

# **PHYS1406: Physics of Sound and Music**

**Spring 2023**

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# Topics we'll cover this semester

- Preliminaries: Basic math, music, and physics terminology
- Physics of oscillations and waves
- Production of sound (instruments and voice)
- Perception of sound (hearing, loudness, pitch & timbre)
- Auditorium and room acoustics; electrical reproduction of sound
- Musical scales and tuning systems (standardization of musical notes)

**Why are you in this class?**

**What questions about sound & music would you like to know the answer to?**

# What is sound? What differentiates speech, music, & noise?

- Sound is a **pressure wave** in air (or some other medium, which could be a liquid or solid).
- The pressure wave consists of alternating regions of **compression** and **expansion** of the air molecules.
- **Energy is transferred** from the source of sound to our ears, while the individual air molecules just oscillate back-and-forth in place.
- noise: chaotic, unorganized sound
- speech & music: organized sound
- **musical notes** have a **definite pitch** (low or high), while noise does not

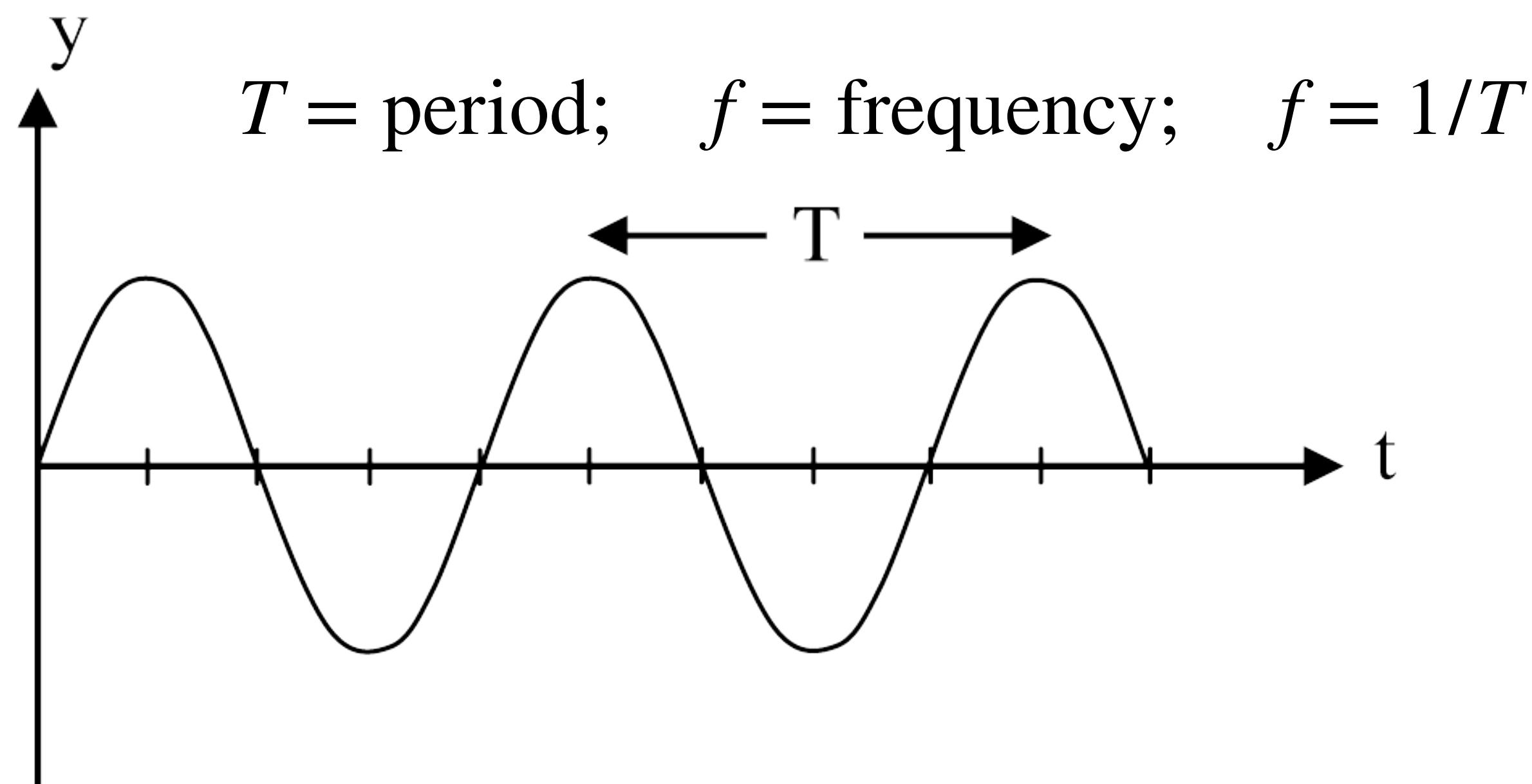
# Demos: sound measuring devices & musical instruments

- Measuring devices
  - **oscilloscope**: shows how the sound pressure wave changes in time
  - **FFT analyzer**: shows how much sound energy is associated with different pitch components
  - **spectrogram**: shows how the pitch content of a sound changes in time
- Musical instruments and sound-making devices:
  - whistle, singing, speaking
  - penny whistle, recorder, funny plastic recorder, train whistle, other wind instruments
  - plucked guitar string, bowed violin string
  - bell, drum, shakers, marimba bar, other percussion instruments
  - ratchet, crumpled paper, applause

# Range of human hearing

<https://www.szynalski.com/tone-generator/>

- Normal range: 20 Hz - 20,000 Hz
- What is frequency? Number of repetitions (oscillations, cycles, ...) in a given time interval
- Example: Heart rate: 70 beats/1 minute = 1.14 beats/sec
- Hertz (Hz): 1 Hz = 1 cycle/sec



# **1. Preliminaries**

# Basic math review

- Entering numbers on a calculator: What's the value of  $1/2\pi$ ? **Ans:**  $1 \div (2 \times \pi) = 0.16$  not  $1 \div 2 \times \pi = 1.57$
- Fractions: What's the value of 2 divided by  $3/2$ ? **Ans:**  $2 \div (3/2) = 2 \times (2/3) = 4/3 = 1.33$
- Powers (exponential notation): What's the value of  $2^4$ ?  $10^3$ ?  $10^{-2}$ ?

**Ans:**  $2^4 = 2 \times 2 \times 2 \times 2 = 16$ ;  $10^3 = 1000$ ;  $10^{-2} = 1/10^2 = 0.01$

- Prefixes:

nano	micro	milli	centi	kilo	mega	giga	tera
$10^{-9}$	$10^{-6}$	$10^{-3}$	$10^{-2}$	$10^3$	$10^6$	$10^9$	$10^{12}$

- Comparing two numbers: Compare the heights of two people, one who is 5.5 ft tall versus another who is 72 inches all.

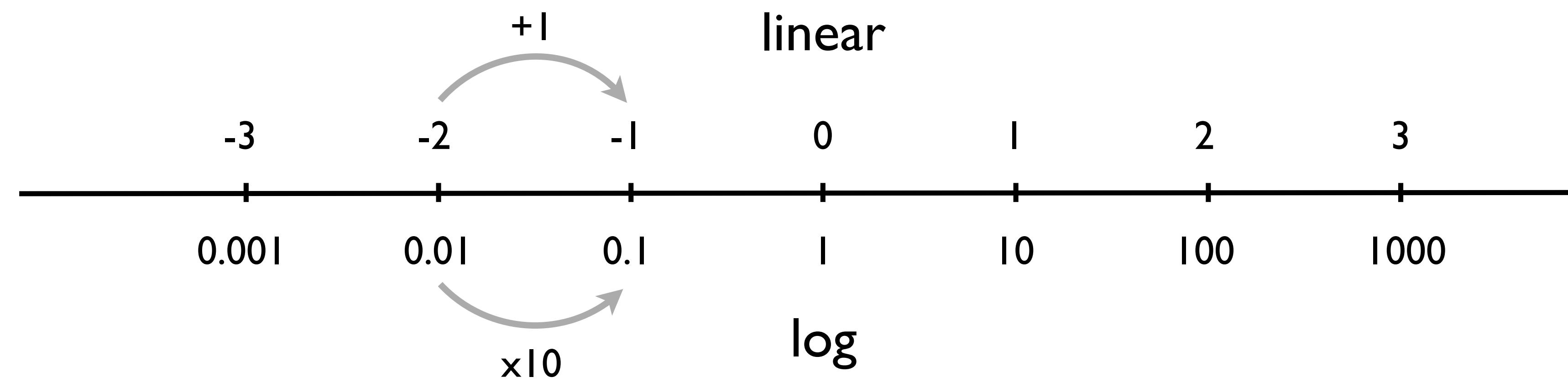
**Ans:** First convert 5.5 ft to 66 inches. Then subtract ( $72 \text{ in} - 66 \text{ in} = 6 \text{ in}$ ) or divide ( $72 \text{ in}/66 \text{ in} = 1.09$ ) or calculate percent difference ( $100 \times (72 - 66)/66 = 9\%$ ). For music applications, taking ratios or percent differences are most convenient and useful

- Converting units: The speed of sound in air at room temperature (25 celsius) is 346 m/s. What is its value in ft/s? miles/s?

**Ans:** Using the conversion factors ( $1 \text{ m} = 3.28 \text{ ft}$  and  $1 \text{ mi} = 5280 \text{ ft}$ ), we find:

$$346 \frac{\text{m}}{\text{s}} \times \frac{3.28 \text{ ft}}{\text{m}} = 1135 \frac{\text{ft}}{\text{s}} \approx 1000 \frac{\text{ft}}{\text{s}} \text{ and } 1135 \frac{\text{ft}}{\text{s}} \times \frac{1 \text{ mi}}{5280 \text{ ft}} = 0.21 \frac{\text{mi}}{\text{s}} \approx \frac{1 \text{ mi}}{5 \text{ s}}$$

# Linear vs logarithmic scales

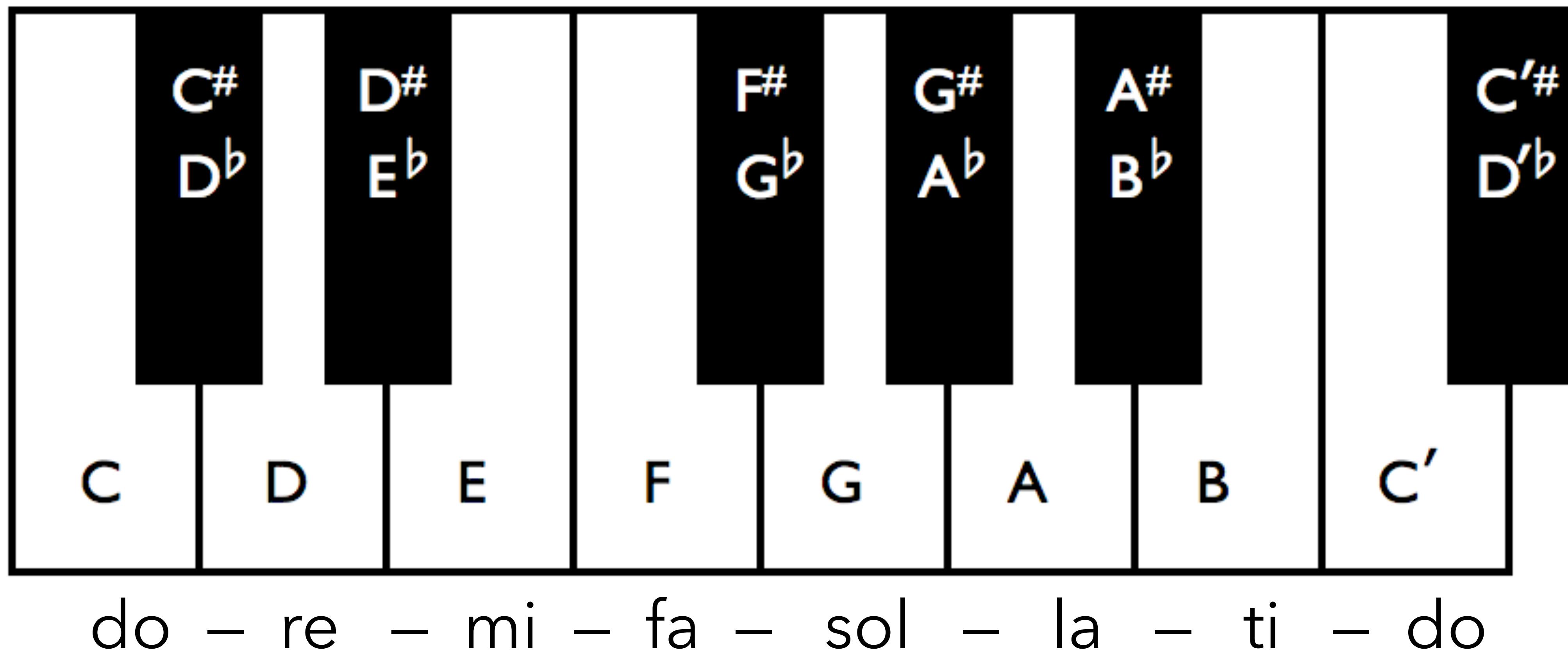


# Music terminology

- Pitch: fundamental frequency
- Timbre: richness of a sound, associated with contributions from higher harmonics. It's what makes a guitar sound different from a flute, etc., even though they are all playing the same musical note.
- Octave: Factor of 2 in frequency (e.g., C3 to C4)
- Chromatic, diatonic, and pentatonic scales: divide the octave into 12, 7, and 5 pieces (intervals)
  - <https://www.youtube.com/watch?v=jaMA8LWW3C0> (pentatonic scale; all black keys in C-major scale)
- Equal temperament: musical scale where all semitone intervals are equal to one another (6% higher in frequency)
- Musical intervals:
  - **fifth** (C to G; 7 semitones; frequency ratio = 3/2), **fourth** (C to F; 5 semitones; frequency ratio = 4/3), **major third** (C to E; 4 semitones; frequency ratio = 5/4), **minor third** (E to G; 3 semitones; frequency ratio = 6/5)
- Chord: Major chord C-E-G

# Chromatic and diatonic scales

C - C# - D - Eb - E - F - F# - G - Ab - A - Bb - B - C'



# Physics terminology

- Position, displacement: position = location of an object in space, specified by its distance from a reference point and its direction relative to reference axes; displacement = change in position  $\Delta x$ ; units for both are m, in, ft, mi, ...
- Time, duration: time = reading on a clock; duration = difference in times  $\Delta t$ ; units for both are s, min, hr, year, ...
- Velocity, speed, acceleration: velocity = displacement/duration; speed = distance traveled/duration; acceleration = change in velocity/duration; velocity and acceleration have both magnitude and direction; units of velocity and speed are m/s, mi/hr, ...; units of acceleration are m/s<sup>2</sup>, mph/s, ...
  - (i) uniform circular motion: changing position, velocity, and acceleration even though speed = constant
  - (ii) mass on a spring: changing position, velocity, and acceleration; velocity = 0 at the turning points of the motion; acceleration = 0 at the equilibrium position where the speed is greatest
- Force, mass, Newton's 2nd law: force = that which produces an acceleration; mass = resistance that an object offers to changes in its state of motion;  $a = F/m$  or  $F = ma$  (units of force are Newtons or lbs; units of mass are grams or kilograms)
- Density, pressure, atmospheric pressure: density = mass/volume or mass/length; pressure = force/area; units of pressure are N/m<sup>2</sup> or lb/in<sup>2</sup> = psi; 1 atm =  $10^5$  N/m<sup>2</sup> = 14.5 psi

# Exercise

- Calculate the pressure exerted by a 120 lb woman standing on the floor, wearing stilettos having approximately circular heels with radius 0.25 in. Compare to the pressure exerted by a 10,000 lb elephant whose four feet are approximately circles with radius 10 in.
- **Ans:** Recall that the area of a circle is  $\pi r^2$ , where  $r$  is the radius.

$$\text{Woman: } P = F/A = 120 \text{ lb}/(2 \times \pi(0.25 \text{ in})^2) \approx 300 \text{ lb/in}^2$$

$$\text{Elephant: } P = F/A = 10000 \text{ lb}/(4 \times \pi(10 \text{ in})^2) \approx 8 \text{ lb/in}^2$$

