PHYS1406: Physics of Sound and Music

Spring 2022

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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

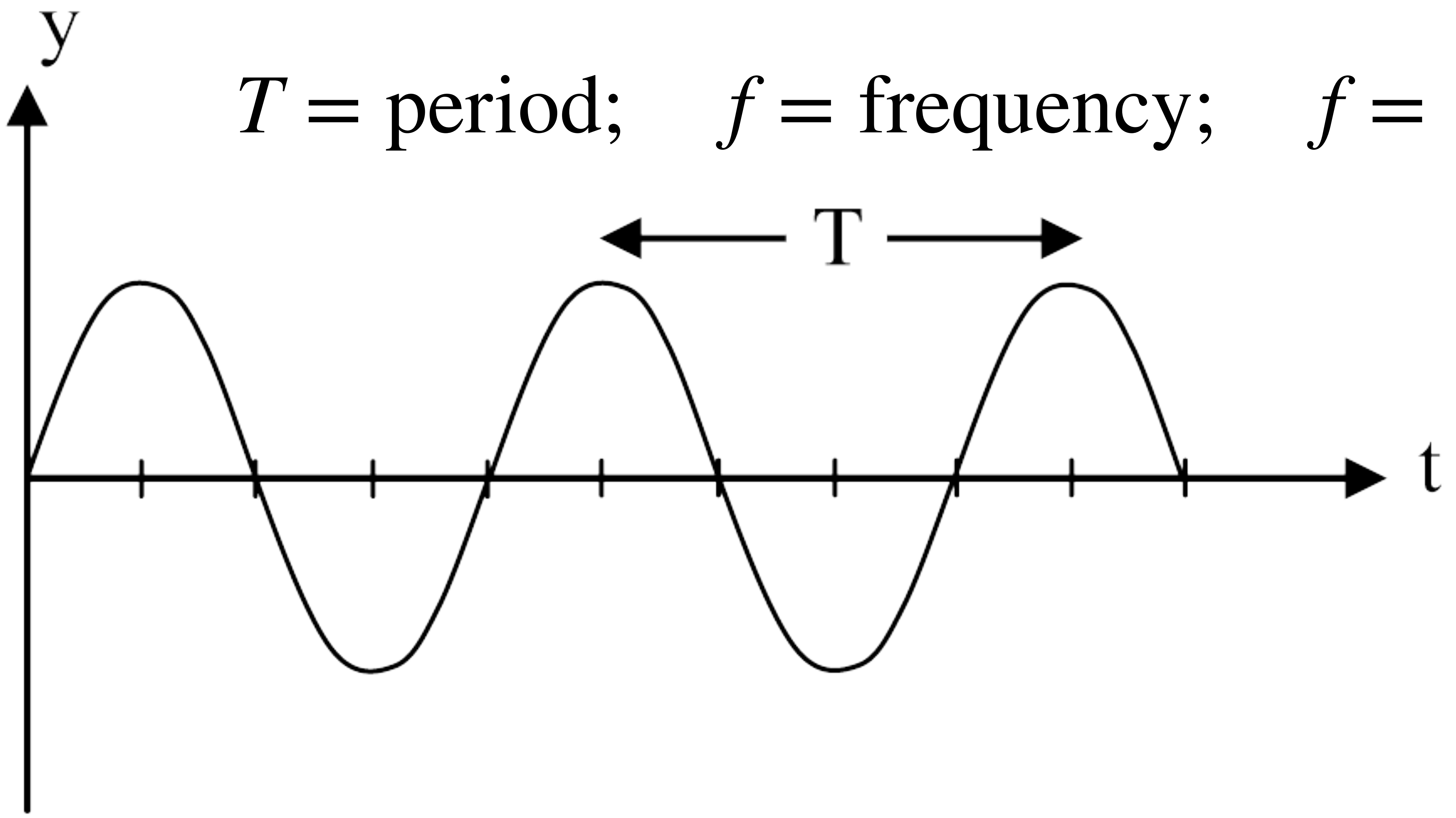
- Measuring devices
  - **oscilloscope**: shows how the sound pressure wave changes in time
  - **FFT analyzer**: shows how much sound energy is associated with different pitch components
  - **spectrogram**: shows how the pitch content of a sound changes in time
- Musical instruments and sound-making 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

T = period; f = frequency; $f = 1/T$



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.

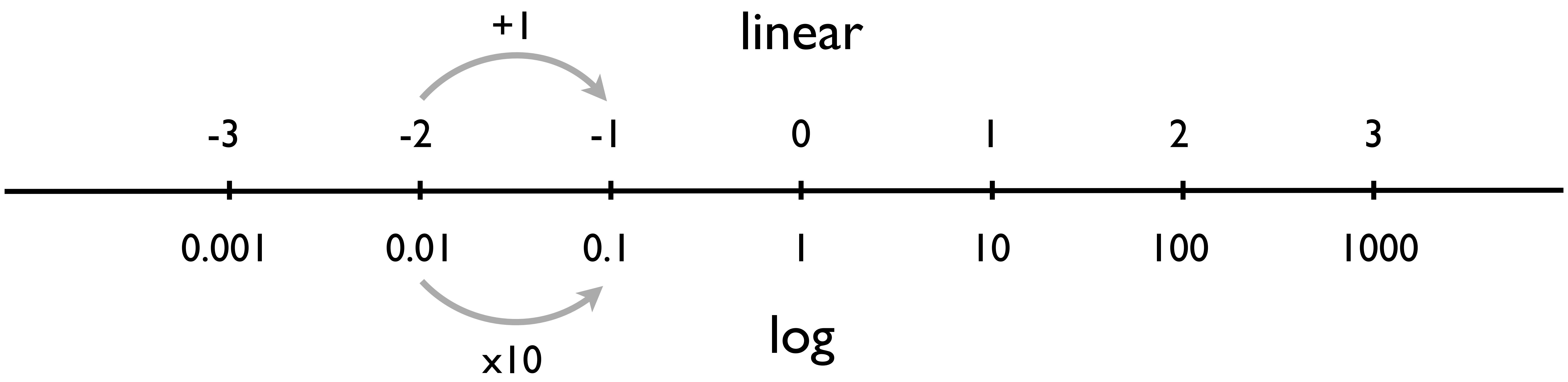
  Ans: First convert 5.5 ft to 66 inches. Then subtract ($72 \text{ in} - 66 \text{ in} = 6 \text{ in}$) or divide ($72 \text{ in}/66 \text{ in} = 1.09$) or calculate percent difference ($100 \times (72 - 66)/66 = 9\,\%$). For music applications, taking ratios or percent differences are most convenient 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 m = 3.28 ft and 1 mi = 5280 ft), we find:

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

Linear vs logarithmic scales

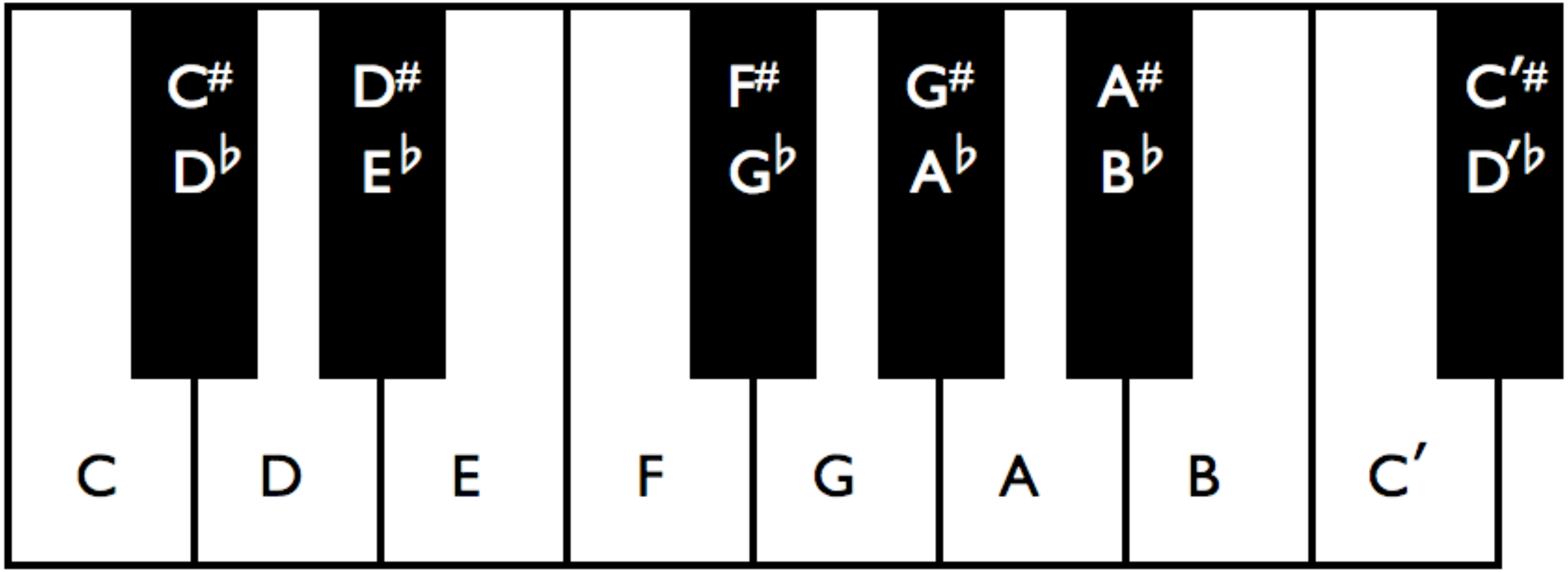


Music terminology

- 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′



do – re – mi – fa – sol – la – ti – do

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 Δx; units for both are m, in, ft, mi, …

- Time, duration: time = reading on a clock; duration = difference in times Δt; 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^2, 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^2 or lb/in^2 = psi; 1 atm = 10^5 N/m^2 = 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 πr^2, where r is the radius.

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

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

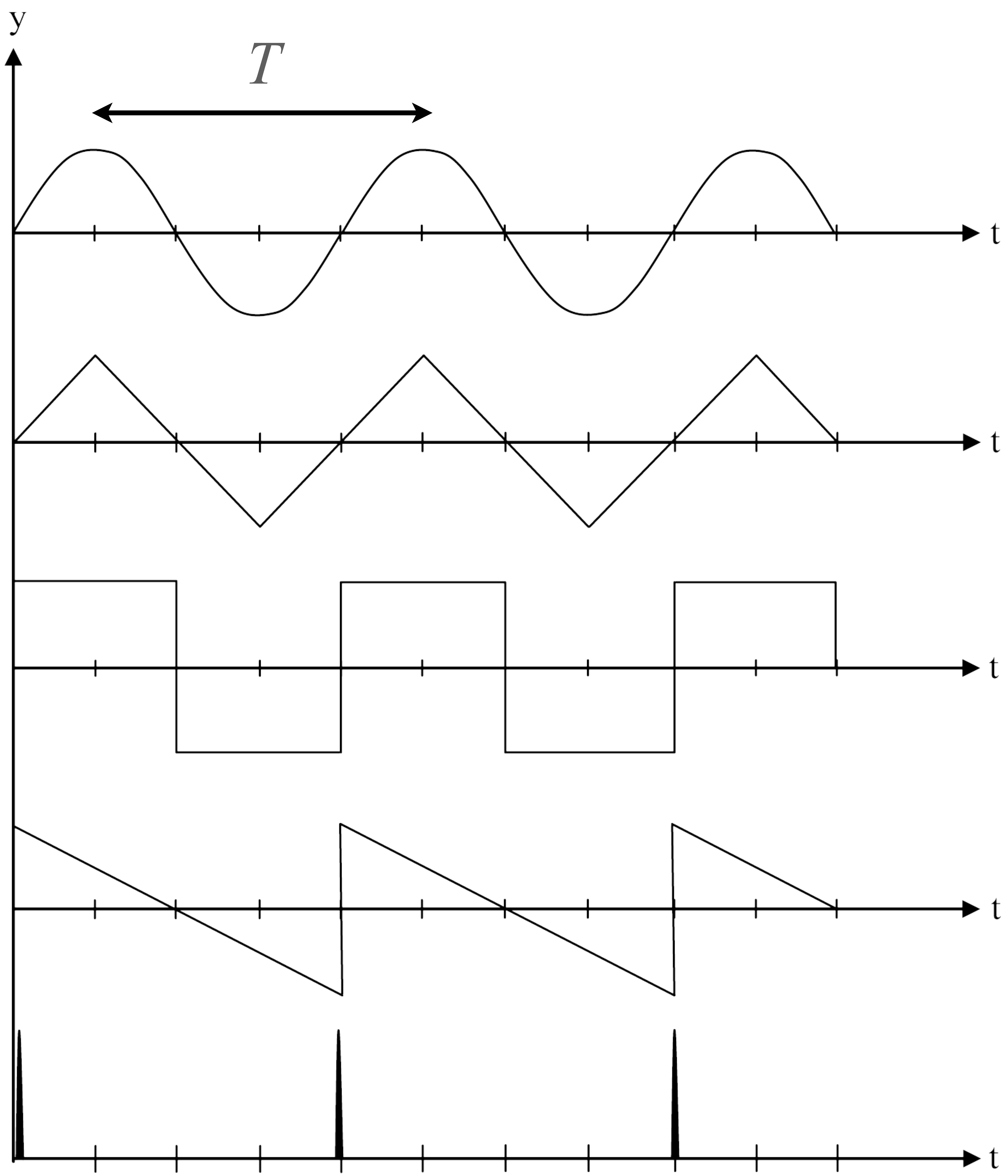
2. Oscillations

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 Hz has T = 50 msec; f = 20,000 Hz has T = 50 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.

