- **Final Exam (cumulative): Tuesday December 14th, 12:30pm to 2:30pm.**
- **You must go to the following locations based on the 1st letter of your last name:**

A to K	NPB1001 (Physics)
L to Z	NRN 137 (Norman Hall)

- **Two more review sessions: Tues. Dec. 7 (Hill) and Thurs. Dec. 9 (Woodard), 6:15 to 8:10pm in NPB1001 (HERE!)**
- **HiTT scores to be emailed to you this week.**
- **Exams to be returned on Wednesday. Exam scores posted via WebAssign by tomorrow evening.**
- **Come and see either Dr. Woodard or myself if you suspect any irregularities (exams, quizzes, etc..)**

Class 42 - Waves II
Chapters 17 - Monday December 6th

- Sound waves and speed of sound
- Interference
  - Spatial
  - Temporal (beating)
- Sound intensity
- Sample problem (HiTT?)
- Sources of musical sound

Reading: pages 445 to 467 (chapter 17) in HRW

Read and understand the sample problems

Assigned problems from chapter 17 (due Dec. 8th!):

82, 14, 17, 30, 36, 42, 46, 47, 52, 64, 78

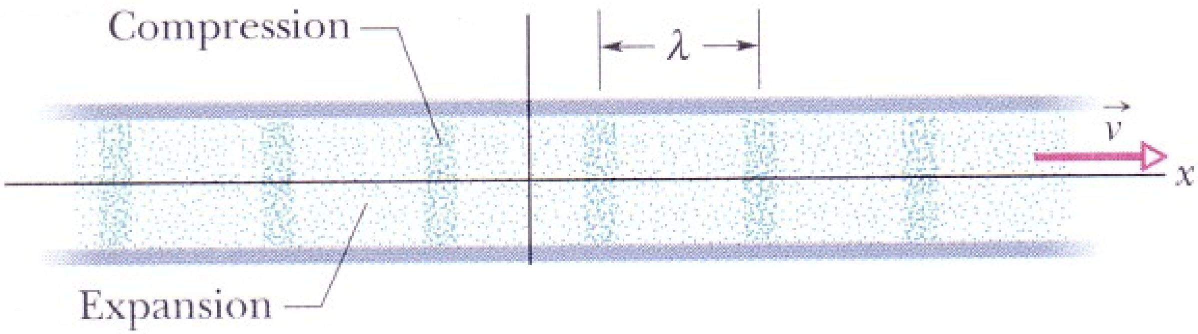
The speed of sound

TABLE 18-1 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

[a] At 0°C and 1 atm pressure, except where noted.

[b] At 20°C and 3.5% salinity.

