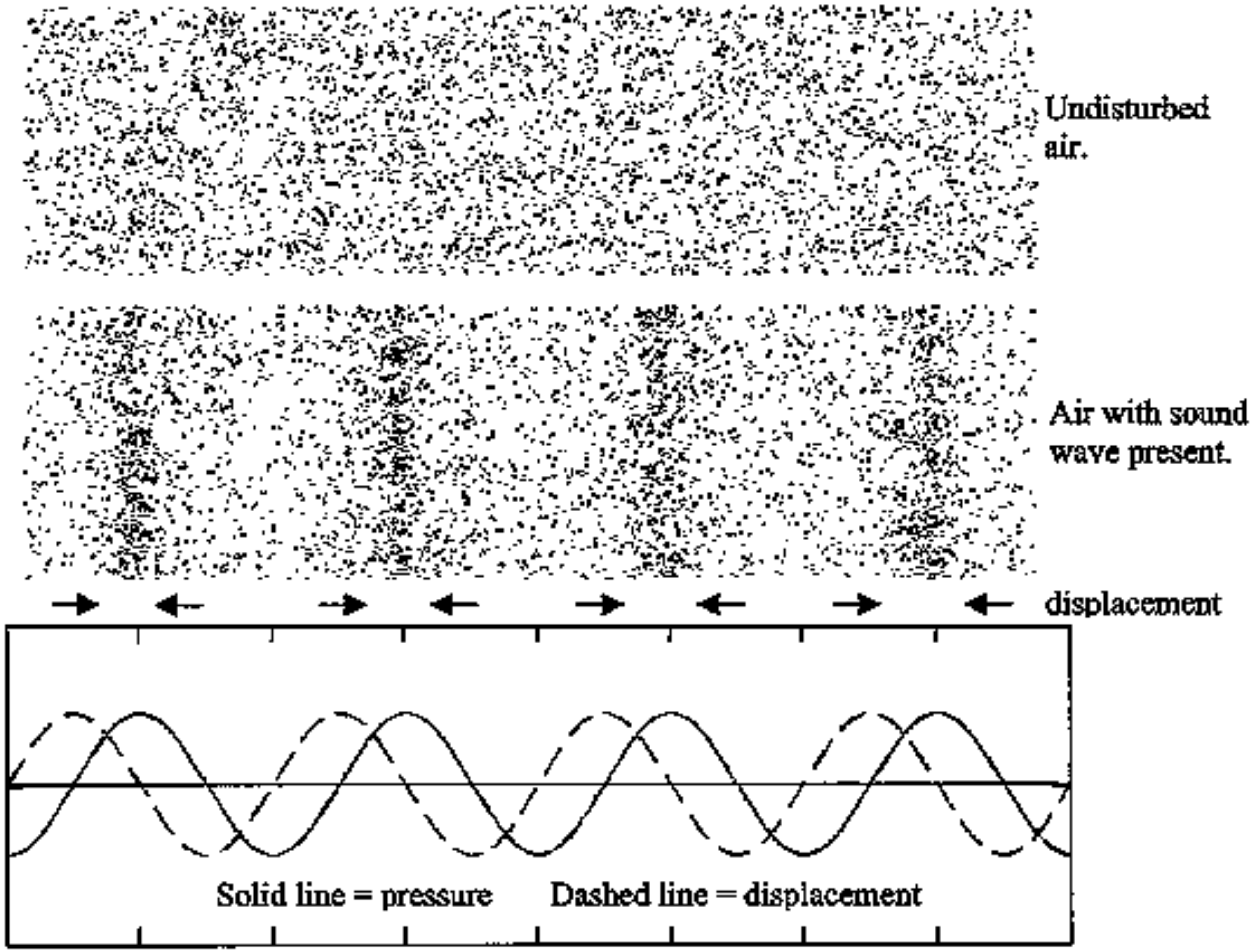
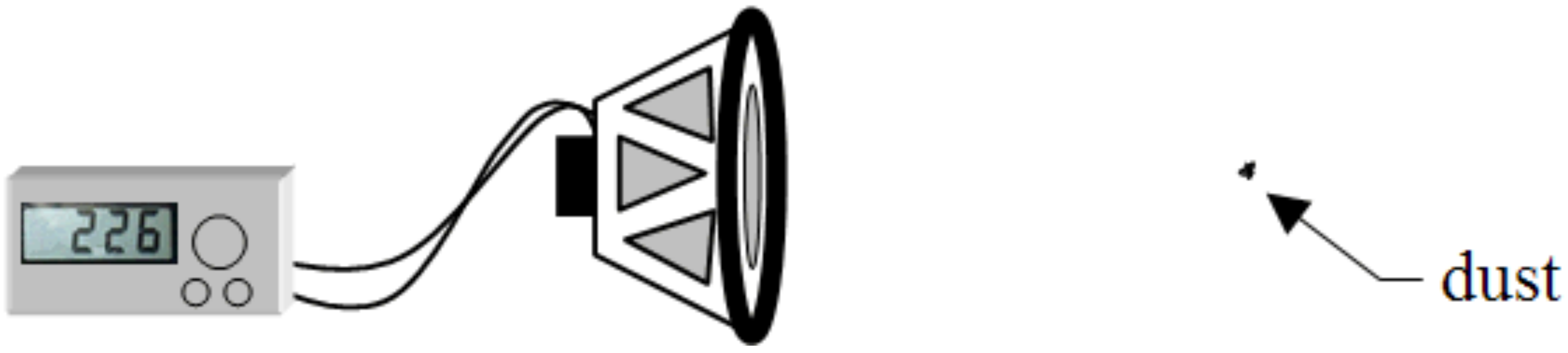
Displacement vs. Excess Pressure



A particle of dust is floating in the air in front of a speaker. The speaker is then turned on produces a sound wave of frequency 226 Hz. Which one of the following statements correctly describes the subsequent motion of the dust particle?



a) The particle of dust will oscillate left and right with a frequency of 226 Hz.

b) The particle of dust will oscillate up and down with a frequency of 226 Hz.

c) The particle of dust will be accelerated toward the right and continue moving in that direction.

d) The particle of dust will move toward the right at constant velocity.

e) The dust particle will remain motionless.

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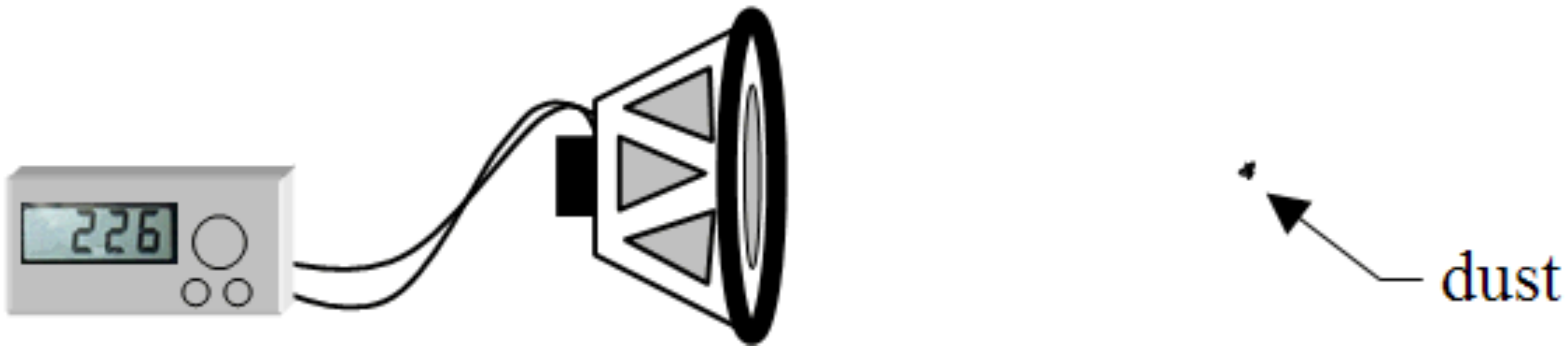

a) The particle of dust will oscillate left and right with a frequency of 226 Hz. The dust particle will not travel across the room; instead, it will vibrate back and forth in place along the direction of wave propagation.

b) The particle of dust will oscillate up and down with a frequency of 226 Hz.

c) The particle of dust will be accelerated toward the right and continue moving in that direction.

d) The particle of dust will move toward the right at constant velocity.

e) The dust particle will remain motionless.