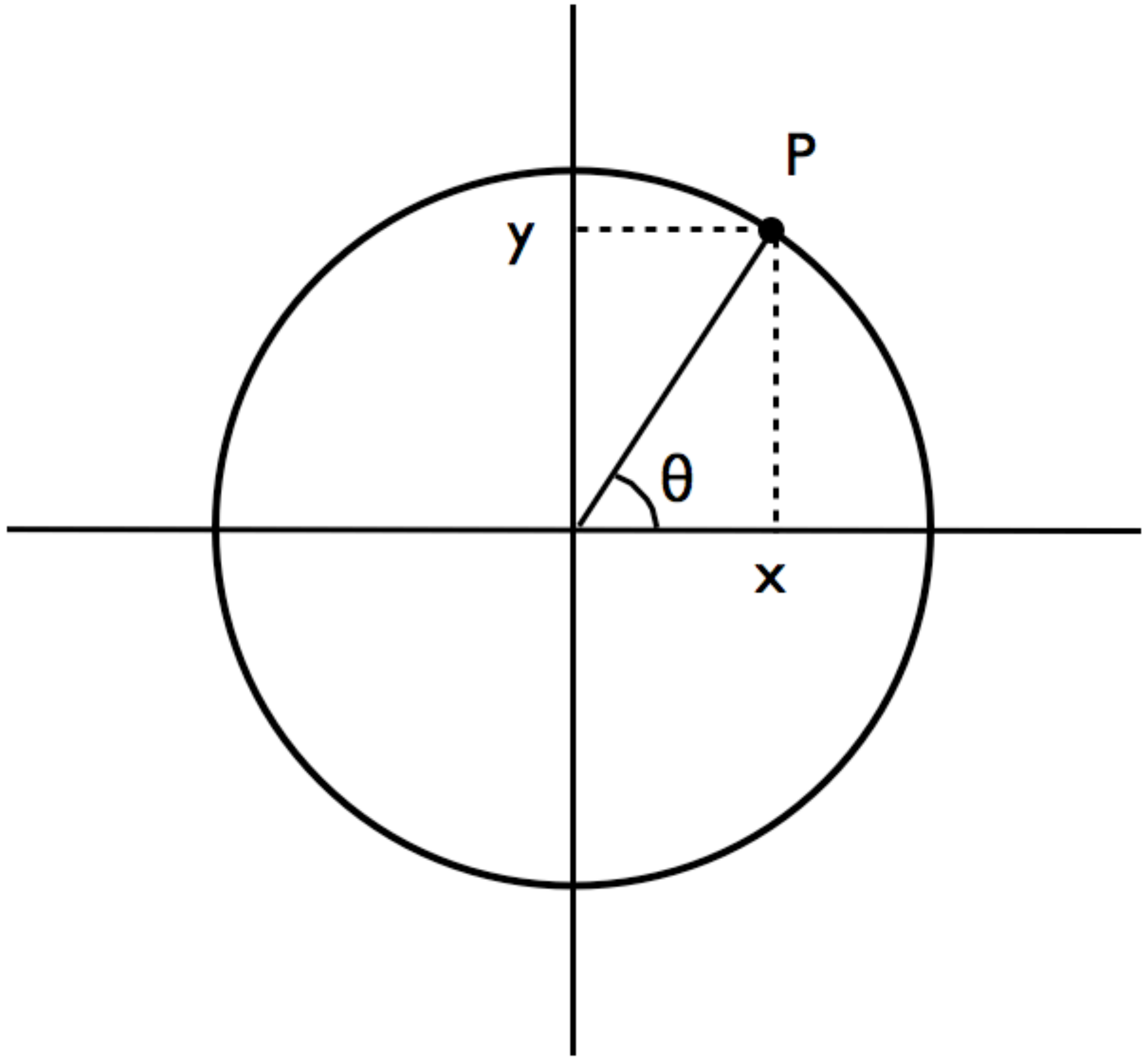
Different waveforms

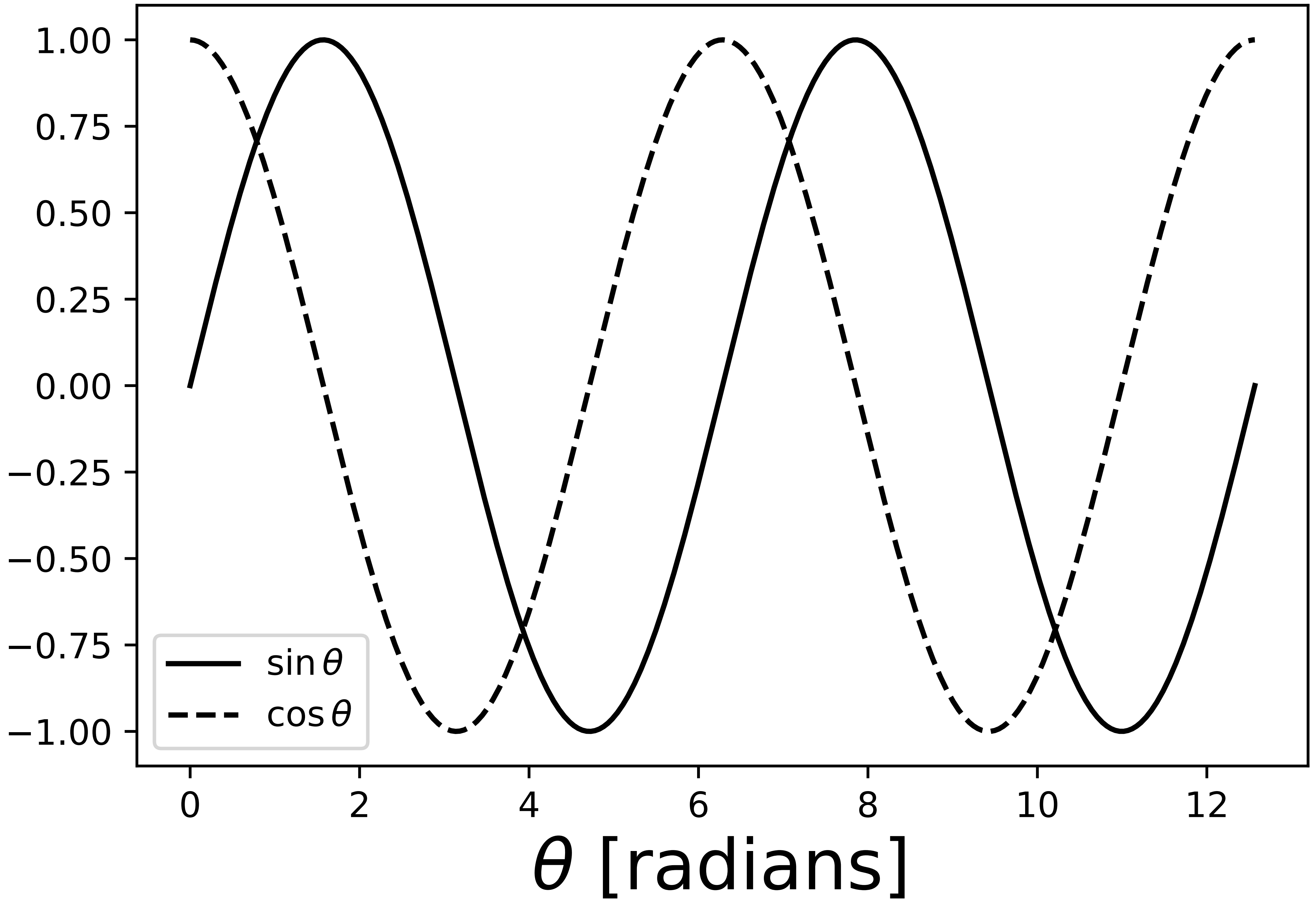
- Demo: Compare sounds
- Although the pitch is the same, the timbre (i.e., sound quality) is different



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 is great if the displacement from equilibrium is twice as large.)

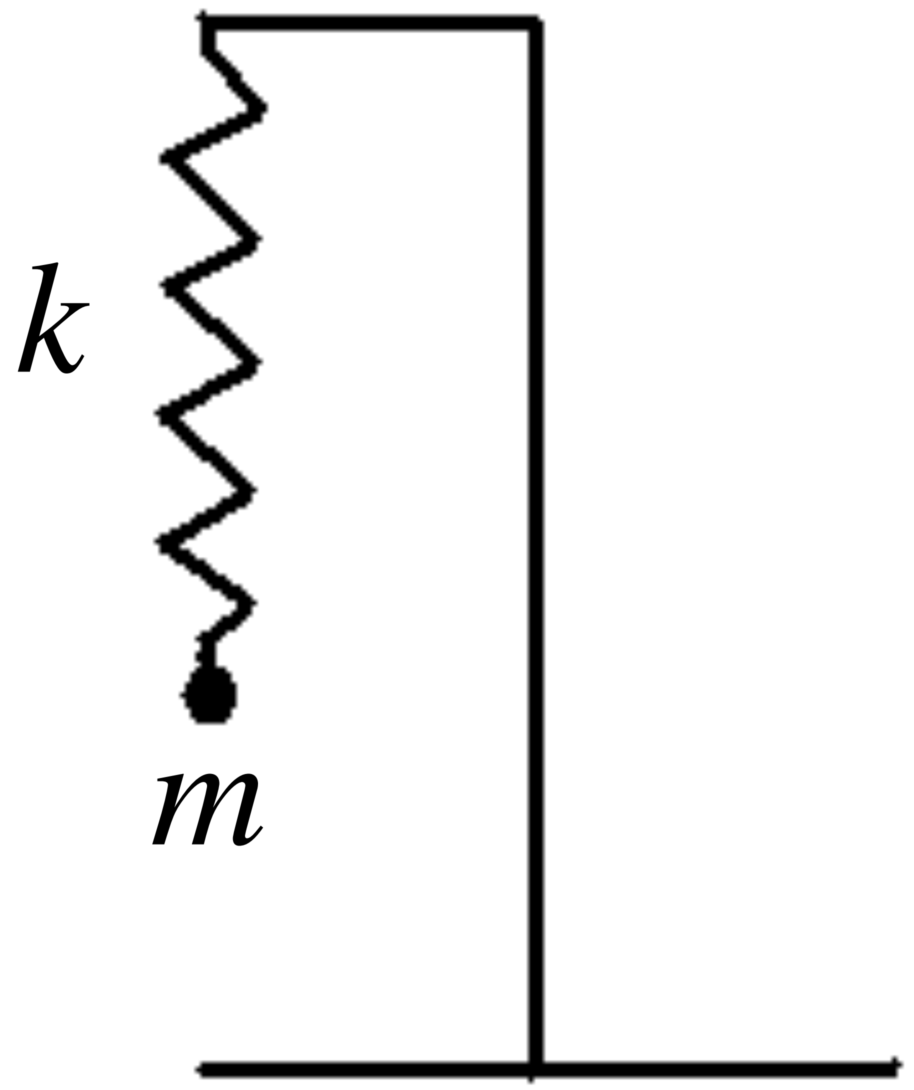




Examples of SHM

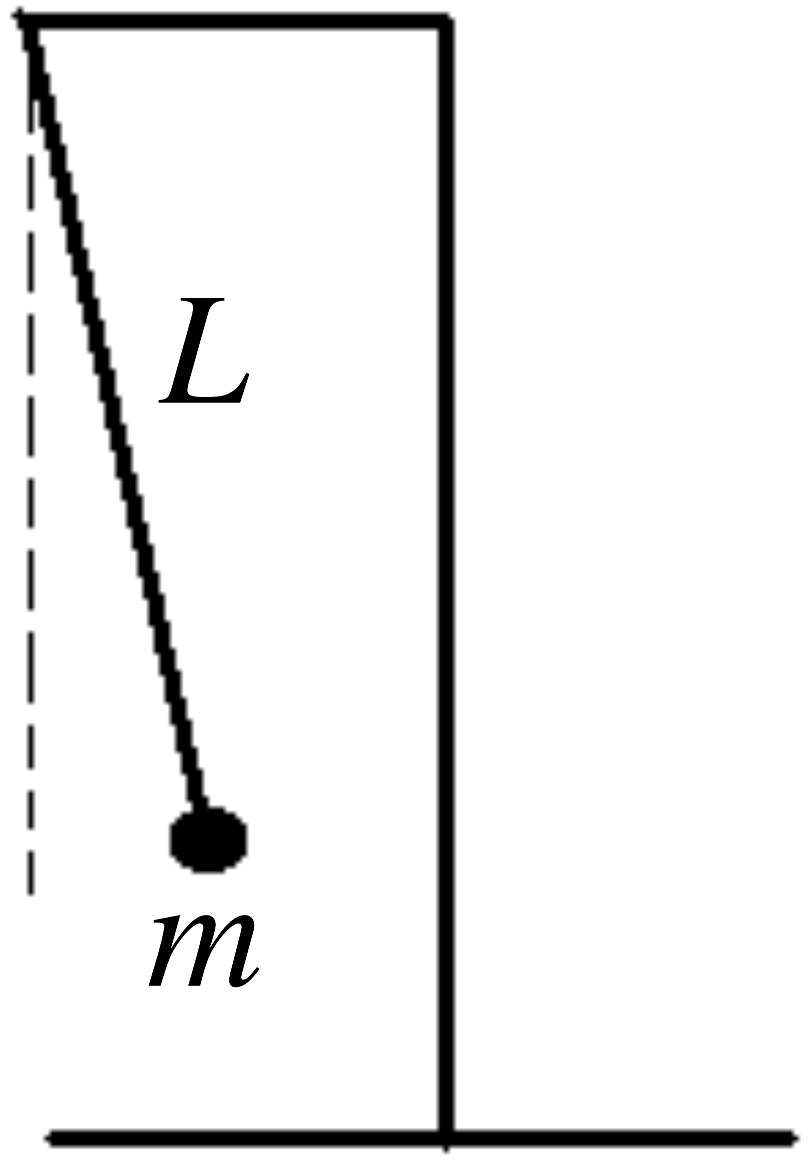
- **Mass on a spring**

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



- **Swinging pendulum bob**

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



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: $f_0 = \dfrac{1}{2\pi}\sqrt{\dfrac{g}{L}}$
- 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