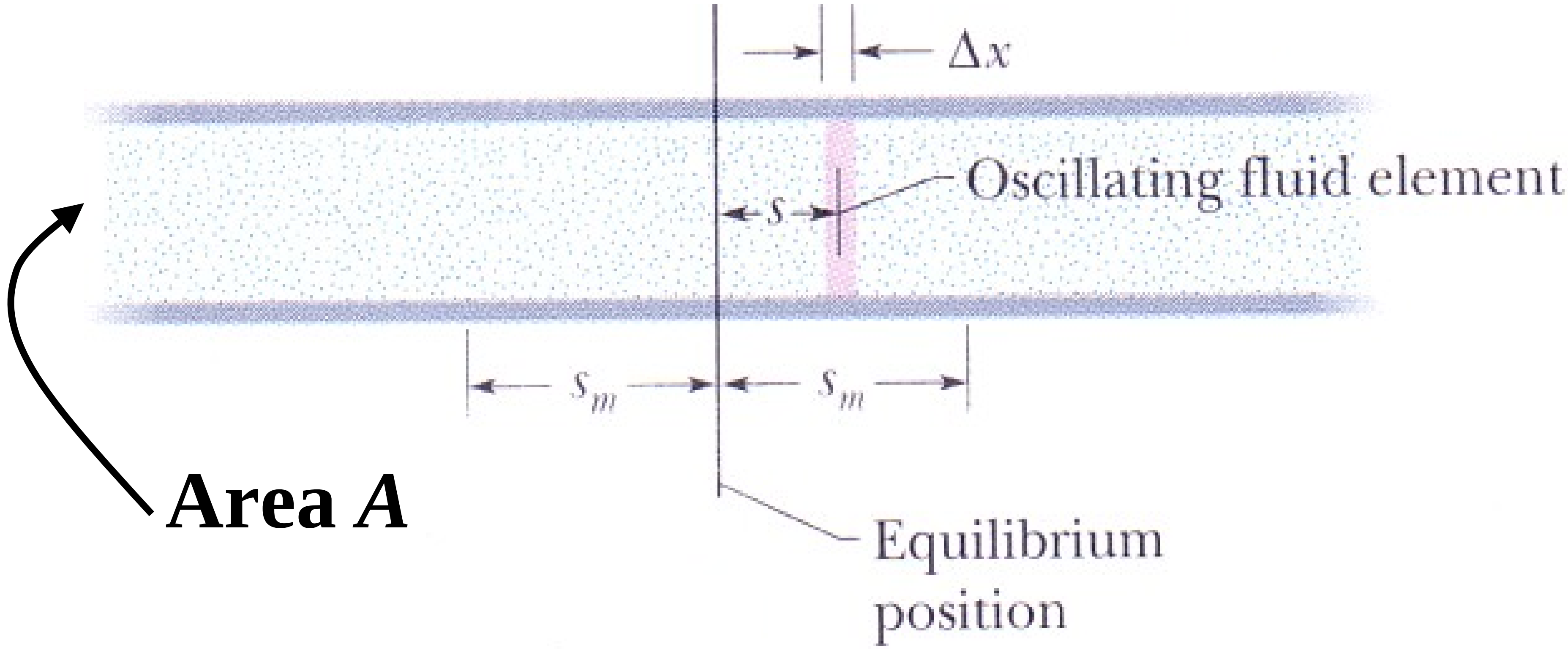


- It should not surprise you that the speed of sound is given by a similar expression to the one for a wave on a string,

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

where B is the bulk modulus of the medium, as defined in chapter 12 (page 318), and ρ is the density or mass per unit volume.

