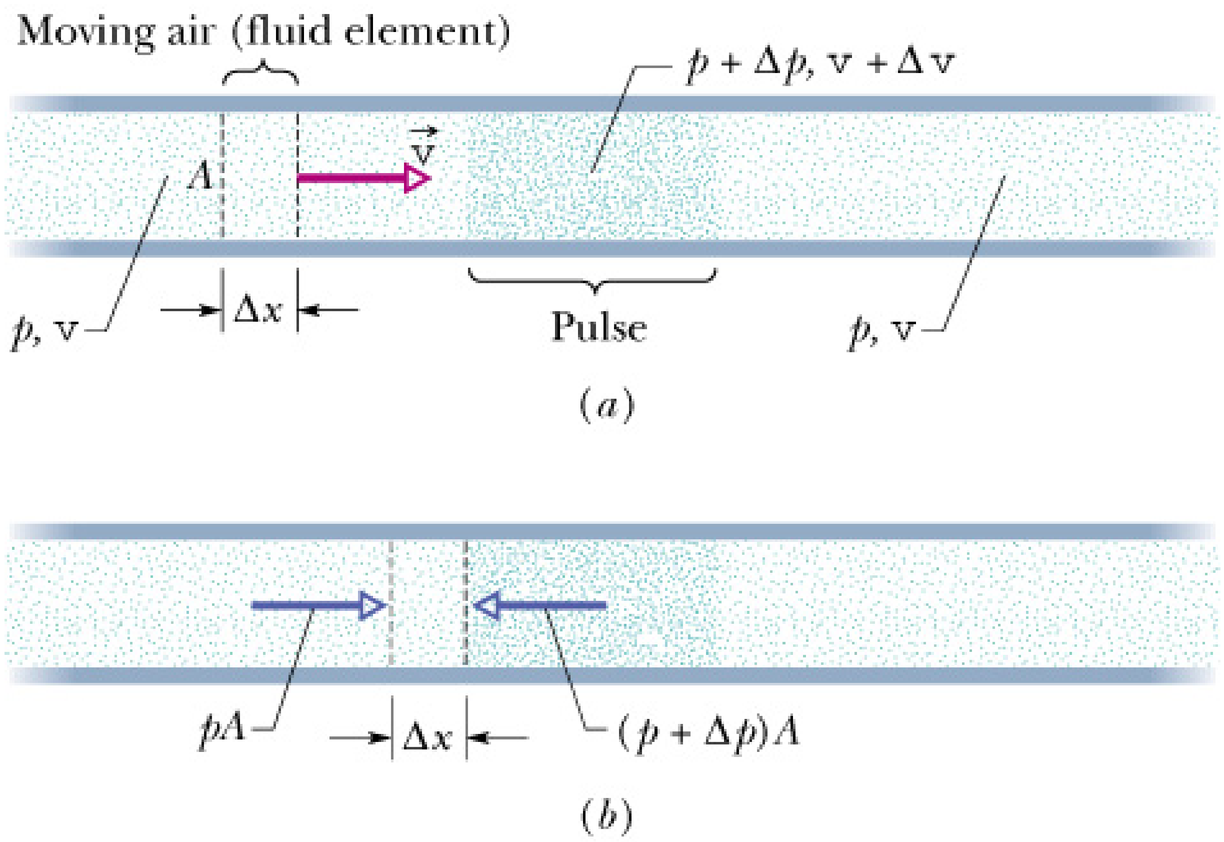
Chapter 17   Waves (Part II)

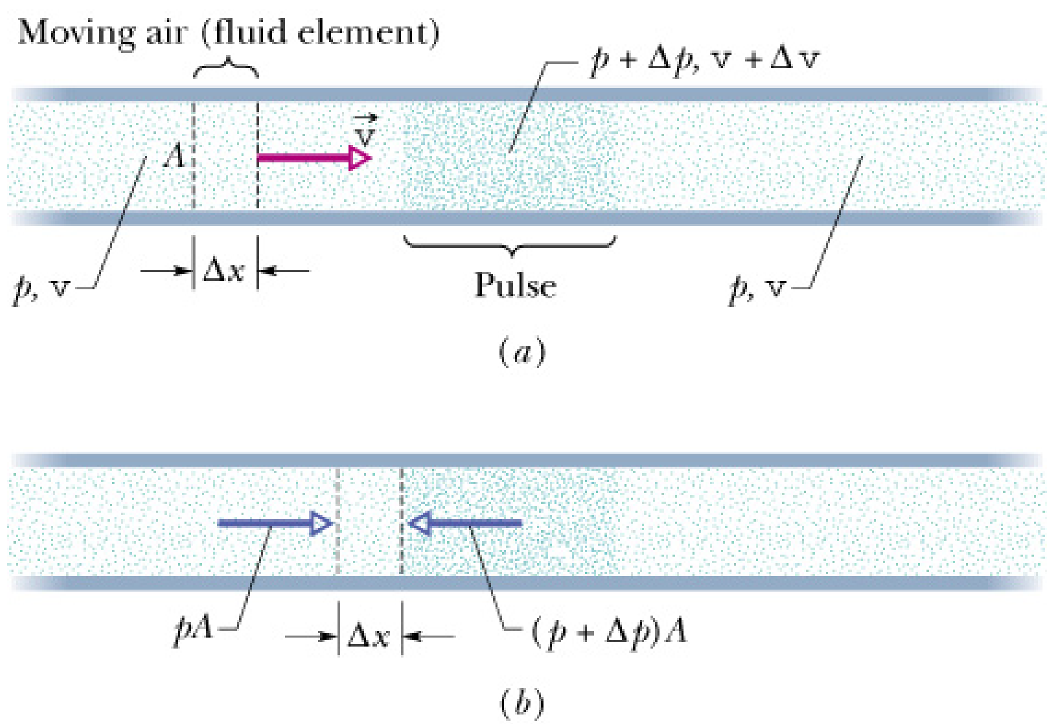
Sound wave is a longitudinal wave.