Longitudinal waves: Key concepts

- Speed of sound:
  - The speed of any mechanical wave, transverse wave or longitudinal wave depends on:
    - the inertial property of the medium to store kinetic energy
    - the elastic property of the medium to store potential energy
  - $v = \sqrt{\dfrac{\text{elastic property}}{\text{inertial property}}}$
  - $v = \sqrt{\dfrac{\tau}{\mu}}$, τ = tension in the string, μ = linear density
  - If medium is air, μ = volume density of air (ρ)

Longitudinal waves: Key concepts

- Speed of sound:
  - $v = \sqrt{\dfrac{\text{elastic property}}{\text{inertial property}}}$
  - $v = \sqrt{\dfrac{\tau}{\mu}}$, τ = tension in the string, μ = linear density
  - If medium is air, μ = volume density of air (ρ)
  - What is τ or more generally, the elastic property?

Longitudinal waves: Key concepts

- Speed of sound:
  - What is τ or more generally, the elastic property?
  - As sound waves pass through air, potential energy associated with periodic compressions and expan- sions of small volume elements of the air
  - The property that determines the extent to which an element of a medium changes in volume when the pressure (force per unit area) on it changes
    - **bulk modulus**, B defined as:
      - $B = -\dfrac{\Delta p}{\Delta V/V}$, what is the unit?
      - Signs of Δp and ΔV are opposite: when we increase pressure, volume decreases: $\Delta p \uparrow \rightarrow \Delta V \downarrow$
      - Sign of B?

Longitudinal waves: Key concepts

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    - **bulk modulus**, B defined as:
      - $B = -\dfrac{\Delta p}{\Delta V/V}$, what is the unit? *pascal* or pressure unit
      - Signs of Δp and ΔV are opposite: when we increase pressure, volume decreases: $\Delta p \uparrow \rightarrow \Delta V \downarrow$
      - Sign of B? +

Longitudinal waves: Key concepts

- Speed of sound:
  - $v = \sqrt{\dfrac{\text{elastic property}}{\text{inertial property}}}$
  - $v = \sqrt{\dfrac{B}{\rho}}$
- Speed of sound in water is greater than speed of sound in air
  - Is it density?
  - No, it is the bulk modulus
  - Water is much more incompressible than air

Table 17-1 The Speed of Sound[a]

Medium	Speed (m/s)
Gases	
Air (0°C)	331
Air (20°C)	343
Helium	965
Hydrogen	1284
Liquids	
Water (0°C)	1402
Water (20°C)	1482
Seawater[b]	1522
Solids	
Aluminum	6420
Steel	5941
Granite	6000

Longitudinal waves: Formal derivation

- Let the pressure of the undisturbed air be p and the pressure inside the pulse be $p + \Delta p$ (Δp is positive due to compression)
- Consider an element of air of thickness Δx and face area A moving toward the pulse at speed v
- This element enters the pulse, encounters region of higher pressure, slow down by Δv

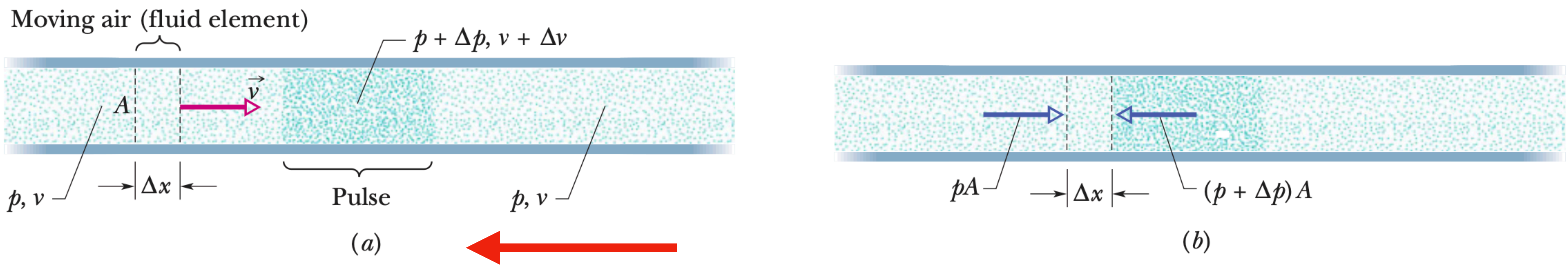
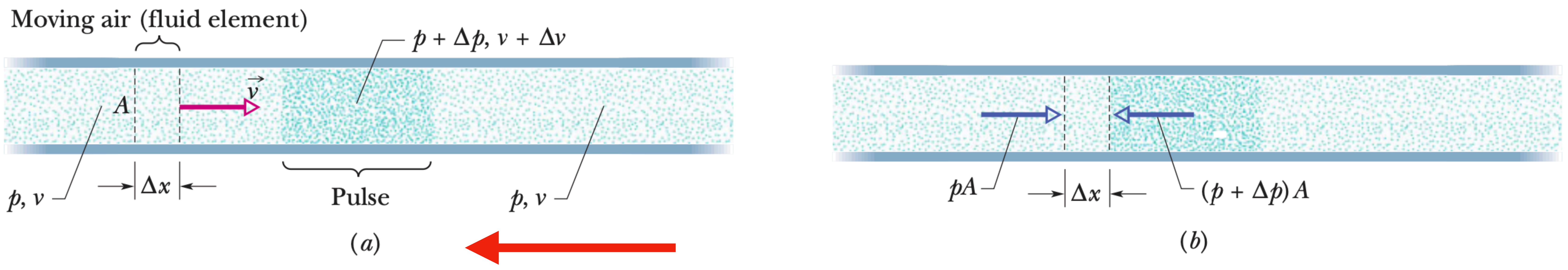


Figure 17-3 A compression pulse is sent from right to left down a long air-filled tube. The reference frame of the figure is chosen so that the pulse is at rest and the air moves from left to right. (*a*) An element of air of width Δx moves toward the pulse with speed v. (*b*) The leading face of the element enters the pulse. The forces acting on the leading and trailing faces (due to air pressure) are shown.

