- **Exam 3: TODAY, 8:20pm to 10:20pm**
- **You must go to the following locations based on the 1st letter of your last name:**

A to F	WEIL270 (Weil Hall)
G to M	**WM 100 (Williamson Hall)**
N to Z	FAB103/105 (Fine Arts B)

- **Final Exam (cumulative): Tuesday December 14th, 12:30pm to 2:30pm.**
- **Room assignments:** **A to K in NPB1001 (in here)**
L to Z in Norman Hall 137
- **Two more review sessions: Dec. 7 (Hill) and Dec. 9 (Woodard), 6:15 to 8:10pm in NPB1001 (HERE!)**

Class 41 - Waves I/II
Chapters 16 and 17 - Friday December 3rd

- QUICK review of wave interference
- Sample problems and HiTT
- Sound waves and speed of sound
- Sources of musical sound
- Course evaluations

Reading: pages 445 to 460 (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

Review - Standing waves

If two sinusoidal waves of the same amplitude and wavelength travel in opposite directions along a stretched string, their interference with each other produces a **standing wave**.

$$y'(x,t) = y_1(x,t) + y_2(x,t)$$

$$= y_m \sin(kx - \omega t) + y_m \sin(kx + \omega t + \phi)$$

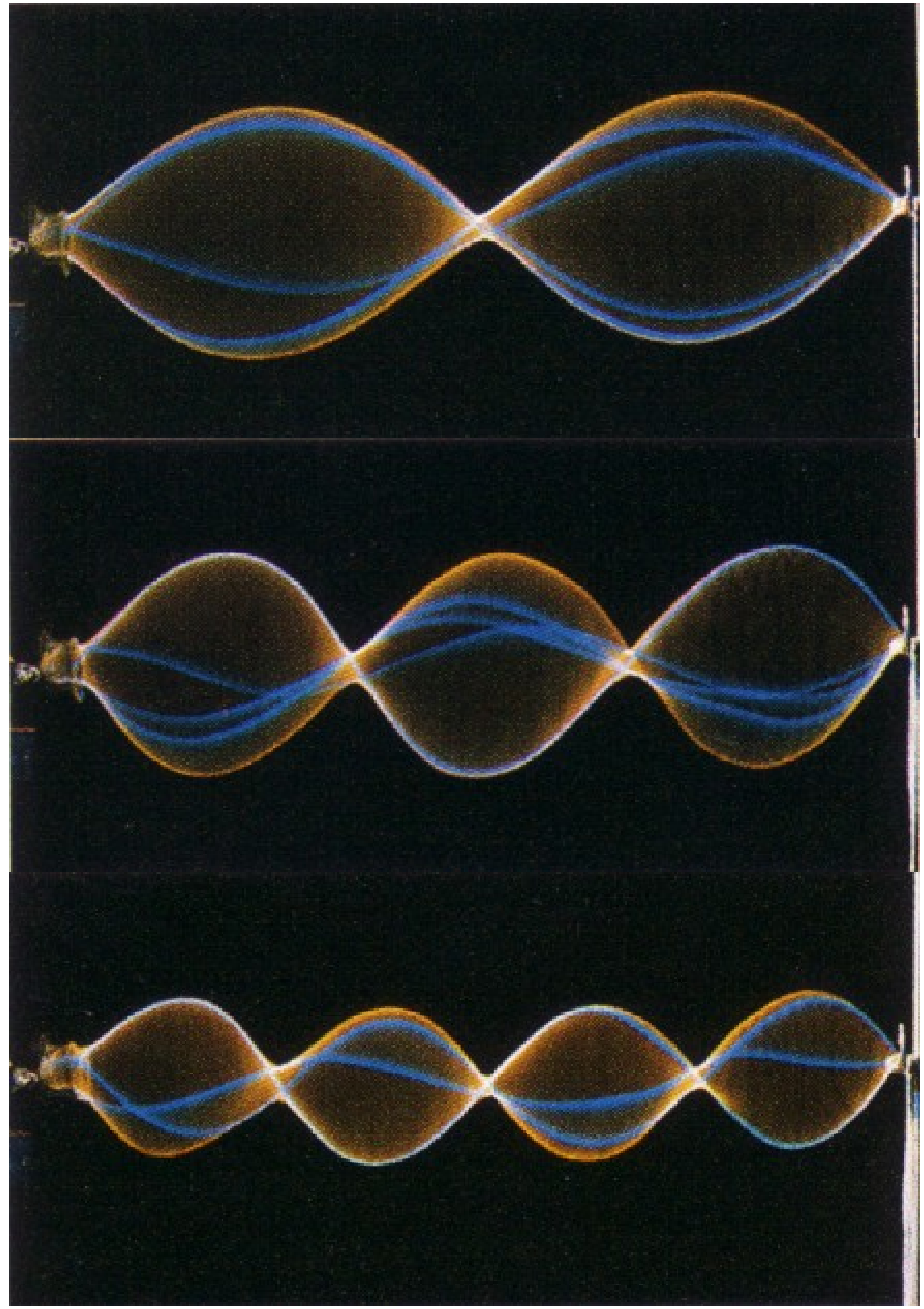
$$= 2y_m \sin\left(kx + \tfrac{1}{2}\phi\right)\cos\left(\omega t - \tfrac{1}{2}\phi\right)$$