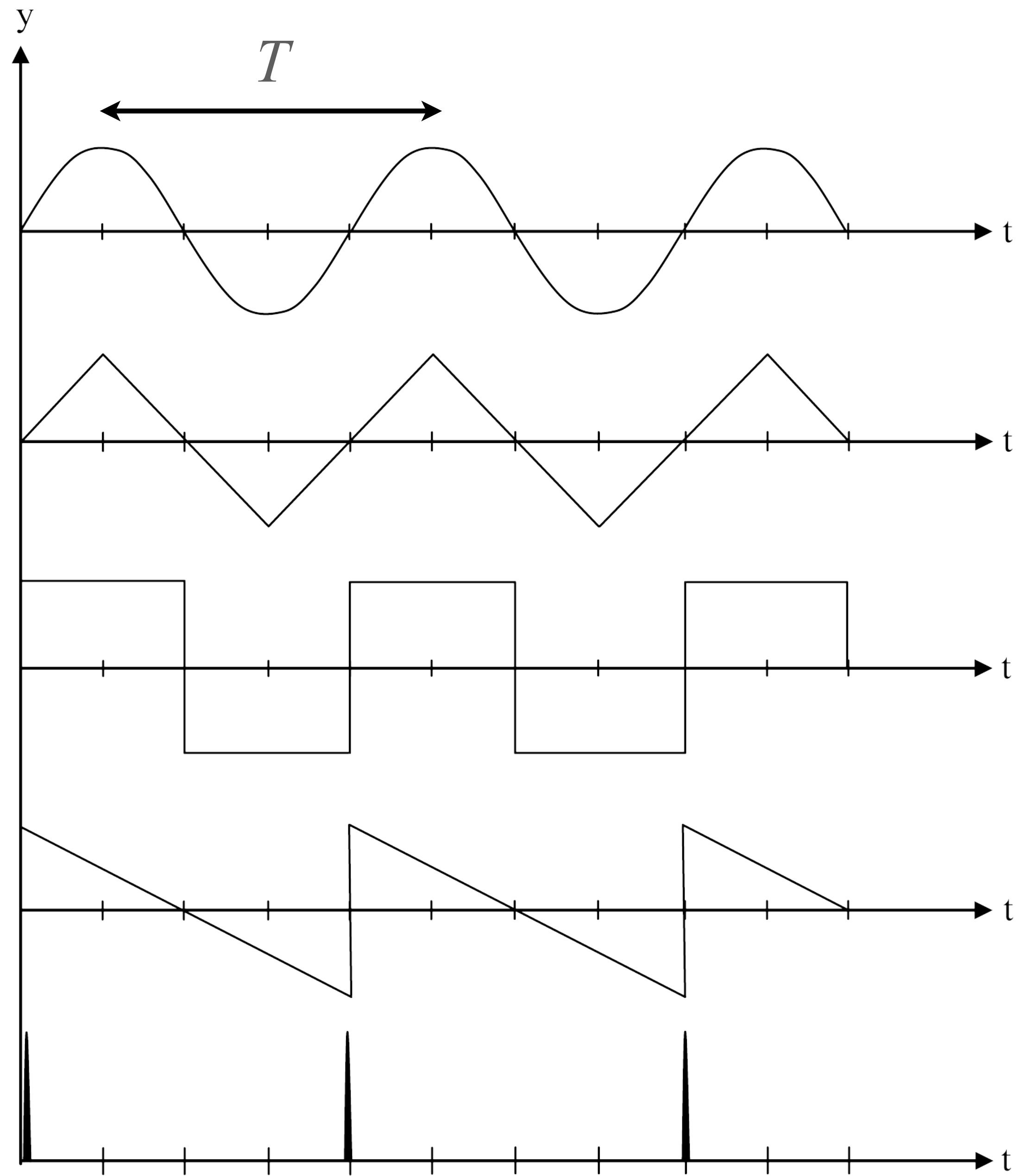
# **2. Oscillations**

# Periodic motion

- Oscillation: any motion that repeats
- Examples: vibrating guitar string; vibrating reed of a bassoon; swinging pendulum bob; mass on a spring; yearly orbital motion of Earth around the Sun; beating heart; ...
- Period ( $T$ ), frequency ( $f$ ): period is the time for one complete oscillation; frequency is the number of oscillations in a given interval of time;  $f = 1/T$  or  $T = 1/f$ . Pitch corresponds to the fundamental frequency of a musical note.
  - **Ques:** What are the periods of sound waves corresponding to the range of human hearing?
  - **Ans:**  $f = 20 \text{ Hz}$  has  $T = 50 \text{ msec}$ ;  $f = 20,000 \text{ Hz}$  has  $T = 50 \text{ microsec}$
- Amplitude: 1/2 the peak-to-peak displacement of an oscillation (related to the loudness of a sound)
- Waveform: the shape of a wave. Different waveforms having the same period (or frequency) sound differently. So the waveform of a sound corresponds to its timbre.

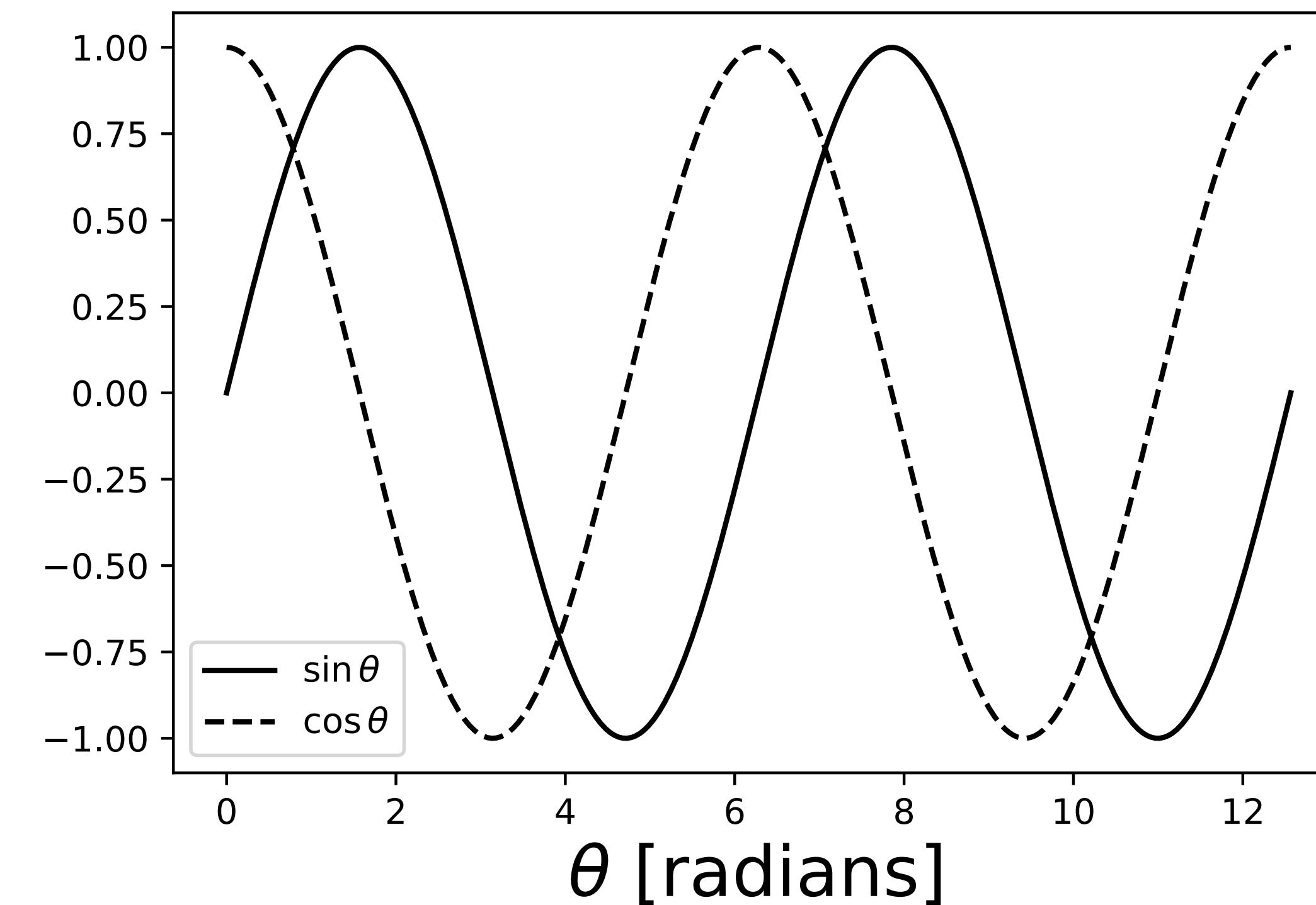
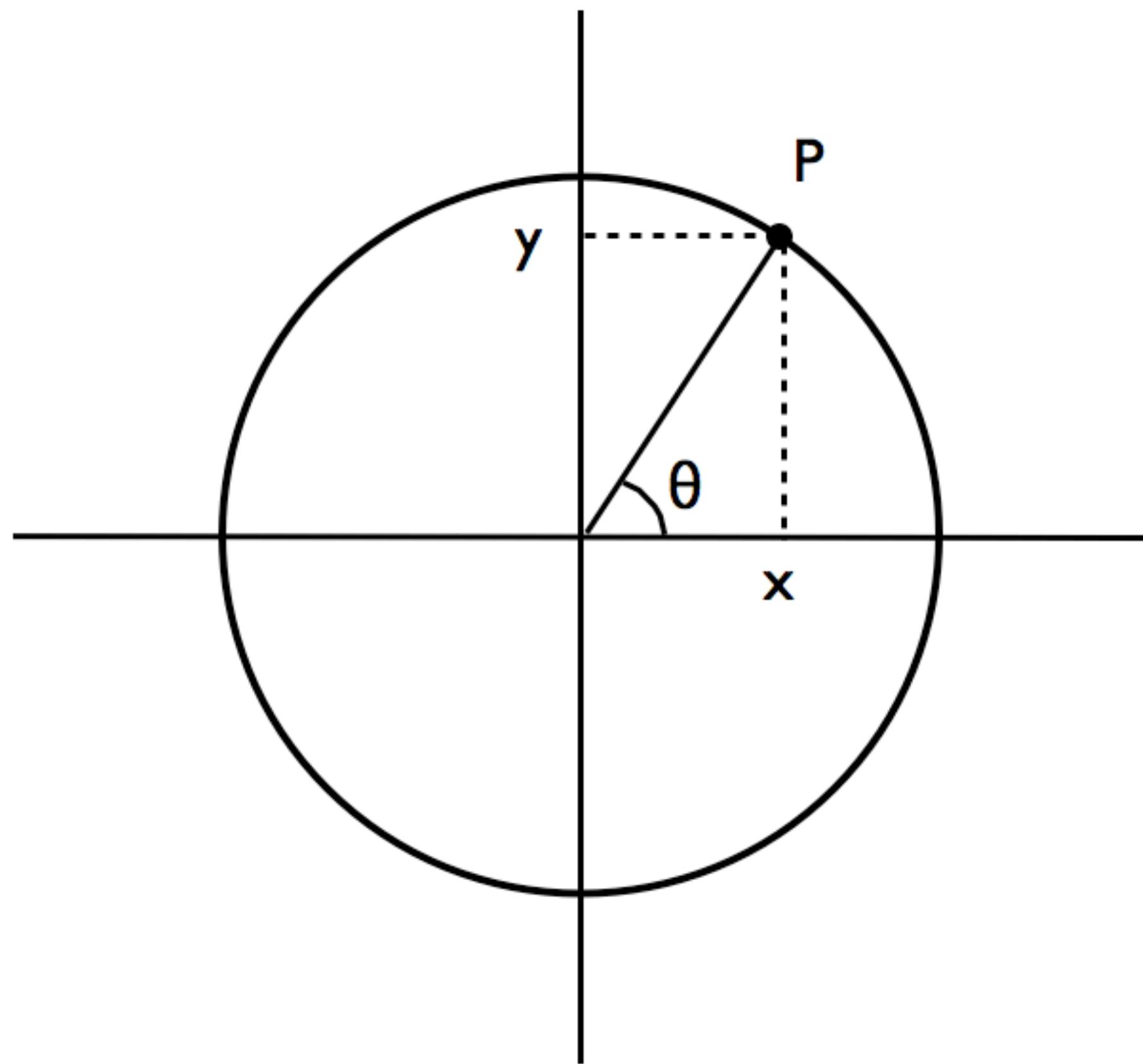
# Different waveforms

- Demo: Compare sounds
- Although the pitch is the same, the timbre (i.e., sound quality) is different



# Simple harmonic motion (SHM)

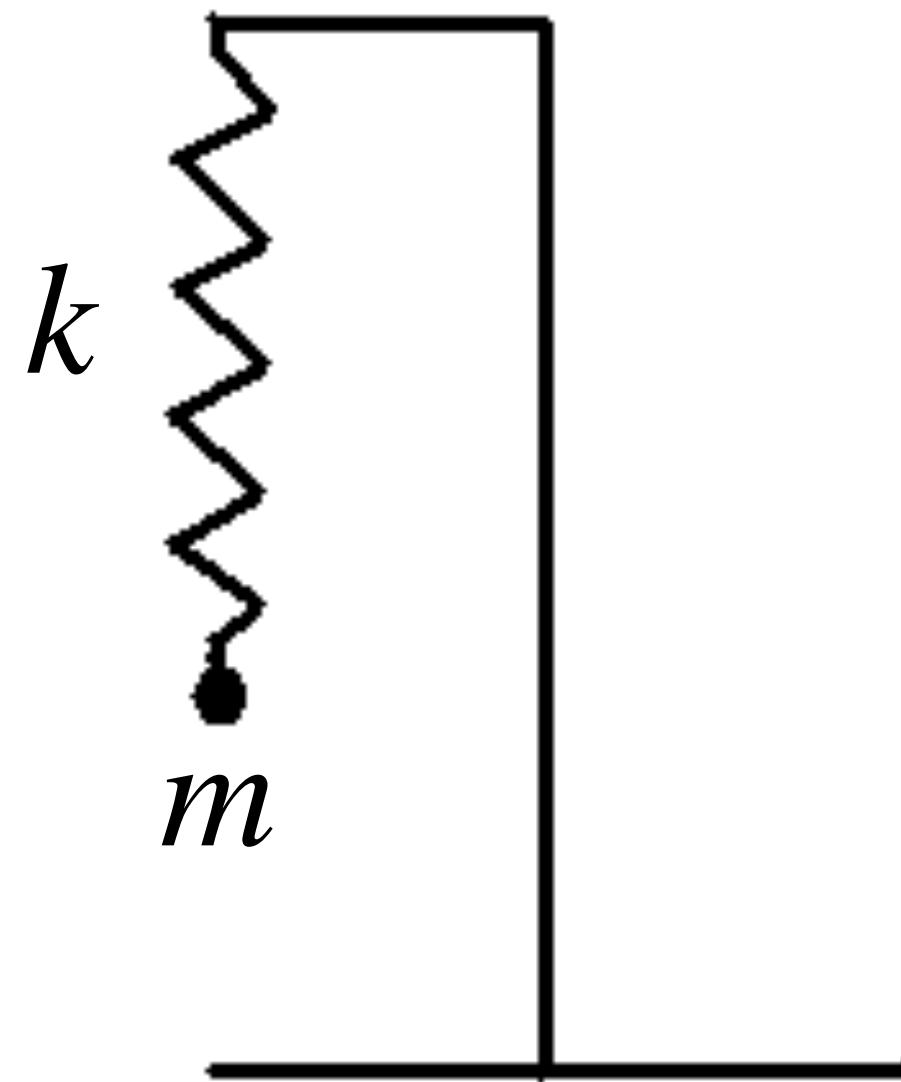
- Produced whenever you have a **linear restoring force** acting on a system that has a **stable equilibrium**.  
(Linear means the restoring force is twice as great if the displacement from equilibrium is twice as large.)



# Examples of SHM

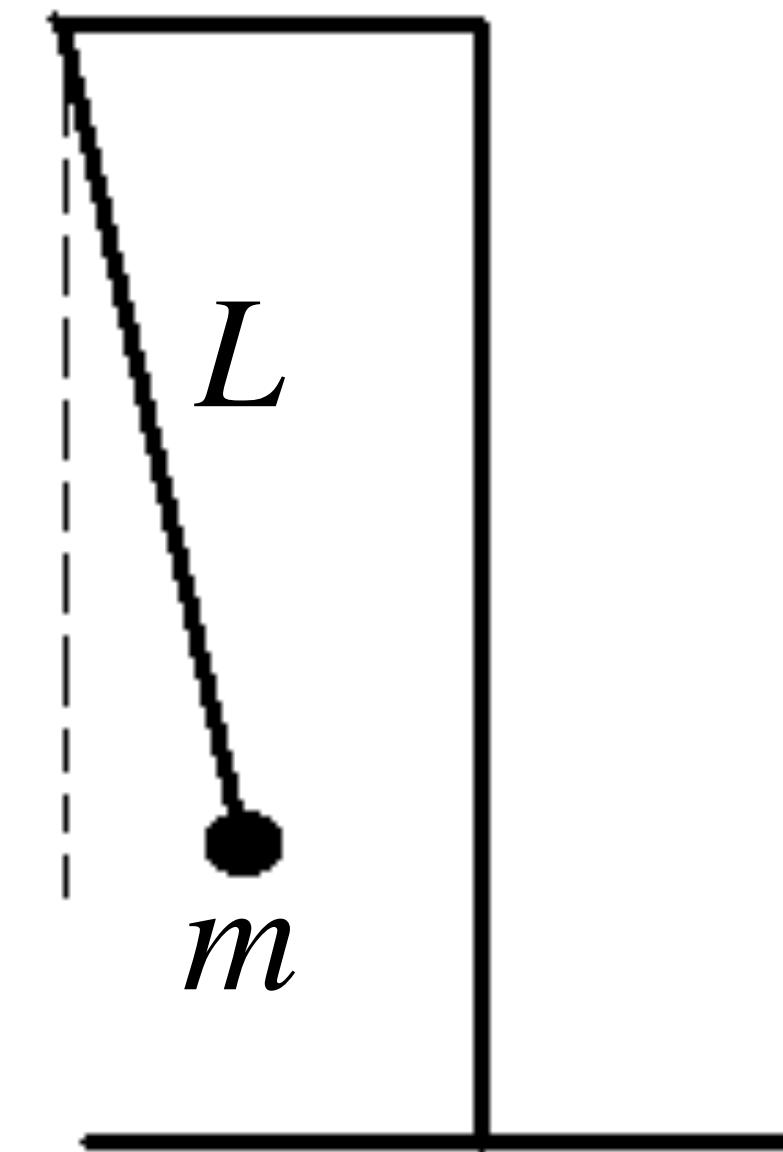
- Mass on a spring

$$T = 2\pi \sqrt{\frac{m}{k}}, \quad f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$



- Swinging pendulum bob

$$T = 2\pi \sqrt{\frac{L}{g}}, \quad f = \frac{1}{2\pi} \sqrt{\frac{g}{L}}$$



# Damping and resonance

- **Demo** with swinging pendulum
- Friction, air resistance, ... cause oscillations to die out. Need to apply a **driving force** to keep them going.
- **Natural frequency** of a swinging pendulum:  $f_0 = \frac{1}{2\pi} \sqrt{\frac{g}{L}}$
- Compare to **driving frequency**  $f$ :
  - $f \ll f_0$ : the pendulum bob follows the motion of the driving force
  - $f \gg f_0$ : the pendulum bob oscillates back and forth, with a very small amplitude, 180 degrees out of phase with the driving motion
  - $f = f_0$ : the amplitude of the swinging motion of the pendulum bob **increases** as the driving force is applied, even for small driving amplitudes. This is called **resonance**.