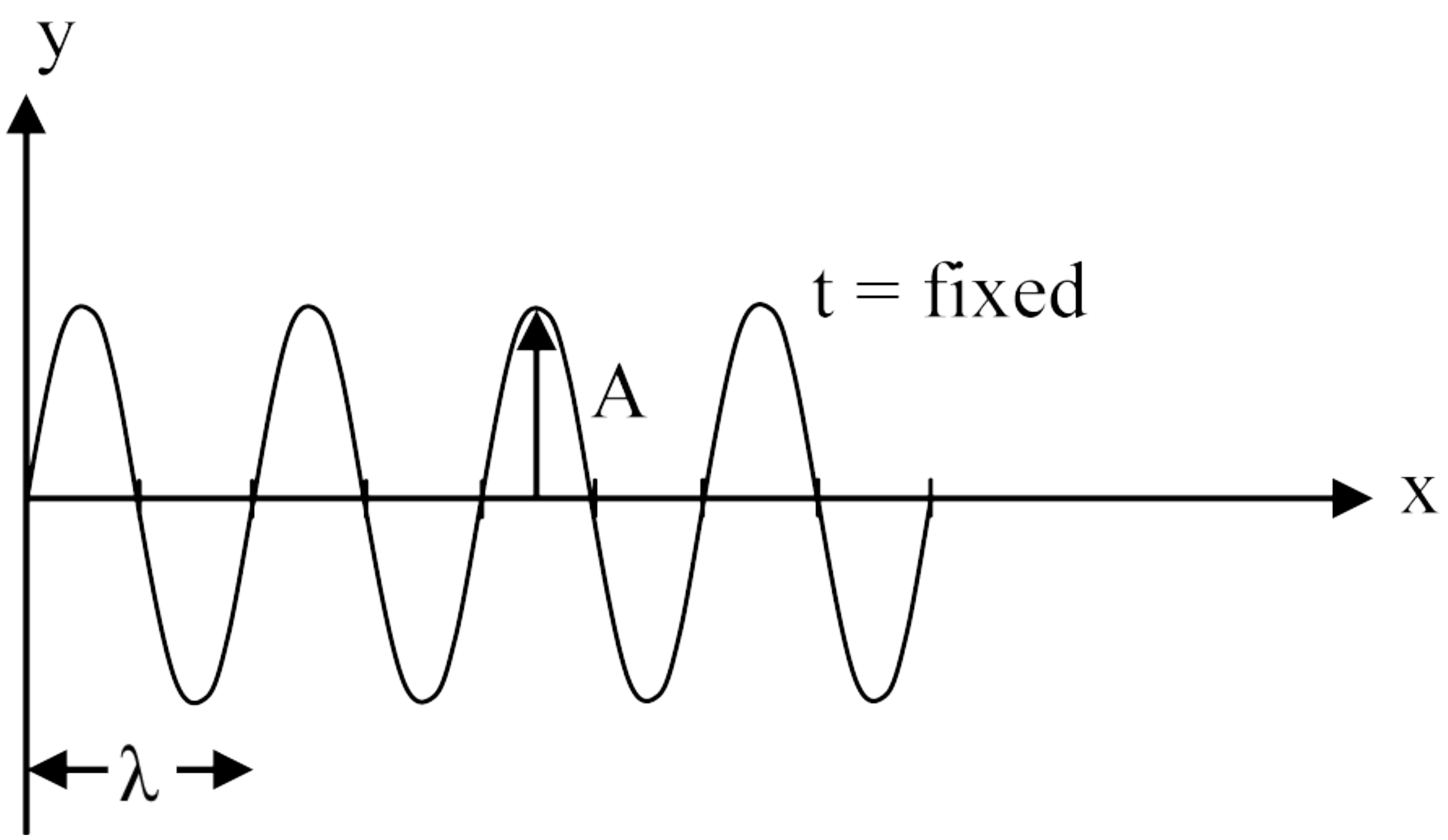
Wave motion, wave velocity

- **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**: $v = \Delta x / \Delta t$
- $v = 346\ \mathrm{m/s}$ (speed of sound in air at room temp, 25 Celsius or 77 Farenheit)
- $v = 331\ \dfrac{\mathrm{m}}{\mathrm{s}}\sqrt{1 + \dfrac{T_C}{273.15}}$ (speed of sound in air increases with increasing temperature)
- $T_C = (5/9)(T_F - 32^\circ)$ (relating Celsius and Farenheit temperature scales)

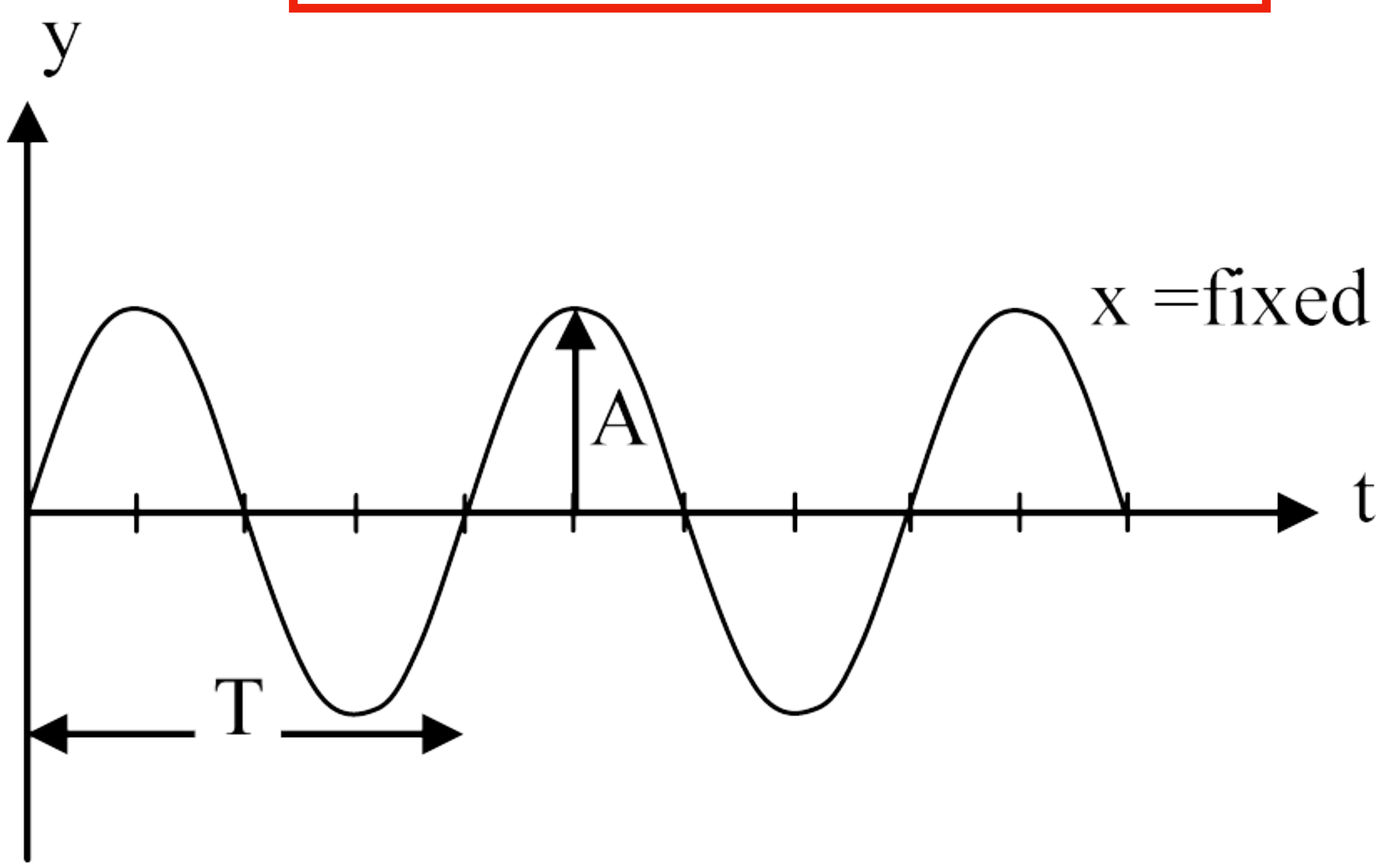
Periodic waves, wavelength

- Produced by **periodic sources**; λ is the **wavelength**

$$\boxed{v = \lambda/T = f\lambda}$$



"**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 $v = 346\ \mathrm{m/s}$ for the speed of sound in air at room temperature.
- **Ans:**
  - $f = 20\ \mathrm{Hz}$ has $\lambda = ??$
  - $f = 20{,}000\ \mathrm{Hz}$ 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 $v = 346\ \mathrm{m/s}$ for the speed of sound in air at room temperature.

- **Ans:**

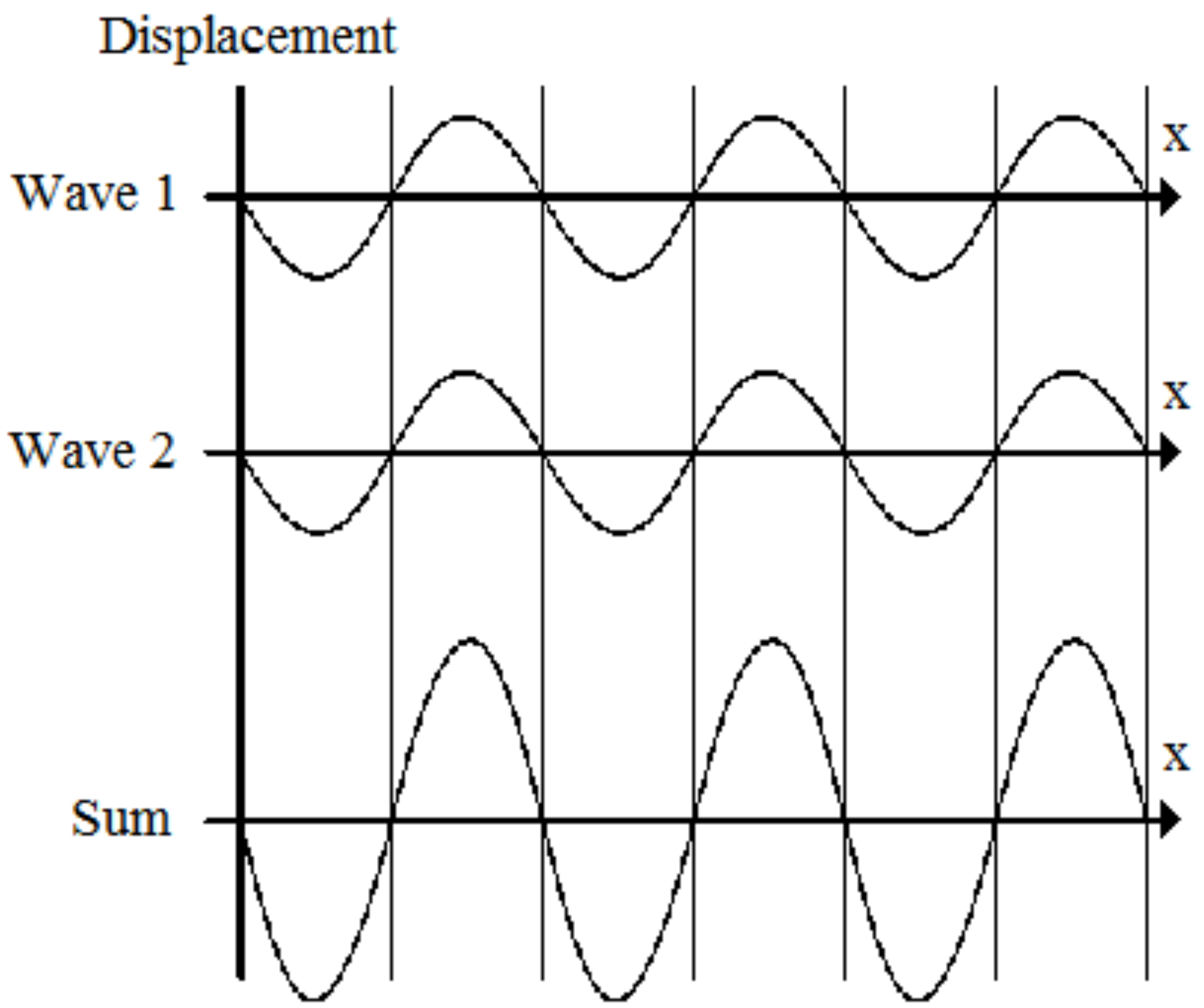
  - $f = 20\ \mathrm{Hz}$ has $\lambda \approx 17\ \mathrm{m}$

  - $f = 20{,}000\ \mathrm{Hz}$ has $\lambda \approx 1.7\ \mathrm{cm}$

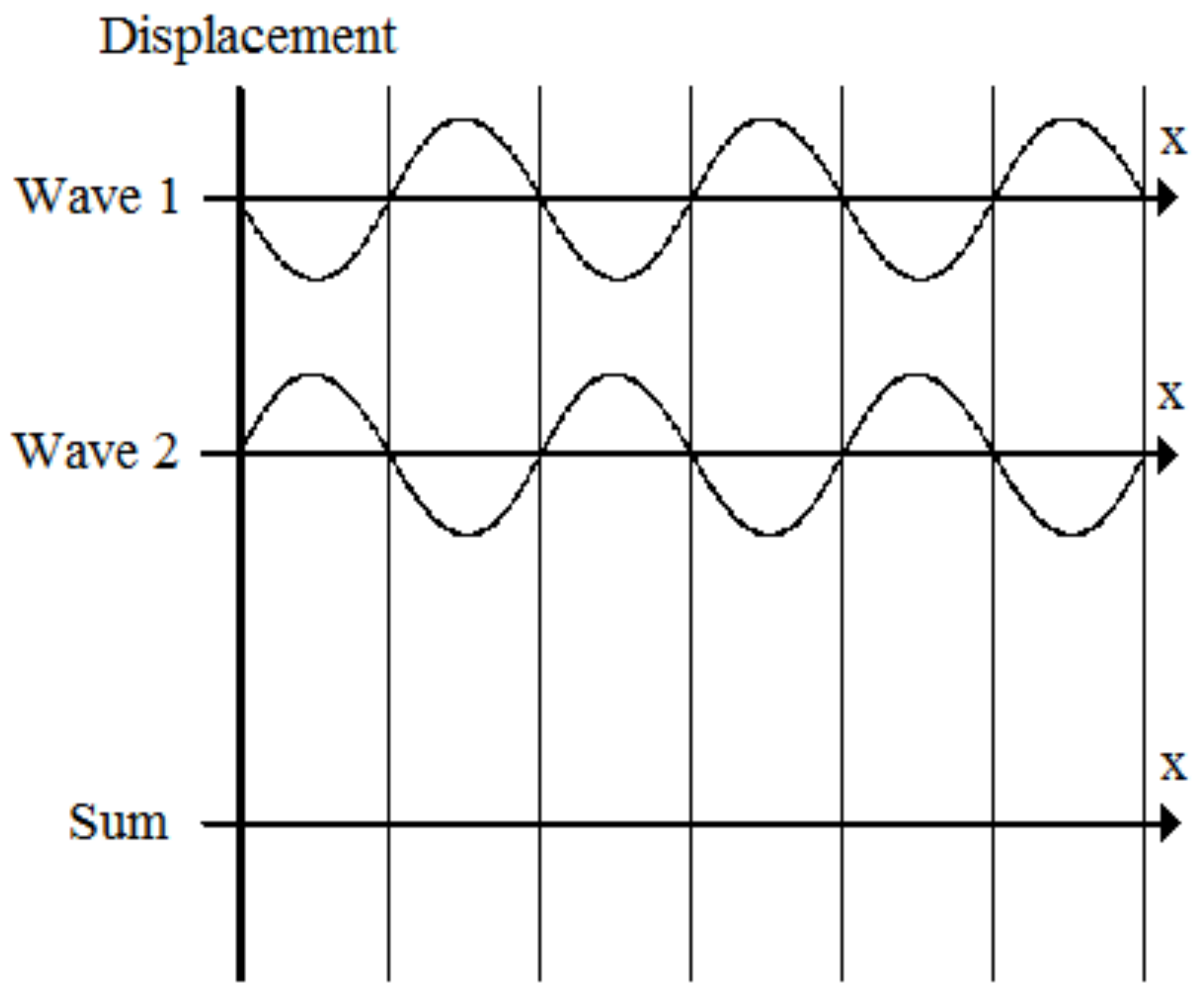
  - Most musical sounds (e.g., concert A, 440 Hz) have wavelengths of order 1 meter