- This is clearly not a traveling wave, because it does not have the form $f(kx - \omega t)$.
- In fact, it is a stationary wave, with a sinusoidal varying amplitude $2y_m\cos(\omega t)$.

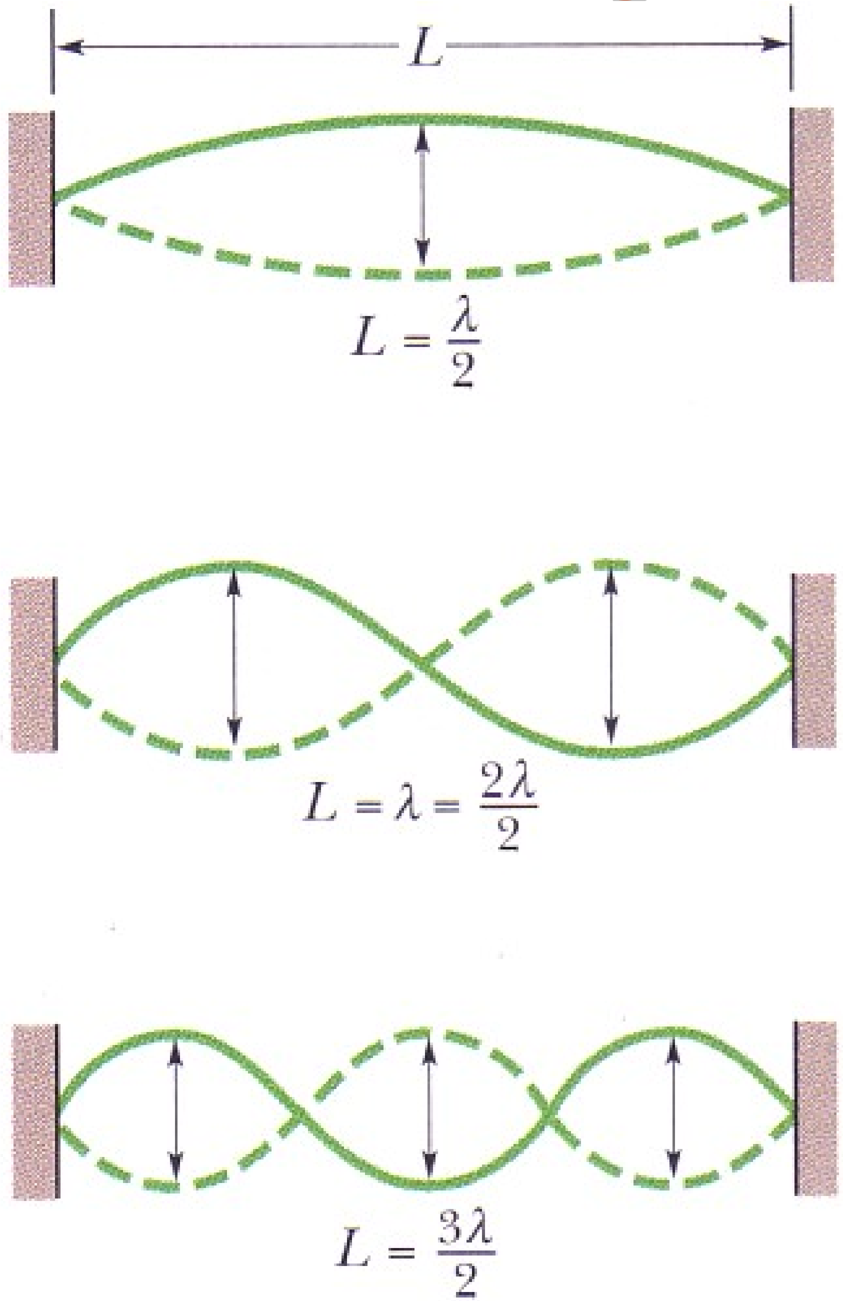
Link 1 **Link 2** **Link 3**

Standing waves and resonance

- At ordinary frequencies, waves travel backwards and forwards along the string.
- Each new reflected wave has a new phase.