# **3. Waves & sound**

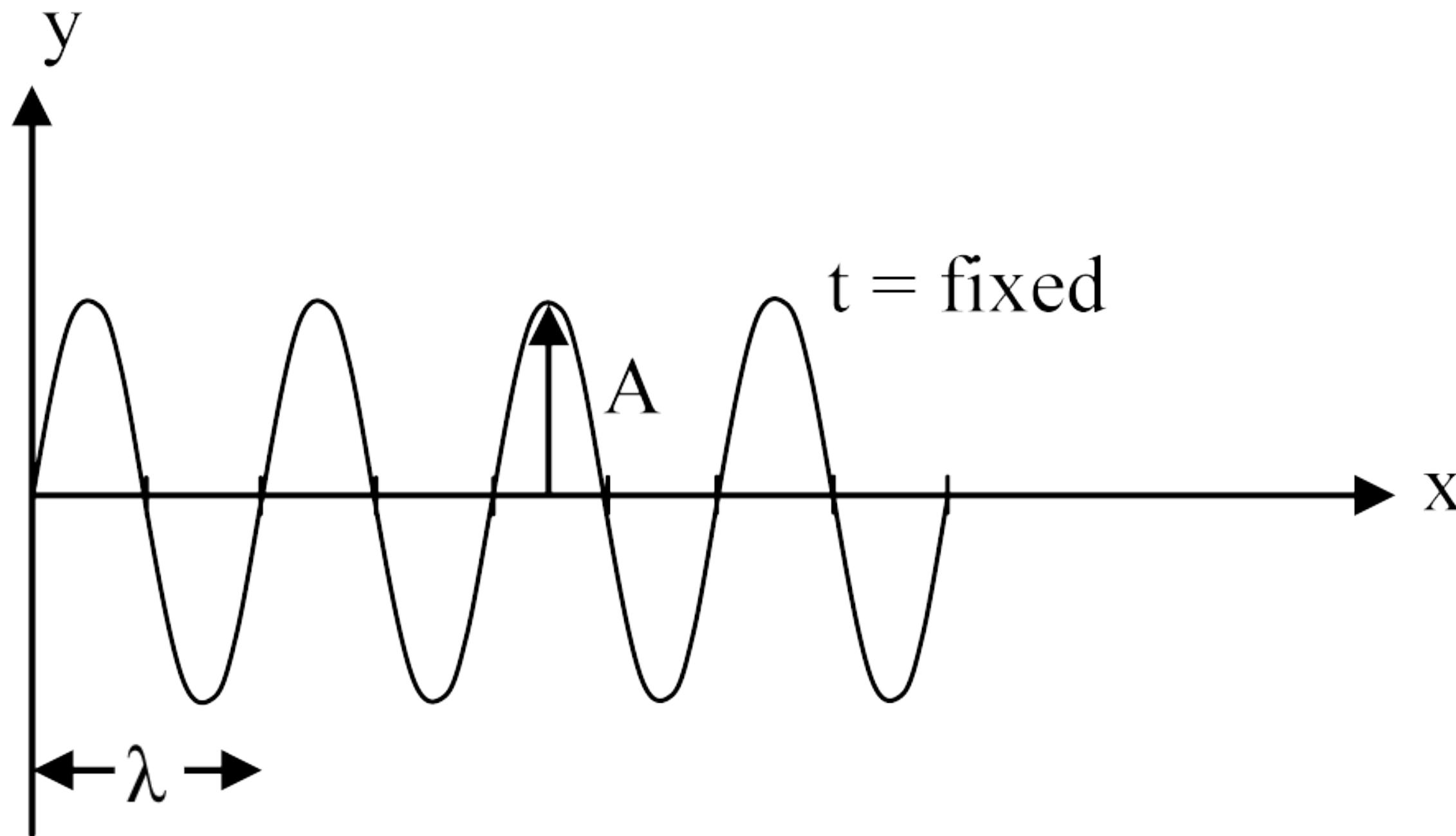
# Wave motion, wave velocity

- **wave**: any “disturbance” that transports energy from one location to another without the transport of matter
- Examples: sound waves in air; light (example of an electromagnetic wave, which can travel through empty space); water waves on the surface of a pond; “wave” at a football game
- **transverse waves**: the disturbance is perpendicular to the direction of wave propagation
- **longitudinal waves**: the disturbance is parallel to the direction of wave propagation
- **wave pulse** vs **periodic waves** traveling waves
- **wave velocity**:  $v = \Delta x / \Delta t$
- $v = 346$  m/s (speed of sound in air at room temp, 25 Celsius or 77 Farenheit)
- $v = 331 \frac{\text{m}}{\text{s}} \sqrt{1 + \frac{T_C}{273.15}}$  (speed of sound in air increases with increasing temperature)
- $T_C = (5/9)(T_F - 32^\circ)$  (relating Celsius and Farenheit temperature scales)

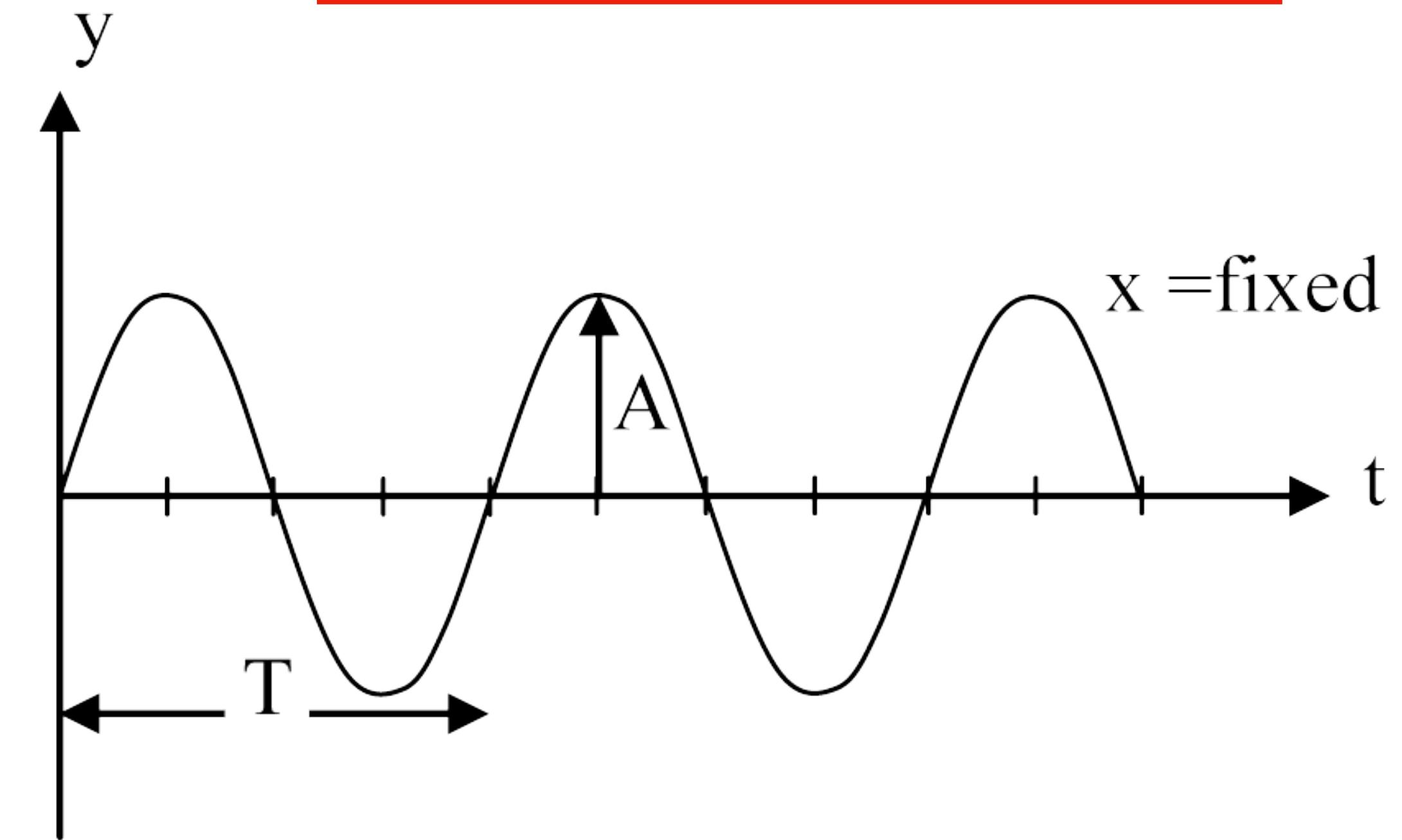
# Periodic waves, wavelength

- Produced by **periodic sources**;  $\lambda$  is the **wavelength**

$$v = \lambda/T = f\lambda$$



**"snap shot"** at a fixed time, showing how the displacement varies with position



**fixed location**, showing how the displacement varies with time

# Exercise

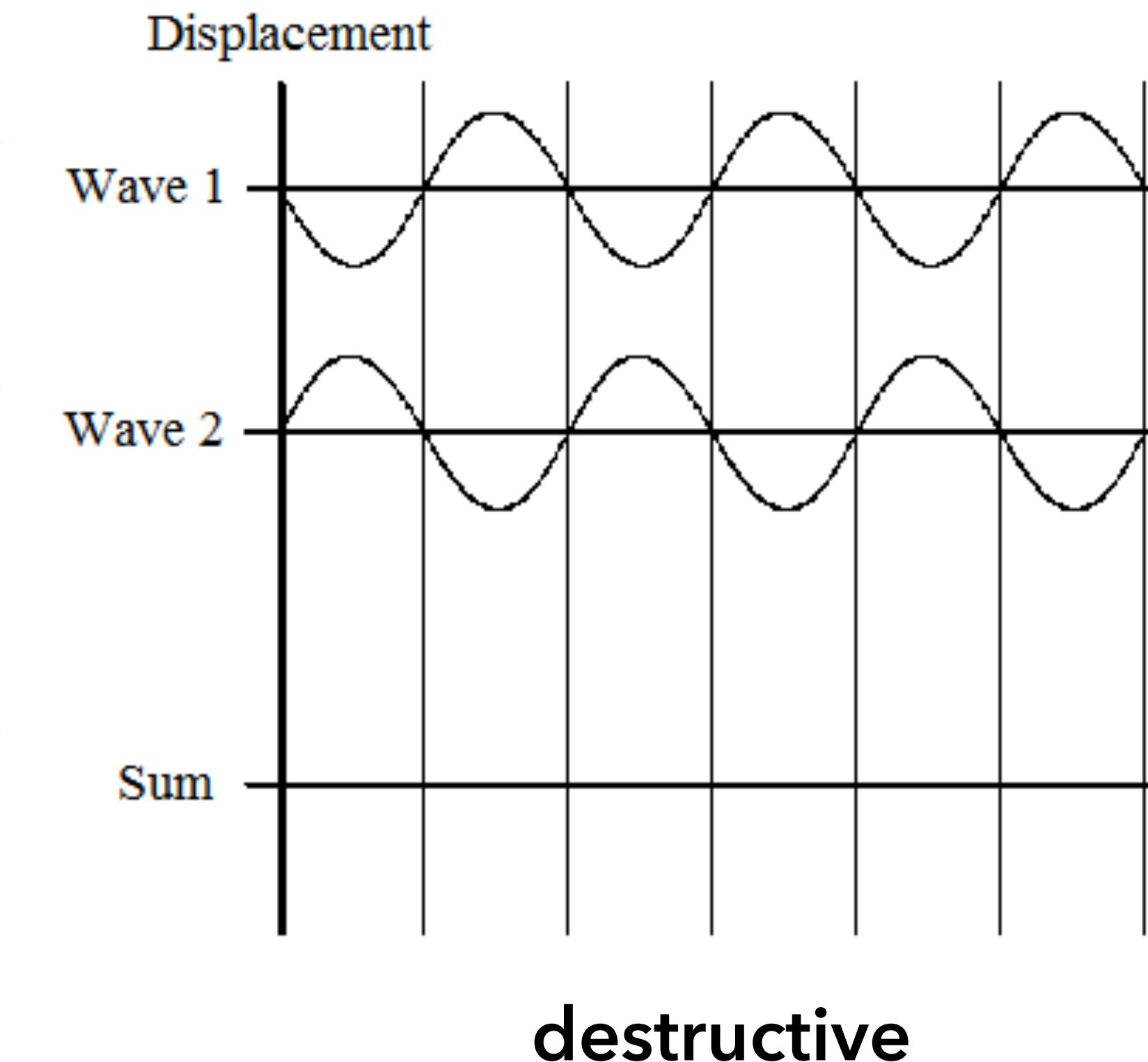
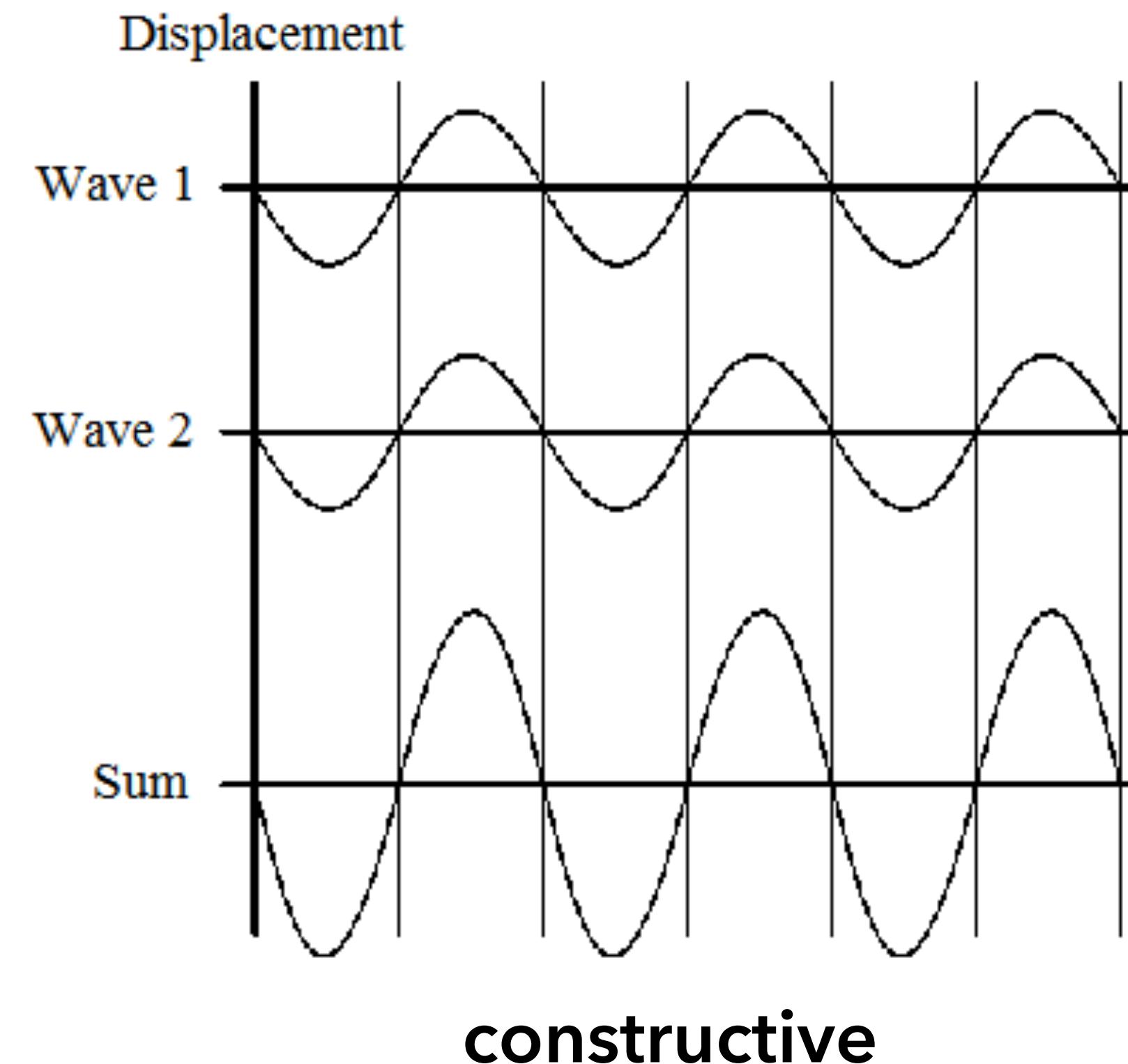
- Calculate the wavelengths of sound corresponding to the range of human hearing. Use  $v = 346 \text{ m/s}$  for the speed of sound in air at room temperature.
- **Ans:**
  - $f = 20 \text{ Hz}$  has  $\lambda = ??$
  - $f = 20,000 \text{ Hz}$  has  $\lambda = ??$
  - Most musical sounds (e.g., concert A, 440 Hz) have wavelengths of roughly ??