The speed of sound

Speed of a transverse wave on a stretched string

$$v = \sqrt{\frac{\tau}{\mu}} = \sqrt{\frac{\text{elastic property}}{\text{inertia property}}}$$



The speed of sound

Speed of a sound wave (longitudinal):

$$v = \sqrt{\frac{\tau}{\mu}} = \sqrt{\frac{\text{elastic property}}{\text{inertia property}}}$$

Speed of sound in gases & liquids is described by the bulk modulus B (= – Δp/(ΔV/V)) and density ρ:

$$v = \sqrt{\frac{B}{\rho}}$$

Speed of sound:

air(20^{o}C): 343 m/s, water(20^{o}C): 1482 m/s

The speed of sound

Speed of a sound wave (longitudinal):

$$v = \sqrt{\frac{\tau}{\mu}} = \sqrt{\frac{\text{elastic property}}{\text{inertia property}}}$$

Speed of sound in a solid is described by Young's modulus E and density ρ:

$$v = \sqrt{\frac{E}{\rho}}$$

Speed of sound in aluminum: $E = 7 \times 10^{10}$ Pa, $\rho = 2.7 \times 10^3 \text{ kg/m}^3$ => $v = 5100$ m/s,

In general, $v_{solid} > v_{liquid} > v_{gas}$

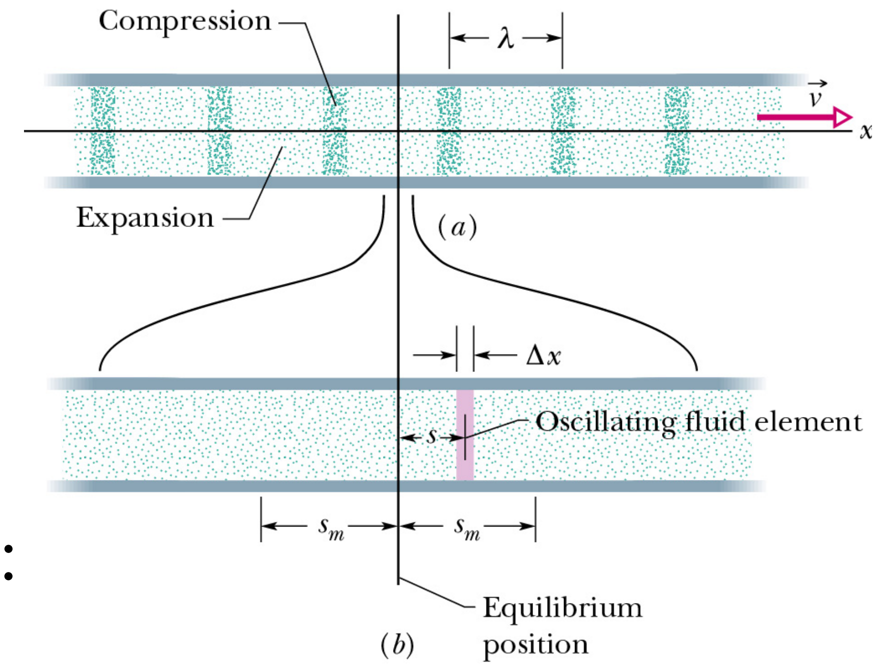
Traveling Sound Wave

- To describing the sound wave, we use the displacement of an element at position x and time t:

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

s_m: displacement amplitude

$k = 2\pi/\lambda \qquad \omega = 2\pi/T = 2\pi f$

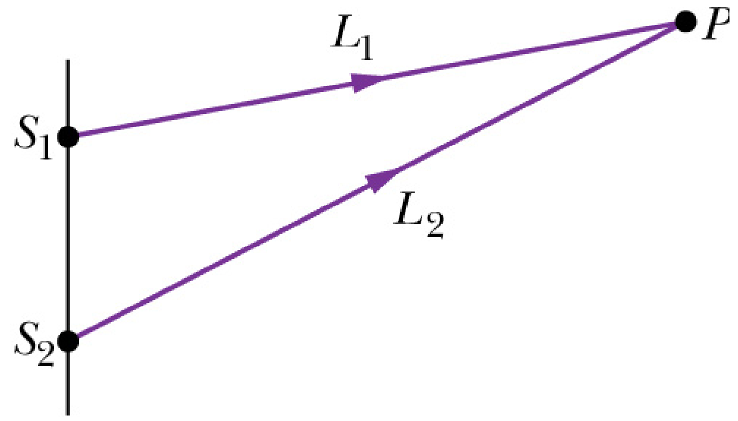


- As the wave moves, the air pressure at each point changes:

$\Delta p(x, t) = \Delta p_m \sin(kx - \omega t)$

Pressure amplitude: $\Delta p_m = (v\rho\omega)s_m$

Interference

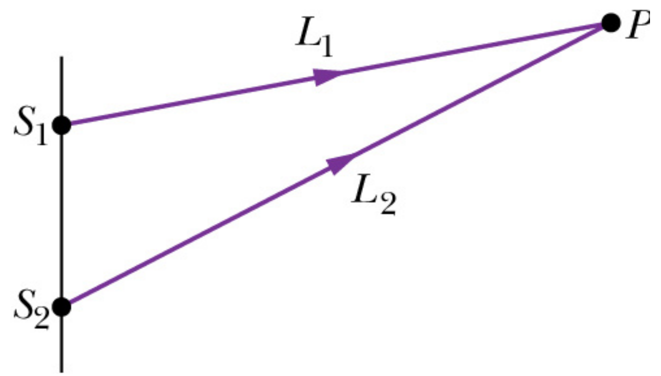


Two sound waves traveling in the same direction, how they would interfere at a point P depends on the phase difference between them.

If the two waves were in phase when they were emitted, phase difference then depend on path length difference $\Delta L = L_1 - L_2$:

$$\Delta\phi/2\pi = \Delta L/\lambda$$

Interference



Two sound waves traveling in the same direction, how they would interfere at a point P depends on the phase difference between them.