- The interference is basically a mess, and no significant oscillations build up.



Standing waves and resonance



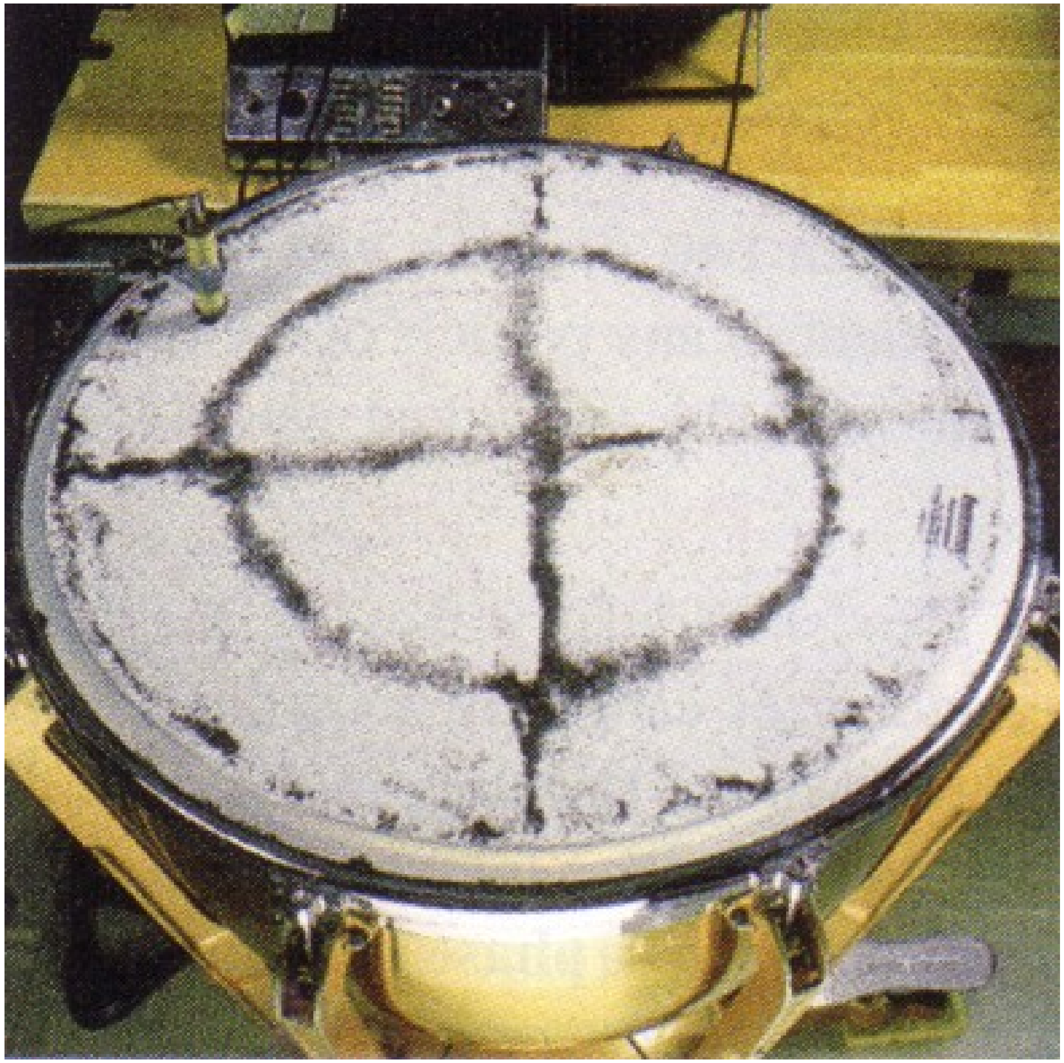
- Standing waves occur whenever the phase of the wave returning to the oscillating end of the string is precisely in phase with the forced oscillations.
- Thus, the trip along the string and back should be equal to an integral number of wavelengths, *i.e.*