# Exercise

- Calculate the wavelengths of sound corresponding to the range of human hearing. Use  $v = 346 \text{ m/s}$  for the speed of sound in air at room temperature.
- **Ans:**
  - $f = 20 \text{ Hz}$  has  $\lambda \approx 17 \text{ m}$
  - $f = 20,000 \text{ Hz}$  has  $\lambda \approx 1.7 \text{ cm}$
  - Most musical sounds (e.g., concert A, 440 Hz) have wavelengths of order 1 meter

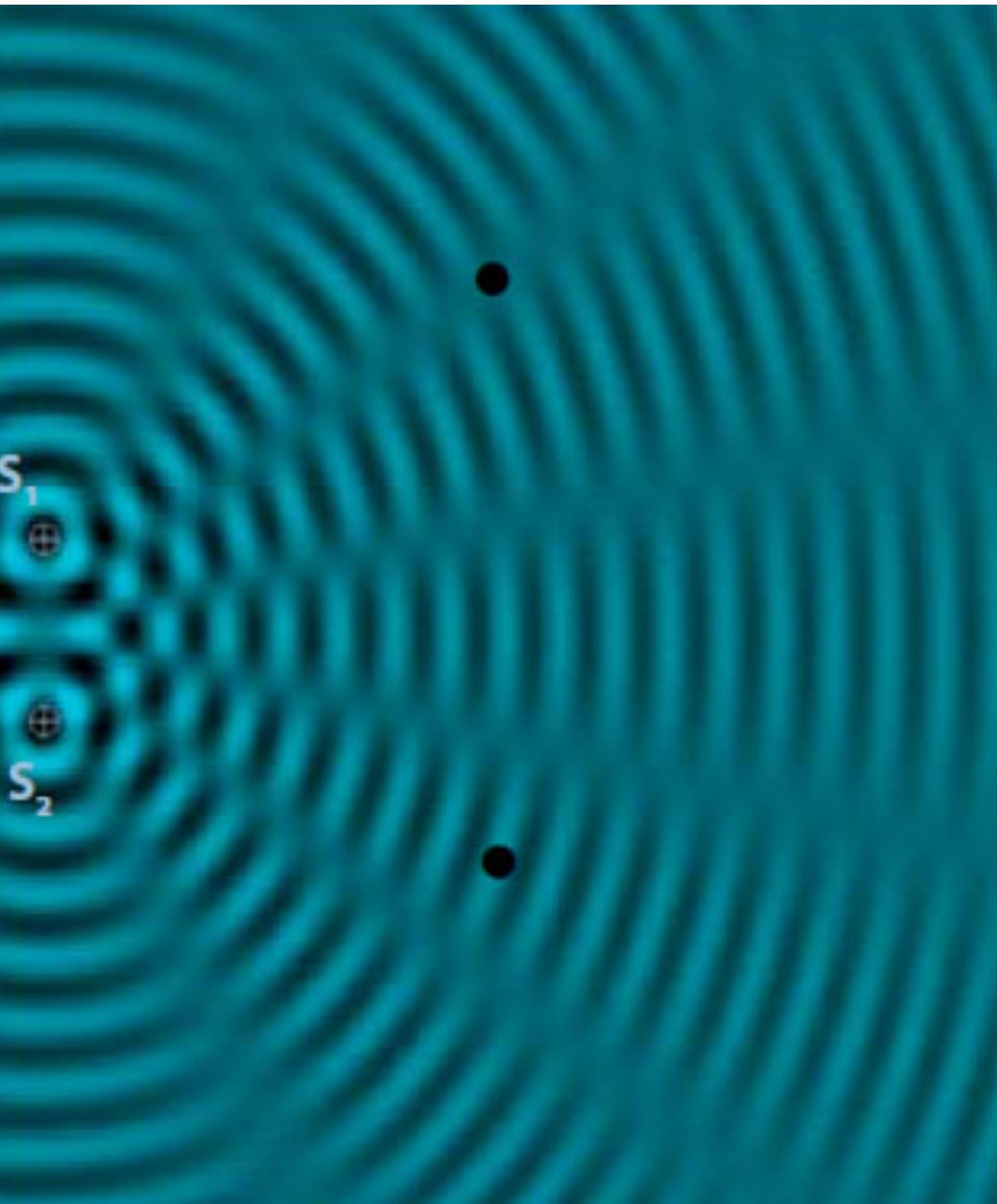
# Superposition / interference

- the **combination of two waves** is another wave
- **constructive & destructive** interference depends on the **phase** difference (**matlab demo**: "sumsines")



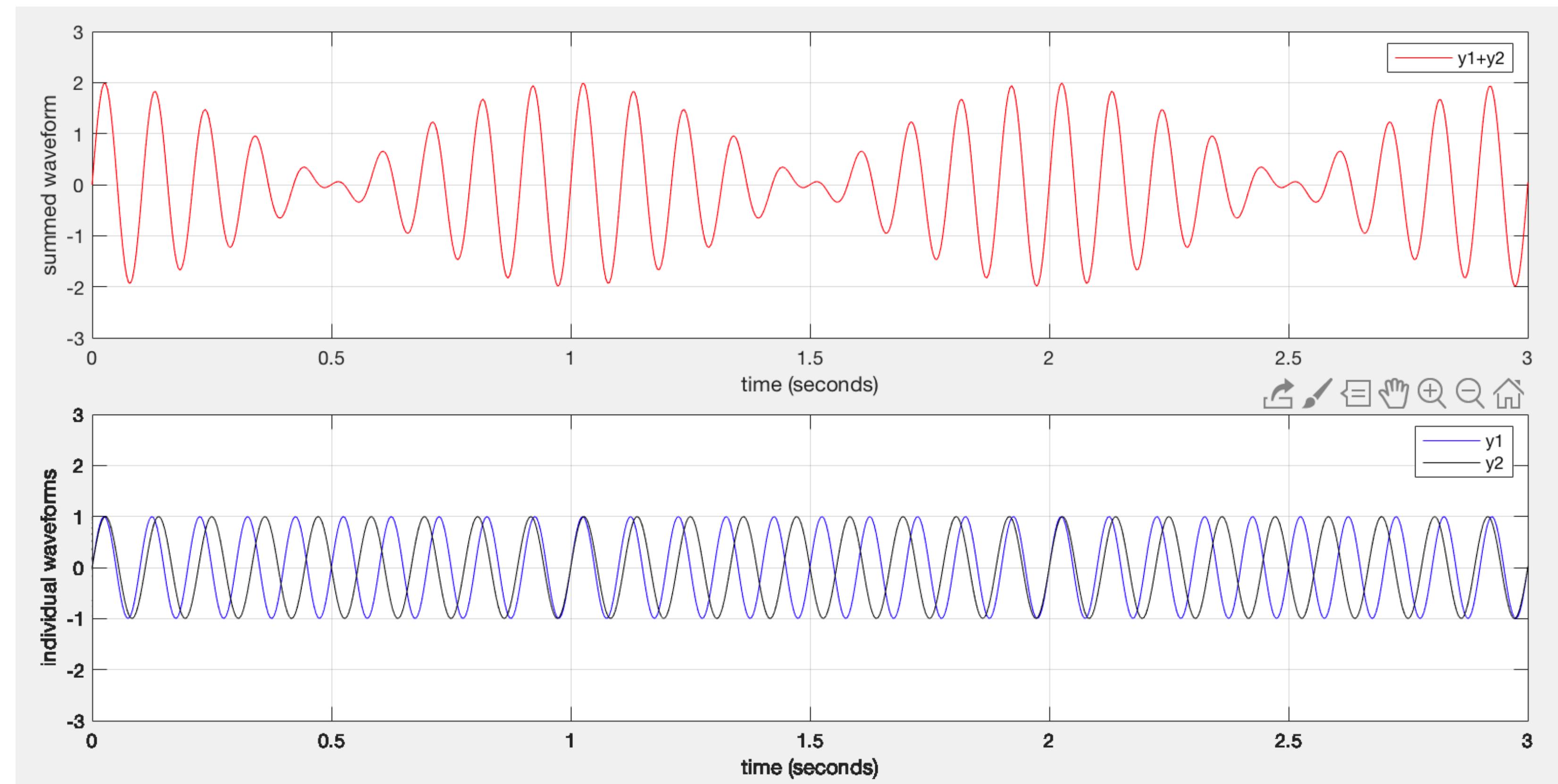
# Interference in space

- Water waves in a ripple tank or sound waves produced by two speakers
- **PhET demo:** wave interference



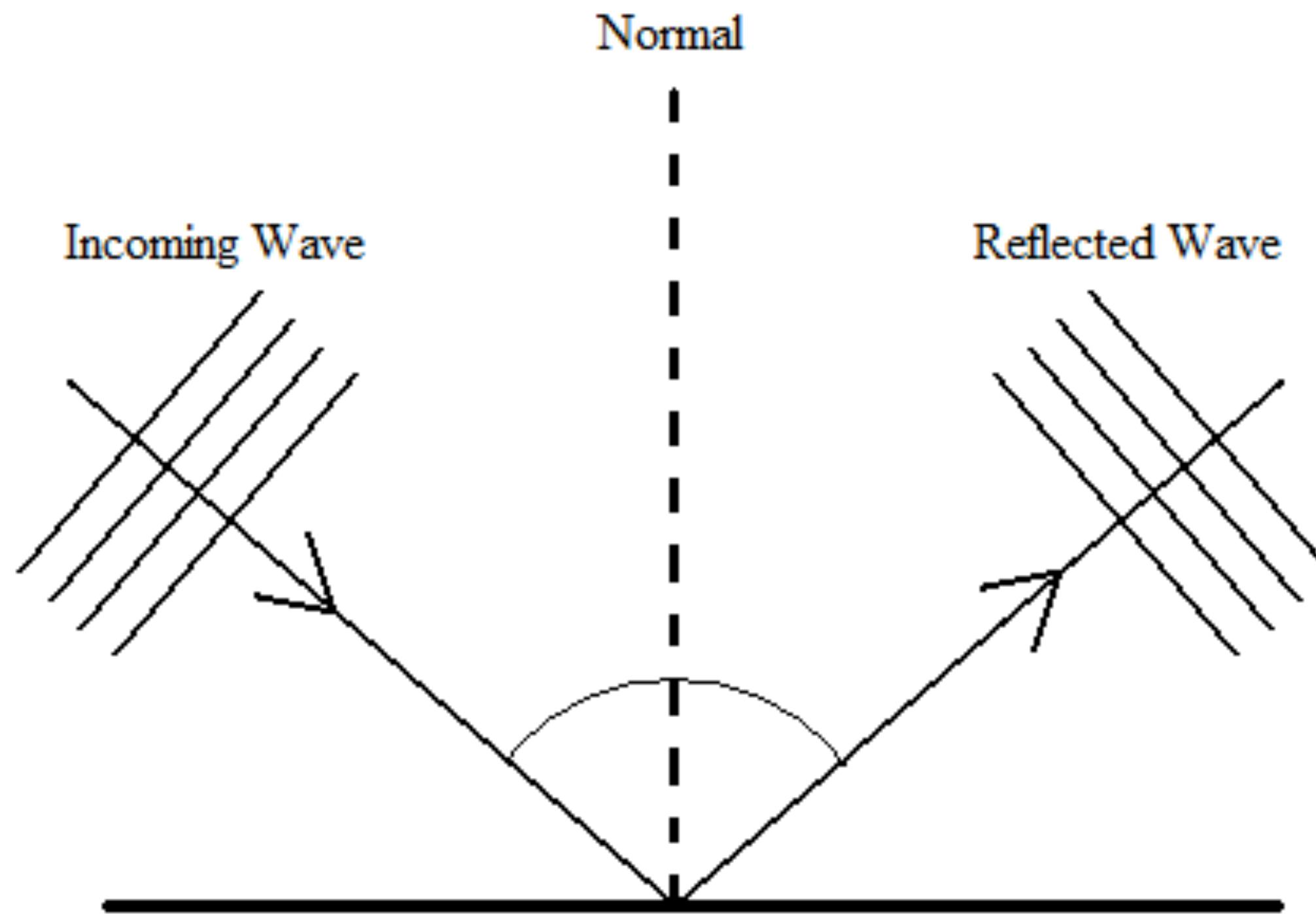
# Interference in time - “beats”

- Interference in time of two periodic waves having different frequencies (**matlab demo**: “beats”, and using signal generators)
- Beat frequency:  
 $f_{\text{beat}} = |f_1 - f_2|$
- “Beatless” tuning of instruments

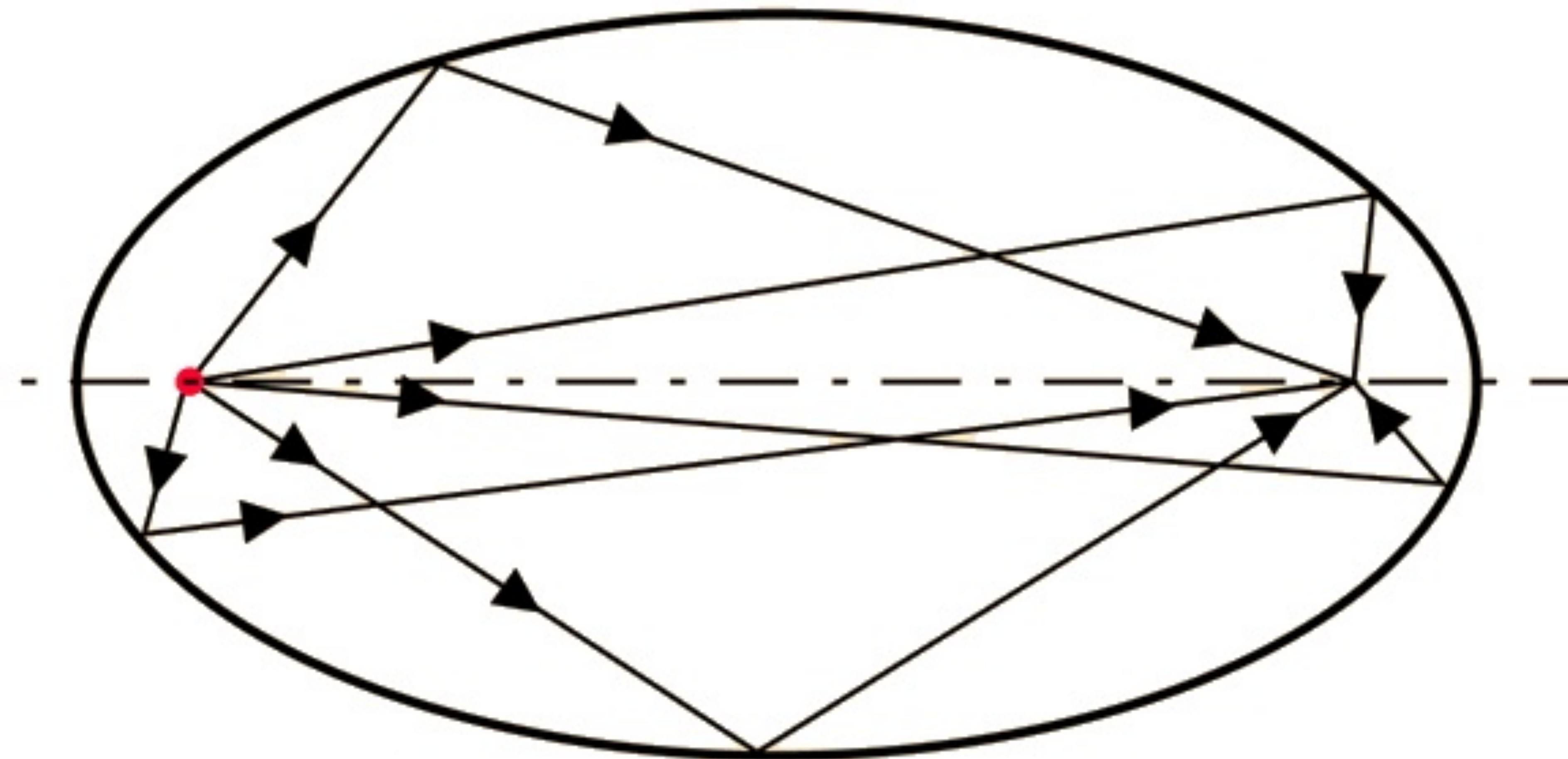


# Reflection

- **Change in direction** of a wave when it encounters an interface between two media
- **Demos** with plane, concave, and convex mirrors