$$\Delta\phi/2\pi = \Delta L/\lambda$$

If $\Delta\phi = m\,(2\pi)$ or $\Delta L/\lambda = m$ $(m = 0, 1, 2 \ldots)$

We have fully constructive interference

If $\Delta\phi = (2m+1)\pi$ or $\Delta L/\lambda = m + ½$ $(m = 0, 1, 2 \ldots)$

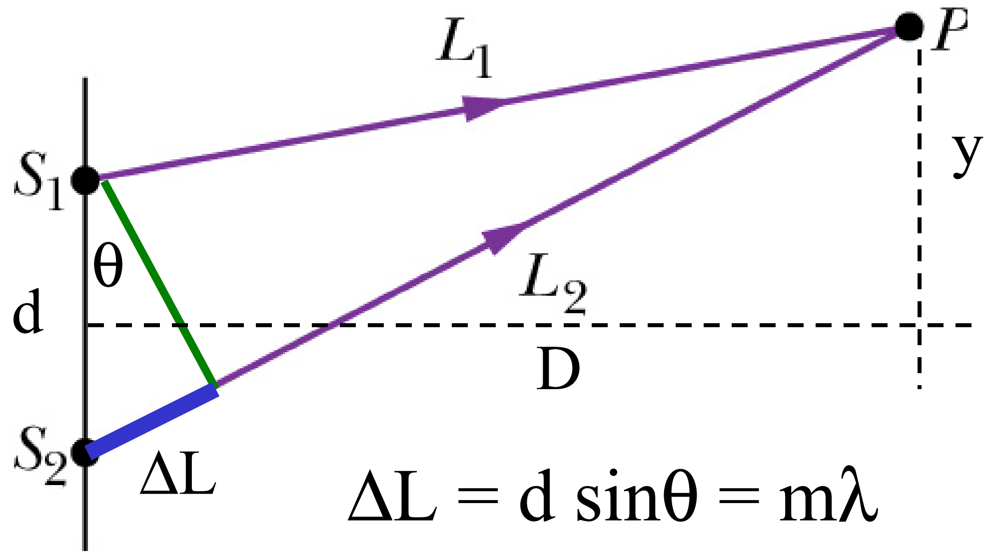
We have fully destructive interference

Interference

For distant points,

$$\Delta L = d \sin\theta$$

$$\Delta\phi/2\pi = \Delta L/\lambda$$



$$\Delta L = d \sin\theta = m\lambda$$

$$y/D = \tan\theta$$

If $\Delta\phi = m\,(2\pi)$ or $\Delta L/\lambda = m$ $(m = 0, 1, 2 \ldots)$

We have fully constructive interference $\Delta L = d \sin\theta = m\lambda$

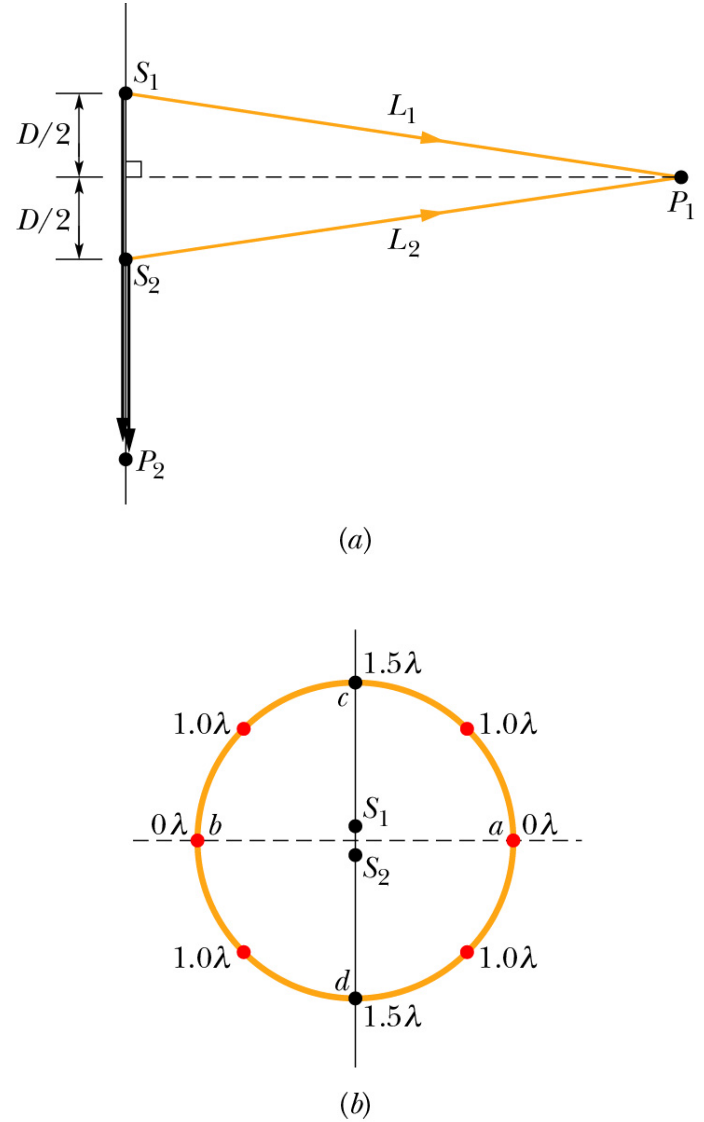
If $\Delta\phi = (2m+1)\pi$ or $\Delta L/\lambda = m + ½$ $(m = 0, 1, 2 \ldots)$

We have fully destructive interference $d \sin\theta = (m + ½)\,\lambda$

In the figure, two point sources S_1 and S_2, which are in phase and separated by distance $D = 1.5\lambda$, emit identical sound waves of wavelength λ.

A) What is the path length difference and what type of interference occurs at point P_1?

B) How about P_2?



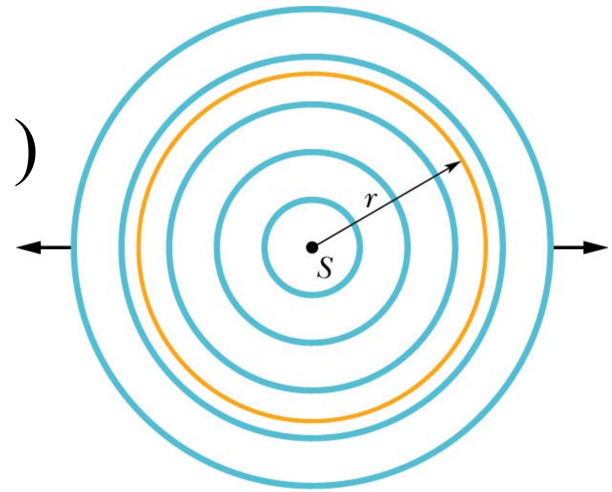
Intensity and Sound Level

- Intensity of a sound wave at a surface is defined as the average power per unit area

$$I = P/A$$

For a wave $s(x, t) = s_m \cos(kx - \omega t)$

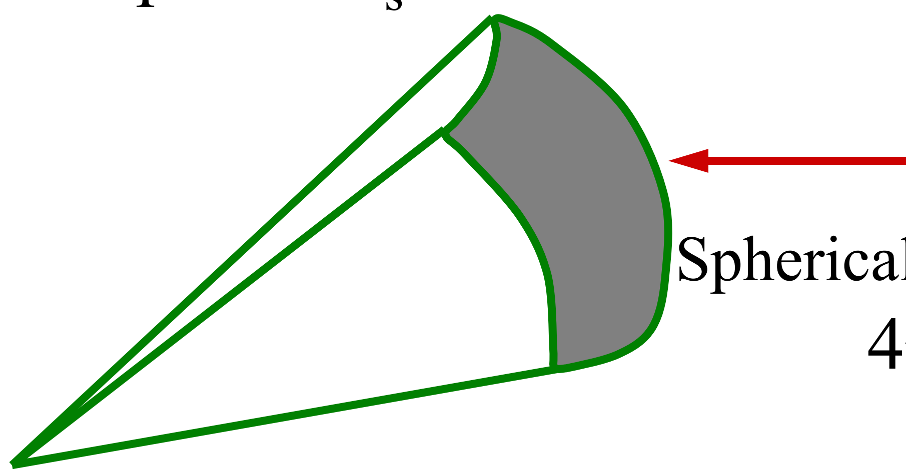
$I = \frac{1}{2} \rho v \omega^2 s^2_m$ $\qquad v = \omega / k$



Variation of intensity with distance.