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

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

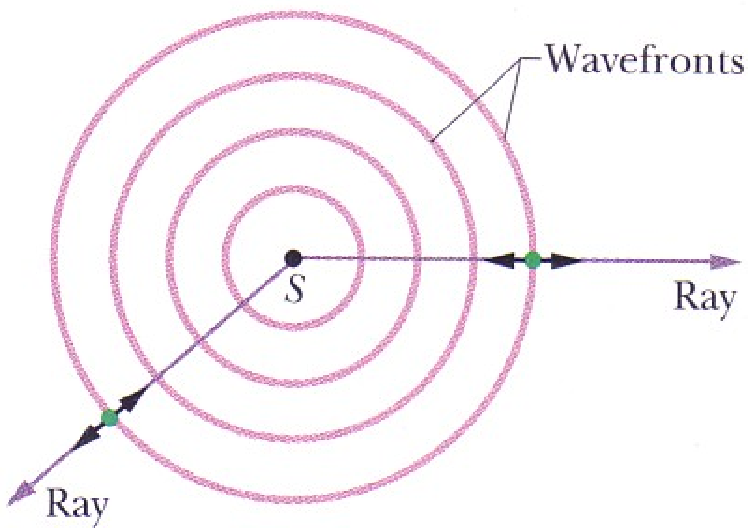
- Each of the frequencies f_1, f_1, f_1, *etc*, are called harmonics, or a harmonic series; n is the harmonic number.

Standing waves and resonance



- Here is an example of a two-dimensional vibrating diaphragm.
- The dark powder shows the positions of the nodes in the vibration.

Sound waves



- Sound waves are longitudinal.
- They travel in a medium; either gas, liquid or solid.
- 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.
- Rays are lines perpendicular to the wavefronts, and indicate the direction of travel of the wave.
- The wavefronts are spherical close to a point source.
- At large distances, the wavefronts are approximately planar.