Superposition / interference

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



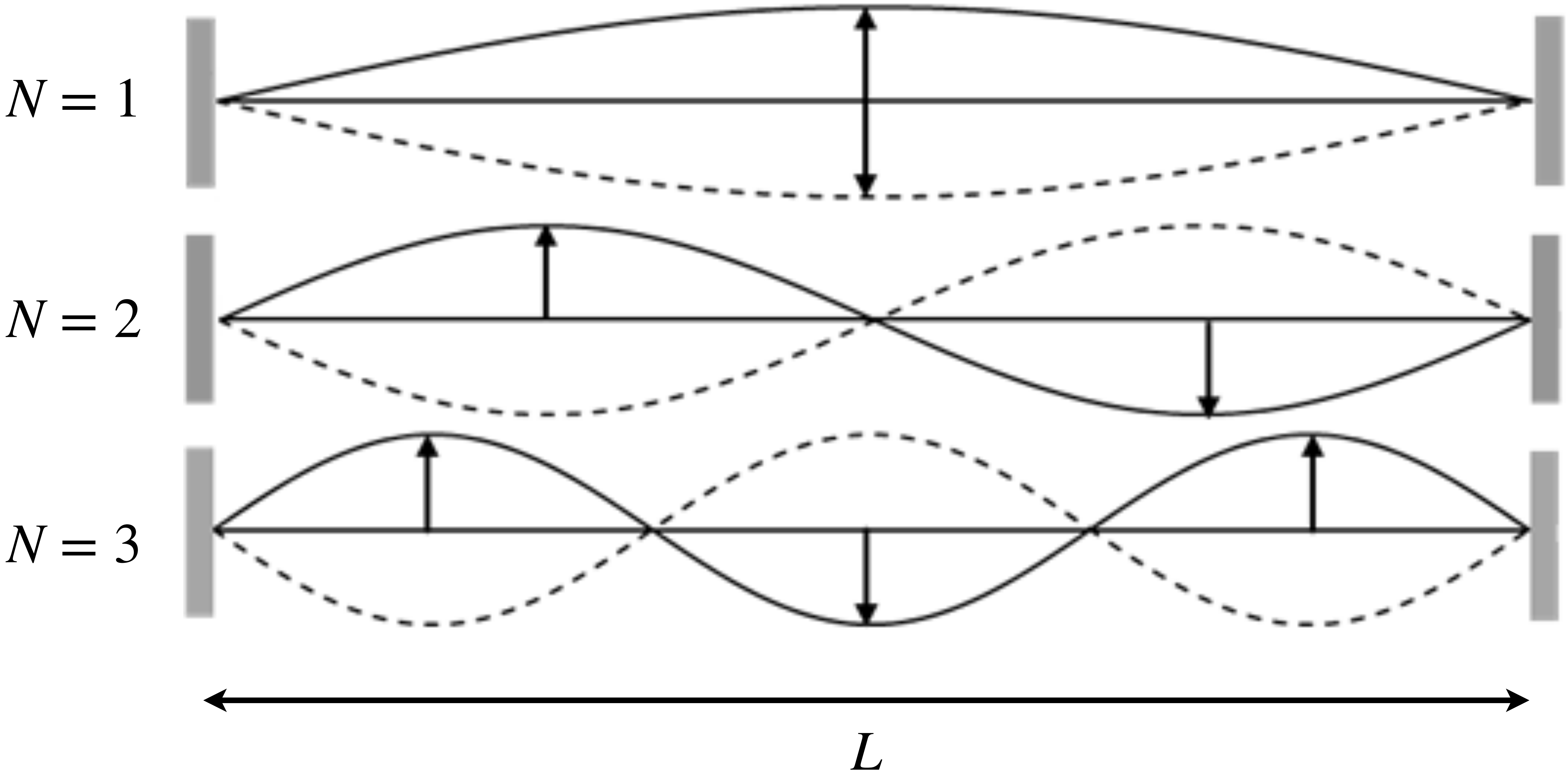
constructive



destructive

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”)



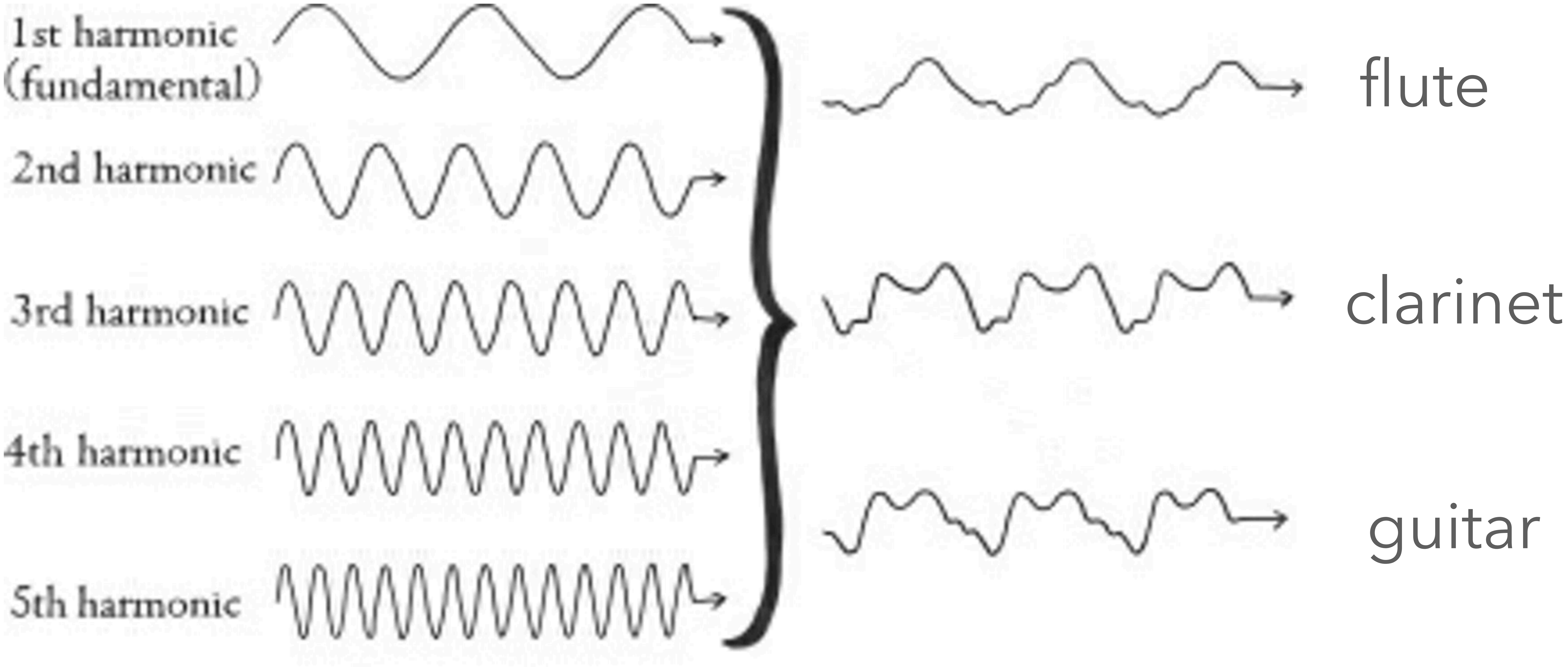
$$v = \sqrt{\frac{\text{string tension}}{\text{mass density}}} = \sqrt{\frac{F}{\mu}}$$

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

$$f_N = Nf_1$$ (Nth harmonic)

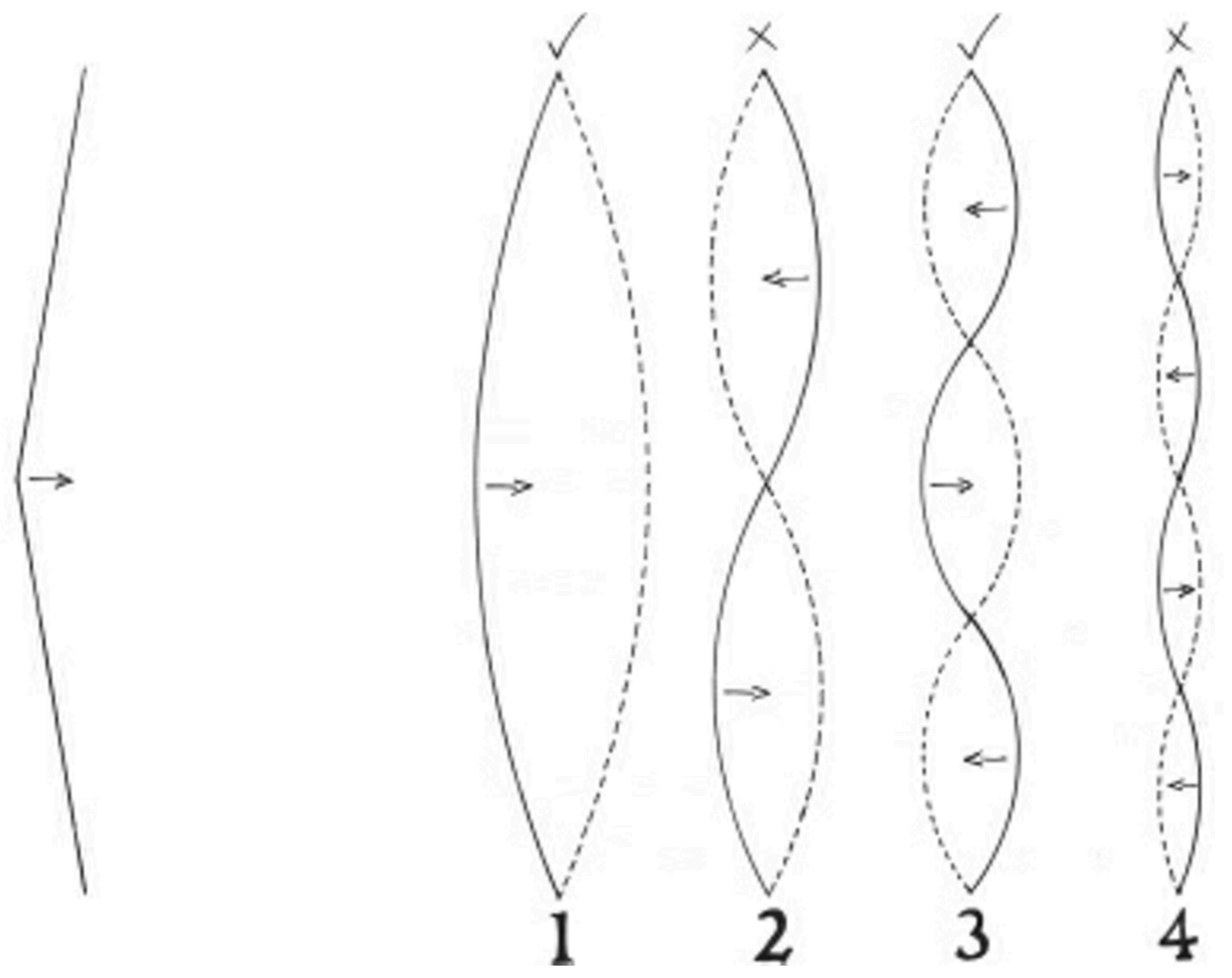
$$f_1 = \frac{v}{2L}$$ (fundamental)