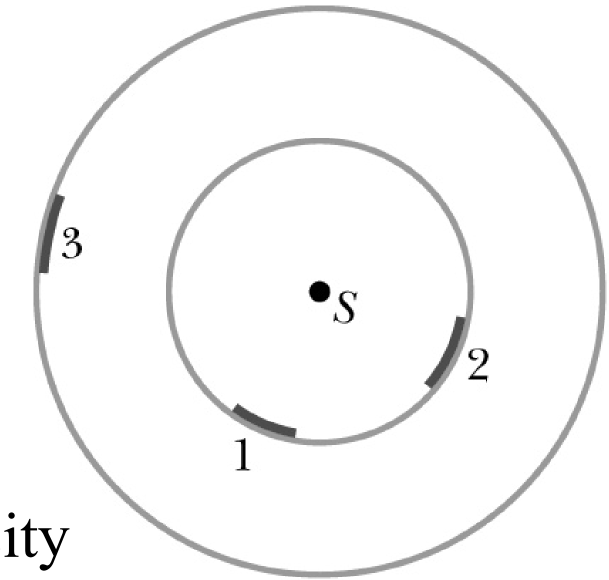
A point source with power P_s

$$I = P_s / 4\pi r^2$$



Spherical surface area: $4\pi r^2$

The figure indicates three small patches 1, 2, and 3 that lie on the surfaces of two imaginary spheres; the spheres are centered on an isotropic point source S of sound.



A) Rank the patches according to the intensity of the sound on them, greatest first.

$$I = P_s/4\pi r^2$$

$r_1 = r_2 \Rightarrow I_1 = I_2$

$r_3 > r_1 \Rightarrow I_3 < I_1$

B) If the rates at which energy is transmitted through the three patches by the sound waves are equal, rank the patches according to their area, greatest first.

$r_1 = r_2 \Rightarrow A_1 = A_2$

$$I = P_s/A$$

$r_3 > r_1 \Rightarrow A_3 > A_1$

The decibel Scale

The deci(bel) scale is named after Alexander Graham Bell

Sound level β is defined as

$$\beta = (10\ \text{dB}) \log (I/I_0)$$

Unit for β: dB(decibel)

I_0 is a standard reference intensity, $I_0 = 10^{-12}\ \text{W/m}^2$

Threshold of hearing: 10^{-12}W/m^2

Threshold of pain (depends on the type of music): 1.0W/m^2

An increase of 10 dB => sound intensity multiplied by 10.

- **The decibel scale**
  - Sound intensity range for human ear: $10^{-12} - 1\ \mathrm{W/m^2}$
  - More convenient to use logarithm for such a big range.
  - Sound level β is defined as

$$\beta = (10\ \mathrm{dB})\log(I/I_0)$$

Unit for β: dB(decibel)

I_0 is a standard reference intensity, $I_0 = 10^{-12}\ \mathrm{W/m^2}$

<u>Examples</u>:

at hearing threshold: $I = I_0$, $\beta = 10\log 1 = 0$,

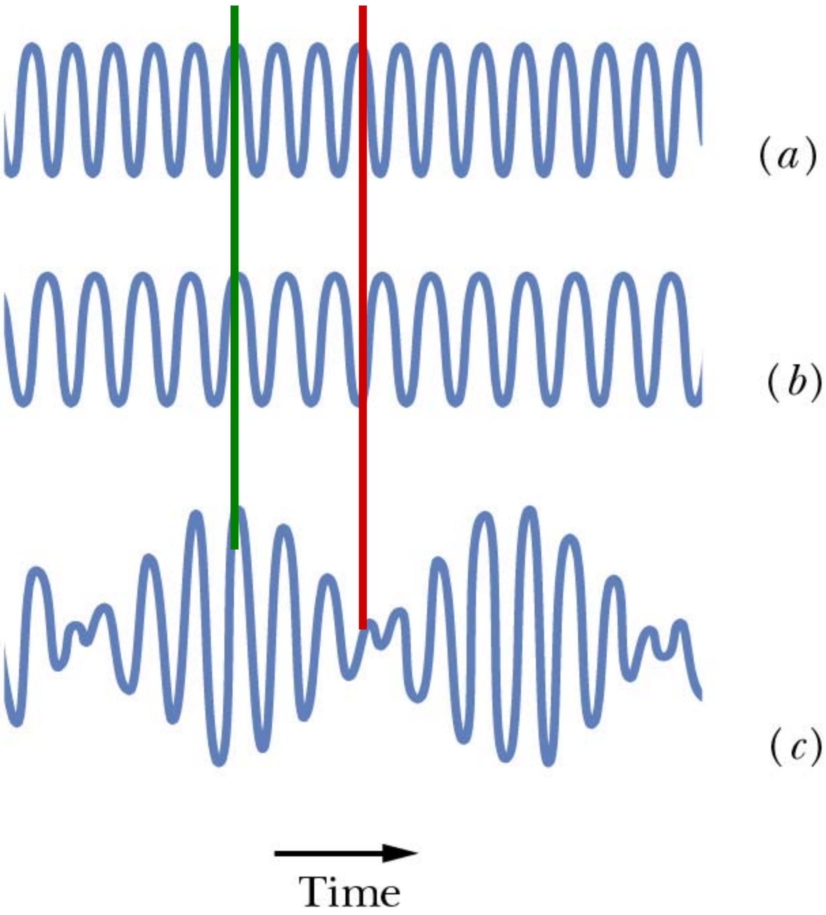
normal conversation: $I \sim 10^6 I_0$, $\beta = 10\log 10^6 = 60\ \mathrm{dB}$