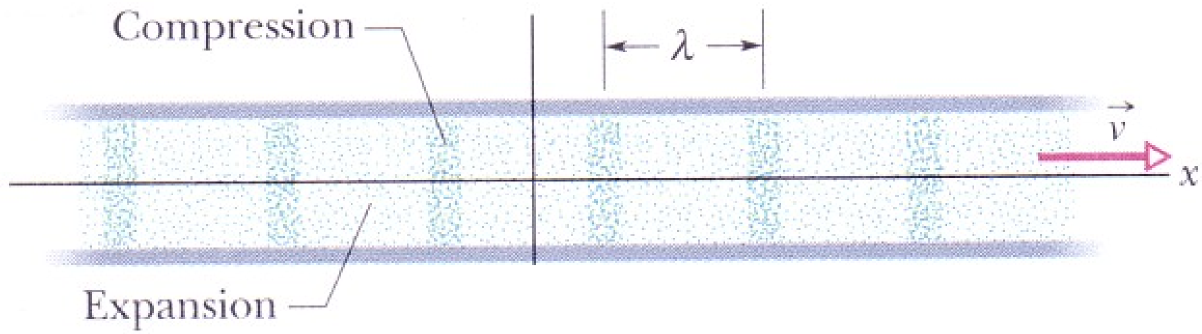
The speed of sound

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.



- Recall the velocity of a wave on a string,

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

The speed of sound

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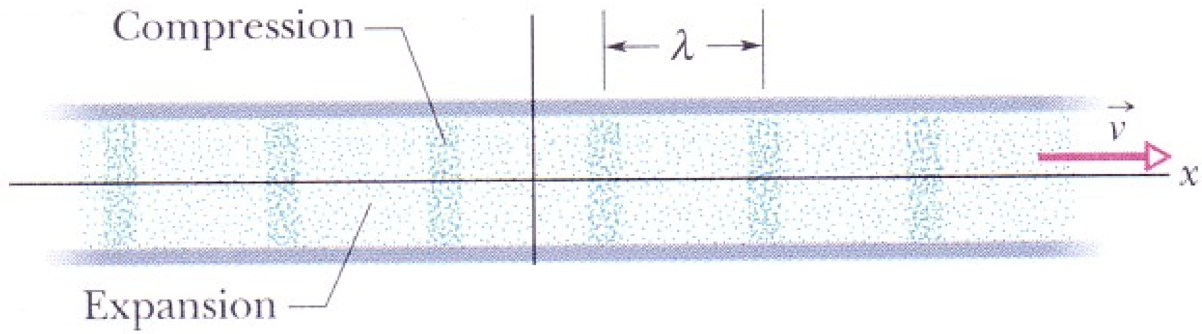
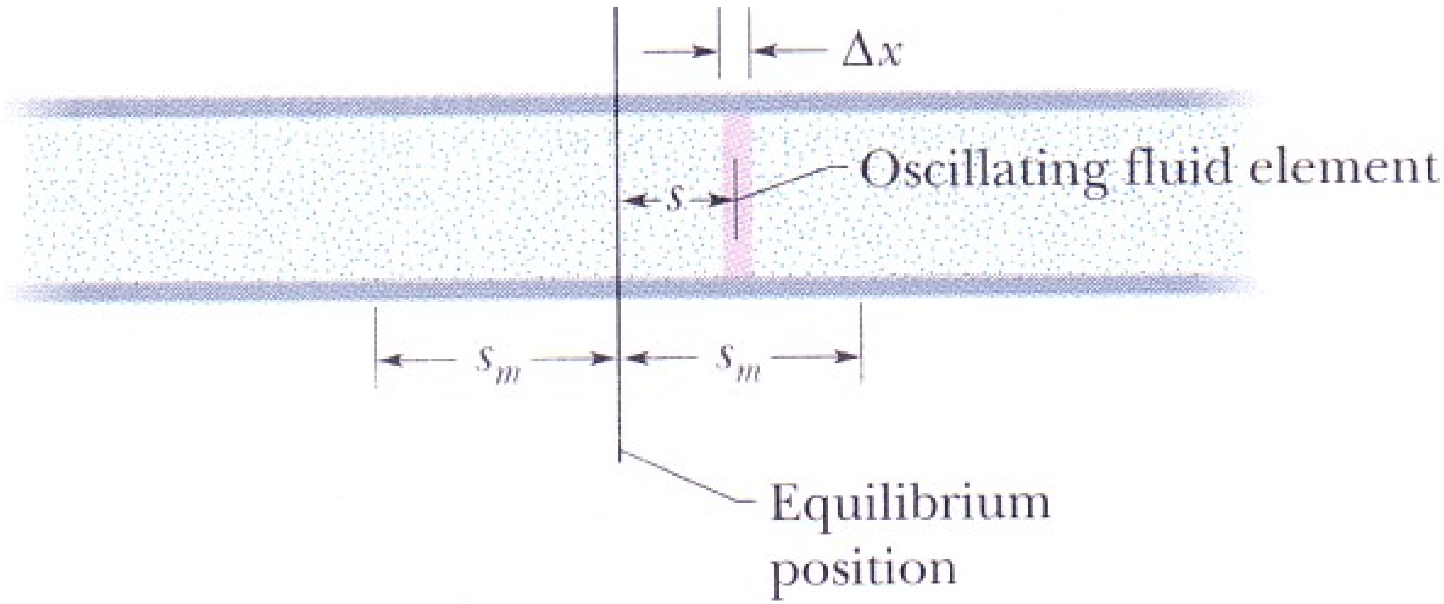