Traveling sound waves

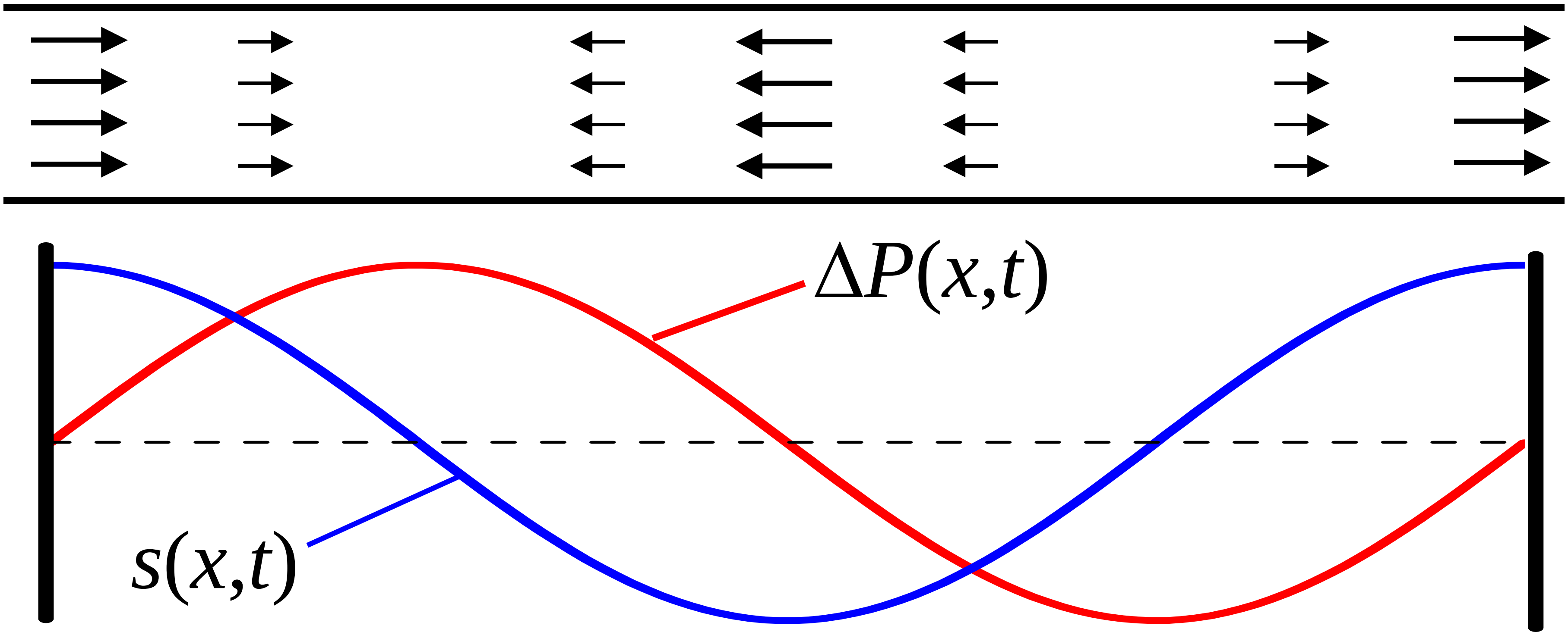


Longitudinal displacement: $s(x,t) = s_m \cos(kx - \omega t)$

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

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

Traveling sound waves



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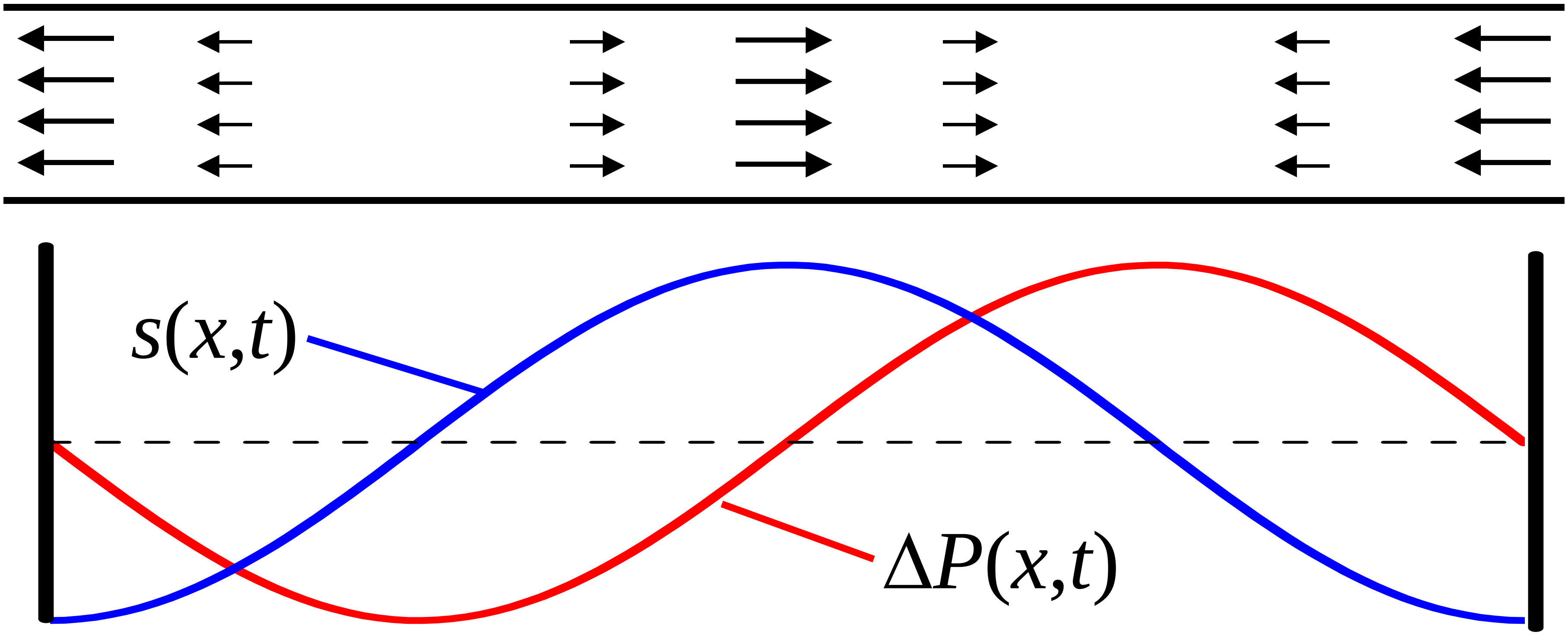
Traveling sound waves



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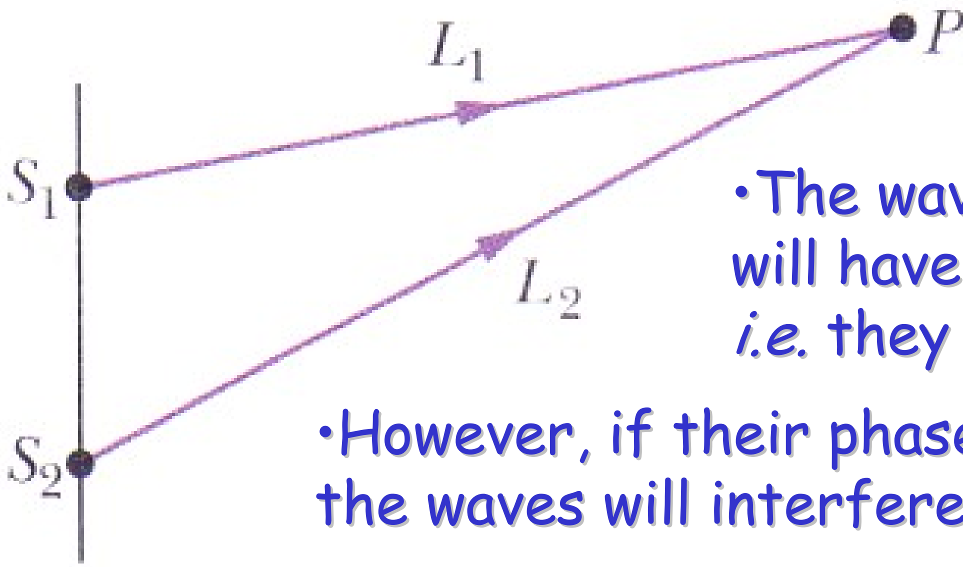
Interference - spatial