Rock concert: $I = 0.1\ \mathrm{W/m^2}$, $\beta = 10\log(0.1/10^{-12})$
$= 110\mathrm{dB}$

Beats

Two sound waves with frequencies f_1 and f_2 ($f_1 \sim f_2$) reach a detector, the intensity of the combined sound wave vary at beat frequency f_b

$$f_b = f_1 - f_2$$

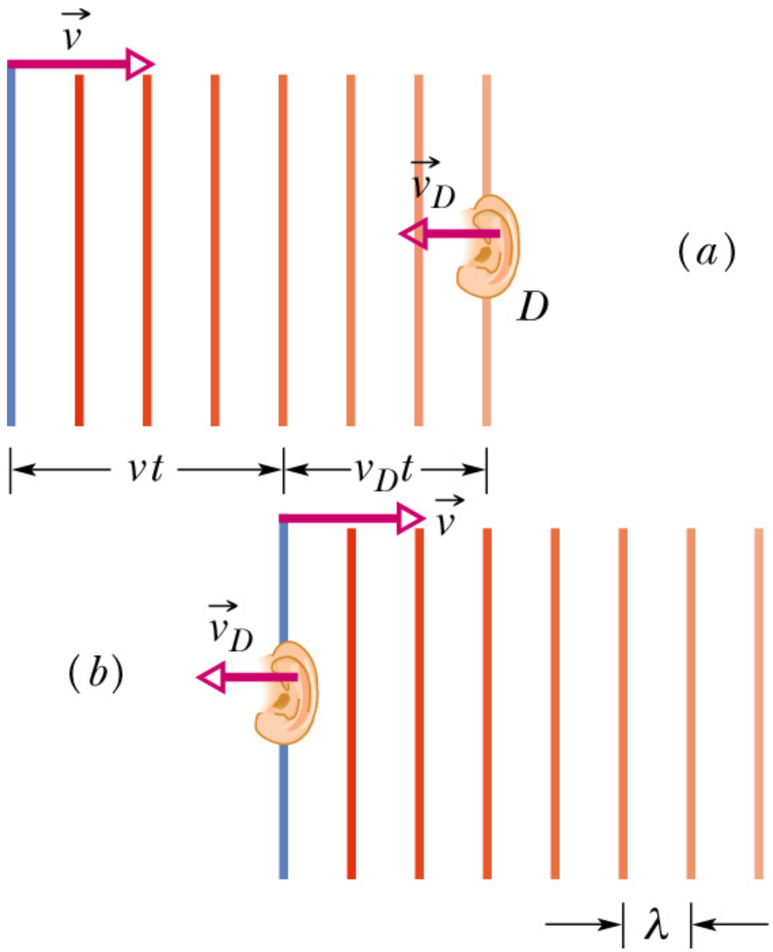


The Doppler effect

When the source or the detector is moving relative to the media, a frequency which is different from the emitted frequency is detected.

This is called **Doppler effect.**

- **Case 1**: <u>source stationary, the detector is moving towards</u> the source:



The detected frequency is:

$$f' = f\frac{v + v_D}{v}$$

Note: f ' is *greater* than f.

Case 2: <u>source stationary, detector moving away</u> from the source:

$$f' = f\frac{v - v_D}{v}$$

f ' is *smaller* than f.

Cases 3 & 4: <u>source moving, detector stationary</u>

$$f' = f\frac{v}{v \pm v_S}$$

Source is moving toward detector, "–" sign, $f' > f$

Source is moving away from detector, "+" sign, $f' < f$

General formula for Doppler effect

$$f' = f\,\frac{v \pm v_D}{v \mp v_S}$$

v: speed of sound

v_D: detector speed

v_S: source speed

Rules:

Moving ***towards*** each other: frequency ***increases***

Moving ***away from*** each other: frequency ***decreases***

For numerator,

if detector is moving ***towards*** the source, "+"

if detector is moving ***away from*** the source, "–"

For denominator,

if source is moving ***away from*** the detector, "+"

if source is moving ***towards*** the detector, "–"