Longitudinal waves: Formal derivation

- Δv is negative
- The pulse takes Δt time to go through the element:
- $\Delta t = \dfrac{\Delta x}{v}$



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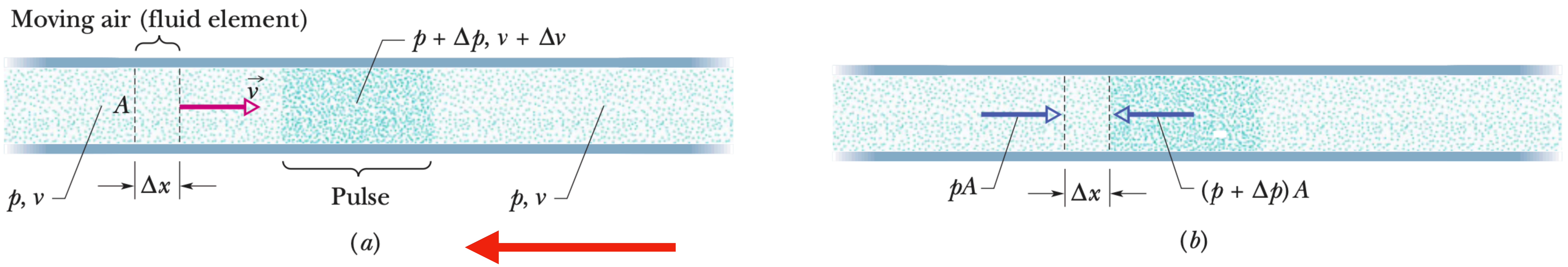
Longitudinal waves: Formal derivation

- Let's apply Newton's second law:
  - During Δt, the average force on the element's trailing face is pA toward the right, and the average force on the leading face is $(p + \Delta p)A$ toward the left
  - Average net force:
    - $F = pA - (p + \Delta p)A = -\Delta pA$



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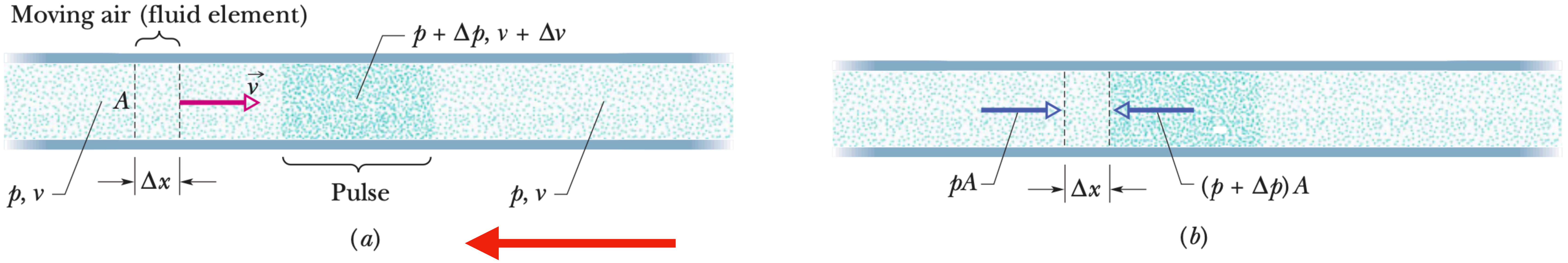
Longitudinal waves: Formal derivation

- Average net force:
    - $F = pA - (p + \Delta p)A = -\Delta pA$
- Volume: $A\Delta x$, Mass: $\Delta m = \rho\Delta V = \rho A\Delta x = \rho Av\Delta t$
- Acceleration: $a = \dfrac{\Delta v}{\Delta t}$



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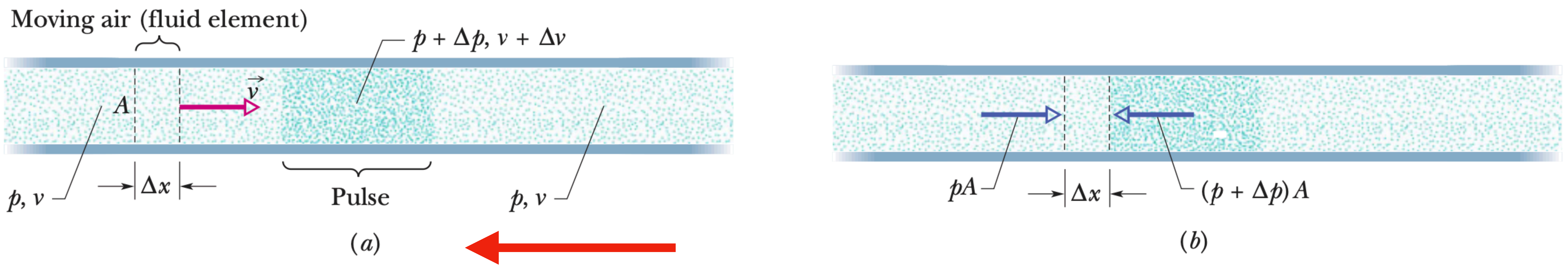
Longitudinal waves: Formal derivation

- Acceleration: $a = \dfrac{\Delta v}{\Delta t}$
- Newton's second law: $F = ma$
- $-\Delta pA = (\rho A v \Delta t)\dfrac{\Delta v}{\Delta t}$
- $\rho v^2 = -\dfrac{\Delta p}{\Delta v / v}$



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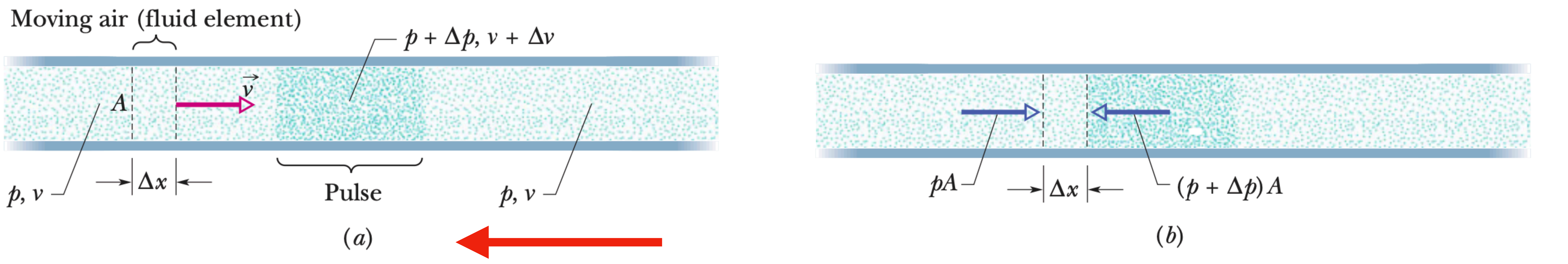
Longitudinal waves: Formal derivation

- $\rho v^2 = -\dfrac{\Delta p}{\Delta v / v}$
- $\dfrac{\Delta V}{V} = \dfrac{A \Delta v \Delta t}{A v \Delta t} = \dfrac{\Delta v}{v}$ (air that occupies a volume V outside the pulse is compressed by an amount $\Delta V (= A \Delta v \Delta t)$ as it enters the pulse)



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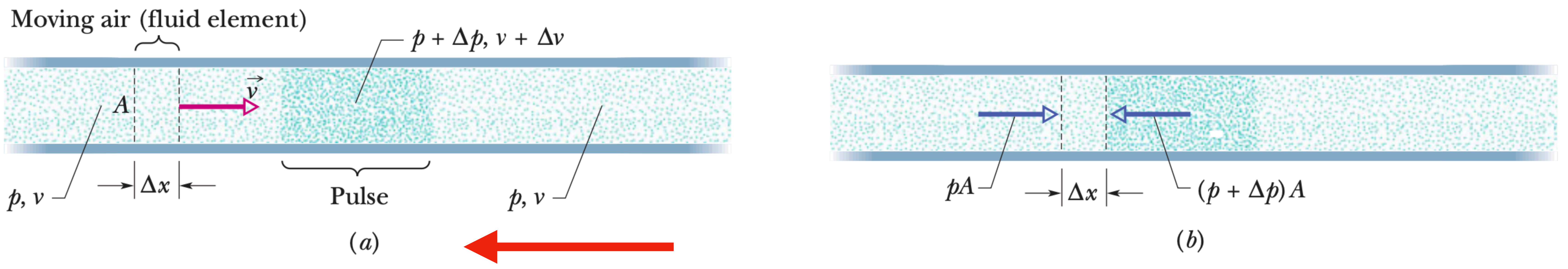
- $\rho v^2 = -\dfrac{\Delta p}{\Delta v / v} = -\dfrac{\Delta p}{\Delta V / V} = B$



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The graph shows measured data for the speed of sound in water and the density of the water versus temperature.