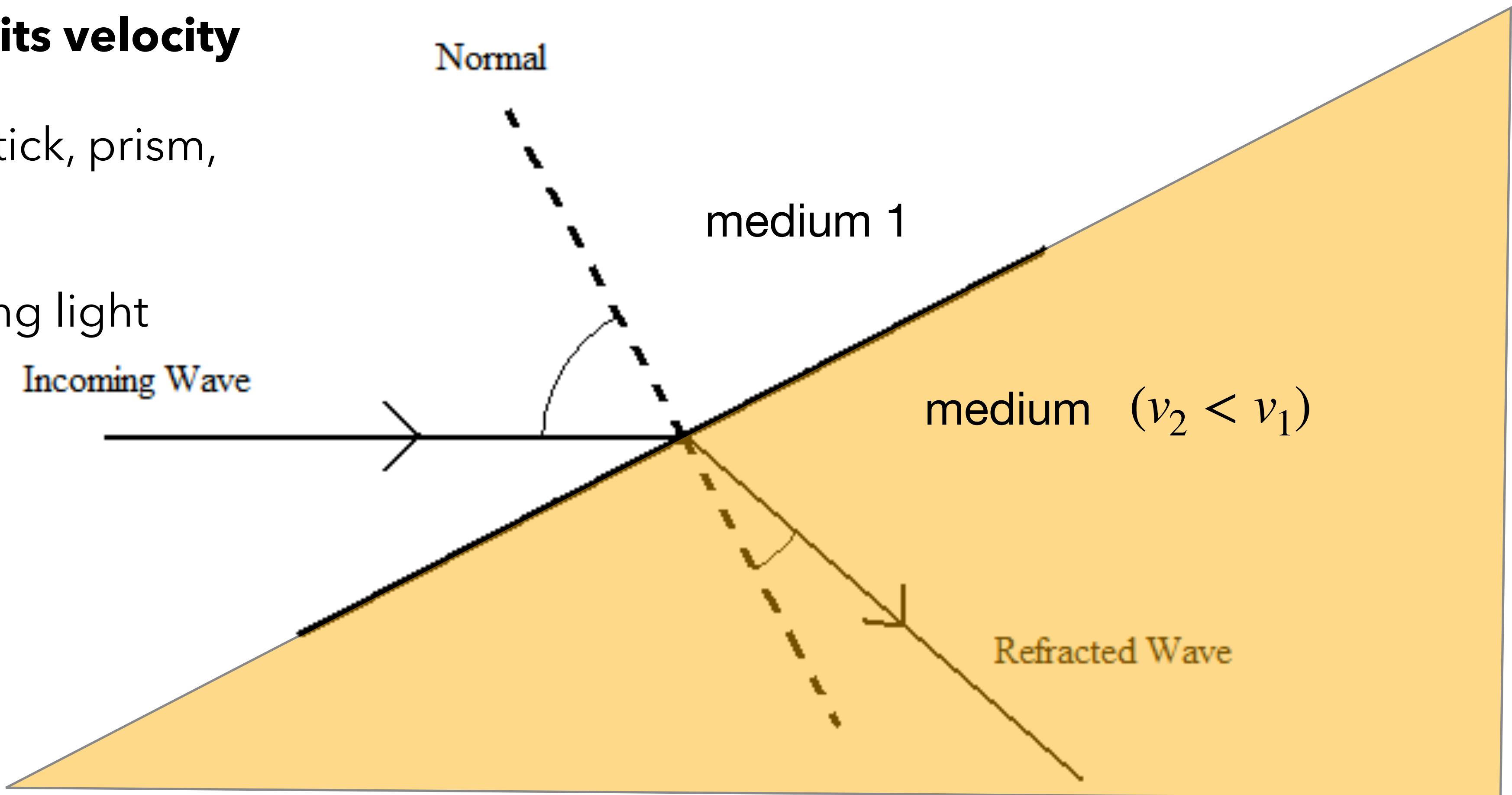


# Reflections - whispering chamber

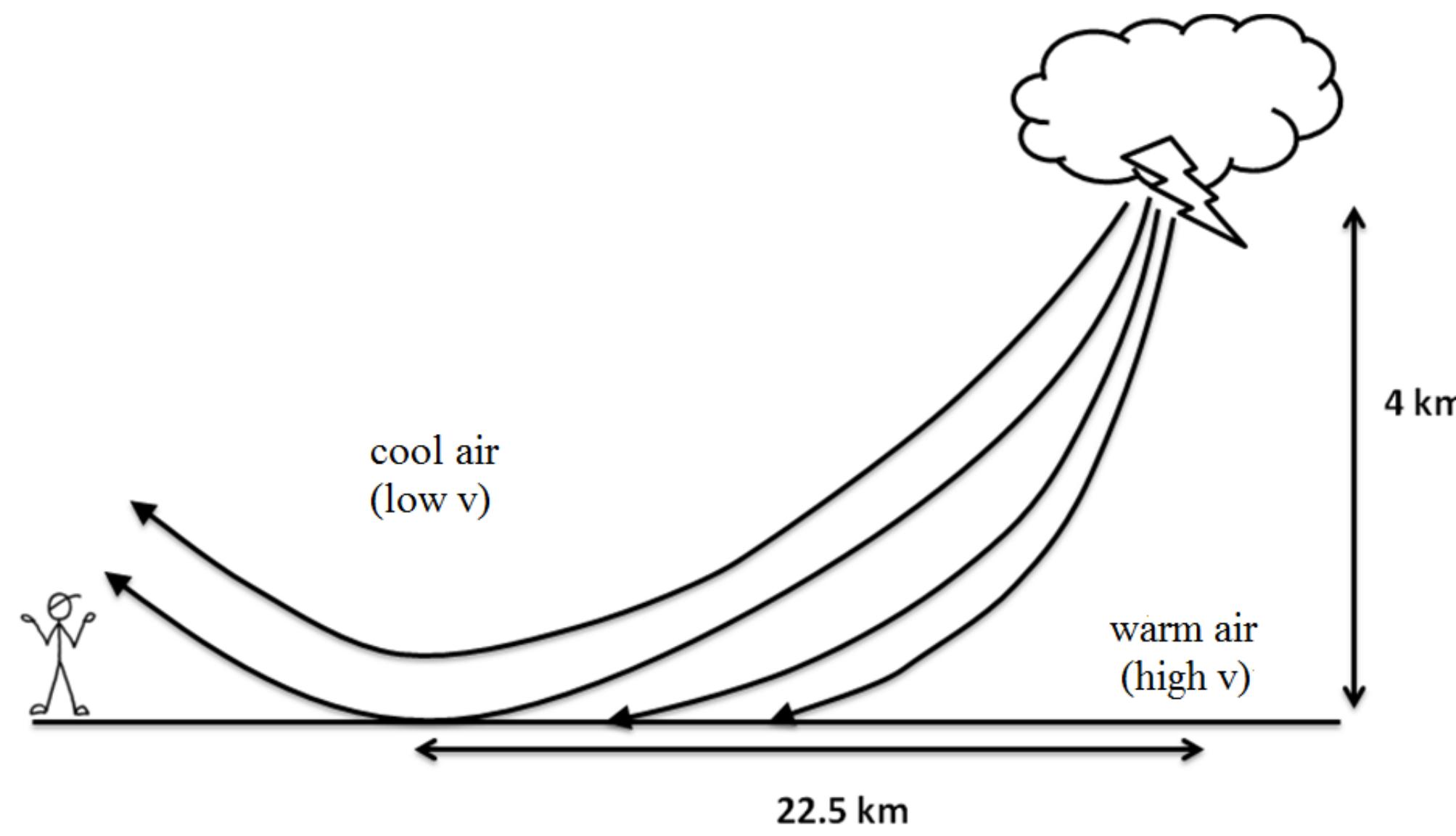


# Refraction

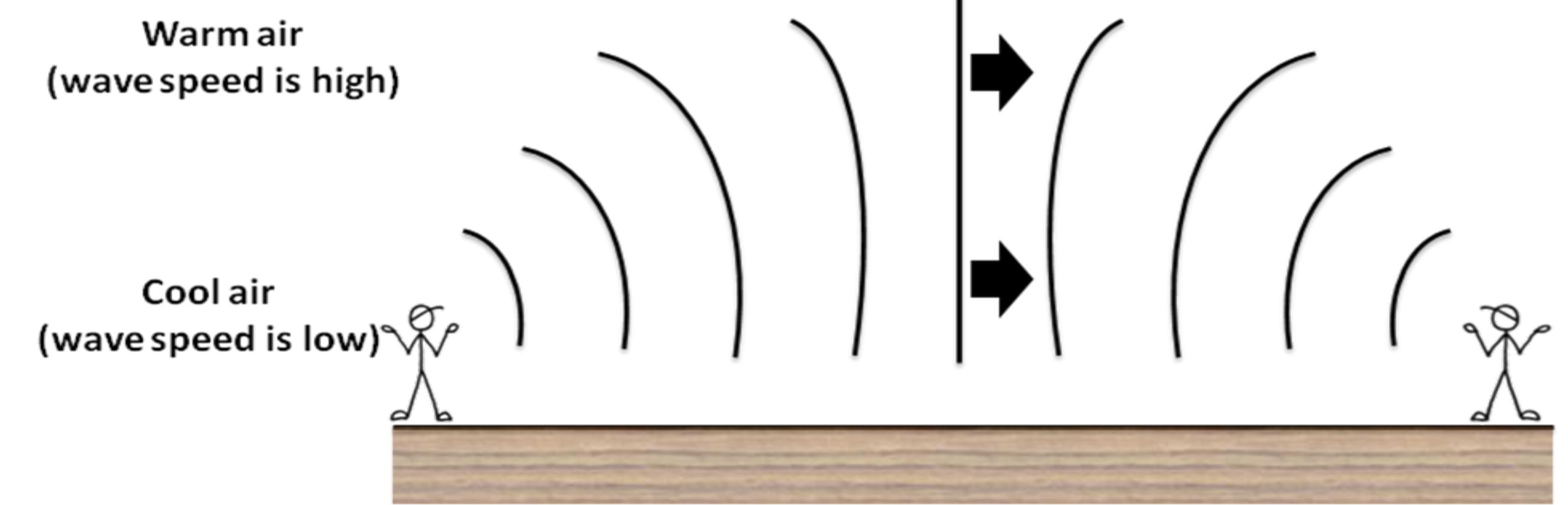
- **Change in direction** of a wave due to a **change in its velocity**
- **Demos** with light (stick, prism, and laser)
- **PhET demo:** bending light



# Examples of refraction of sound



Usual temperature distribution



Temperature inversion

# Understanding refraction

Life guard



beach

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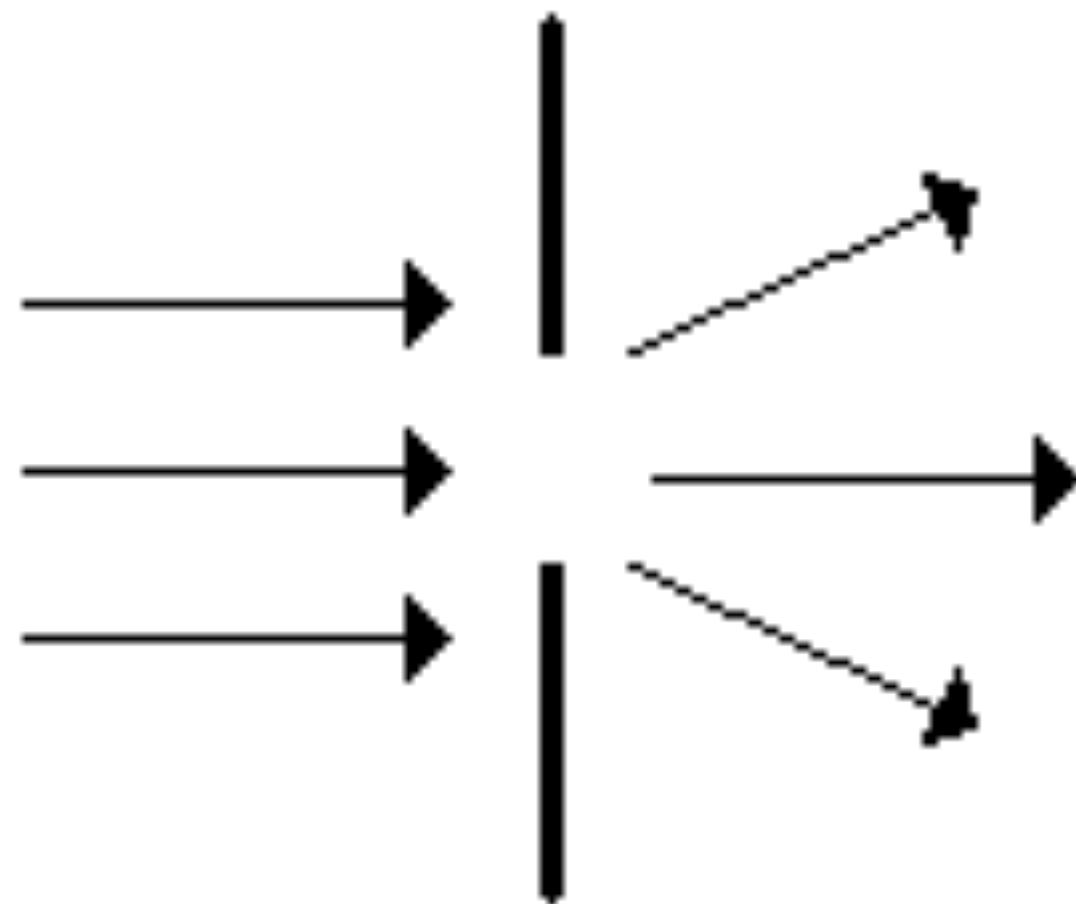
water