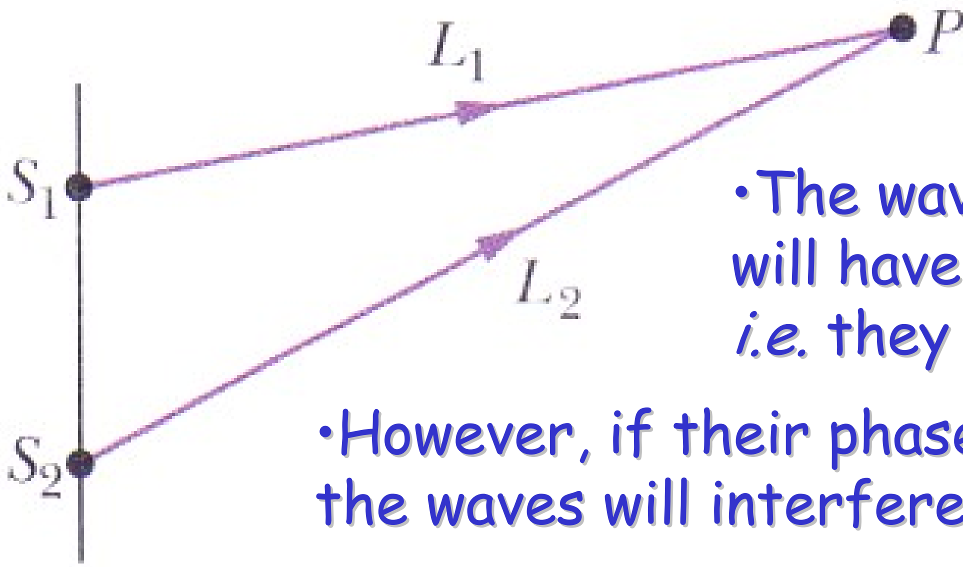
- The waves reaching P from S_1 and S_2 will have traveled different distances, *i.e.* they will not be in phase.
- However, if their phase difference is a multiple of 2π, the waves will interfere constructively.
- On the other hand, if their phase difference is an odd integer multiple of π, the waves will interfere destructively.

$$k\left(L_2 - L_1\right) = k\Delta L = \frac{2\pi}{\lambda}\Delta L = n \times 2\pi, \qquad n = 0,1,2,3..$$

$$\frac{\Delta L}{\lambda} = 0,1,2,...$$

Constructive interference

Interference - spatial



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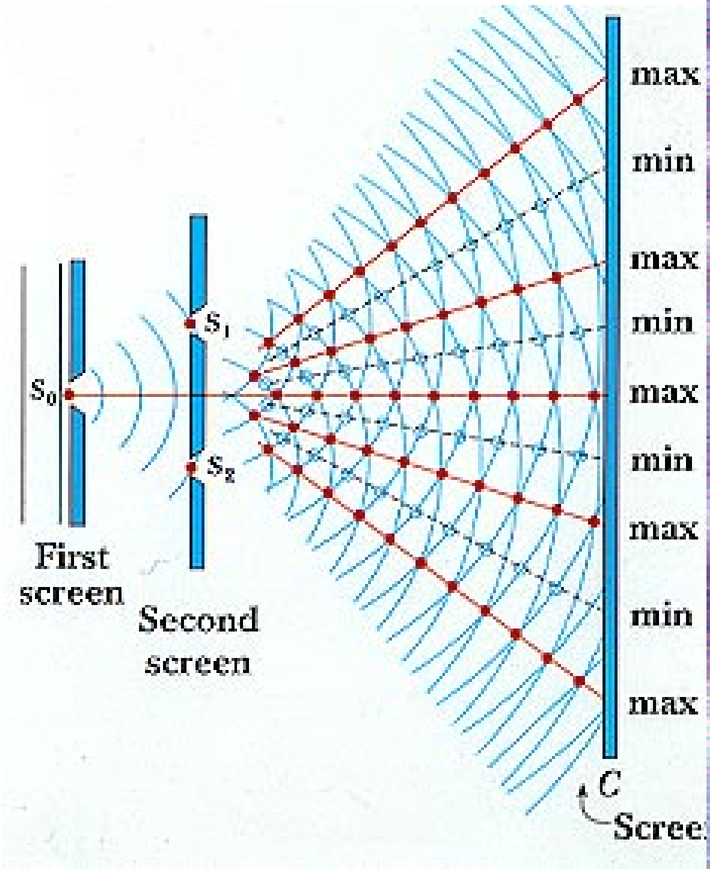
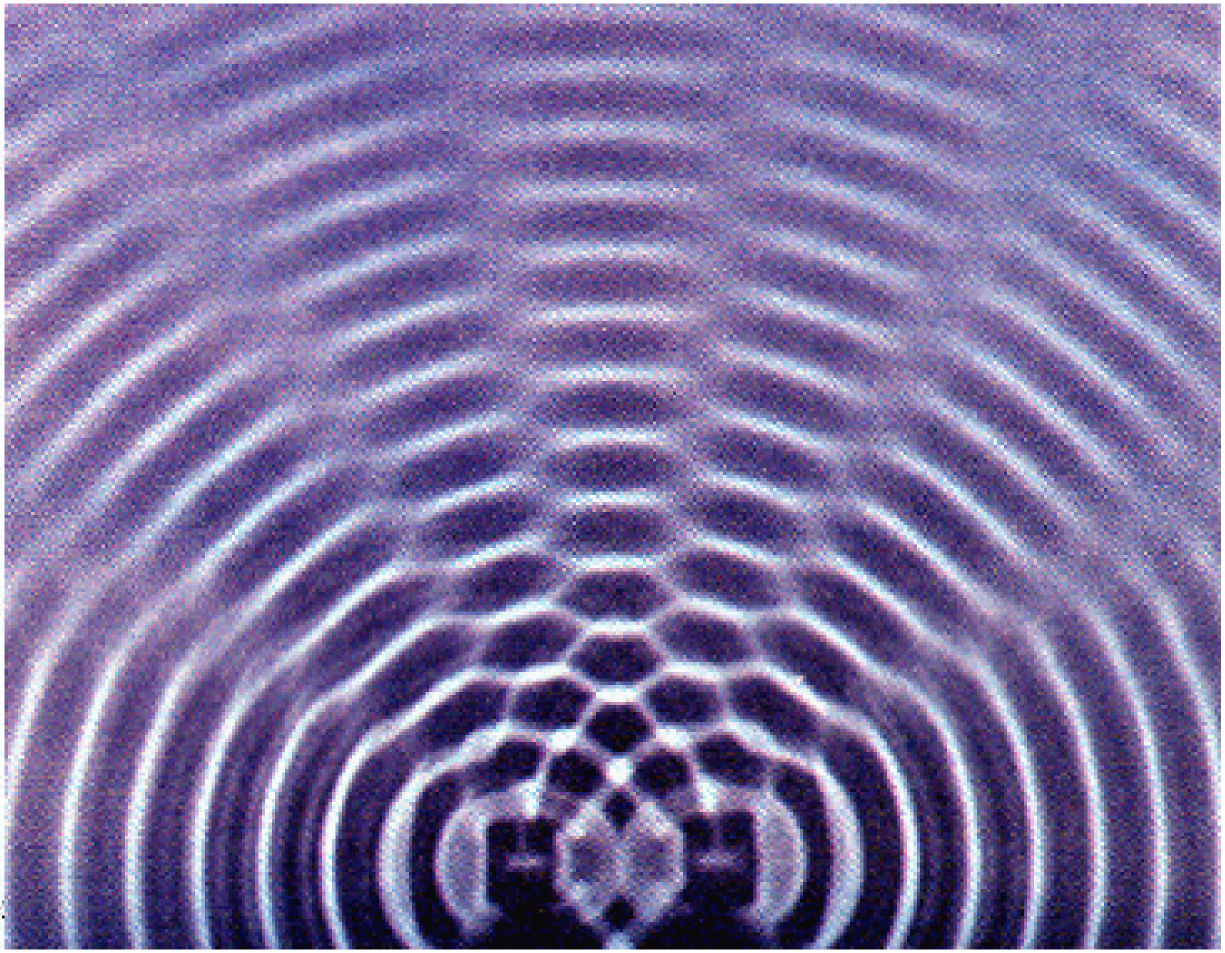
- On the other hand, if their phase difference is an odd integer multiple of π, the waves will interfere destructively.