Timbre – same note but different contributions of harmonics

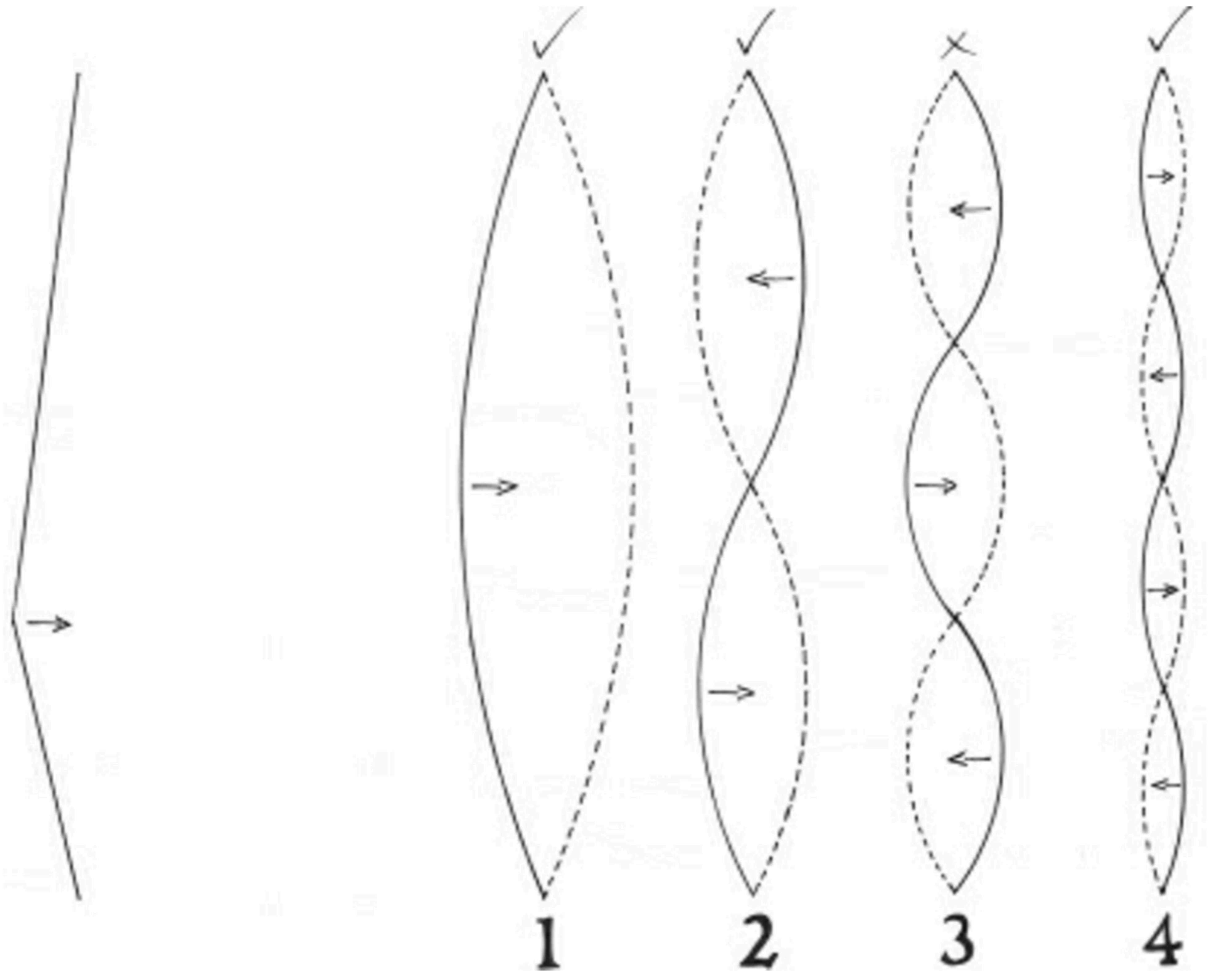


Where you pluck a guitar string changes the timbre

1/2 way from bridge



1/3 of the way from bridge



(**matlab demo**: “pluckedstring”)

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**:

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

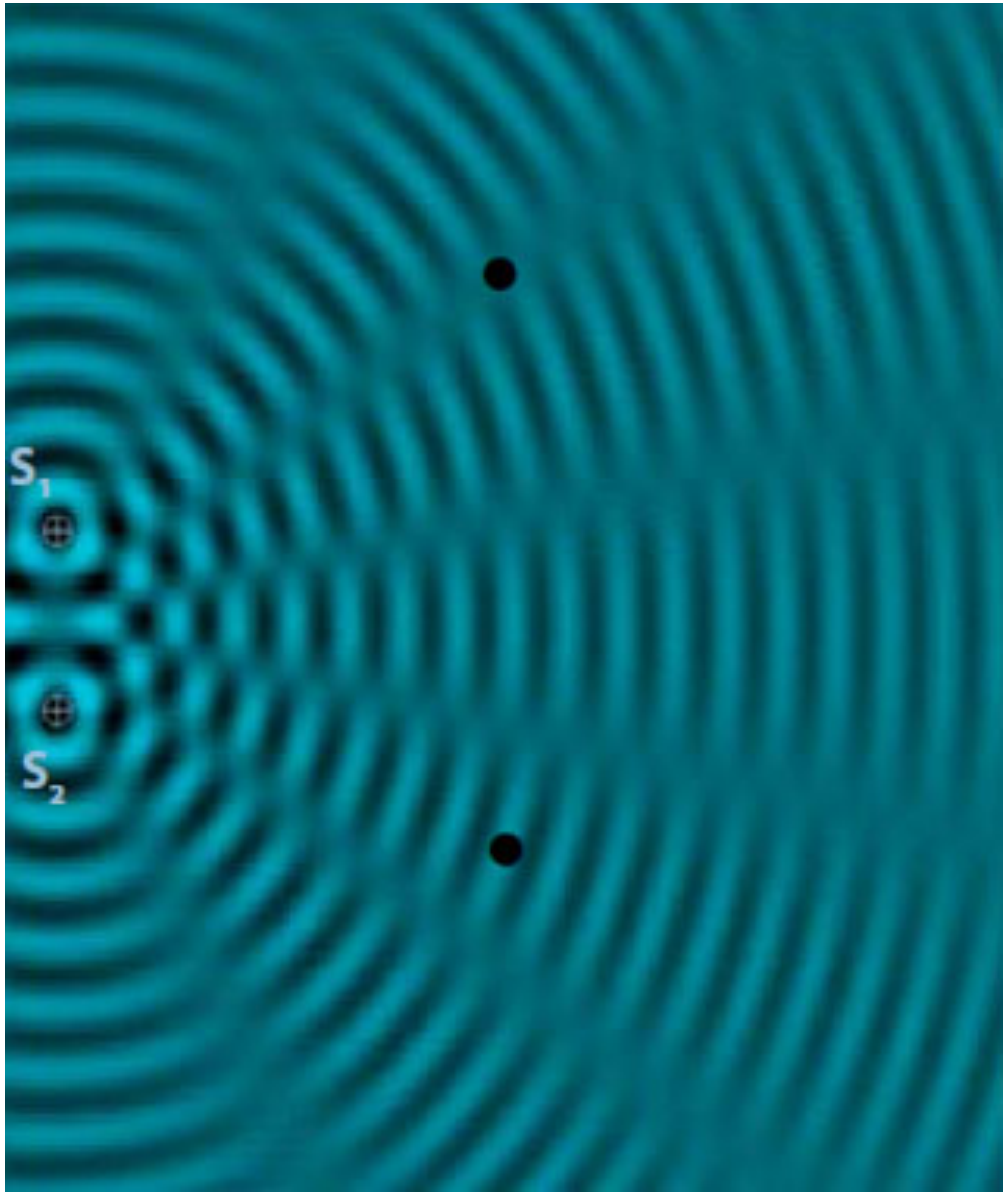
$$f_N = N f_1, \qquad N = 1,2,\cdots$$

- **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

Interference in space

- Water waves in a ripple tank or sound waves produced by two speakers

- **PhET demo**: wave interference

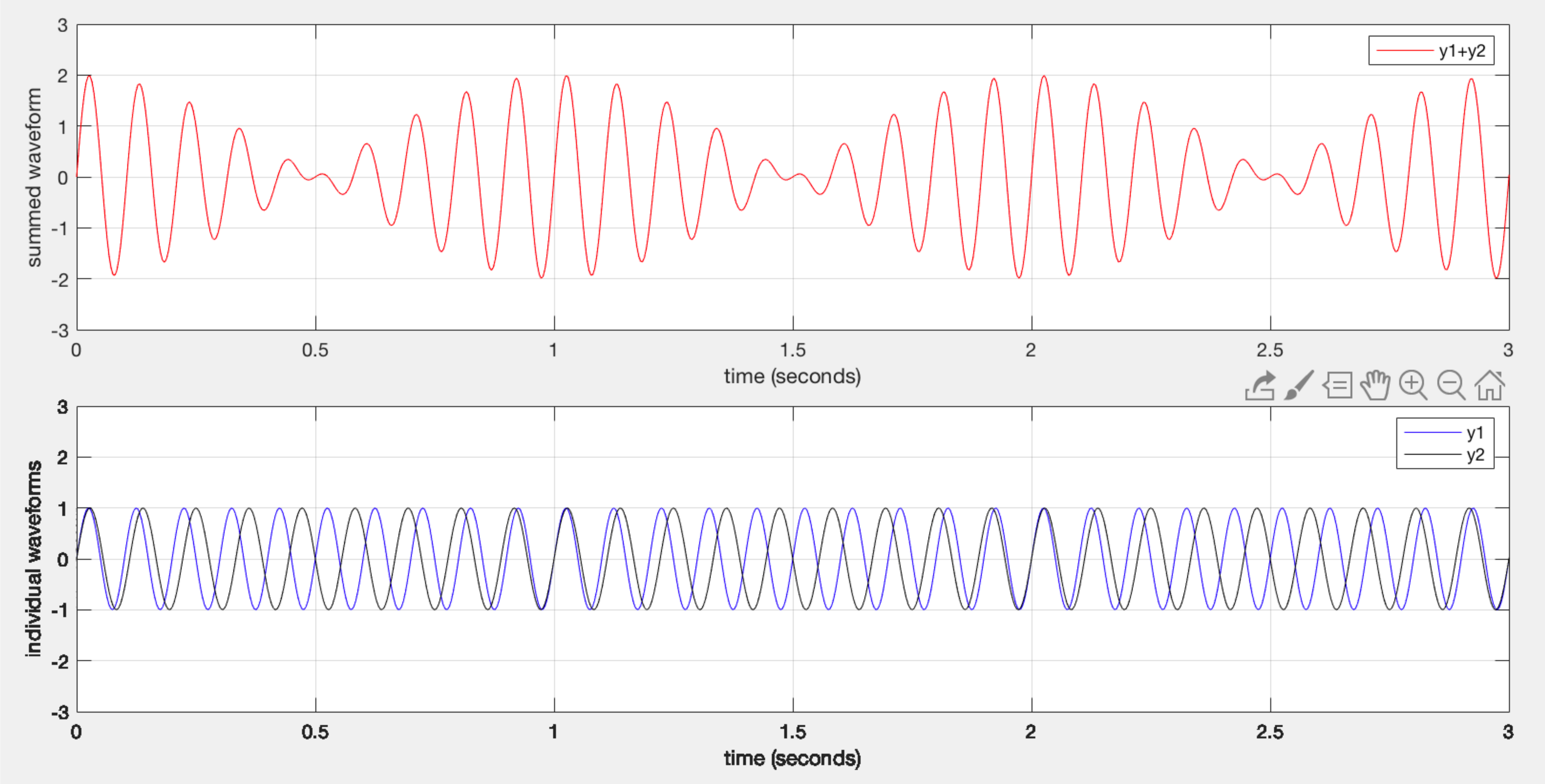


Interference in time - “beats”

- Interference in time of two periodic waves having different frequencies (**matlab demo**: “beats”, and using signal generators)

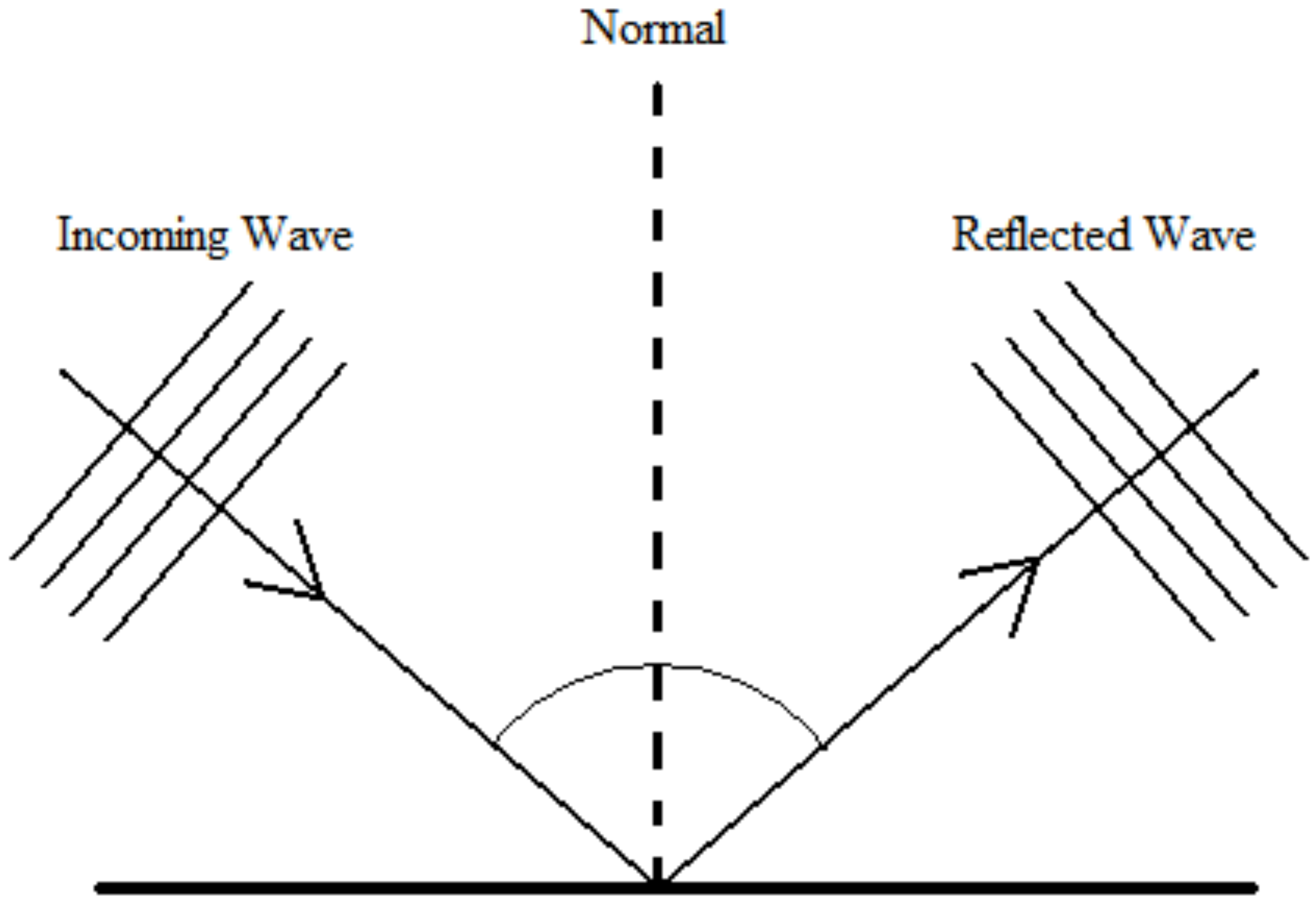
- Beat frequency:
  $f_{\text{beat}} = |f_1 - f_2|$