- Thus, it should not surprise you that the speed of sound is given by a similar expression

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

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

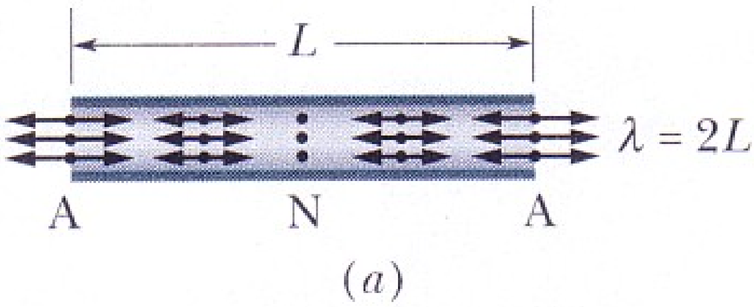


Longitudinal displacement: $s(x,t) = s_m \cos(kx - \omega t)$

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

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

Standing waves in air columns



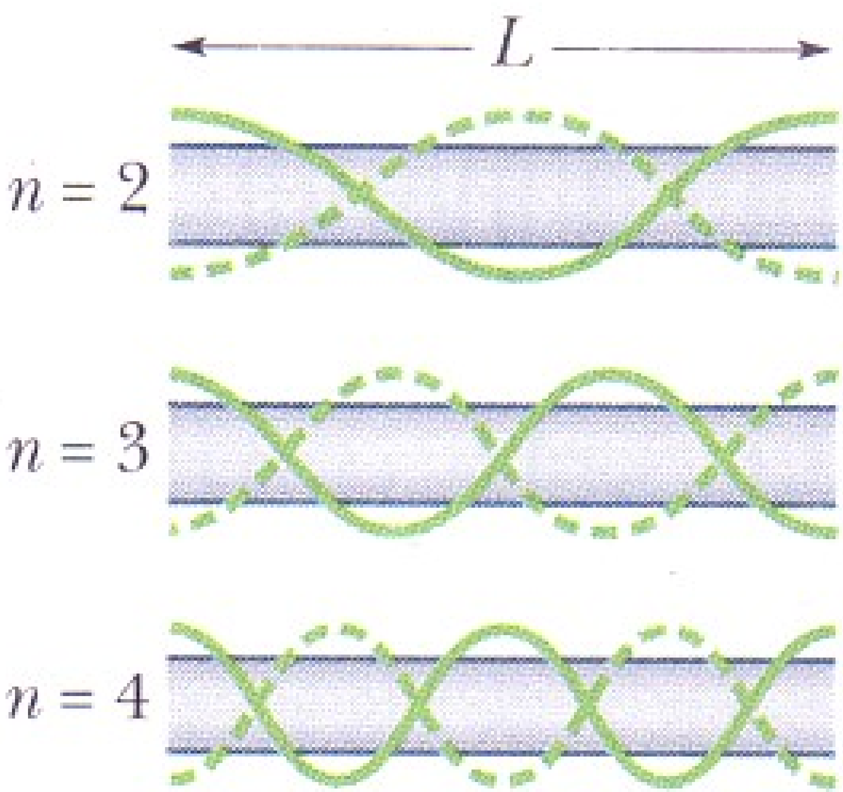
$$\lambda_1 = 2L = 2L/1$$

- 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

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



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

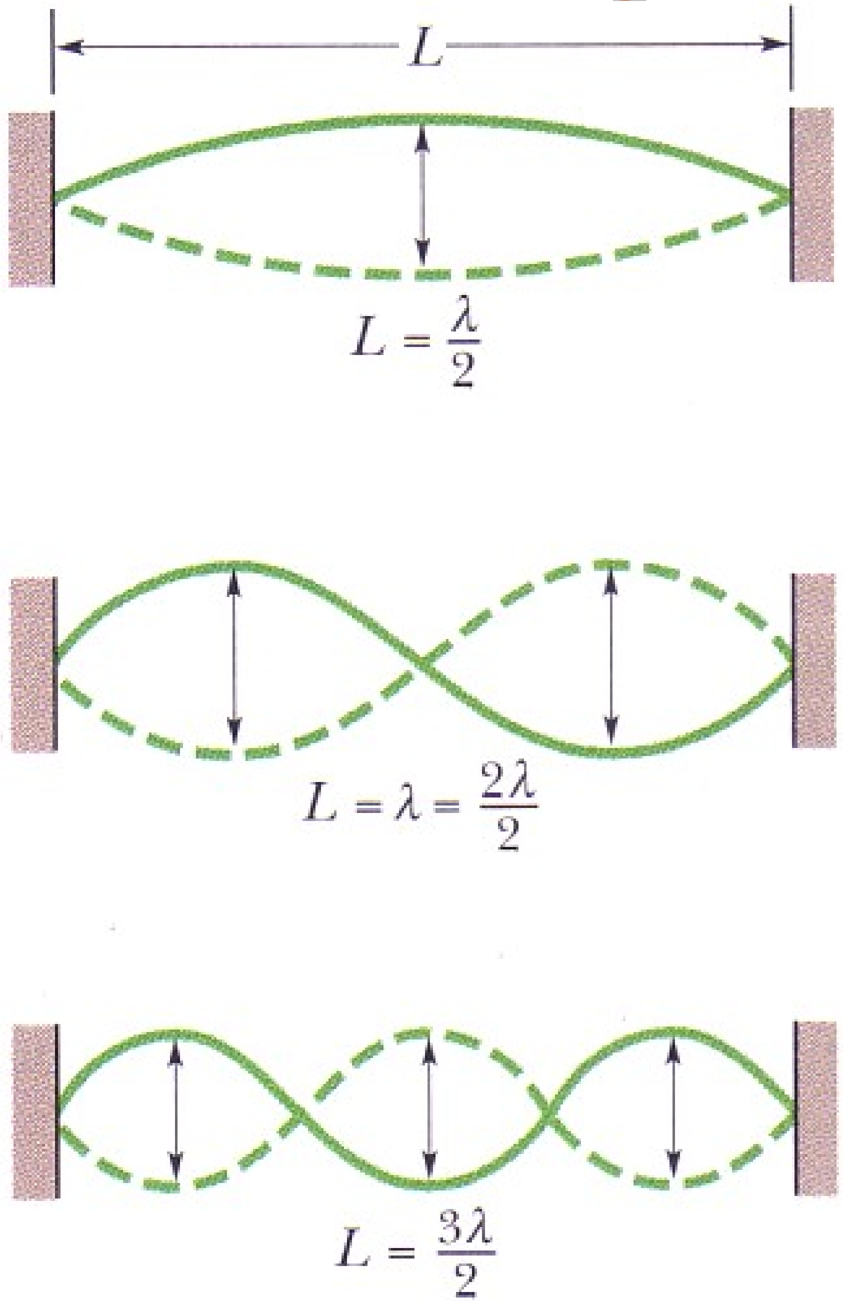
$$\lambda_3 = 2L/3$$

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

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