$$k\Delta L = \frac{2\pi}{\lambda}\Delta L = \left(n + \tfrac{1}{2}\right) \times 2\pi, \qquad n = 0,1,2,3..$$

$$\frac{\Delta L}{\lambda} = 0.5,\, 1.5,\, 2.5, \ldots$$ Destructive interference

Wave interference





Interference - temporal (or beats)

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

- In order to obtain a spatial interference pattern, we placed two sources at different locations, *i.e.* we varied the first term in the phase of the waves.
- We can do the same in the time domain whereby, instead of placing sources at different locations, we give them different angular frequencies ω_1 and ω_2. For simplicity, we analyze the sound at $x = 0$.

$$s = s_1 + s_2 = s_m\left(\cos\omega_1 t + \cos\omega_2 t\right)$$

$$\cos\alpha + \cos\beta = 2\cos\tfrac{1}{2}\left(\alpha - \beta\right)\cos\tfrac{1}{2}\left(\alpha + \beta\right)$$

$$s = 2s_m \cos\tfrac{1}{2}\left(\omega_1 - \omega_2\right)t\cos\tfrac{1}{2}\left(\omega_1 + \omega_2\right)t$$

$$= \left[2s_m \cos\omega' t\right]\cos\omega t$$

$$\omega' = \tfrac{1}{2}\left(\omega_1 - \omega_2\right)$$

$$\omega = \tfrac{1}{2}\left(\omega_1 + \omega_2\right)$$

Interference - temporal (or beats)

$$s = \left[2s_m \cos\omega' t\right]\cos\omega t$$

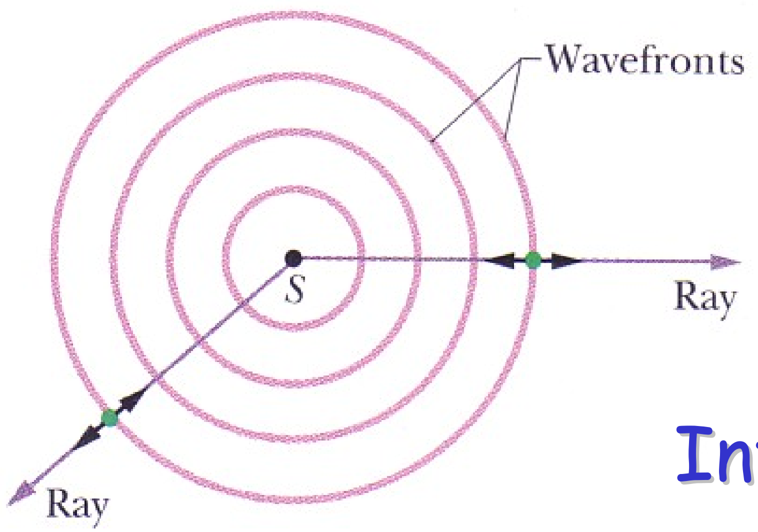
- A maximum amplitude occurs whenever $\omega' t$ has the value $+1$ or -1.
- This happens twice in each time period of the cosine function.
- Therefore, the beat frequency is twice the frequency ω', *i.e.*

$$\omega_{beat} = 2\omega' = \omega_1 - \omega_2$$

$$f_{beat} = 2f' = f_1 - f_2$$

Link 2

Sound wave intensity



- Sound waves radiate in all directions from a point source.
- Wavefronts are surfaces over which the phase (displacement or pressure) of the wave is constant.