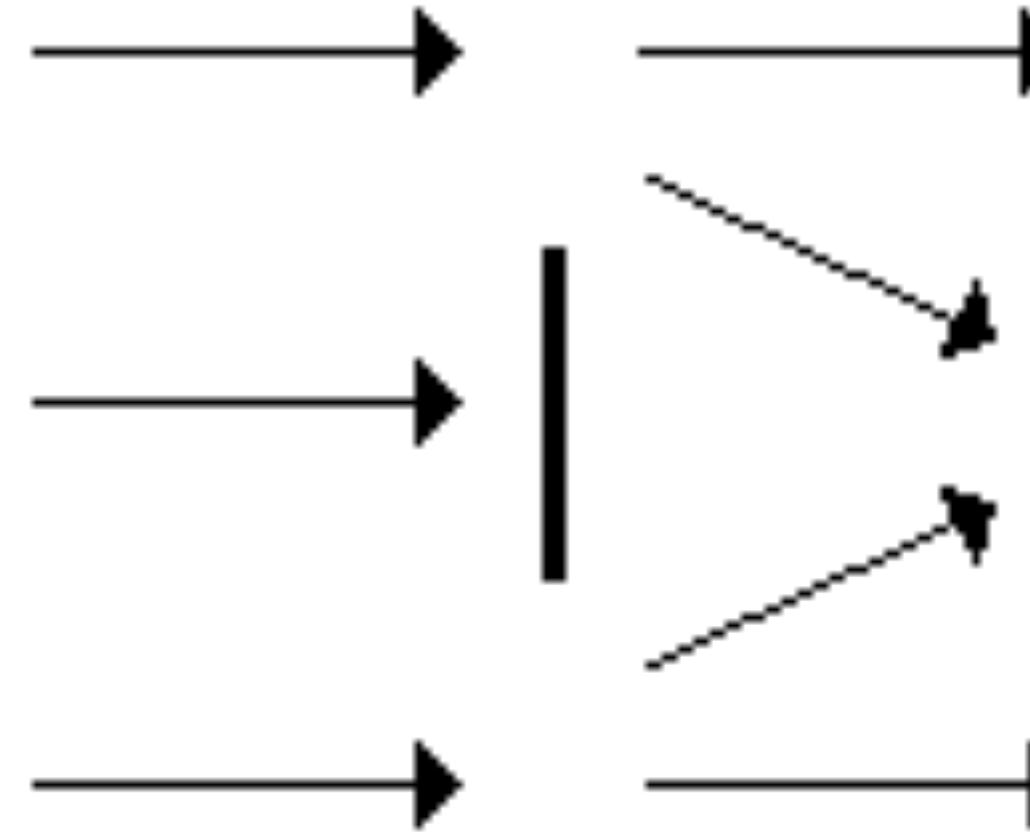
Drowning swimmer

# Diffraction

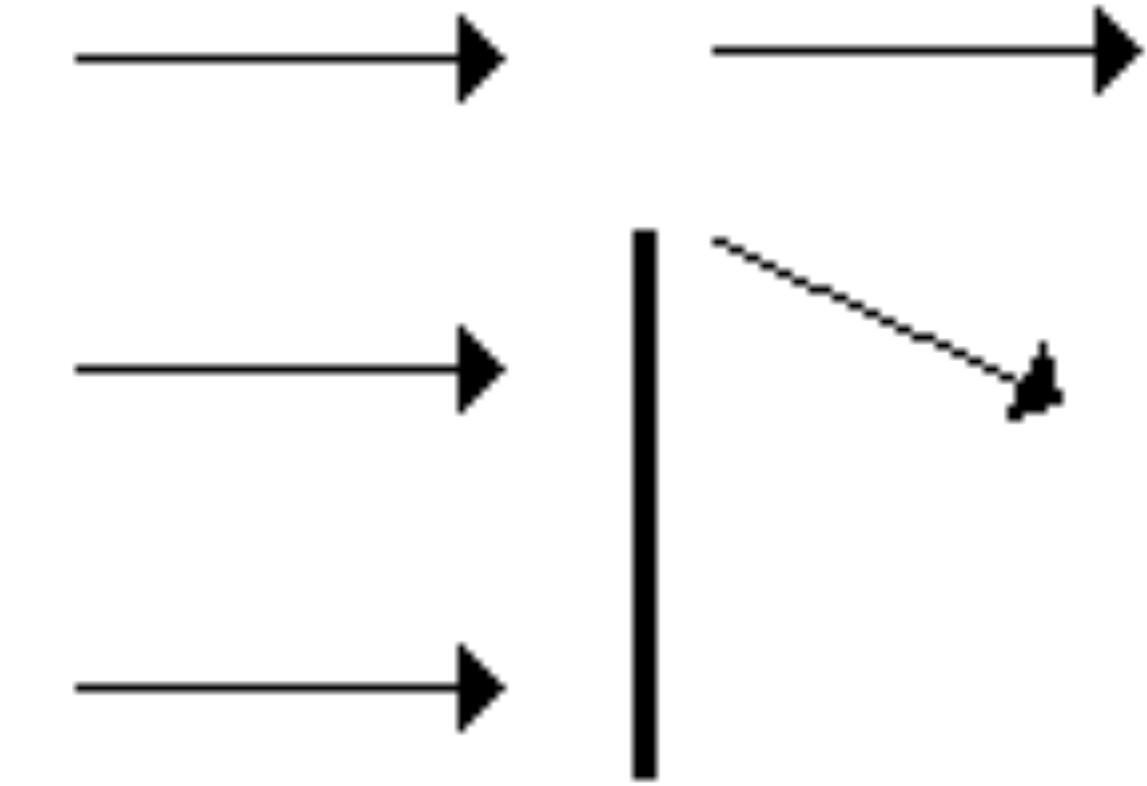
- “**spreading**” of a **wave** as it passes through openings or around barriers ...
- amount of spreading depends on **relative size of wavelength and opening, barrier, ...**
- **a lot of spreading** into shadow regions if the **wavelength is greater than or comparable to the size of opening, ...**
- reason why you can hear somebody speaking in the hallway, but you can't see him / her
- **PhET demo:** wave interference



Opening



Barrier



Edge

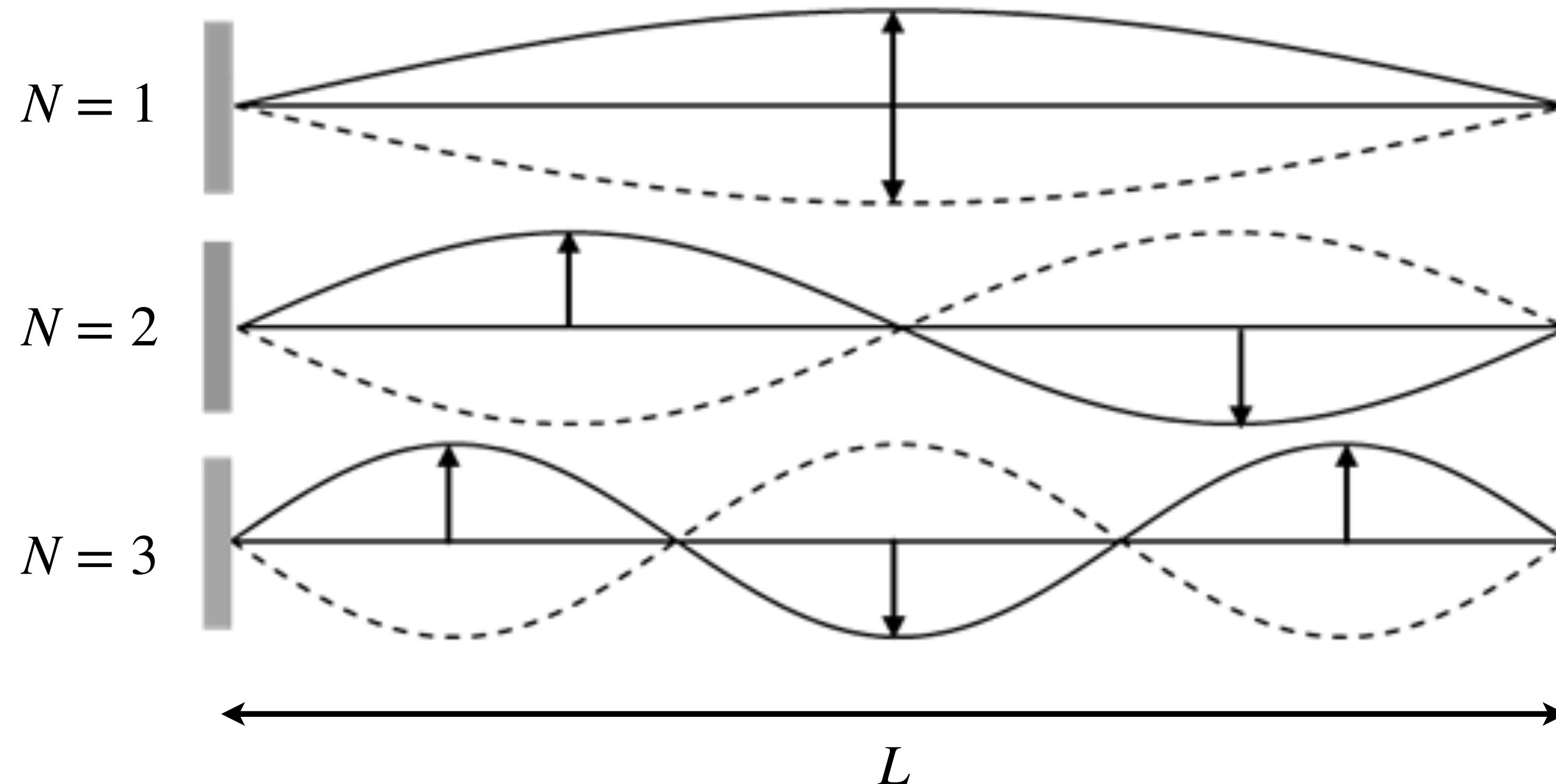
# Doppler effect

- **Change in frequency** due to the motion of the observer or source (e.g., for sound, light, ...)
- Examples: siren on an approaching / receding police car or ambulance; a train whistle; ...
- **Demo** with nerf ball

# **4. Standing waves, harmonics, Fourier's theorem**

# Standing waves on a string / harmonic frequencies

- **Demo:** superposition of right-moving and left-moving waves on a string
- occurs only for certain freqs (**resonance** phenomenon; **matlab demo**: "standingwaves")



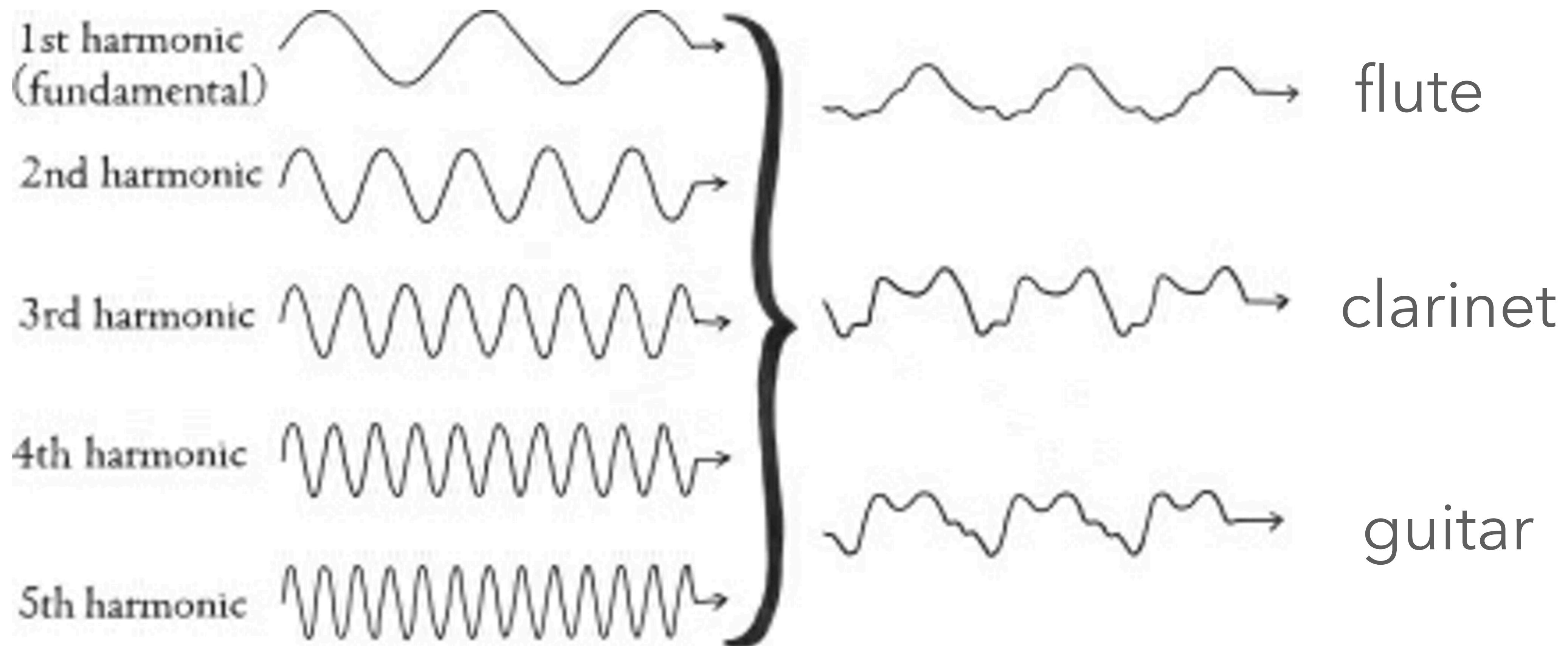
$$v = \sqrt{\frac{\text{string tension}}{\text{mass density}}} = \sqrt{\frac{F}{\mu}}$$

$$\lambda_N = \frac{2L}{N}, \quad N = 1, 2, \dots$$

$$f_N = Nf_1 \quad (\text{Nth harmonic})$$

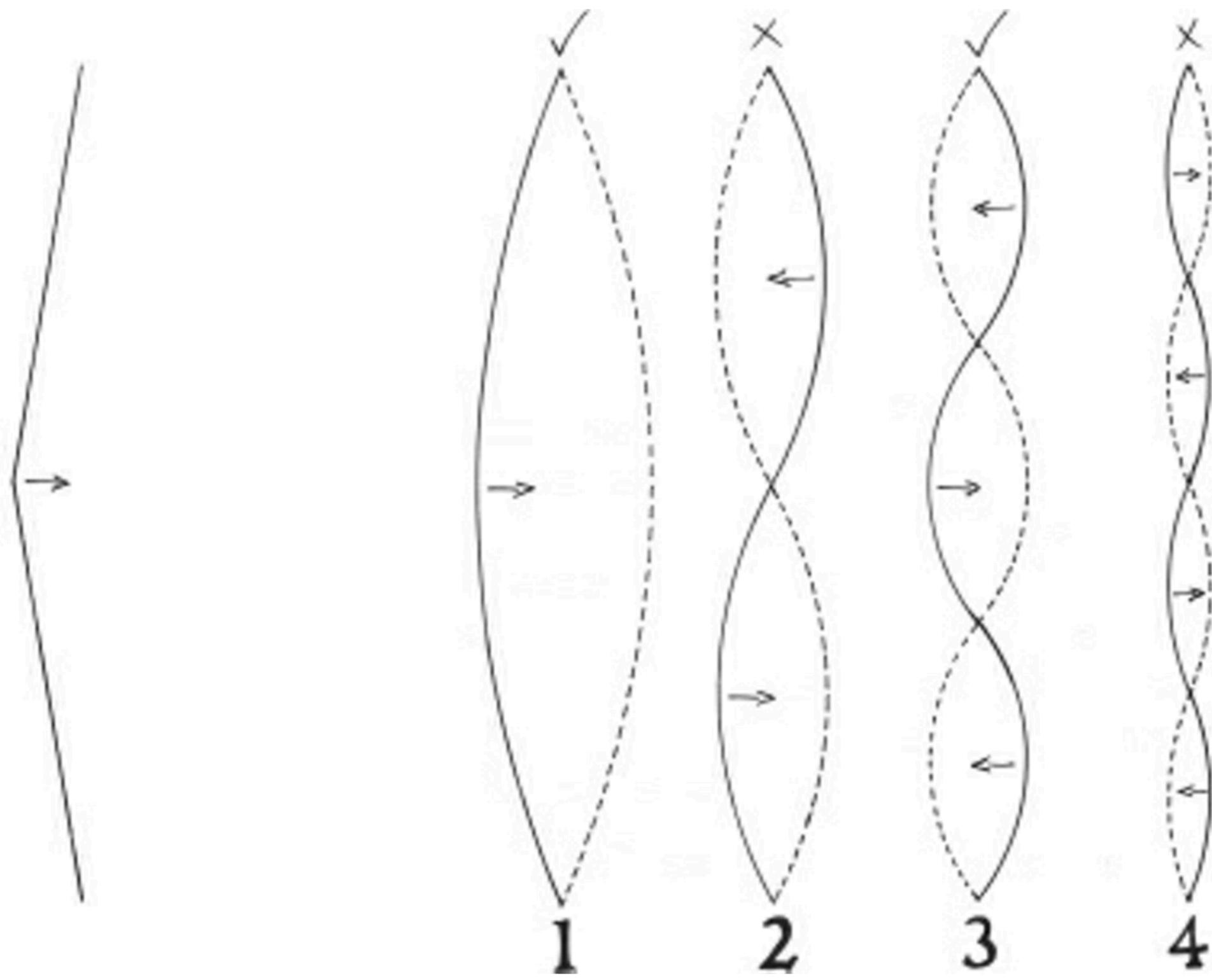
$$f_1 = \frac{v}{2L} \quad (\text{fundamental})$$