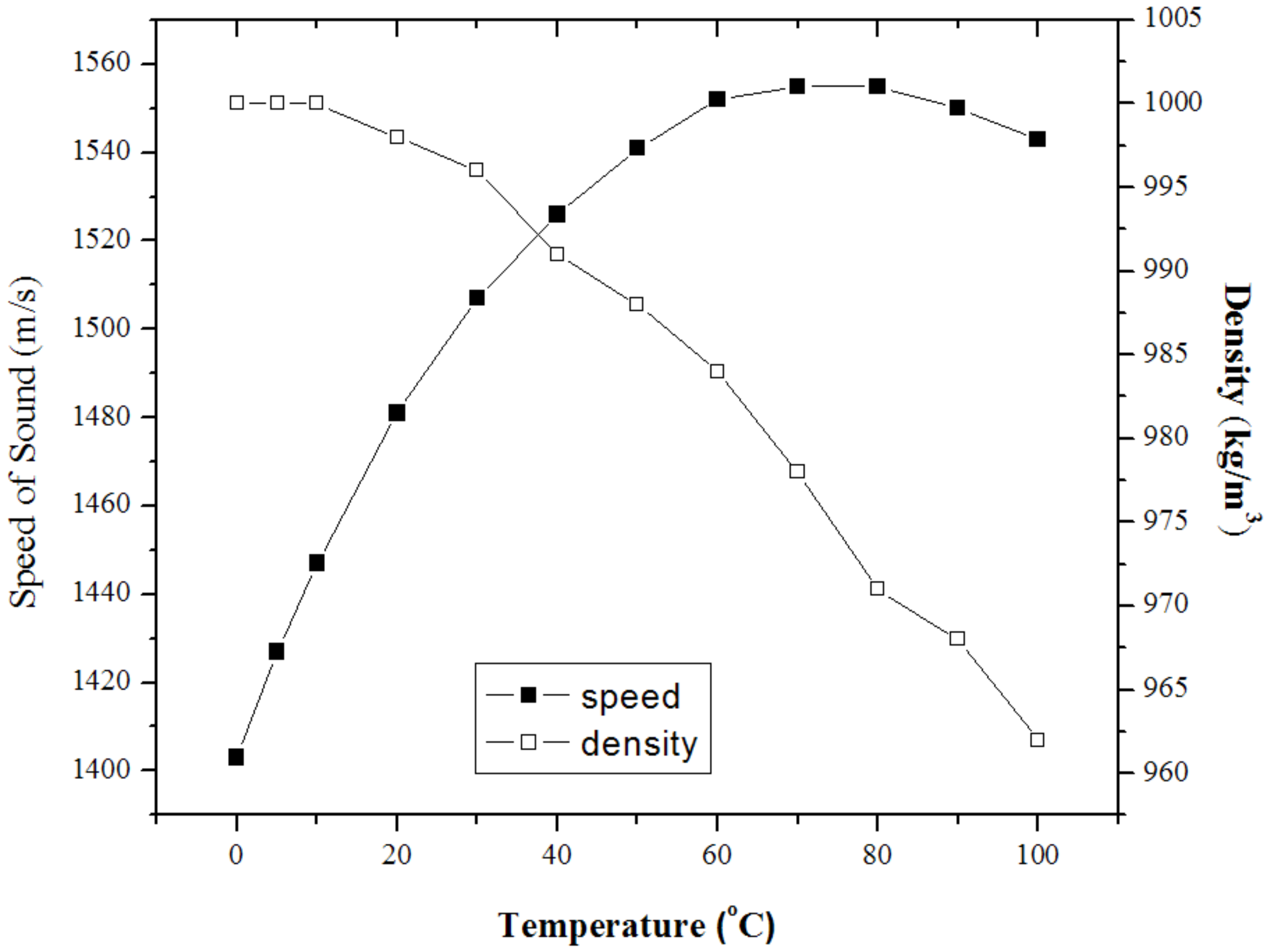
What can we infer about the bulk modulus of water in that temperature range?

a) The bulk modulus of water increases linearly with temperature.

b) The bulk modulus of water decreases non-linearly with temperature.

c) The bulk modulus of water is constant with increasing temperature.

d) The bulk modulus of water increases non-linearly with increasing temperature.



e) The bulk modulus of water increases with temperature until it peaks then it decreases.