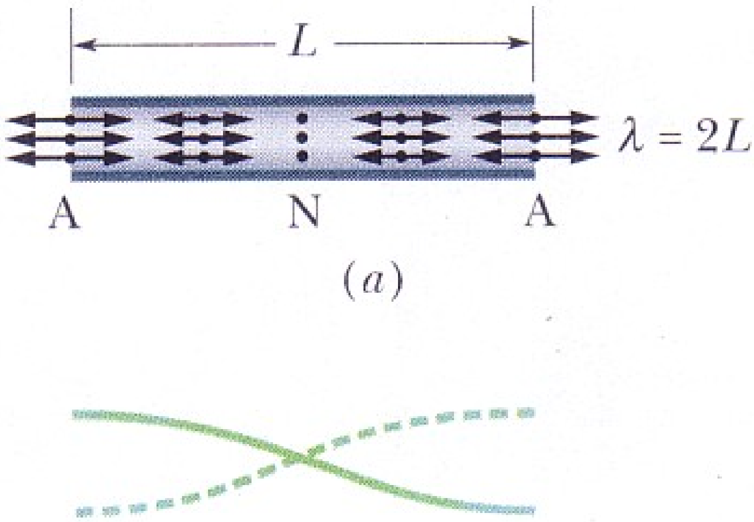
Intensity: $$I = \frac{\text{Power}}{\text{unit area}} = \frac{P_S}{4\pi r^2}$$

- P_S is the power produced a the source.
- The wavefronts are spherical close to a point source.
- At large distances, the wavefronts are approximately planar.

In analogy to waves on a string:

$$I = \tfrac{1}{2}\rho v \omega^2 s_m^2$$

Standing waves in air columns



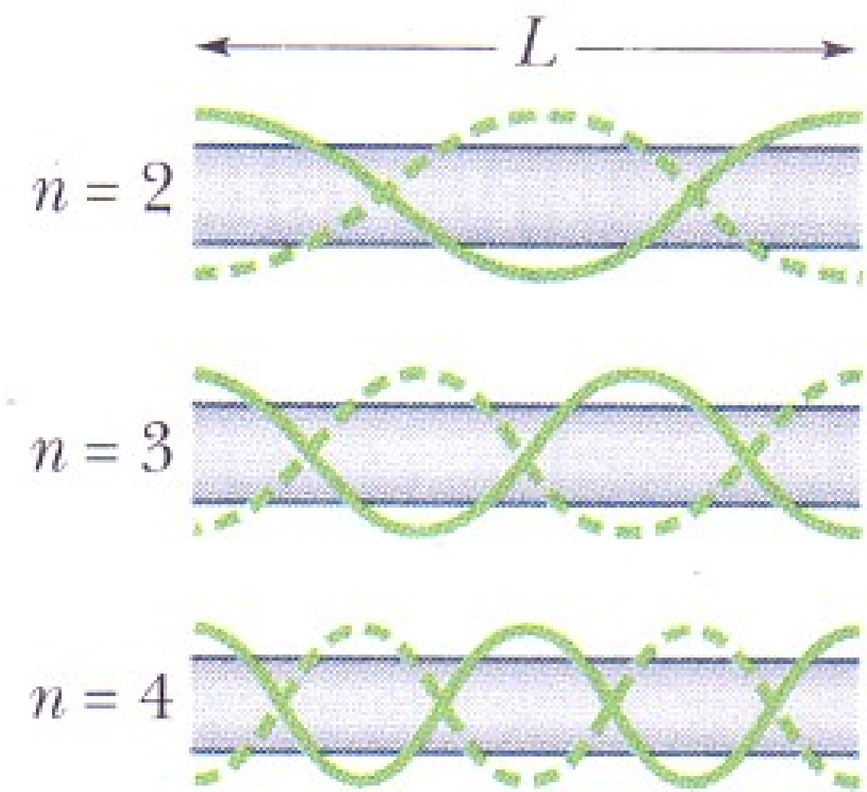
$$\lambda_1 = 2L = 2L/1$$

- Simplest case:
  - 2 open ends
  - Antinode at each end
  - 1 node in the middle
- Although the wave is longitudinal, we can represent it schematically by the solid and dashed green curves.