# Timbre – same note but different contributions of harmonics

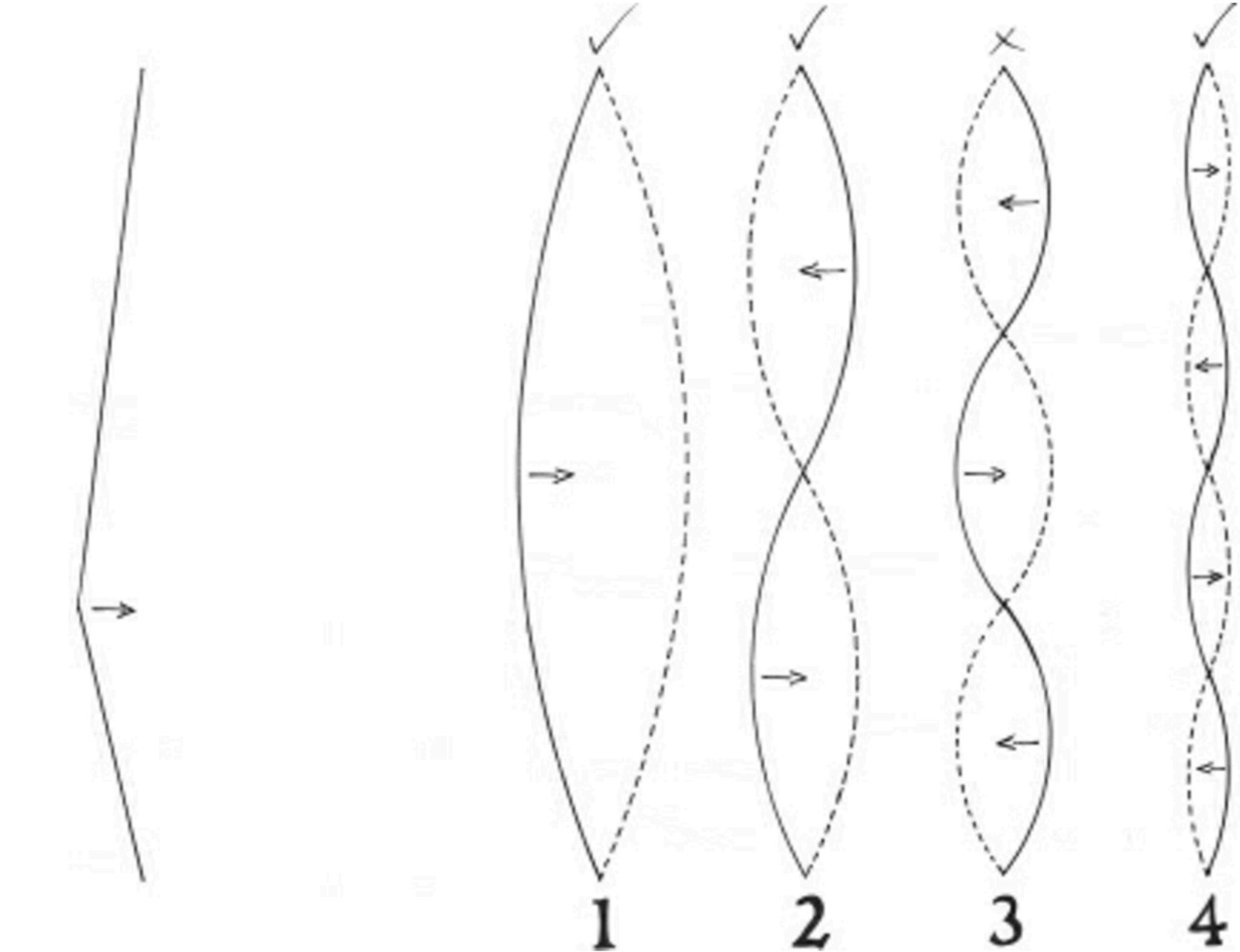


# Where you pluck a guitar string changes the timbre

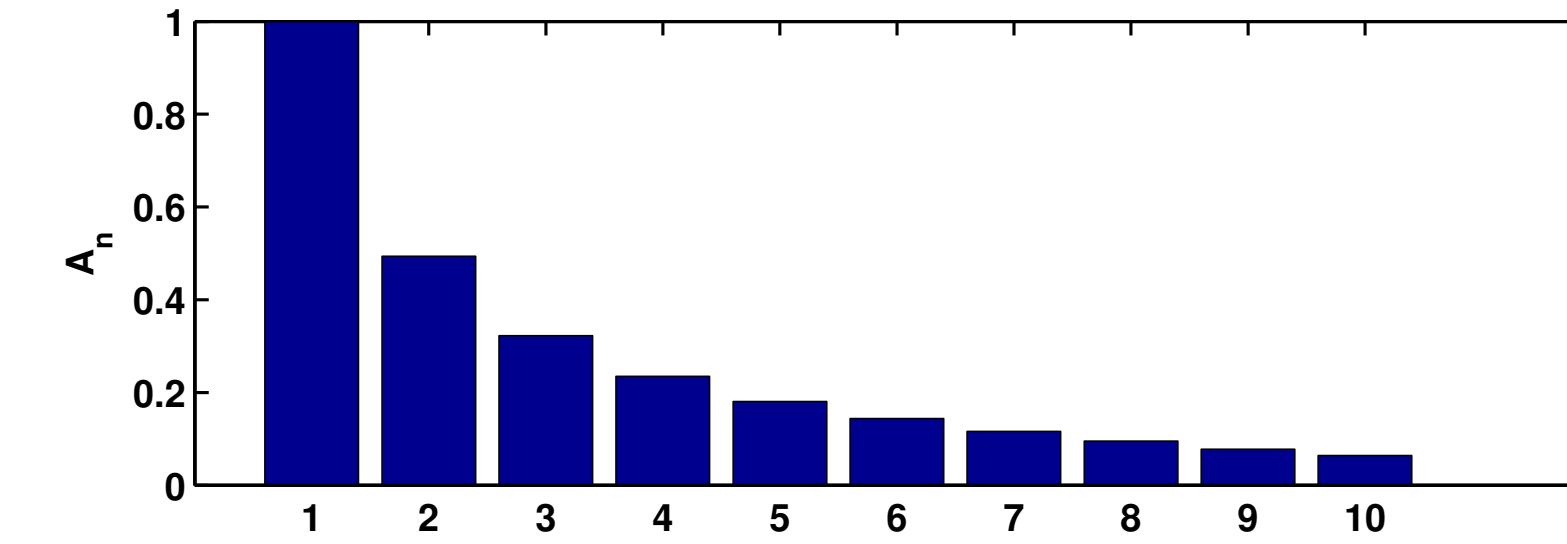
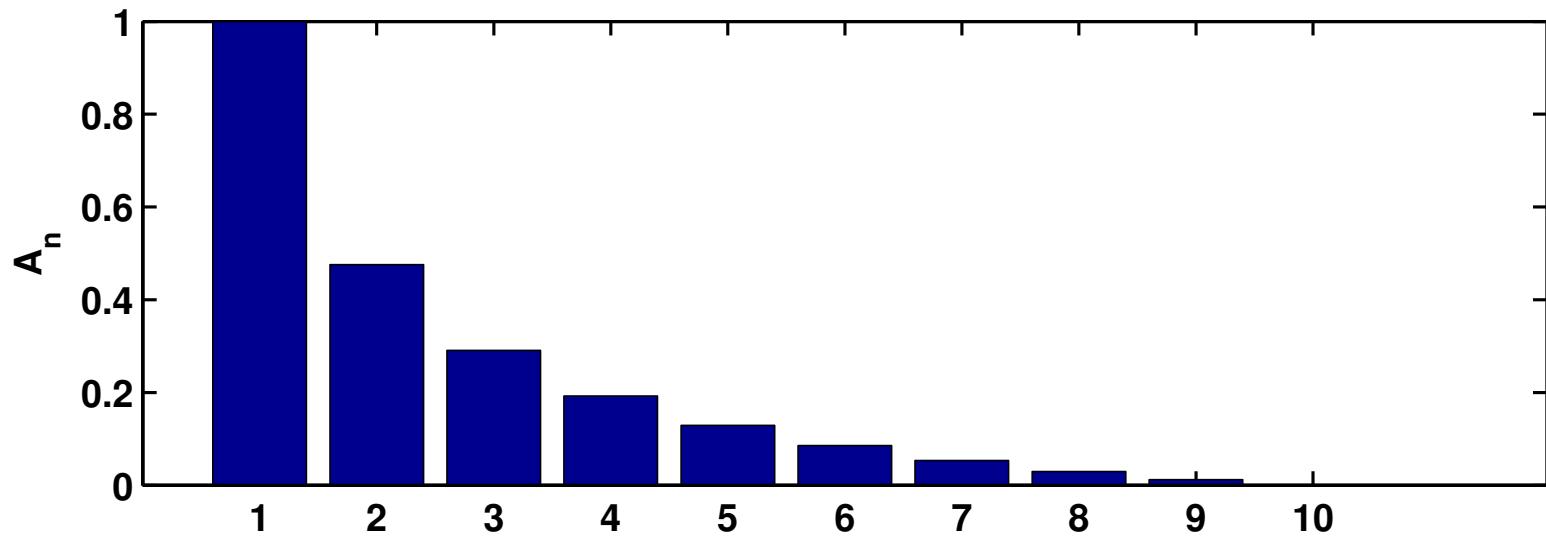
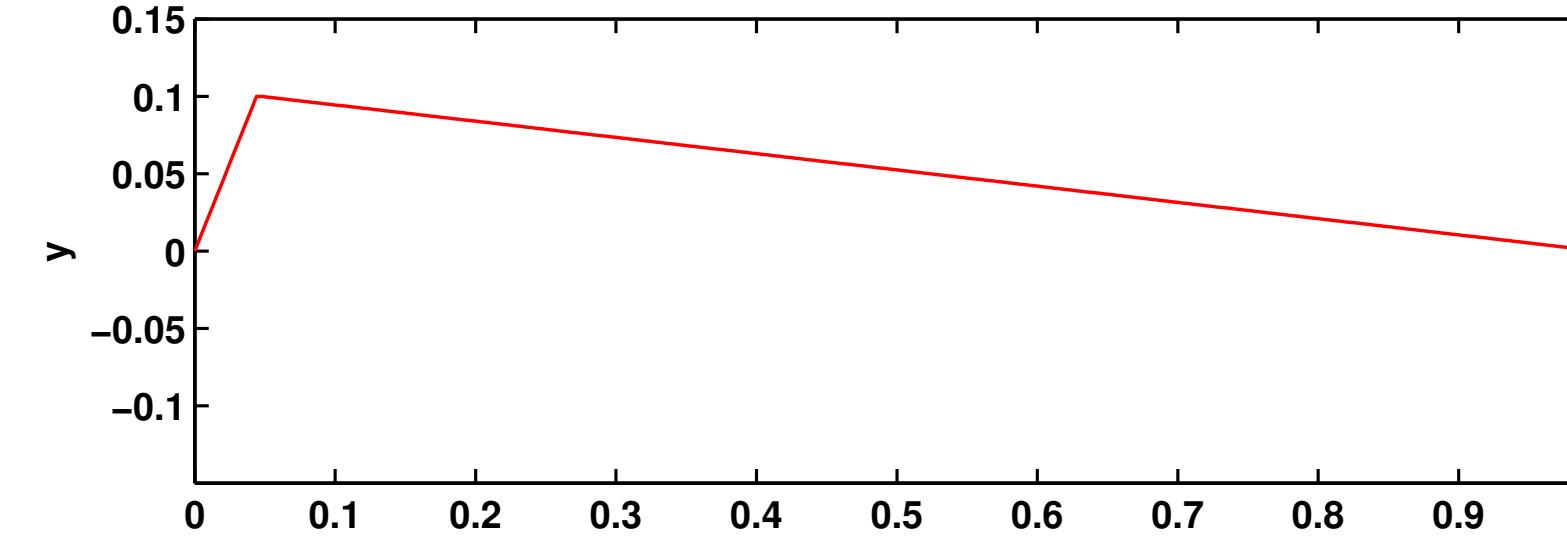
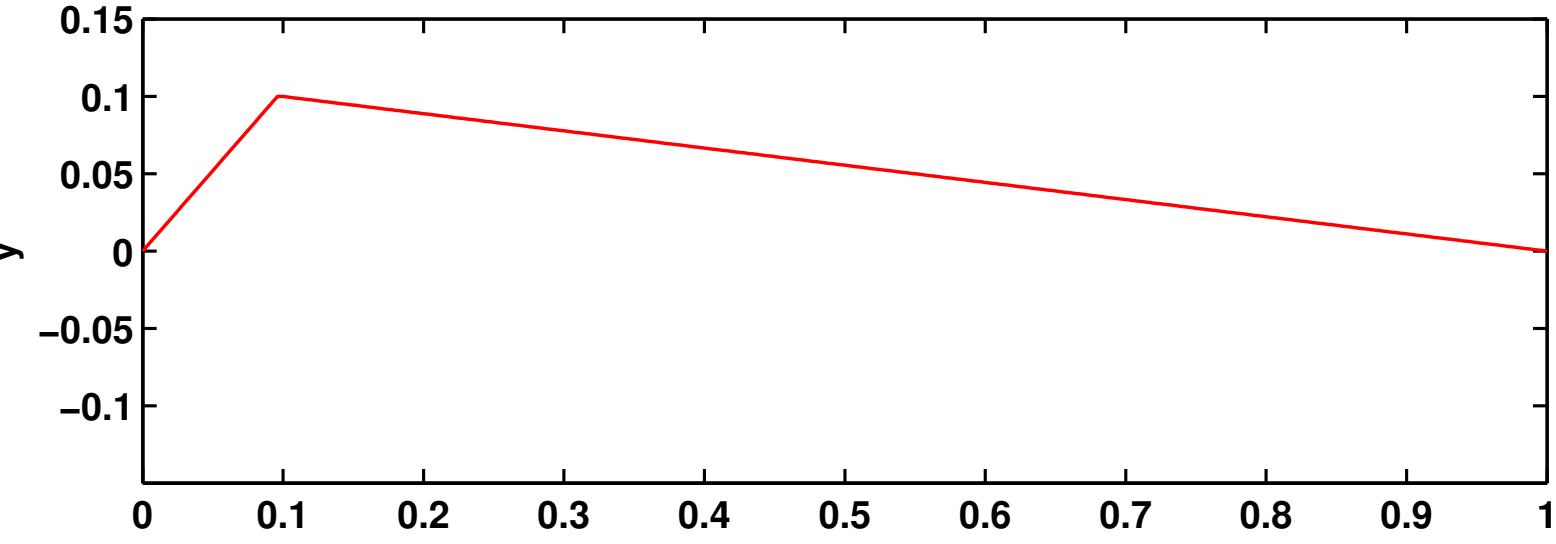
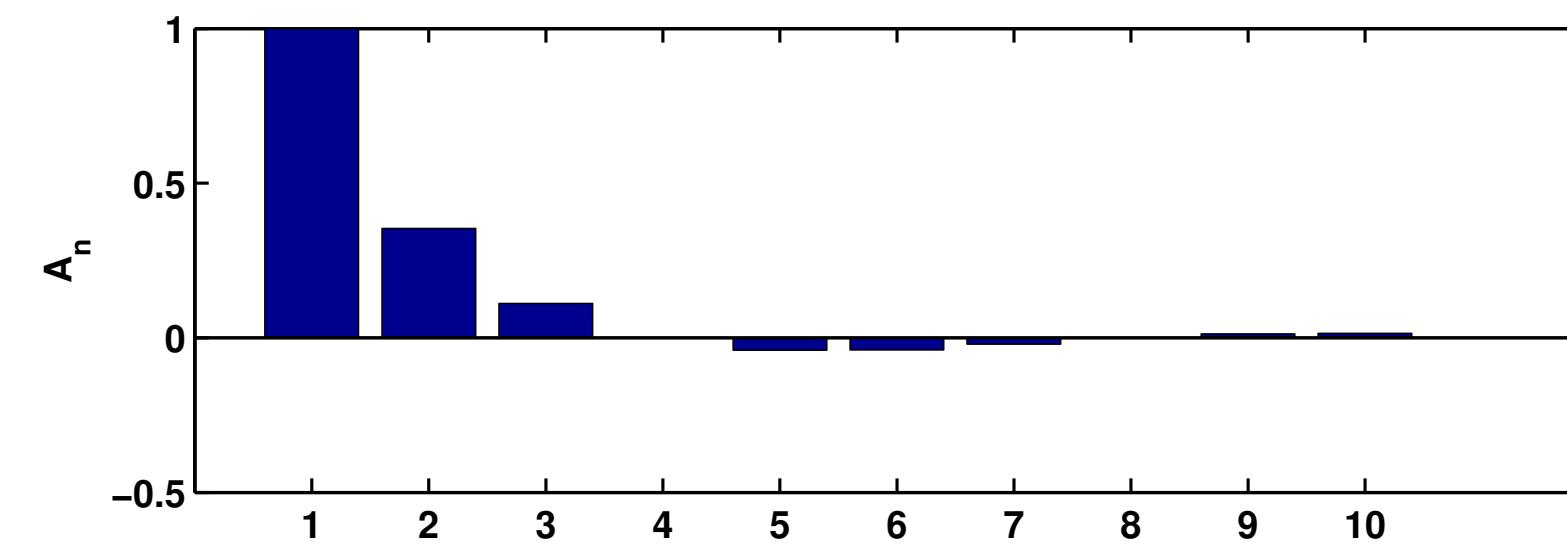
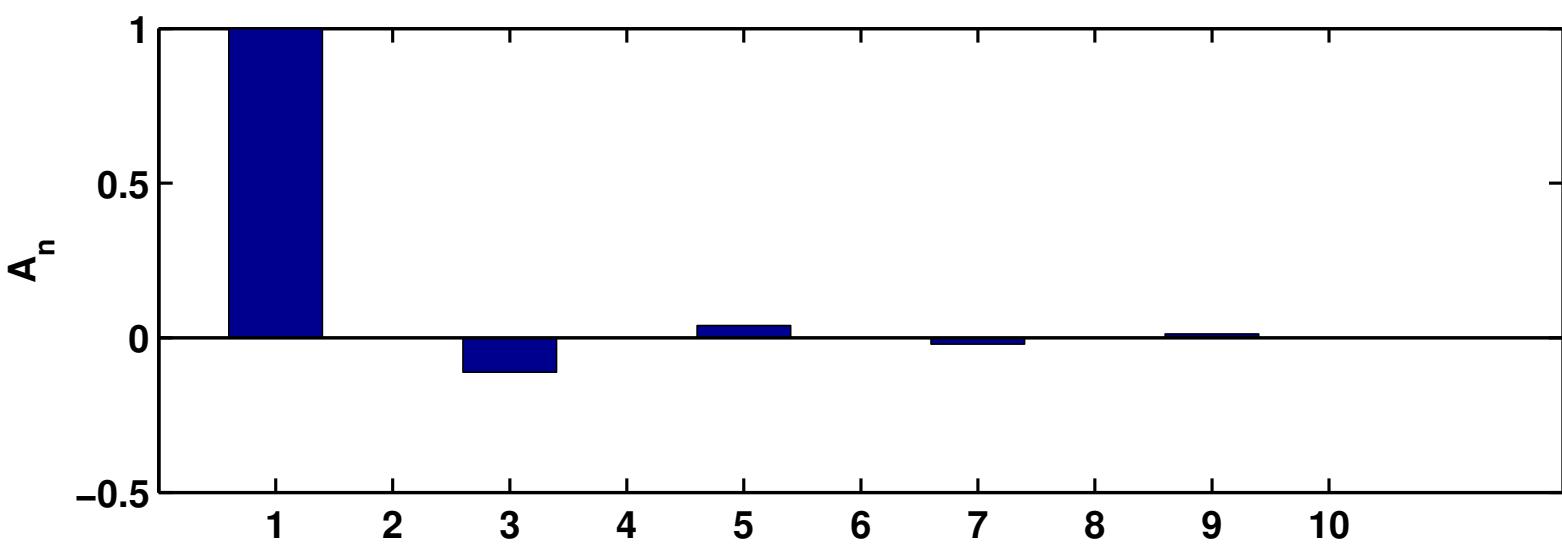
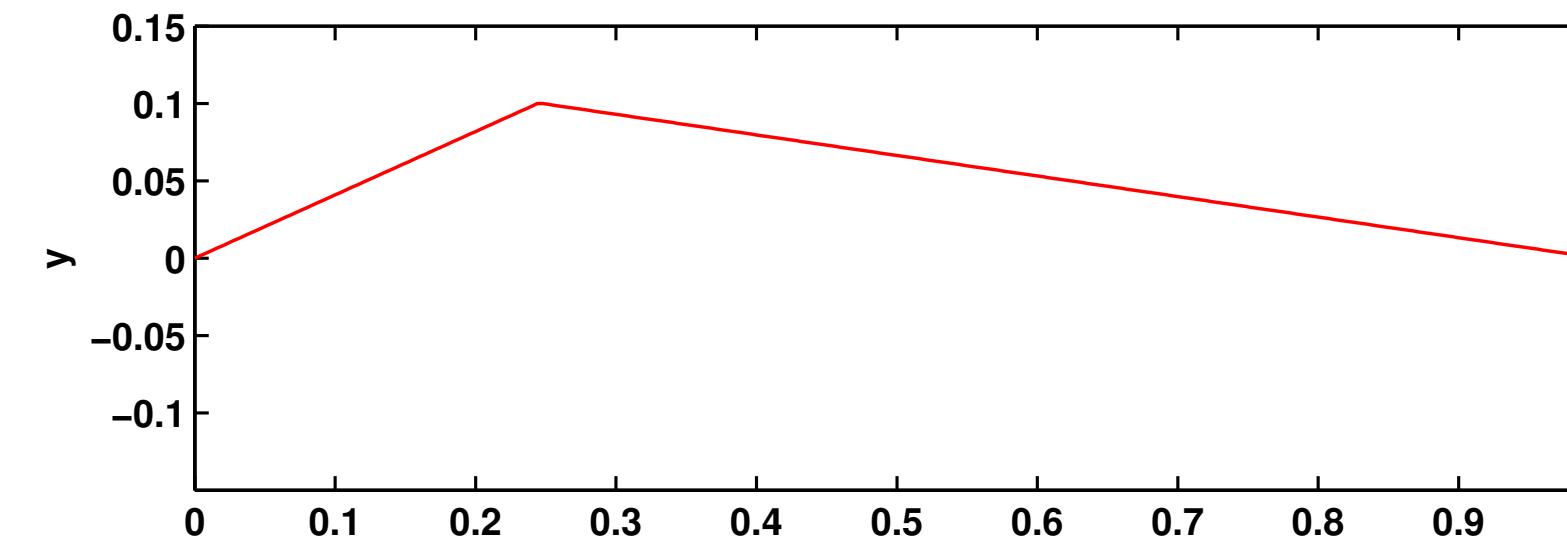
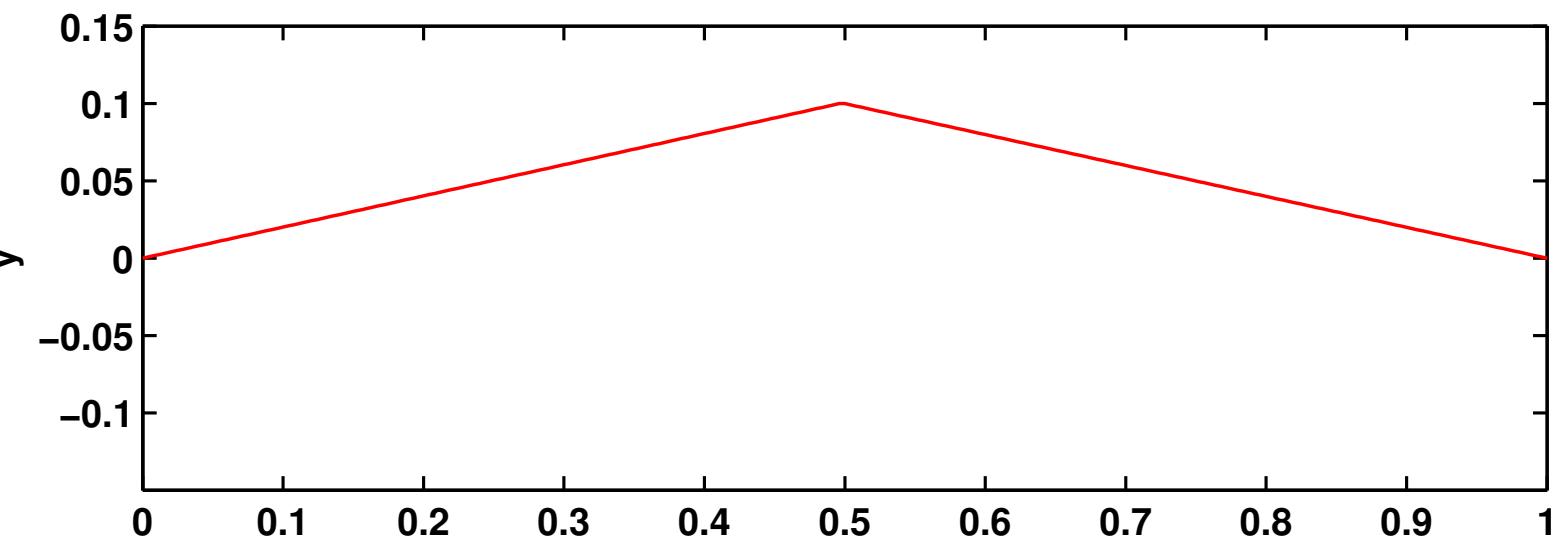
1/2 way from bridge