Doppler effect for Light

Covered in Chapter 37: Relativity

$$f' = f\sqrt{\frac{1 \pm \beta}{1 \mp \beta}}$$

$\beta = v/c$

v: ***relative*** velocity

c: speed of light

Rules: Moving ***towards*** each other: upper signs

Moving ***away from*** each other: lower signs

Motion of Astrophysical Objects

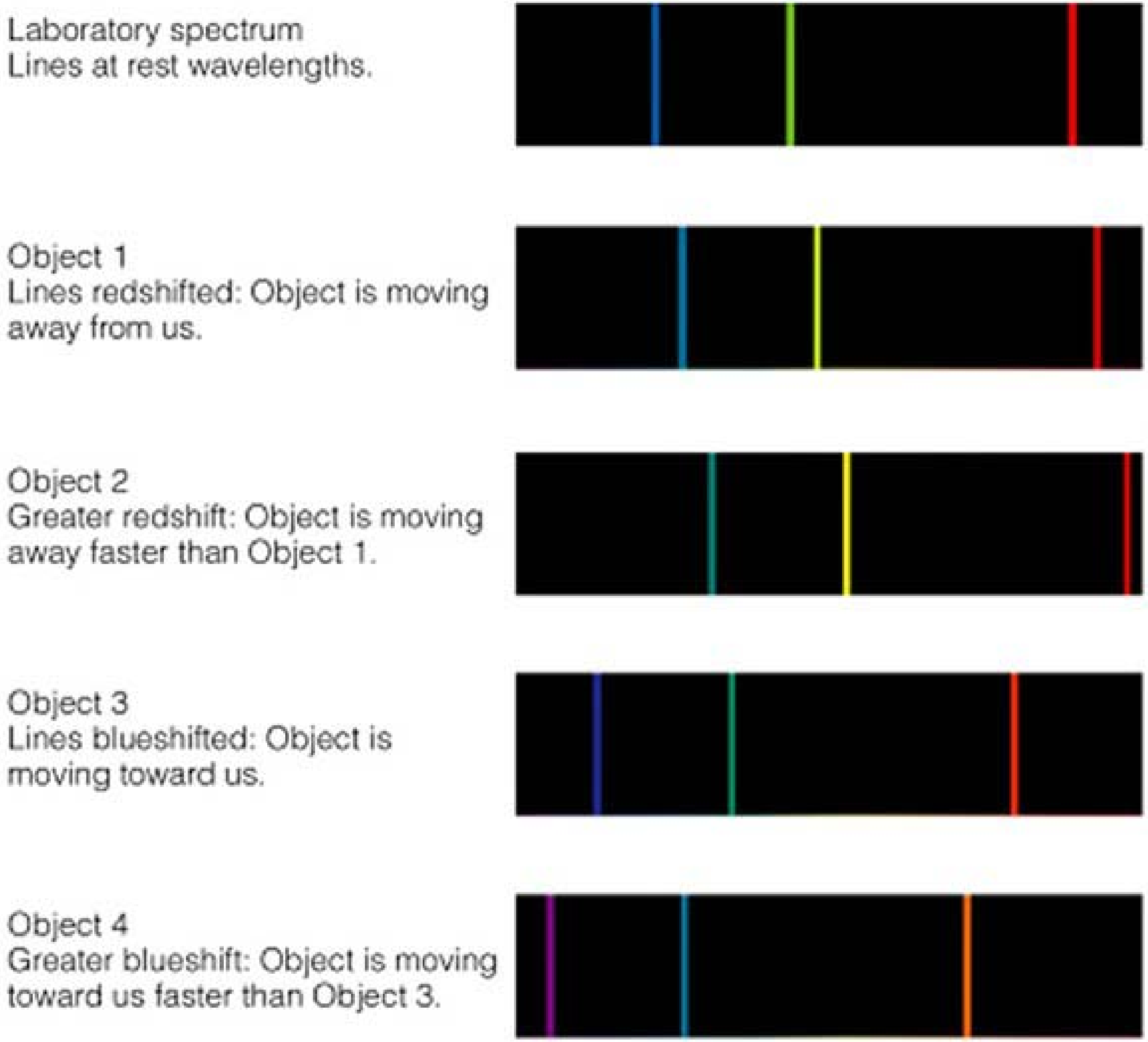
How can we know the speeds of object many light-years distant? And how can we know the rotation speeds of atoms/molecules within those objects?

Atomic energy levels are quantized. This means energies within the atom can change by only discrete amounts.

The Rules of Nature (i.e., physics) are the same throughout the universe.

Compare spectra taken in the lab to those observed from the astrophysical object.