Standing waves in air columns

A harmonic series

$$\lambda_1 = 2L = 2L/1$$



$$\lambda_2 = 2L/2 = L$$

$$\lambda_3 = 2L/3$$

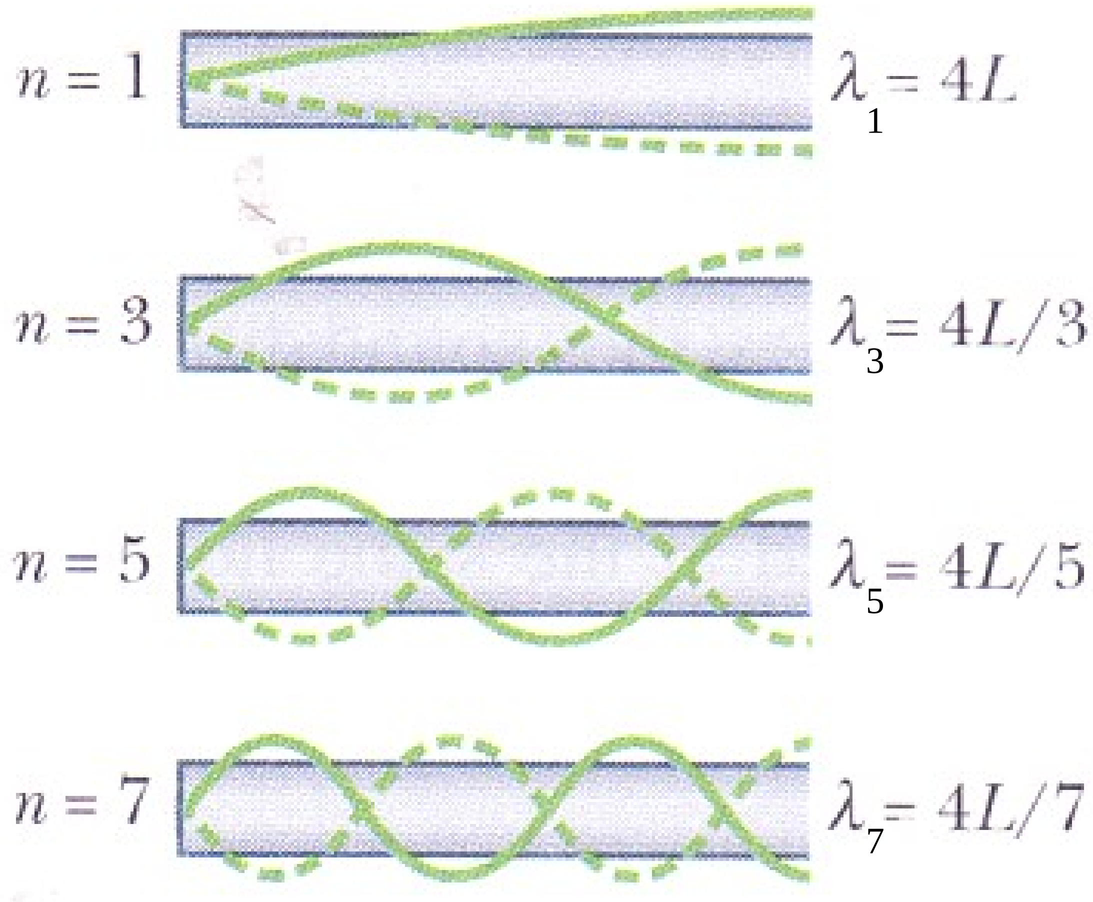
$$\lambda_4 = 2L/4 = L/2$$

$$\lambda = \frac{2L}{n}, \quad \text{for } n = 1, 2, 3, \ldots.$$

$$f = \frac{v}{\lambda} = \frac{nv}{2L}, \qquad \text{for } n = 1, 2, 3, \ldots$$