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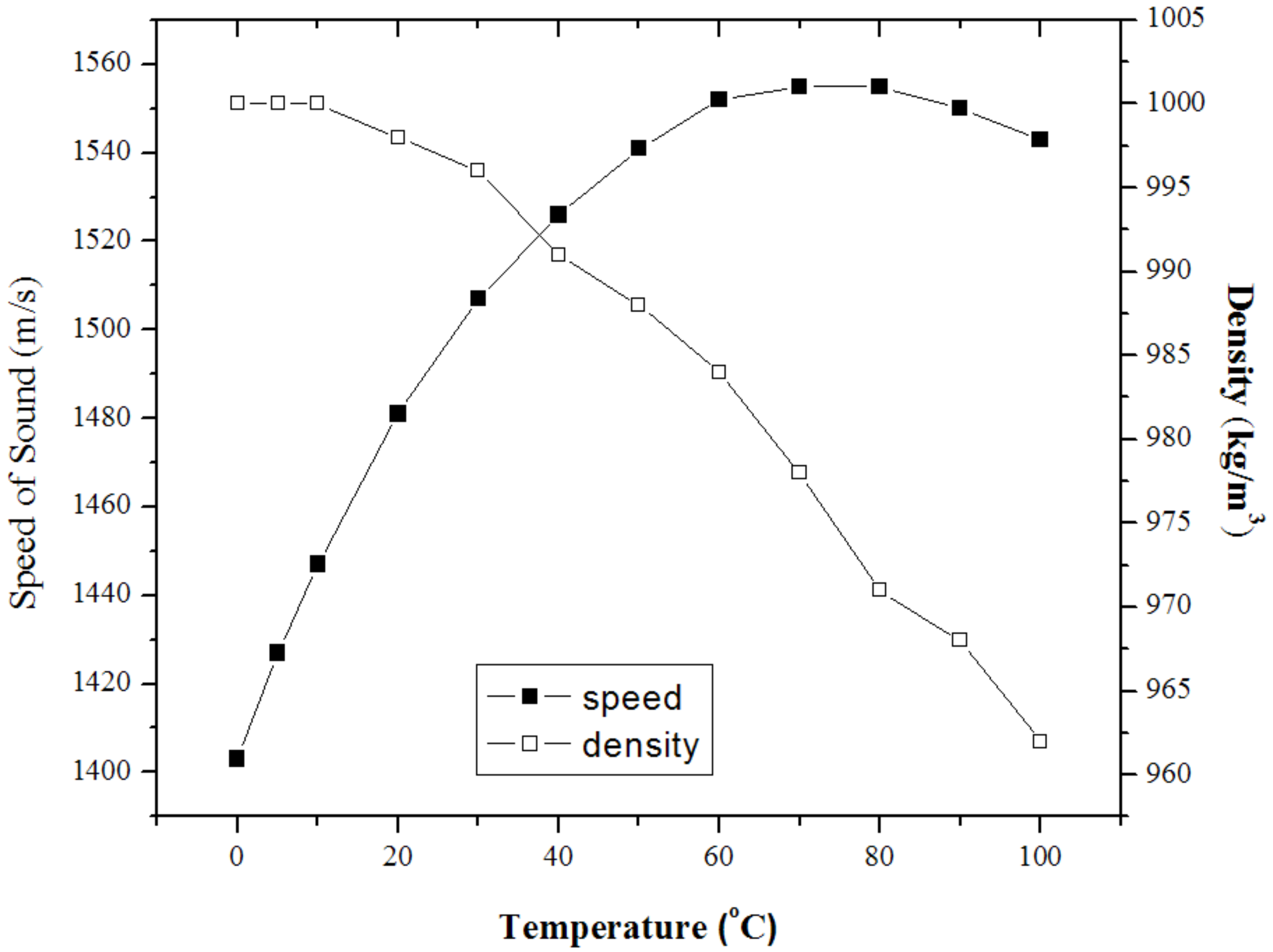
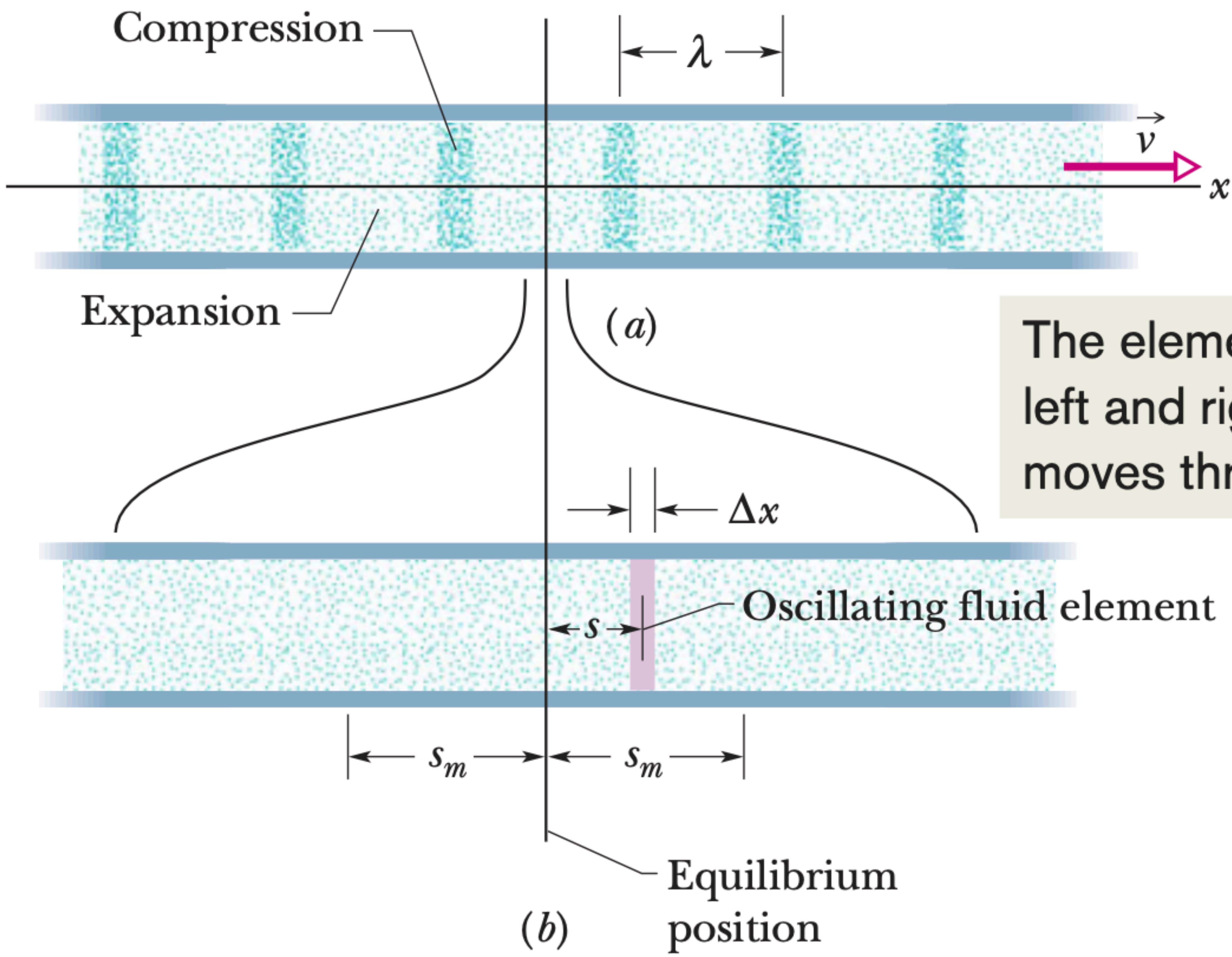


e) The bulk modulus of water increases with temperature until it peaks then it decreases. The Bulk Modulus follows the trend of the speed of sound squared. Since the speed increases to a peak and then falls, the bulk modulus will do the same.

Traveling waves

Figure 17-4 (*a*) A sound wave, traveling through a long air-filled tube with speed v, consists of a moving, periodic pattern of expansions and compressions of the air. The wave is shown at an arbitrary instant. (*b*) A horizontally expanded view of a short piece of the tube. As the wave passes, an air element of thickness Δx oscillates left and right in simple harmonic motion about its equilibrium position. At the instant shown in (*b*), the element happens to be displaced a distance s to the right of its equilibrium position. Its maximum displacement, either right or left, is s_m.



The element oscillates left and right as the wave moves through it.

Displacement and pressure

- Displacement:
  - $s(x, t) = s_m \cos(kx - \omega t)$
  - s_m = maximum displacement
  - k = wave number
  - ω = angular frequency
- Pressure:
  - $\Delta p(x, t) = \Delta p_m \sin(kx - \omega t)$
- Pressure amplitude related to displacement amplitude:
  - $\Delta p_m = (v \rho \omega) s_m$