Doppler effect for Light - Emission Spectra



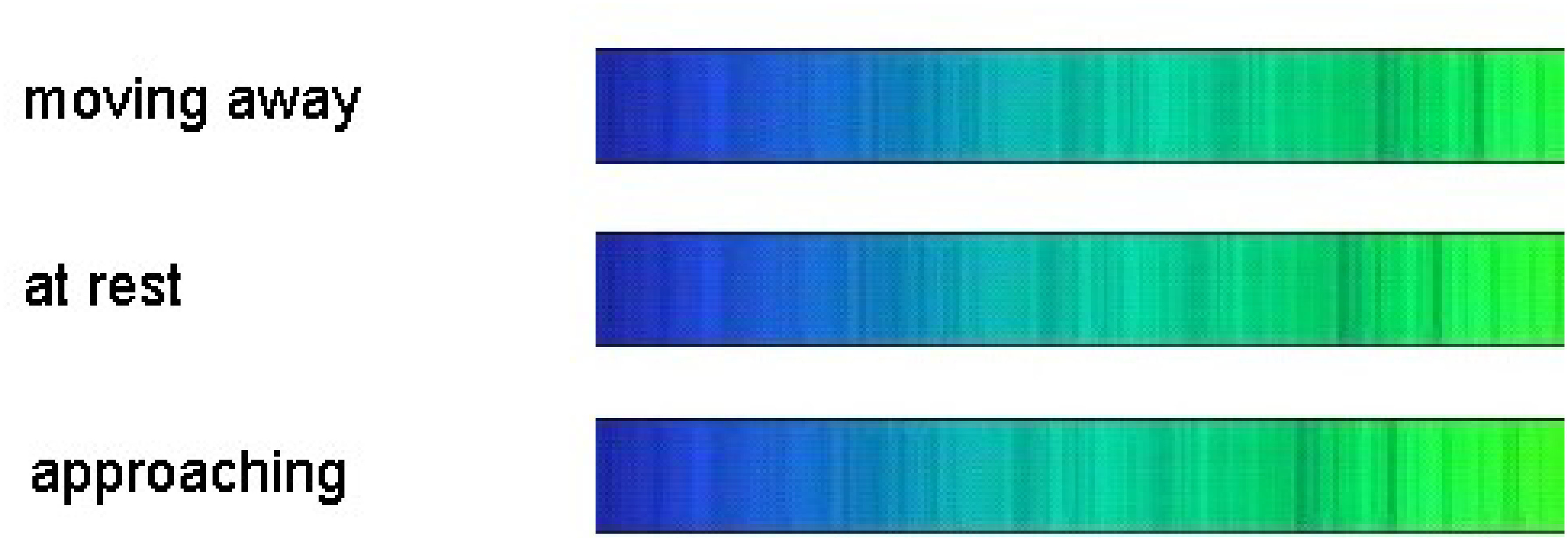
Doppler effect for Light -- Absorption Spectra

$$f' = f\sqrt{\frac{1 \pm \beta}{1 \mp \beta}}$$

$\beta = v/c$

v: ***relative*** velocity

c: speed of light

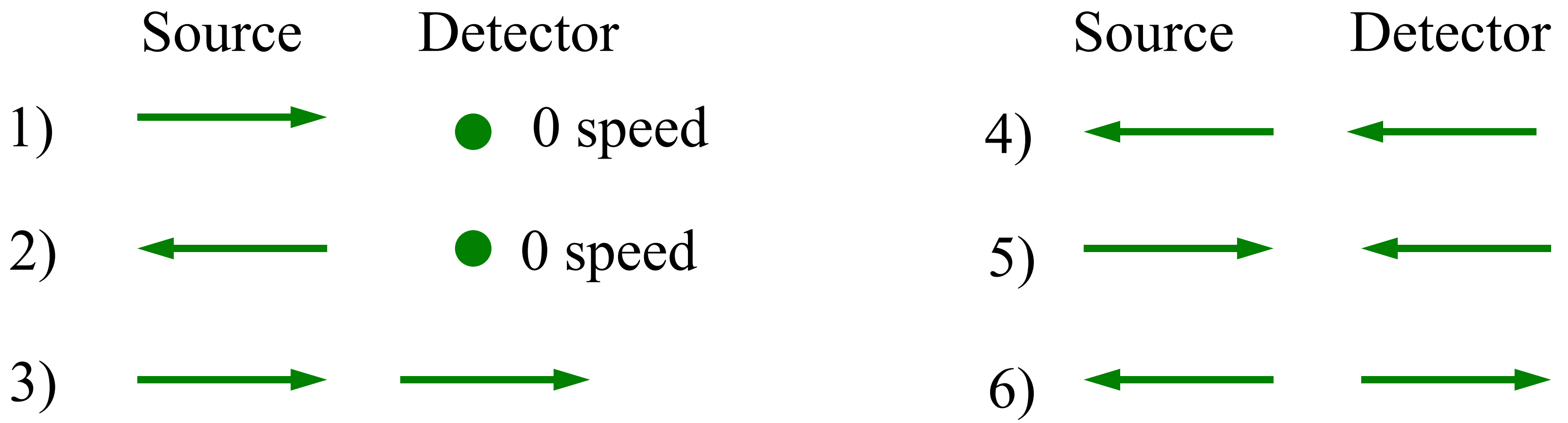


Continuous spectra: Blackbody radiation;

Black bars: Absorption lines by atoms and/or molecules

A Quiz

The figure indicates the directions of motion of a sound source and a detector (us) for six situations in stationary air. The speeds are all the same or zero. Which situation will we hear the highest frequency?



A Quiz

$$f' = f\,\frac{v \pm v_D}{v \pm v_S}$$

f' greatest when $v+v_D$ and $v-v_S$

The figure indicates the directions of motion of a sound source and a detector (us) for six situations in stationary air. The speeds are all the same or zero. Which situation will we hear the highest frequency?