- “Beatless” tuning of instruments

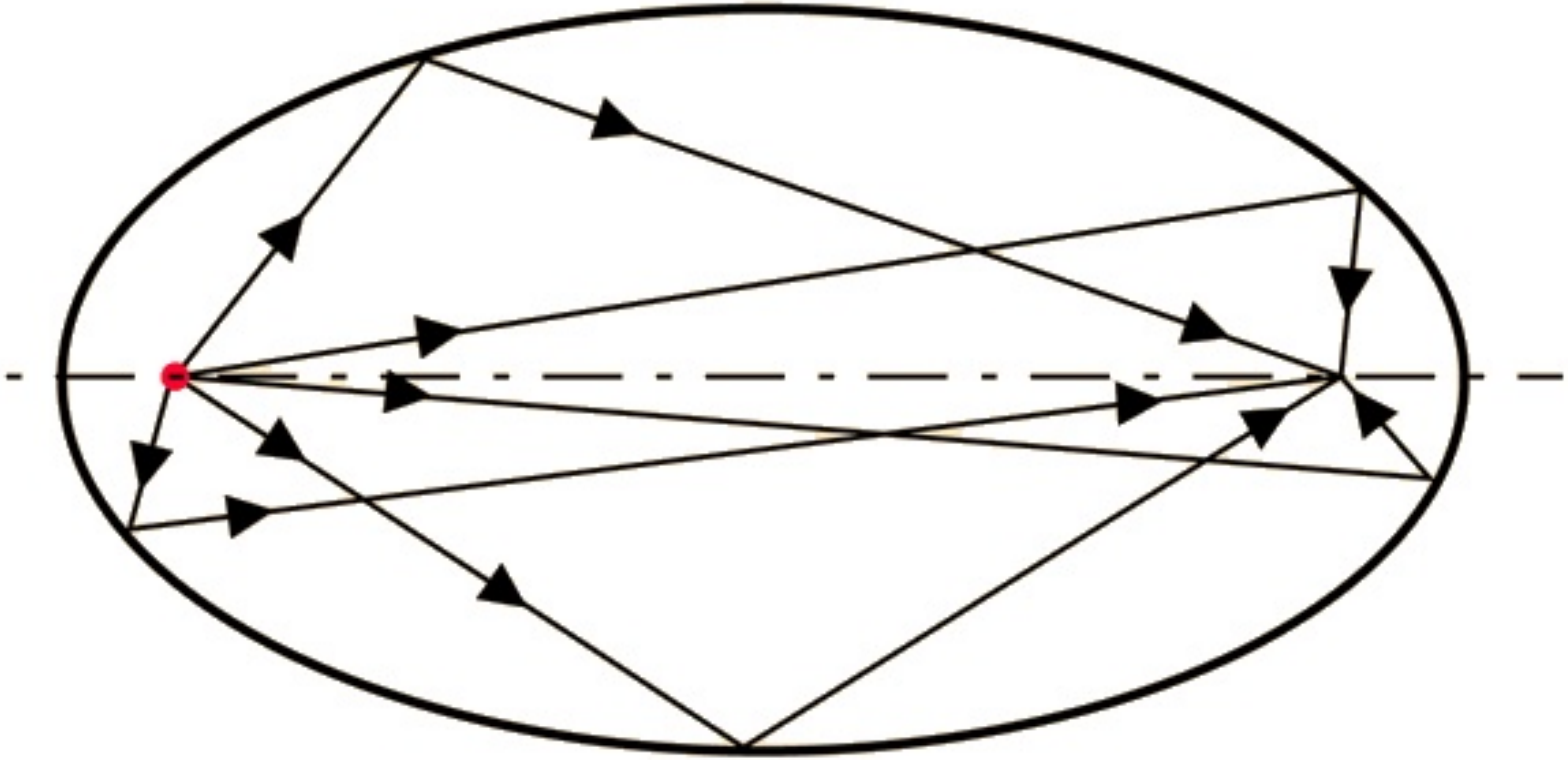


Reflection

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

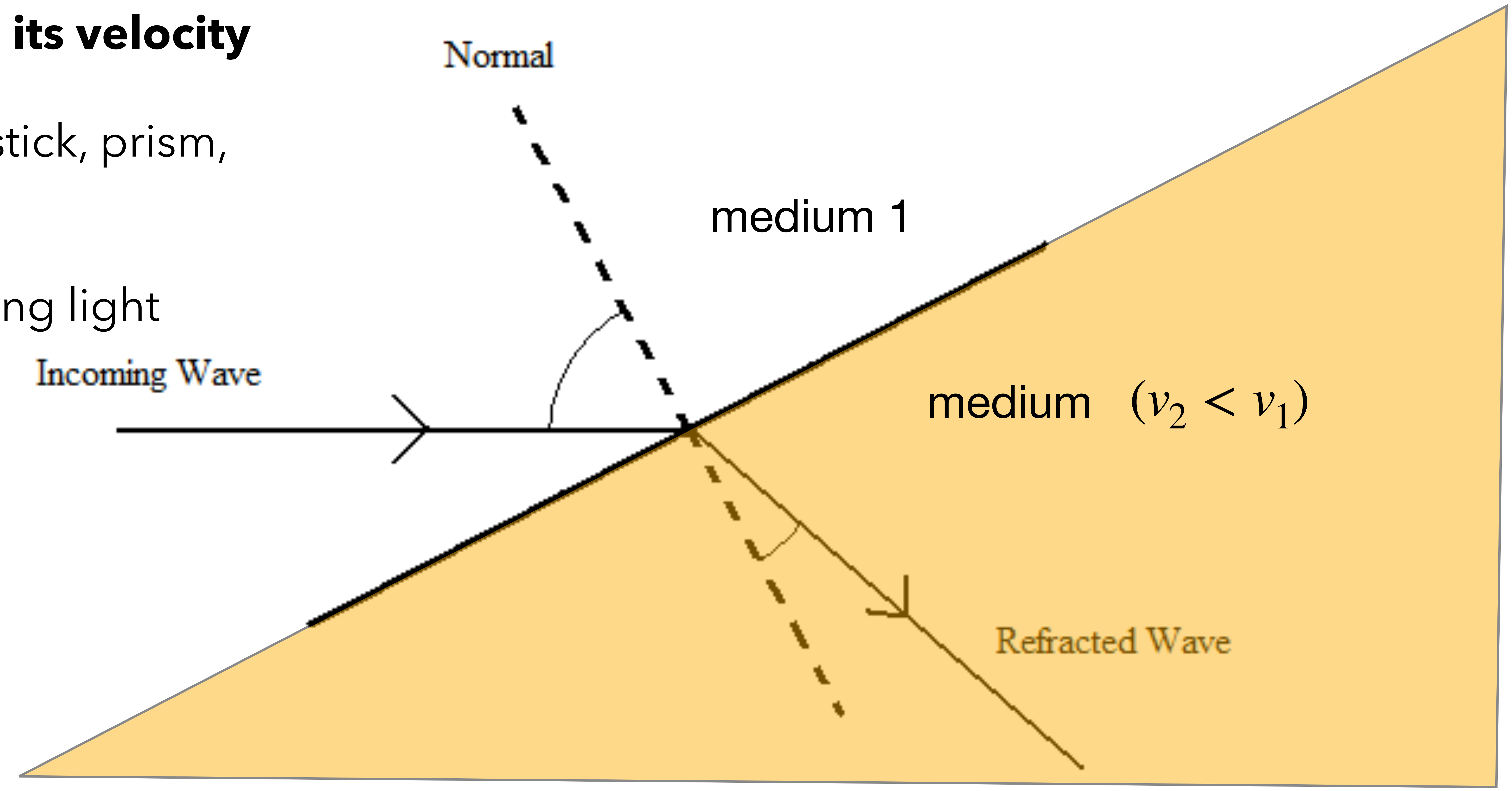


Reflections - whispering chamber

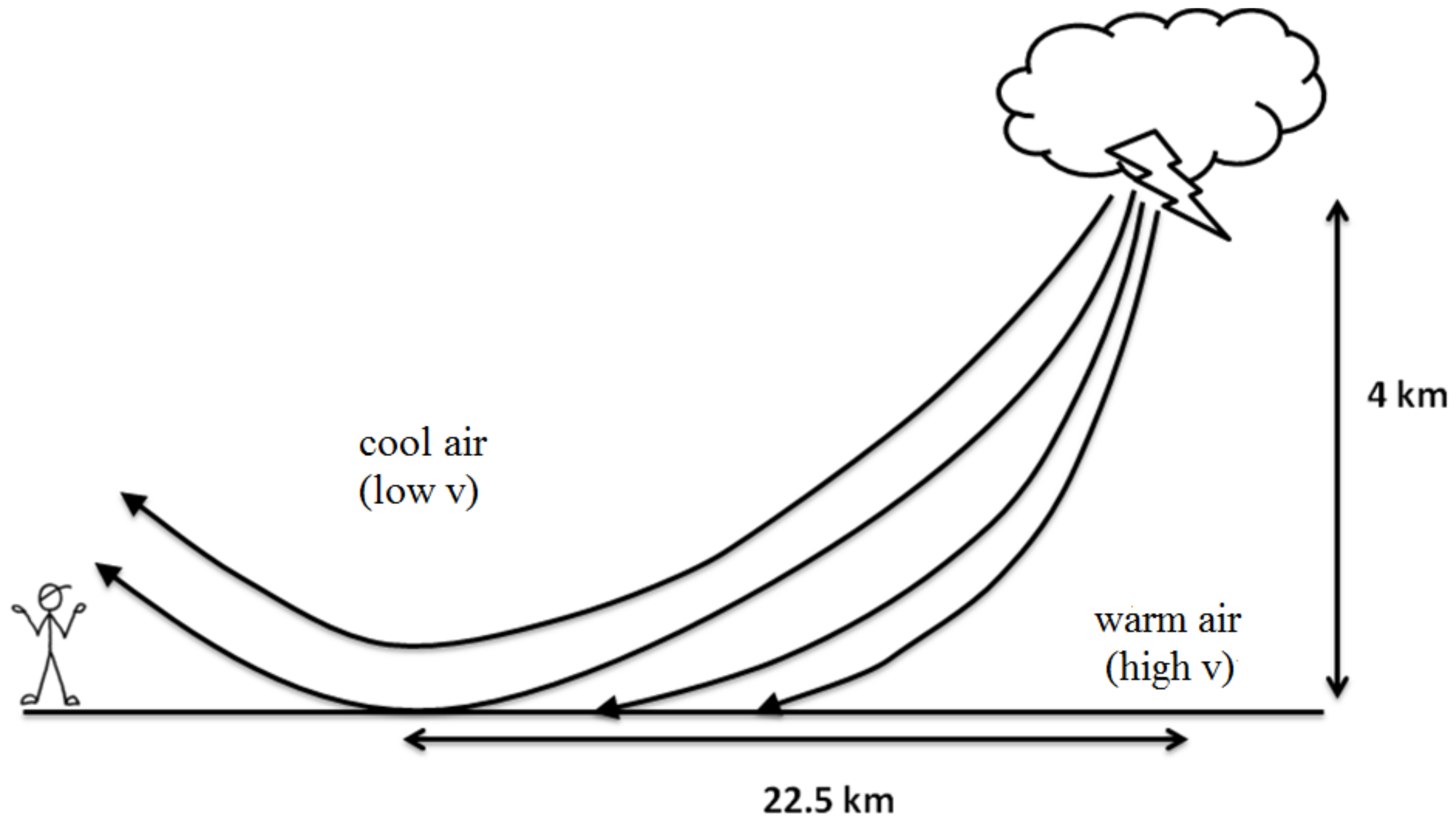


Refraction

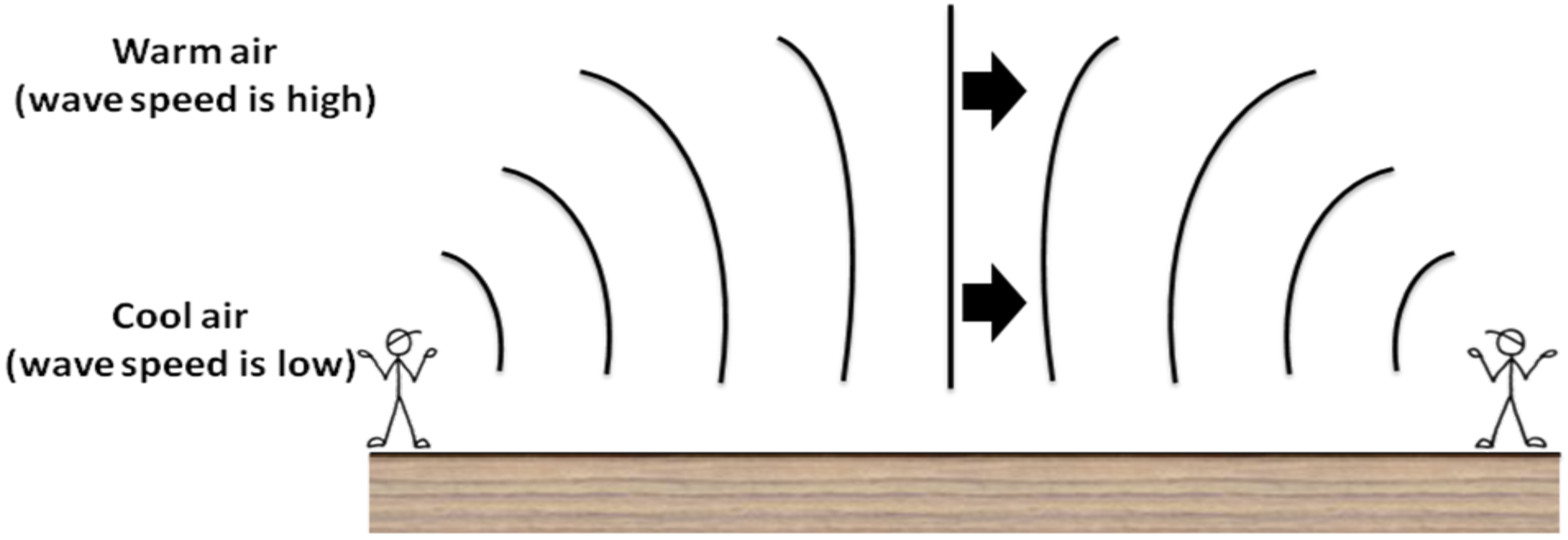
- **Change in direction** of a wave due to a **change in its velocity**
- **Demos** with light (stick, prism, and laser)
- **PhET demo**: bending light