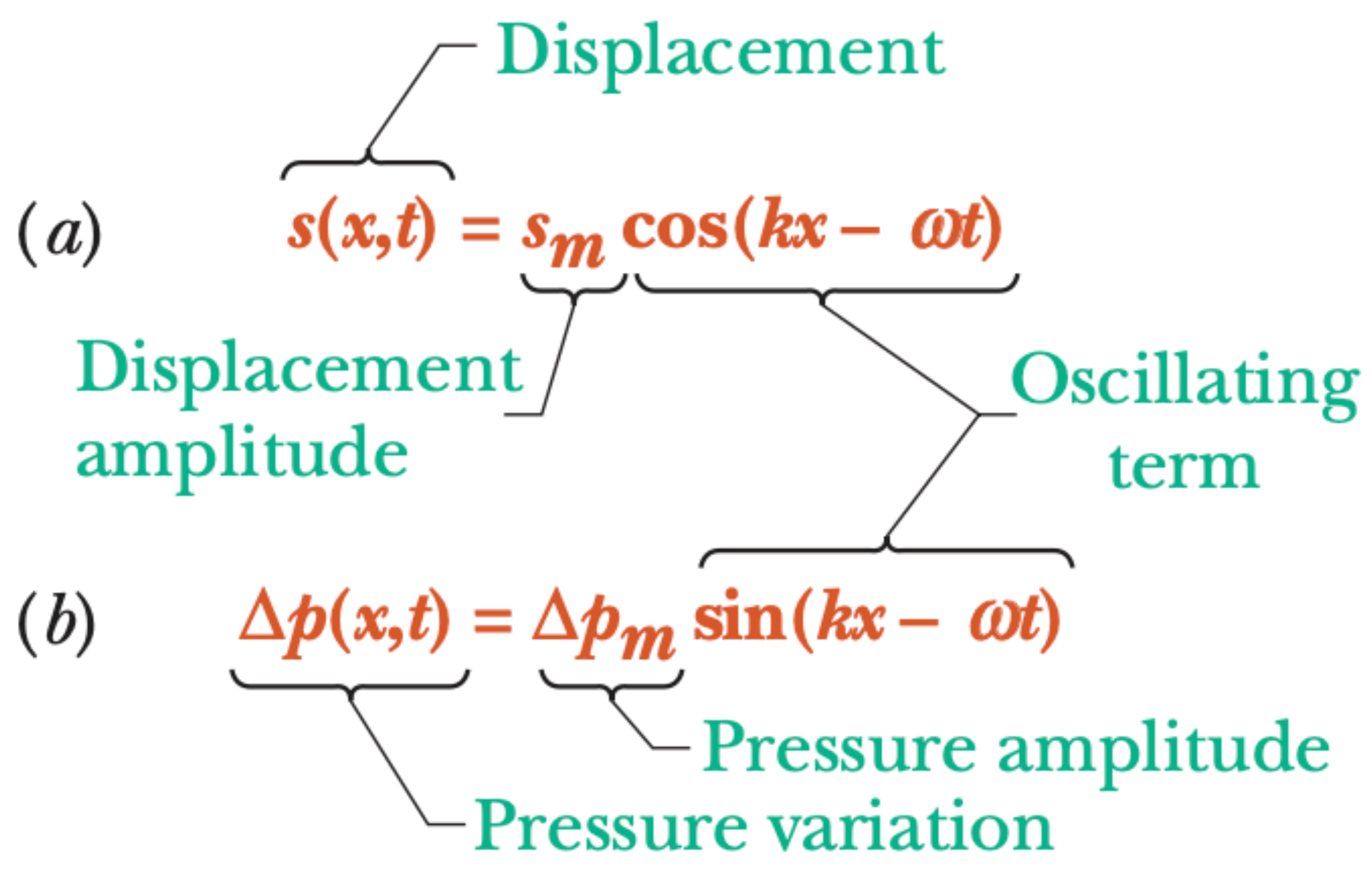
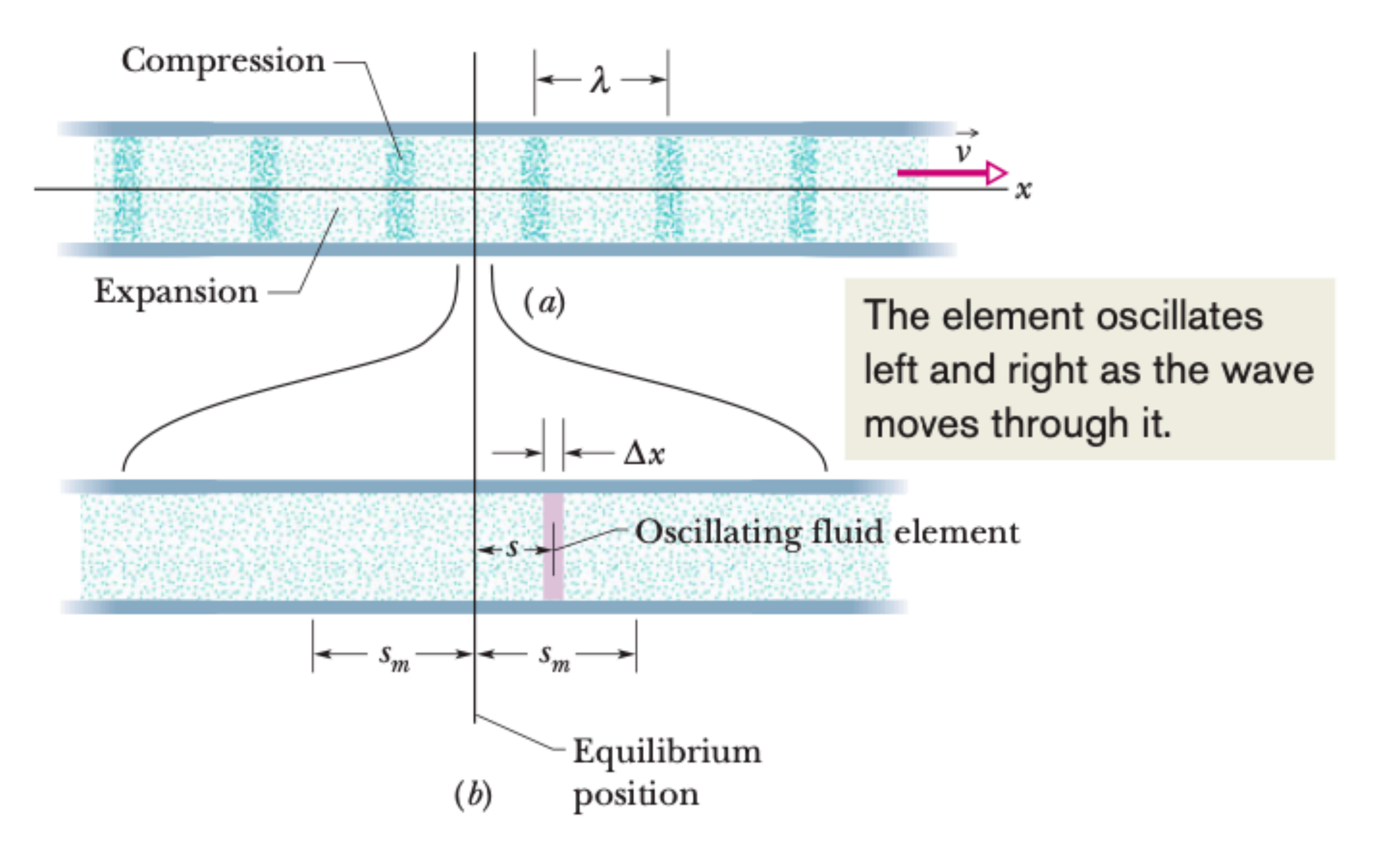


Figure 17-5 (*a*) The displacement function and (*b*) the pressure-variation function of a traveling sound wave consist of an amplitude and an oscillating term.

Displacement and pressure

- Pressure amplitude related to displacement amplitude:
  - $\Delta p_m = (v\rho\omega)s_m$
- Derive from:
  - $\Delta p = -B\dfrac{\Delta V}{V}$
  - $V = A\Delta x,\ \Delta V = A\Delta s$
  - $\Delta p = -B\dfrac{\Delta s}{\Delta x} = -B\dfrac{\partial s}{\partial x}$
  - $\dfrac{\partial s}{\partial x} = \dfrac{\partial}{\partial x}[s_m \cos(kx - \omega t)] = -ks_m \sin(kx - \omega t)$



The longitudinal displacement from equilibrium position x of a mass element of air as a sound wave passes through at time t is given by $s = s_m \cos(kx - \omega t)$.