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

Standing waves and resonance



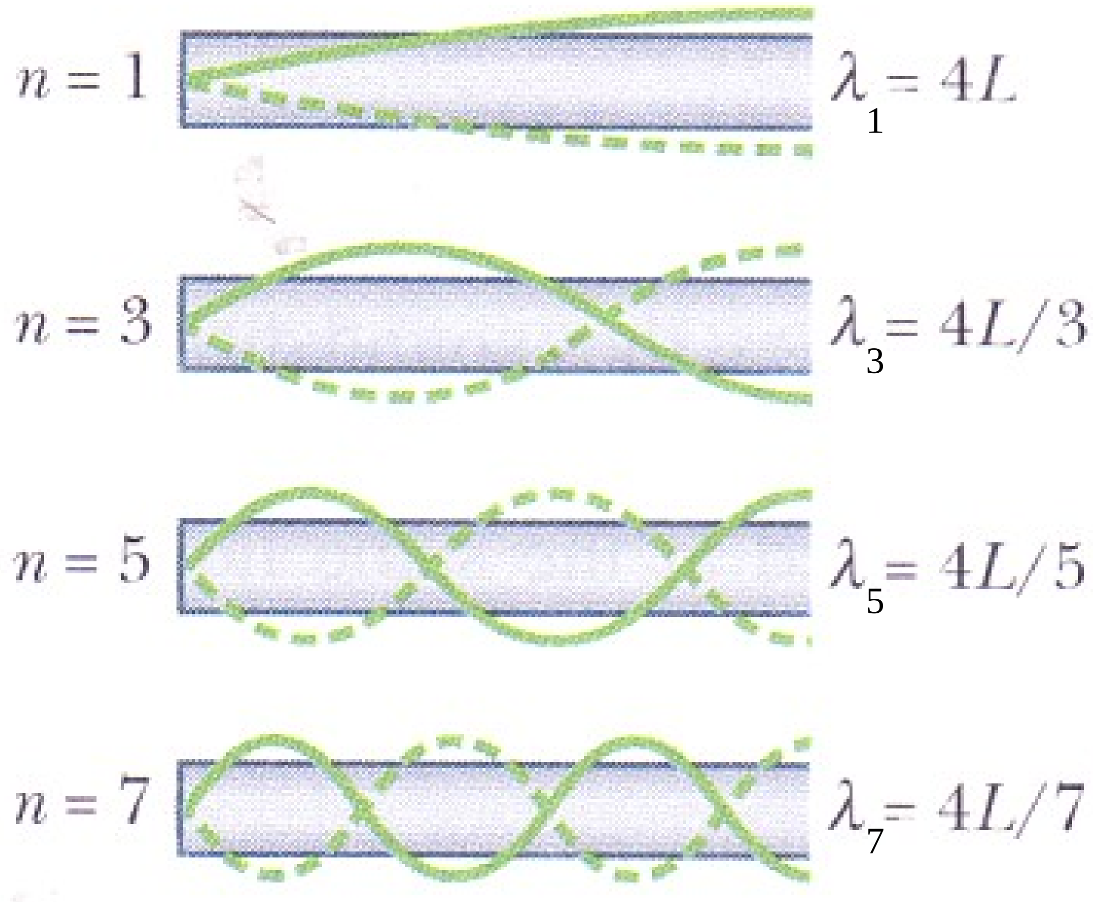
Same harmonic series

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

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

Standing waves in air columns

A different harmonic series



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

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