Examples of refraction of sound

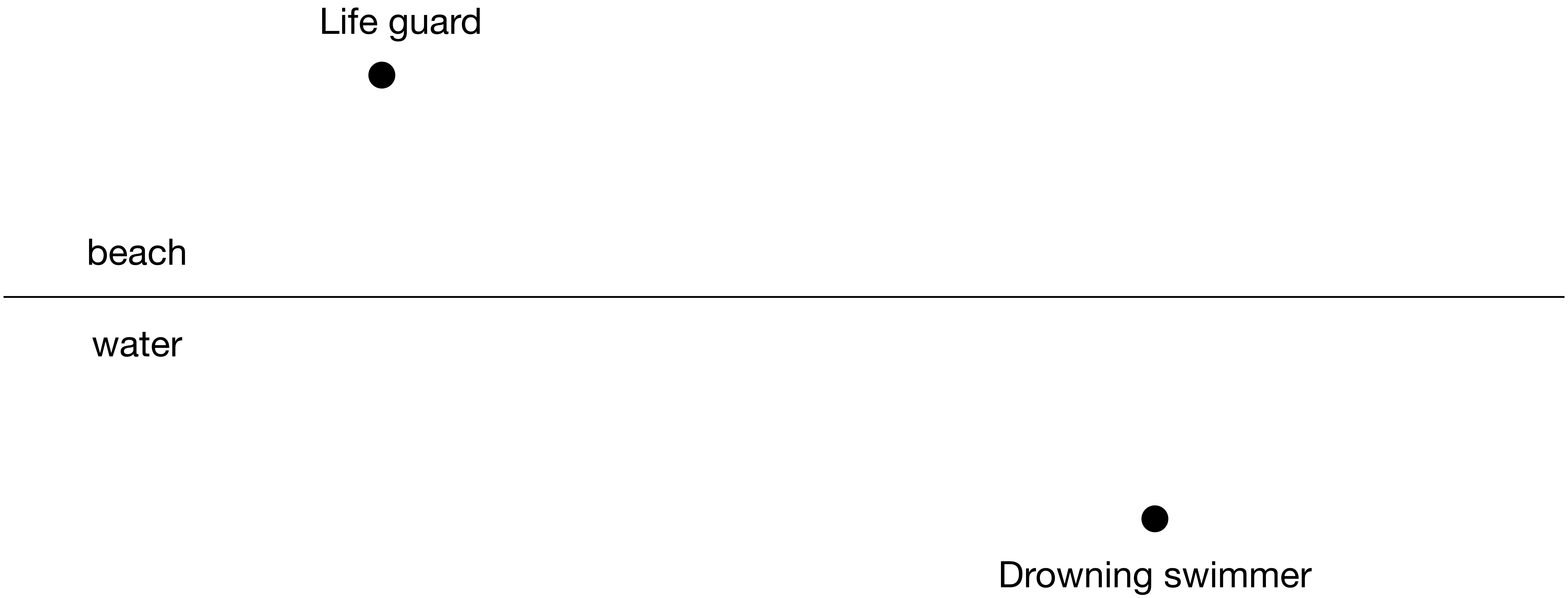


Usual temperature distribution



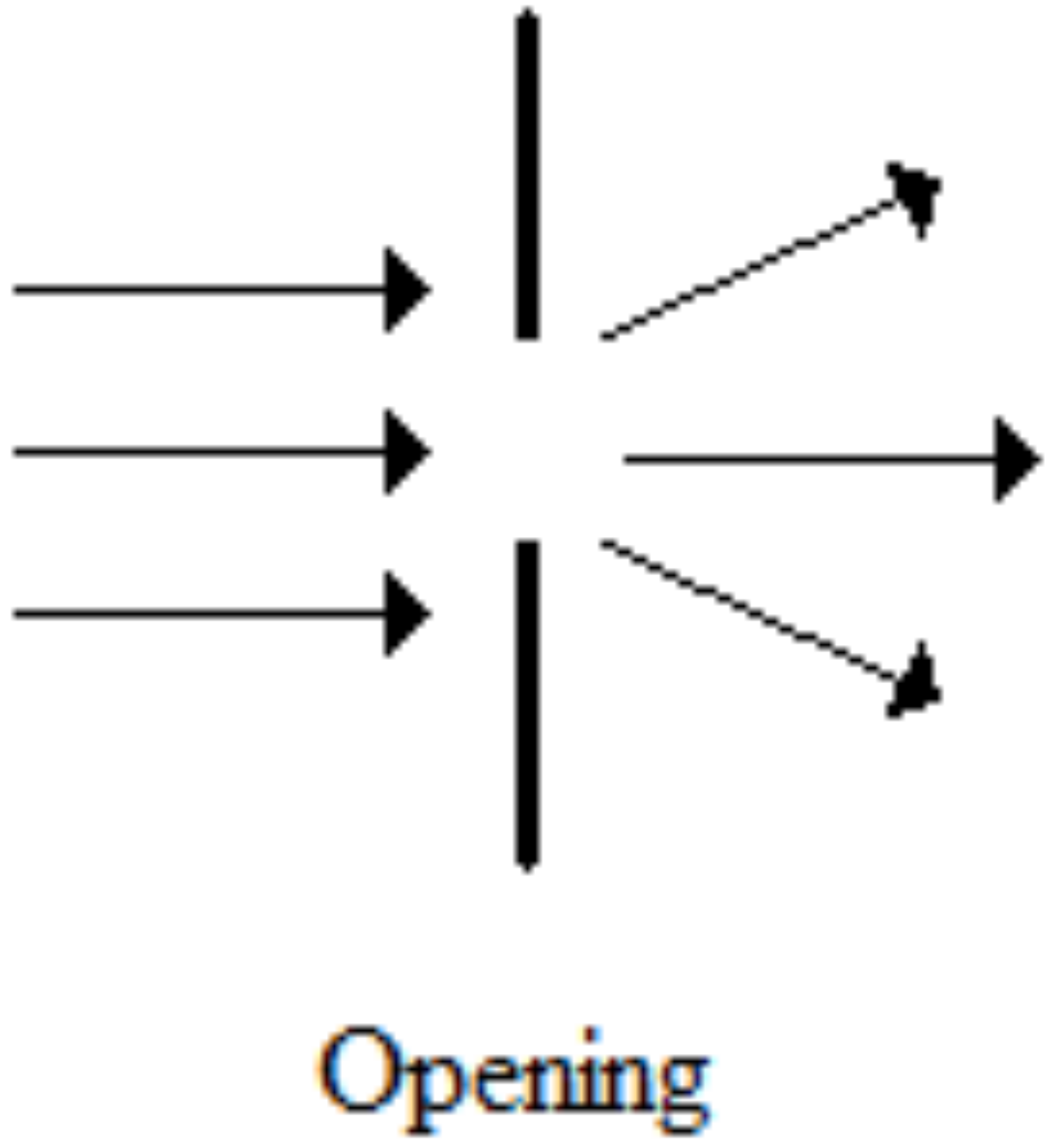
Temperature inversion

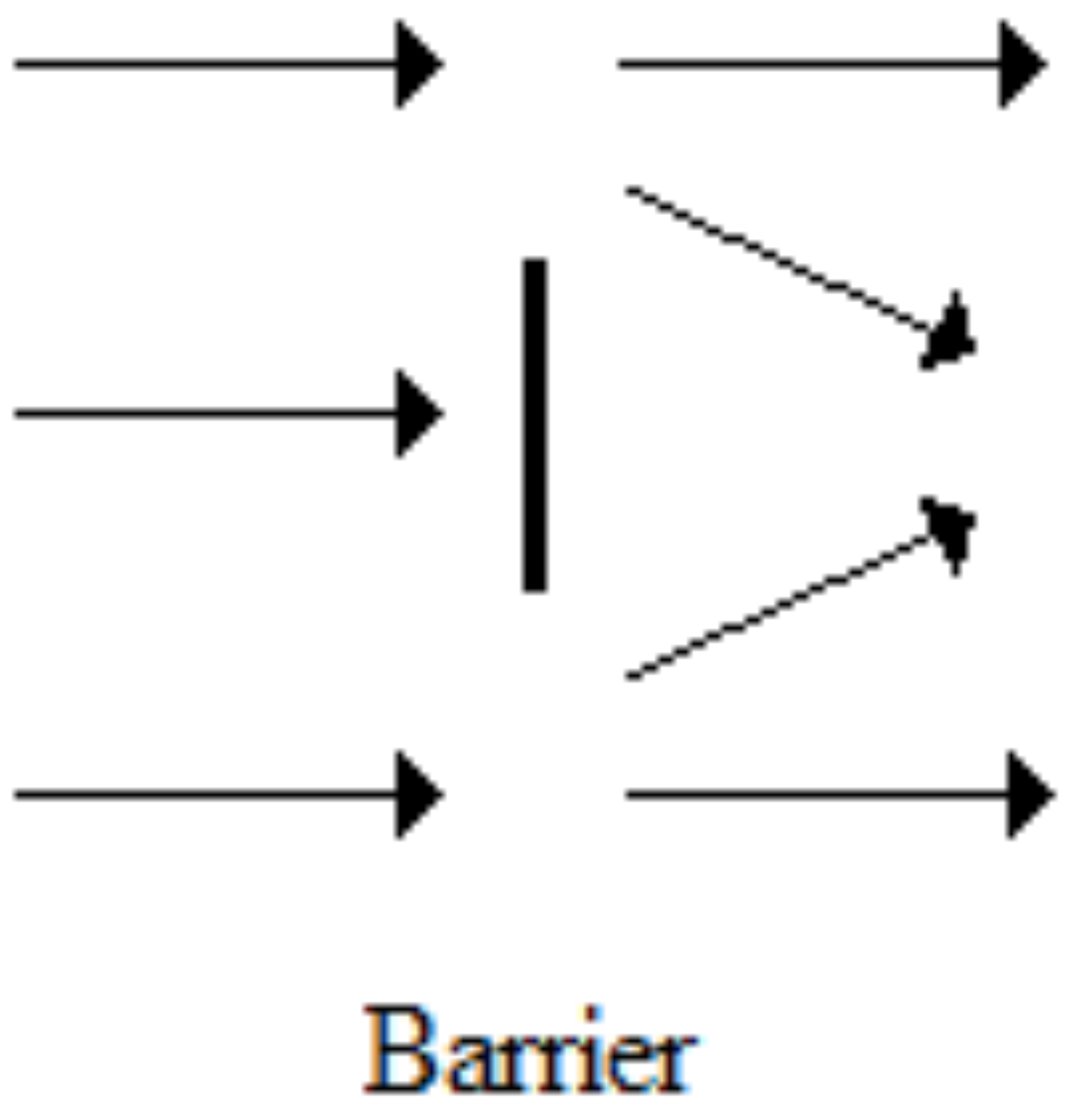
Understanding refraction

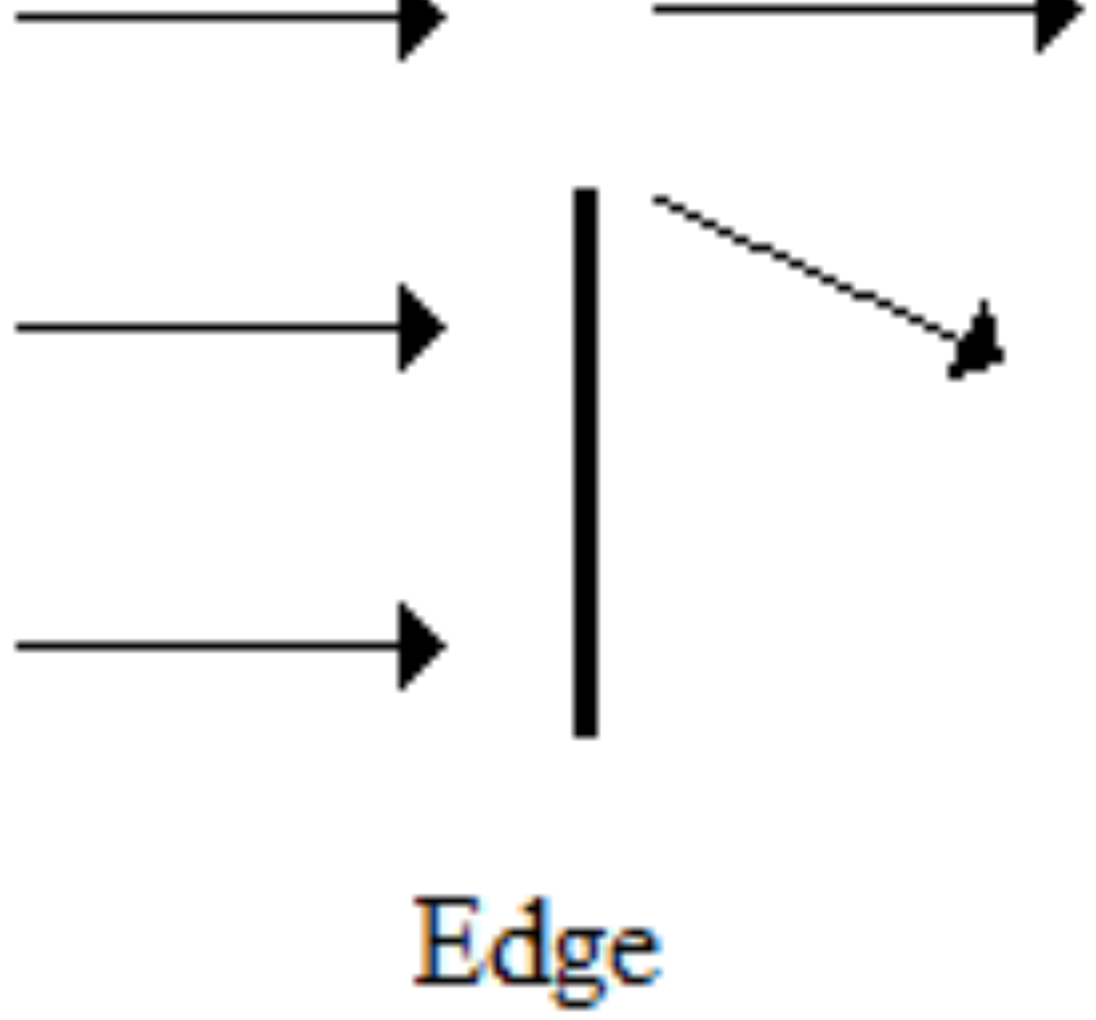


Diffraction

- **“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







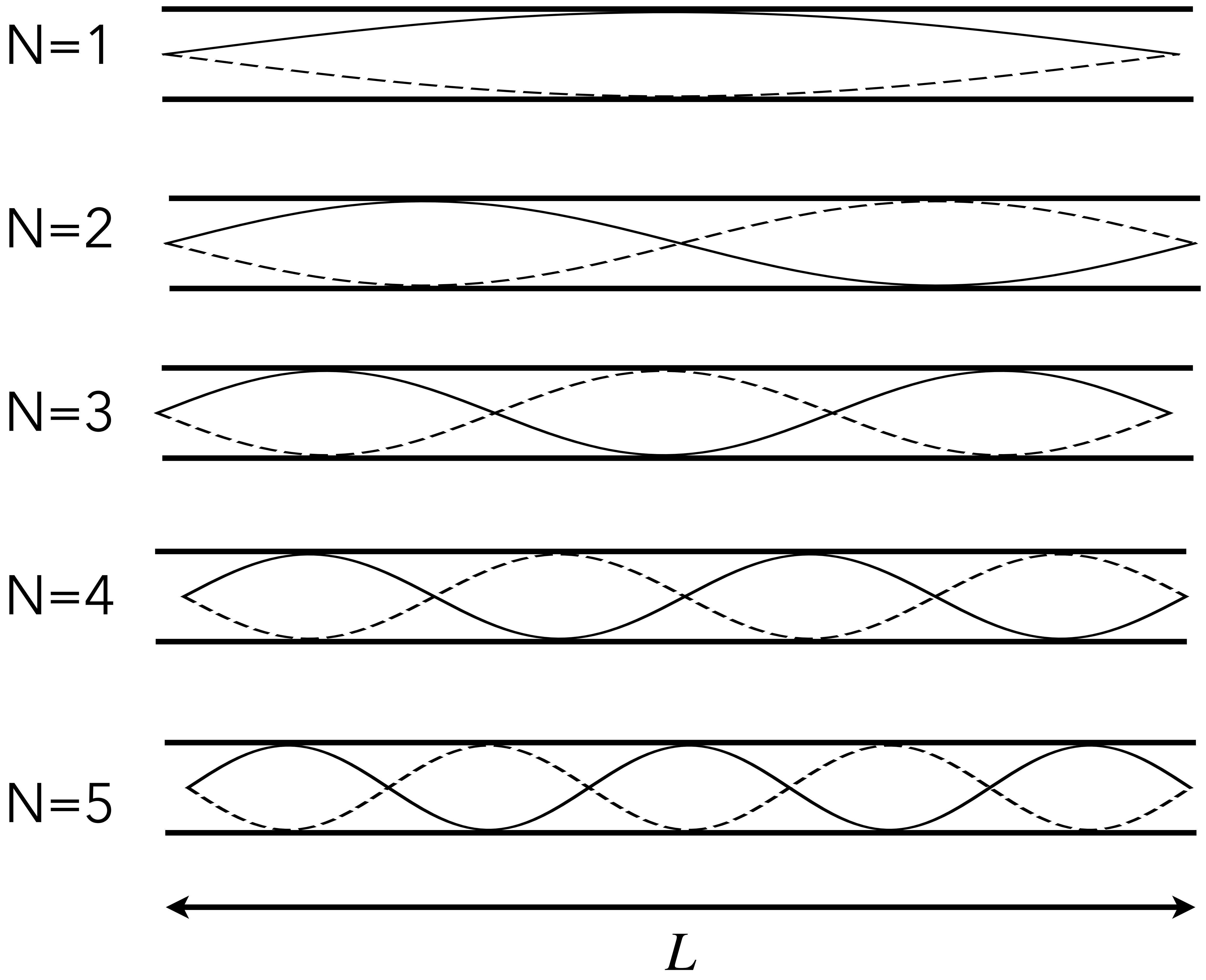
Doppler effect

- **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

Standing waves in a tube

(only odd harmonics!!)

open at both ends



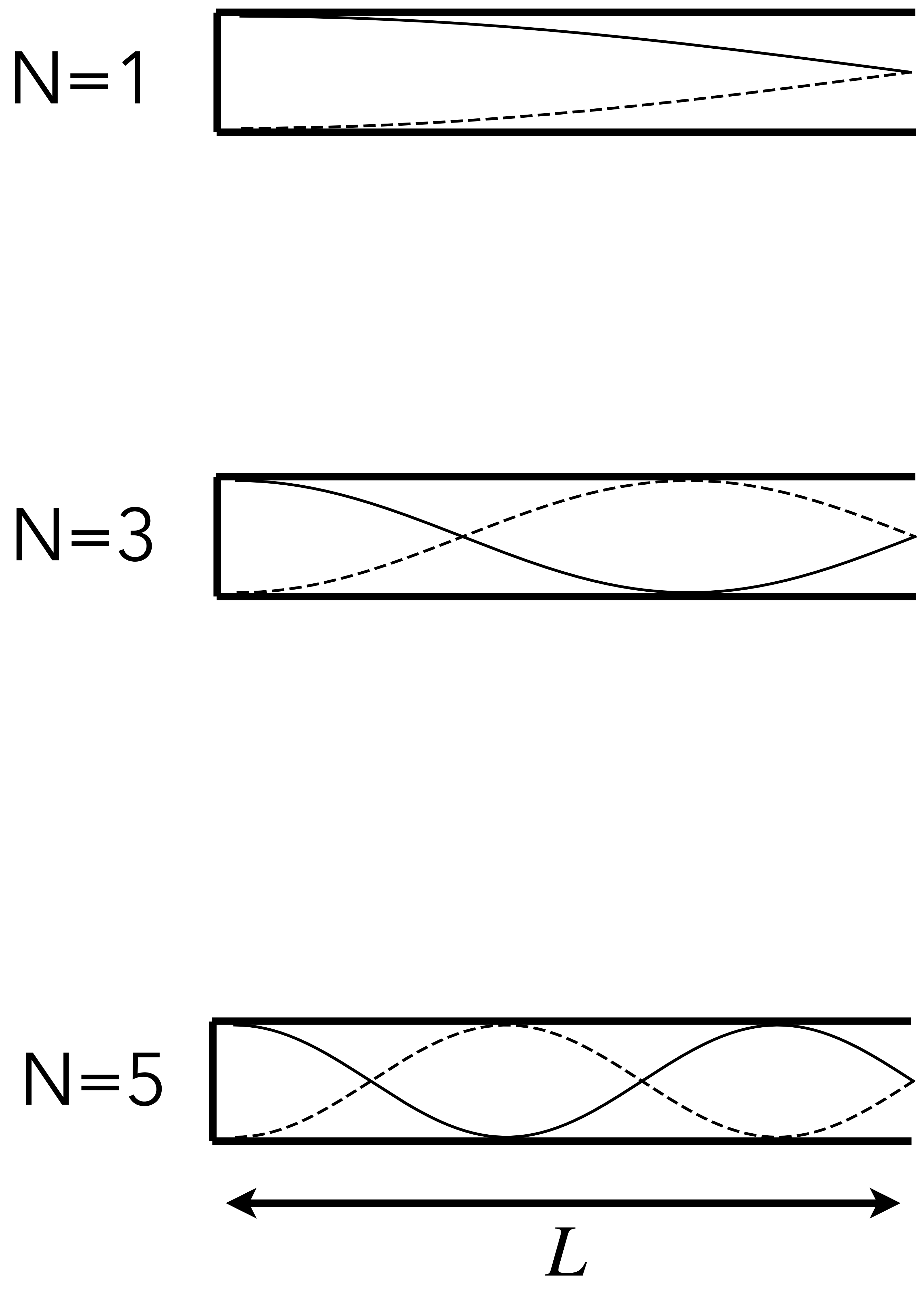
$$\lambda_N = \frac{2L}{N}$$

$$f_N = Nf_1$$