$f = 440$ Hz $\lambda = 2\pi/k = 0.75$ m $s_m = 12\ \mu m$

Calculate the displacement (in μm) from equilibrium at time $t = 0.11$ s of an element whose position is at $x = 1.2$ m.

a. 3.7
b. 2.6
c. 4.5
d. -2.6
e. 5.2

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Problem Solution

Given Parameters:

$$f = 440\,\text{Hz}$$
$$\lambda = 0.75\,\text{m}$$
$$s_m = 12\,\mu\text{m}$$
$$x = 1.2\,\text{m}$$
$$t = 0.11\,\text{s}$$

Wave Function: The longitudinal displacement is given by:

$$s = s_m \cos(kx - \omega t)$$

Step 1: Calculate Angular Wave Number (k)

$$k = \frac{2\pi}{\lambda} = \frac{2\pi}{0.75} = \frac{2\pi}{3/4} = \frac{8\pi}{3}\,\text{rad/m}$$

Step 2: Calculate Angular Frequency (ω)

$$\omega = 2\pi f = 2\pi(440) = 880\pi\,\text{rad/s}$$

Step 3: Calculate the Phase Angle (ϕ) Substitute x and t into the phase term $(kx - \omega t)$:

$$kx = \left(\frac{8\pi}{3}\right)(1.2) = \frac{9.6\pi}{3} = 3.2\pi$$
$$\omega t = (880\pi)(0.11) = 96.8\pi$$
$$\phi = kx - \omega t = 3.2\pi - 96.8\pi = -93.6\pi\,\text{rad}$$

Step 4: Calculate Displacement (s) Substitute the phase back into the wave equation:

$$s = 12\cos(-93.6\pi)$$

Using the periodic property of cosine ($\cos(\theta) = \cos(\theta + 2n\pi)$), we can simplify the angle. We remove integer multiples of 2π:

$$\frac{-93.6\pi}{2\pi} = -46.8$$

We can write -93.6π as:

$$-93.6\pi = -47(2\pi) + 0.4\pi \quad \text{or} \quad -46(2\pi) - 1.6\pi$$

Using the positive reference equivalent:

$$\cos(-93.6\pi) = \cos(0.4\pi)$$

Convert to degrees for visualization:

$$0.4\pi \text{ rad} = 0.4 \times 180^\circ = 72^\circ$$

$$\cos(72^\circ) \approx 0.309$$

Finally, solve for s:

$$s = 12\,\mu\text{m} \times 0.309 = 3.708\,\mu\text{m}$$

Final Answer: The displacement is approximately **3.7 μm**.

Interference

- The interference of two passing sound waves with identical wavelengths passing through a common point depends on their phase difference ϕ
- Sounds waves emitted in phase:
  - $\phi = \frac{\Delta L}{\lambda} 2\pi$
    - where ΔL = path difference
  - Fully constructive interference occurs when ϕ is an integer multiple of 2π
    - $\phi = m(2\pi)$, m = 0, 1, 2
  - Fully destructive interference occurs when ϕ is an odd multiple of 2π
    - $\phi = (2m + 1)\pi$, m = 0, 1, 2

Recap

Transverse Wave Interference (16.4-16.7)

Dan Russell's Acoustics and Vibration Animations

https://www.acs.psu.edu/drussell/demos.html

A function $f(x,t)$ satisfies this PDE:

$$\frac{\partial^2 f}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 f}{\partial t^2}$$

Invent two different functions f(x,t) that solve this equation. Try to make one of them "boring" and the other "interesting" in some way.

A function f satisfies the wave equation:

$$\frac{\partial^2 f}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 f}{\partial t^2}$$

Which of the following functions work?

A) sin [$k(x - vt)$]

B) exp [-$k(x + vt)$]

C) a$(x + vt)^3$

D) All of these.

E) None of these

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C) $a(x + vt)^3$

D) All of these.

E) None of these.

Two different functions f_1 (x,t) and f_2 (x,t) are solutions of the wave equation.

$$\frac{\partial^2 f}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 f}{\partial t^2}$$

Is $(A f_1 + B f_2)$ also a solution of the wave equation?

A) Yes, always

B) No, never

C) Yes, sometimes, depending of f_1 and f_2

Two different functions f_1 (x,t) and f_2 (x,t) are solutions of the wave equation.

$$\frac{\partial^2 f}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 f}{\partial t^2}$$

Is $(A f_1 + B f_2)$ also a solution of the wave equation?

A) Yes, always

B) No, never

C) Yes, sometimes, depending of f_1 and f_2

The 1-D wave equation is $\frac{\partial^2 f}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 f}{\partial t^2}$

One particular "traveling wave" solution to this is

$$f_1(z,t) = A_1\cos(k_1 z - \omega_1 t + \delta_1)$$

There are many *other* solutions, including $f_2(z,t)$ with the SAME functional form, but with higher angular frequency, $\omega_2 > \omega_1$.

What can you say about the *speed* of that new solution?

A) greater than v

B) less than v

C) equal to v

D) indeterminate!

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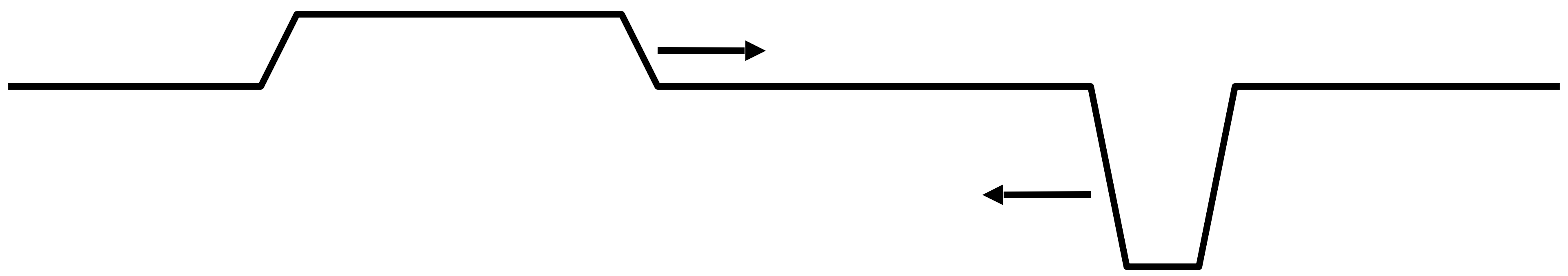
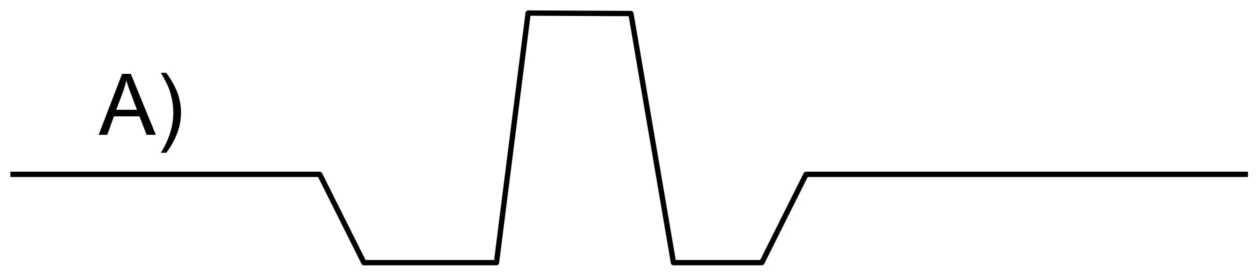
Two impulse waves are approaching each other, as shown. Which picture correctly shows the total ?