1/3 of the way from bridge



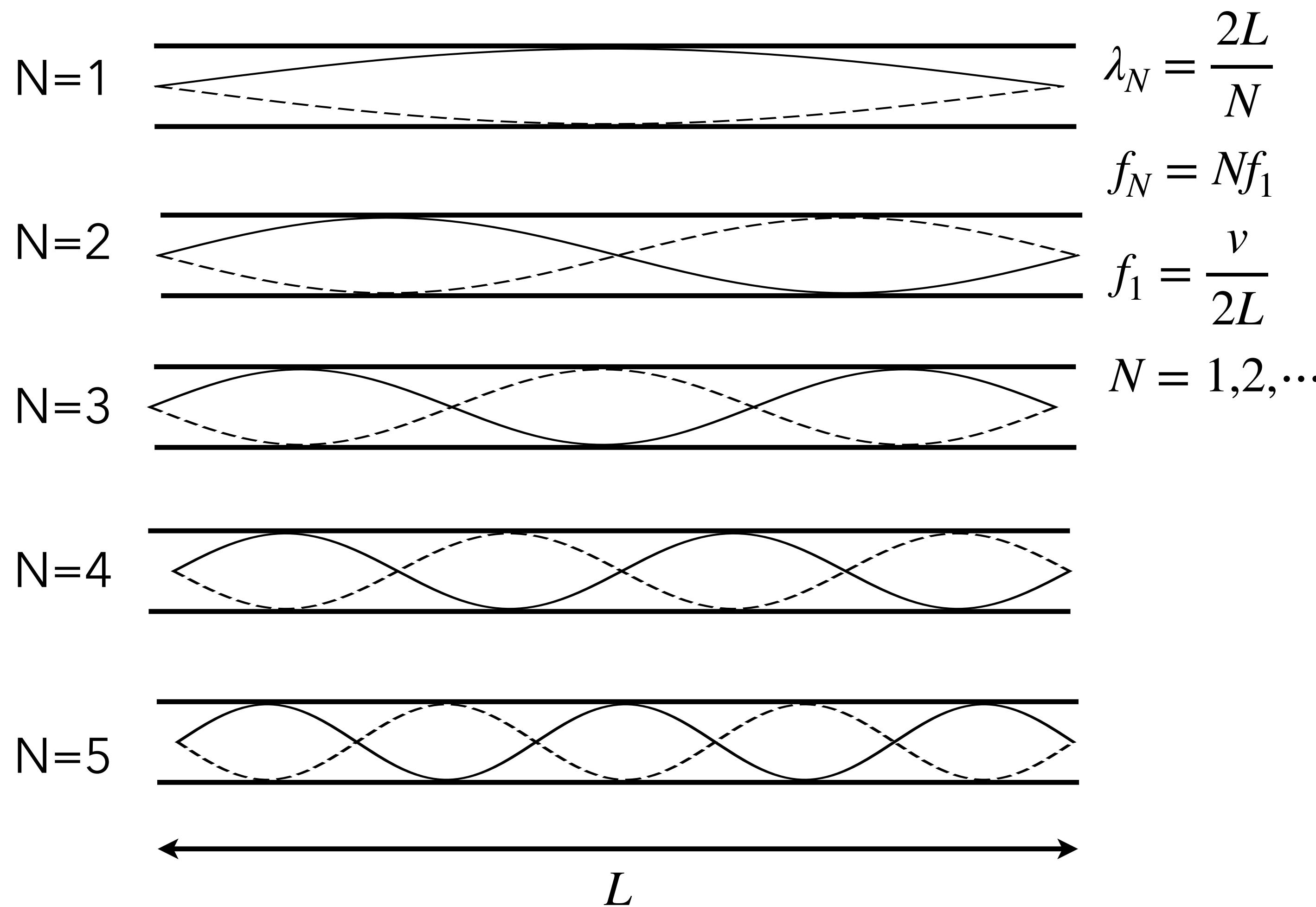
**(matlab demo:** "pluckedstring")



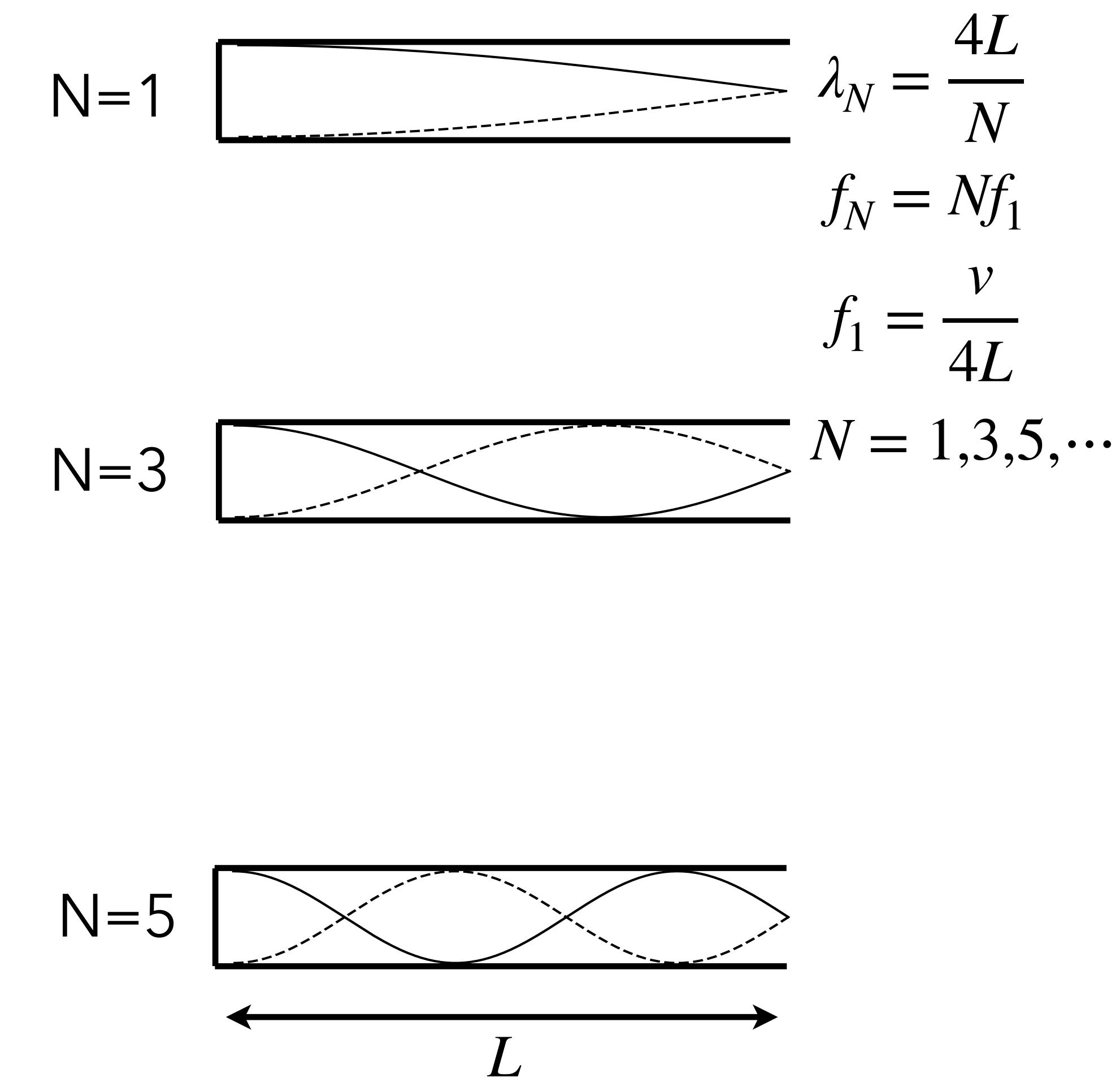
# Standing waves in a tube

(only odd harmonics!!)

open at both ends



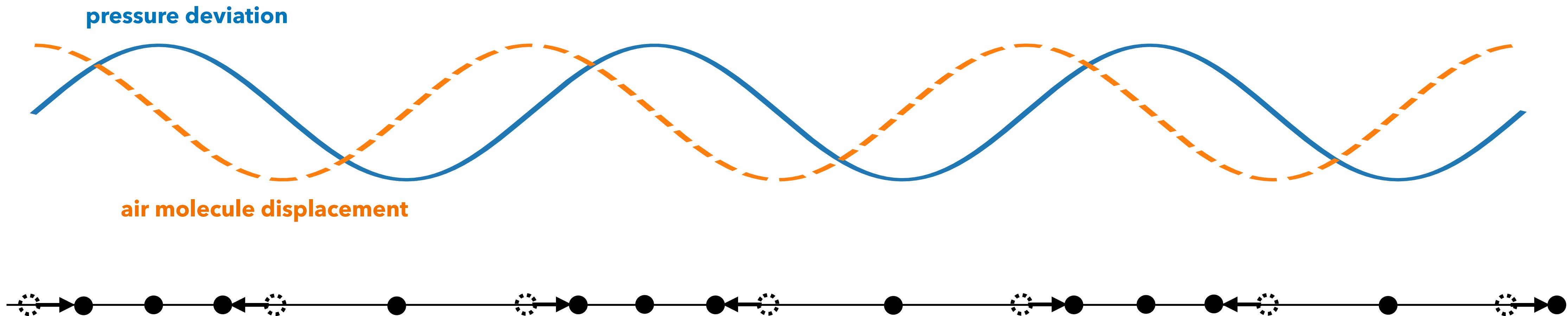
closed at one end



# Effective length, and “slap tube” determination of the speed of sound

- $L_{\text{eff, closed}} = L + 0.61r$  and  $L_{\text{eff, open}} = L + 1.22r$  (where  $r$  is the radius of the tube)
- “slap tube” is closed at one end ( $L = 38.5$  cm, diameter = 2.5 cm)
- Determine fundamental frequency, then solve for wave velocity

# Air molecule displacement vs pressure deviation



# Fourier's theorem

- **standing wave vibrations** are the “**building blocks**” for any complex vibration
- any complex periodic wave can be written as a **sum of harmonics**:

$$y(t) = A_1 \sin(2\pi f_1 t + \phi_1) + A_2 \sin(2\pi f_2 t + \phi_2) + \dots$$

$$f_N = Nf_1, \quad N = 1, 2, \dots$$

- **Ohm's law of hearing**: Phases have little effect on the timbre of the sound
- **Fourier analysis**: decomposing a complex periodic wave into its contributing harmonics
- **Fourier synthesis**: constructing a complex periodic wave by combining harmonics
- **PhET demo**: Fourier - making waves