$$f_1 = \frac{v}{2L}$$

$$N = 1,2,\cdots$$

closed at one end



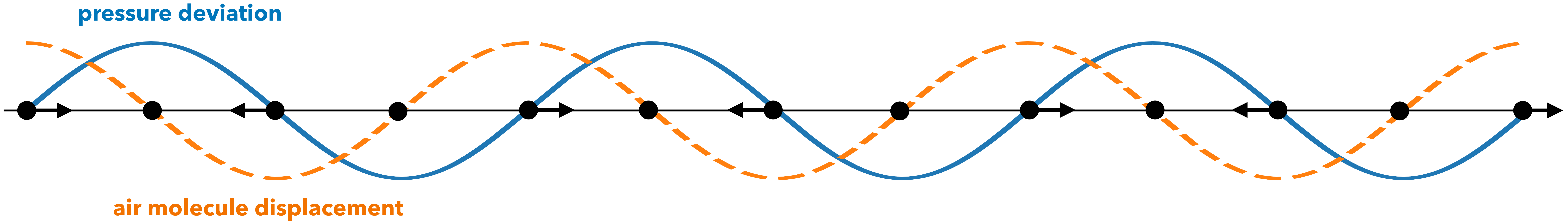
$$\lambda_N = \frac{4L}{N}$$

$$f_N = Nf_1$$

$$f_1 = \frac{v}{4L}$$

$$N = 1,3,5,\cdots$$

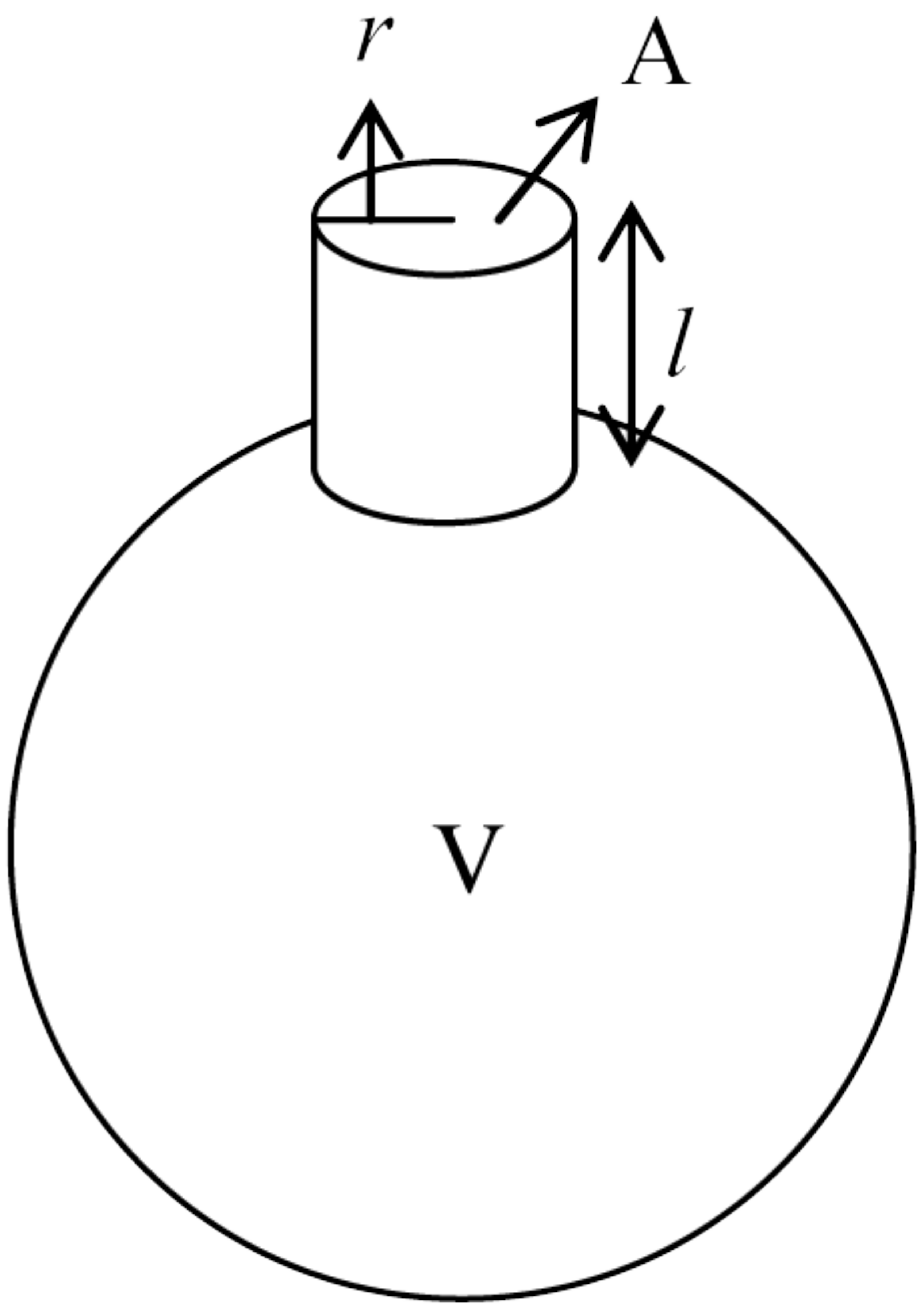
Air molecule displacement vs pressure deviation



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

Helmholtz resonator



$$f = \frac{v}{2\pi}\sqrt{\frac{A}{l_{\text{eff}}V}}$$

- Example:

$$r = 1 \text{ cm}\,,\; l = 2.7 \text{ cm}\,, V = 425 \text{ mL}\,, v = 346 \text{ m/s}$$

$$A = \pi r^2\,,\; 1 \text{ mL} = 10^{-6} \text{ m}^3 \quad \Rightarrow \quad f = 239 \text{ Hz}$$