Standing waves in air columns

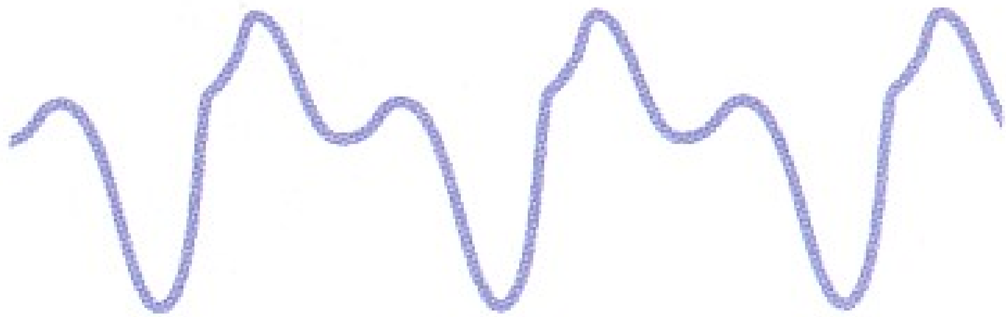
A different harmonic series



$$\lambda = \frac{4L}{n}, \quad \text{for } n = 1,3,5,....$$

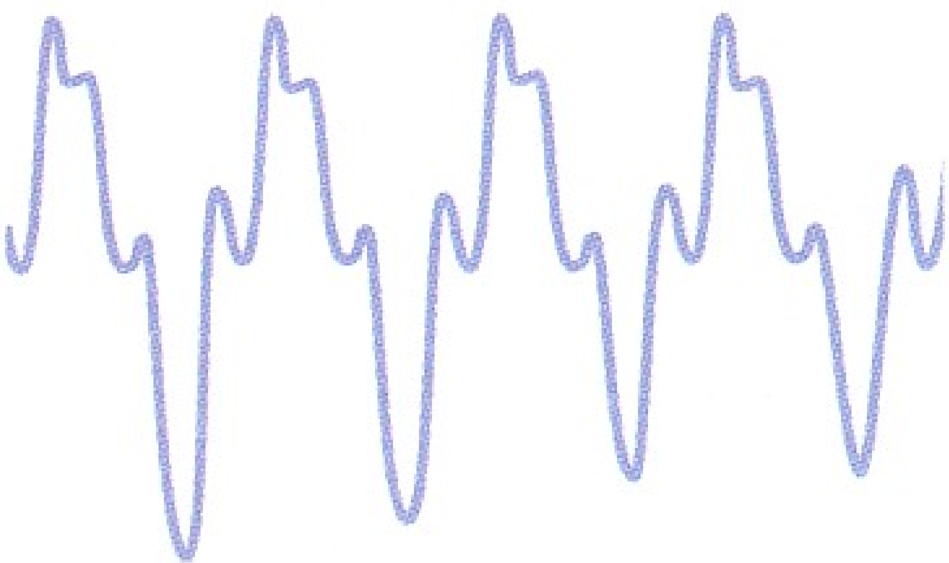
$$f = \frac{v}{\lambda} = \frac{nv}{4L}, \qquad \text{for } n = 1,3,5,...$$

Musical instruments



Flute

Oboe

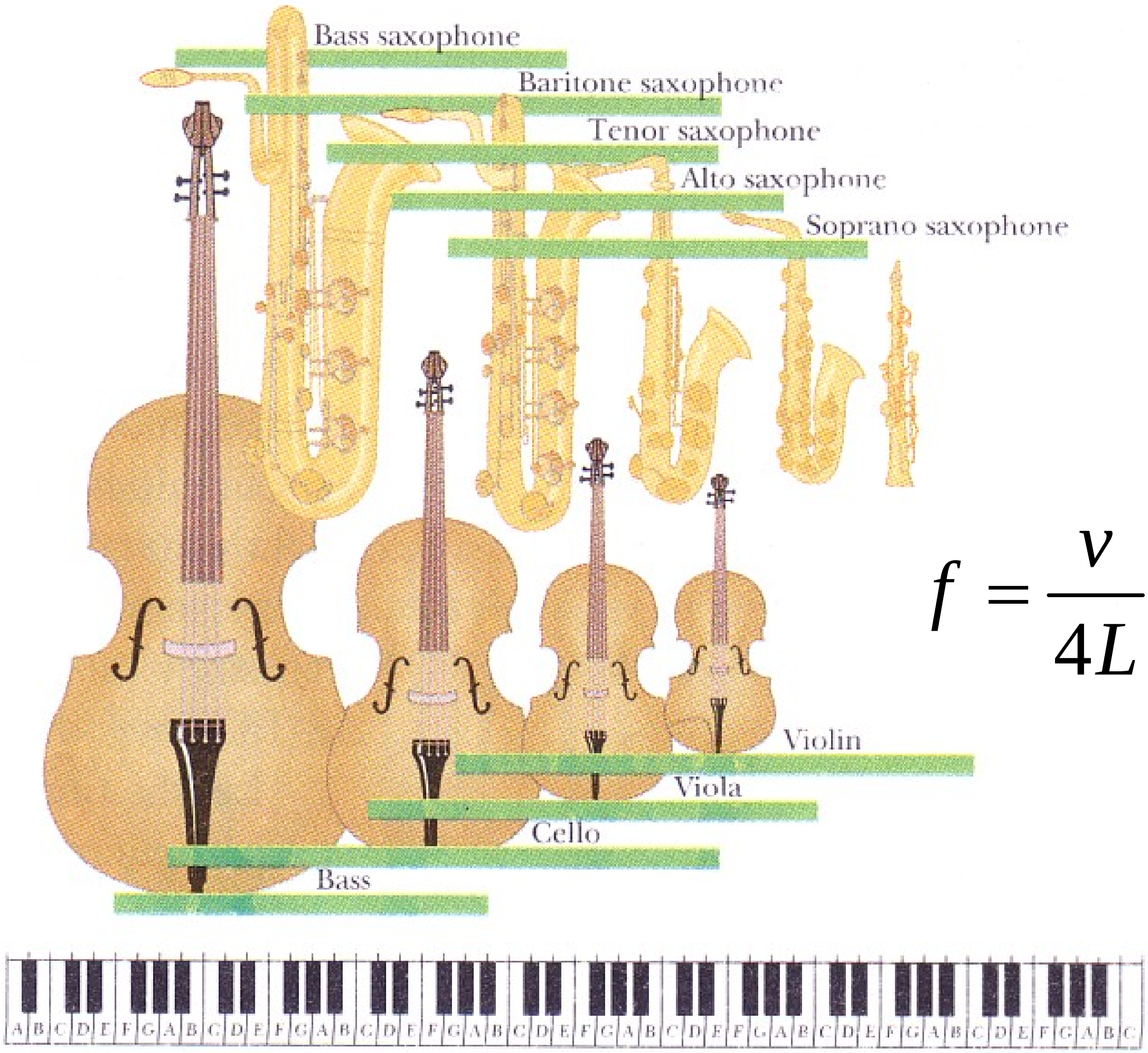


Saxophone

Link1 Link2

Link3

Musical instruments



$$f = \frac{v}{4L} \times \text{number}$$