A)



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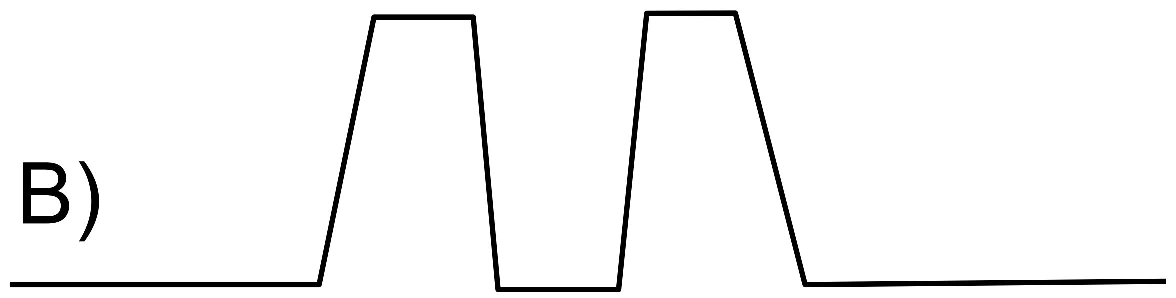
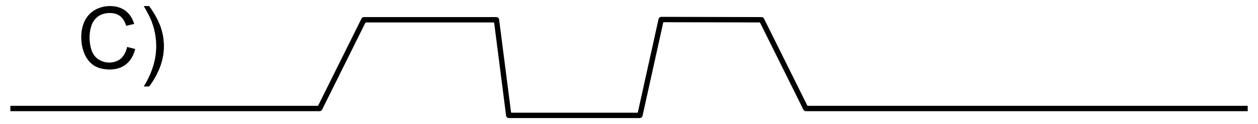
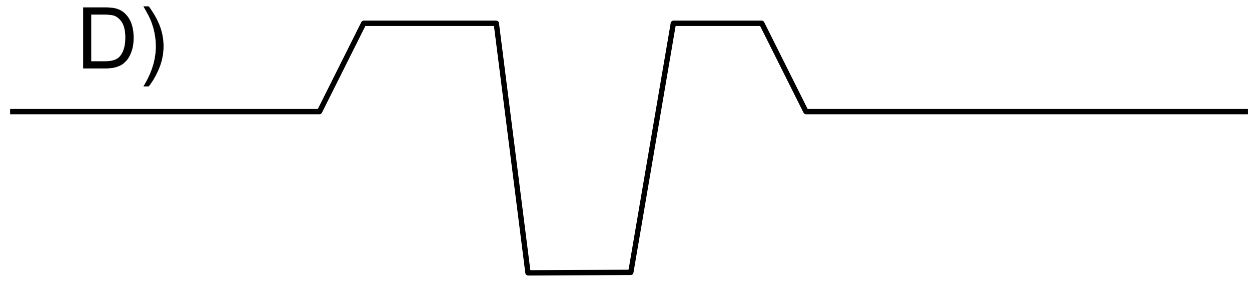


C)



D)



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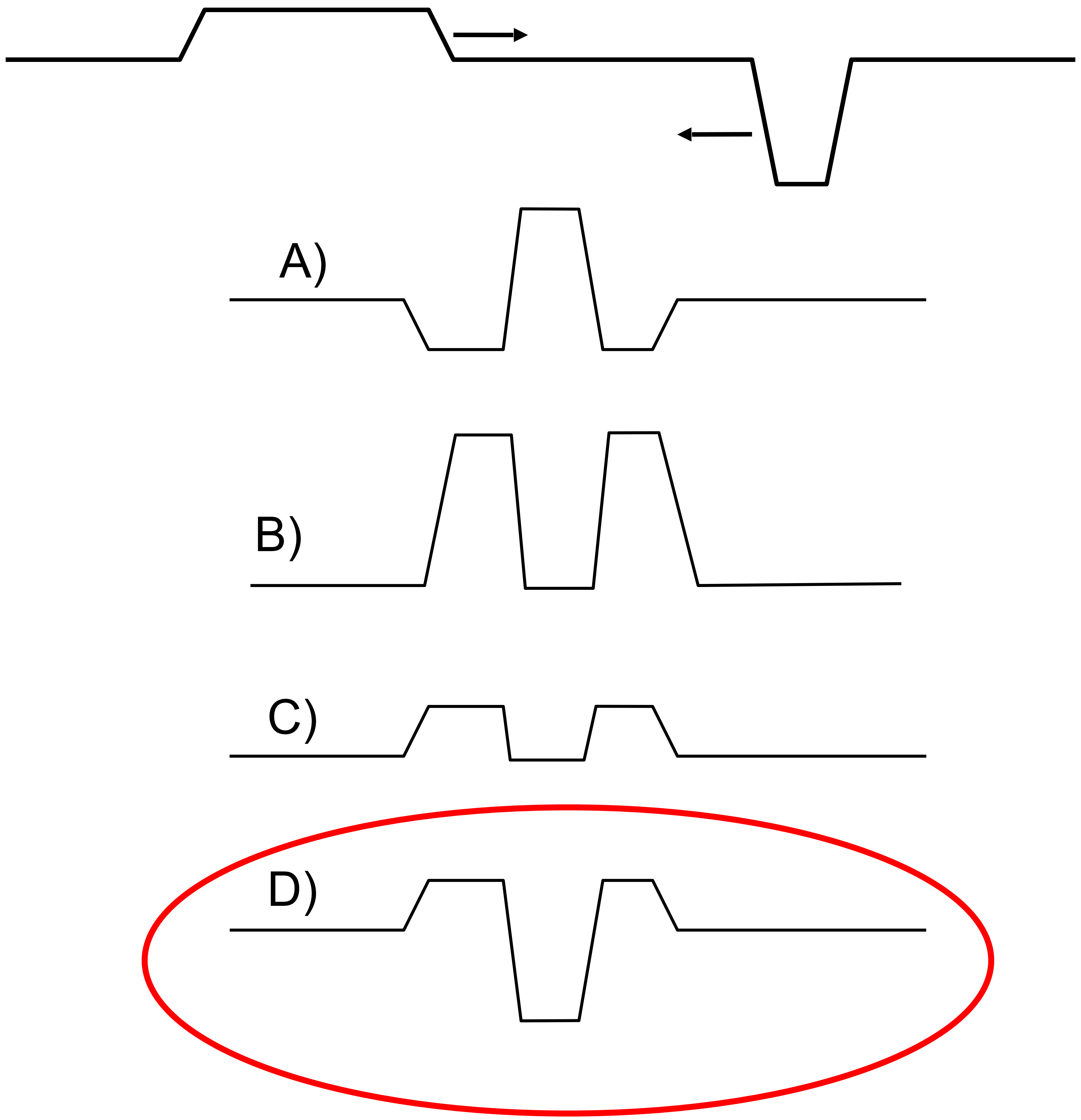

Three sinusoidal waves of the same frequency and wavelength travel from left to right. Their amplitudes are y_m, $y_m/2$, $y_m/2$ and their phase constants are 0, $\pi/2$, π, respectively.

What are

(a)The amplitude of the resultant wave?

(b)The phase constant of the resultant wave?

(c)Plot the resultant wave at $t = 0$ and discuss as t increases.

Three sinusoidal waves of the same frequency and wavelength travel from left to right. Their amplitudes are y_m, $y_m/2$, $y_m/2$ and their phase constants are 0, $\pi/2$, π, respectively.

What are

(a)The amplitude of the resultant wave? $y_m/\sqrt{2}$

(b)The phase constant of the resultant wave? $\pi/4$

(c)Plot the resultant wave at $t = 0$ and discuss as t increases Starts at $y_m/2$ and sine propagates to the right

Additional Material