

PHYS1406: Physics of Sound and Music

Spring 2021

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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

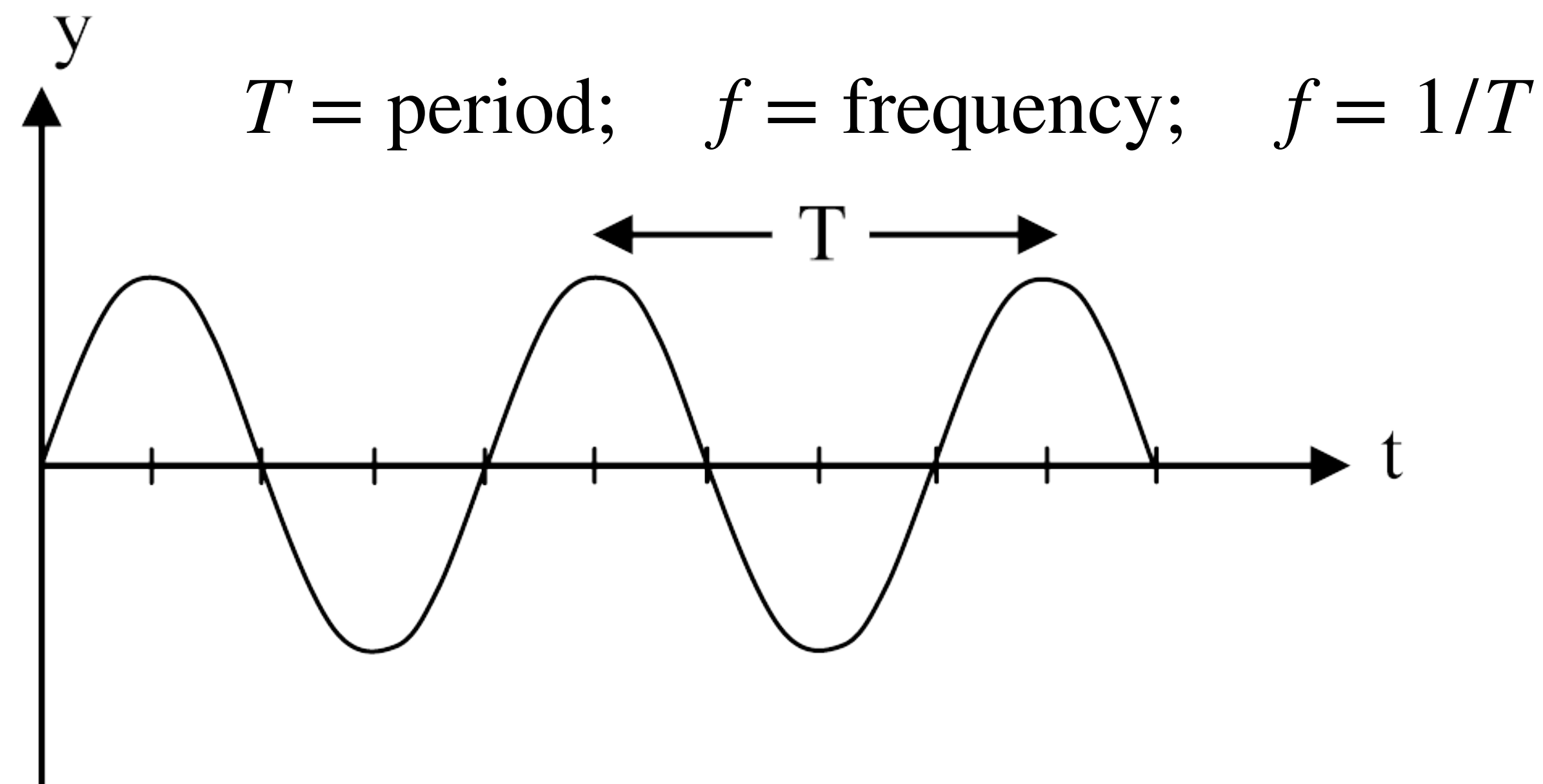
Demos: sound measuring devices & musical instruments

- 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: $2^4 = 2 \times 2 \times 2 \times 2 = 16$; $10^3 = 100$; $10^{-2} = 1/10^2 = 0.01$

- Prefixes:

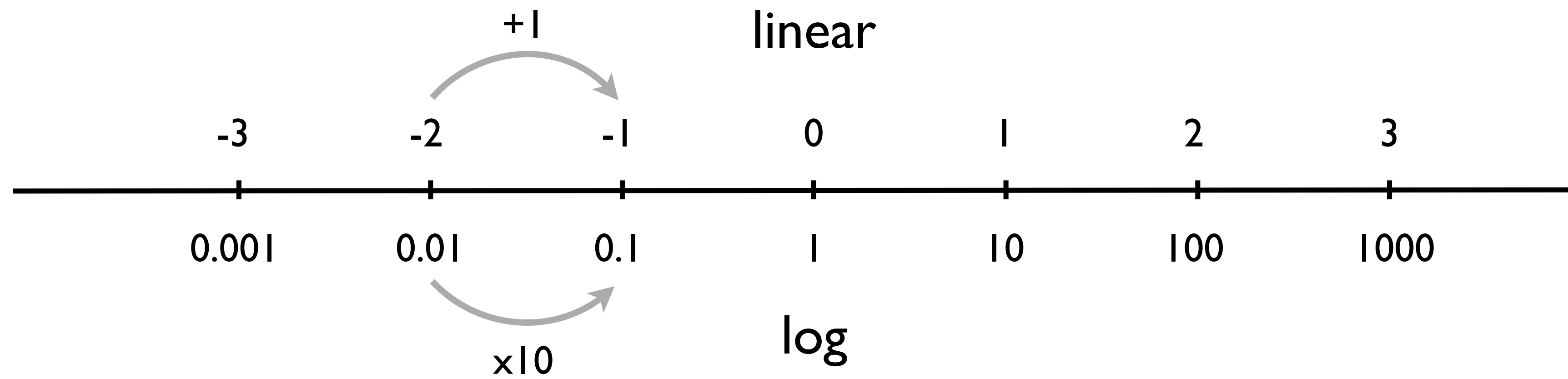
nano	micro	milli	centi	kilo	mega	giga	tera
10^{-9}	10^{-6}	10^{-3}	10^{-2}	10^3	10^6	10^9	10^{12}

- 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

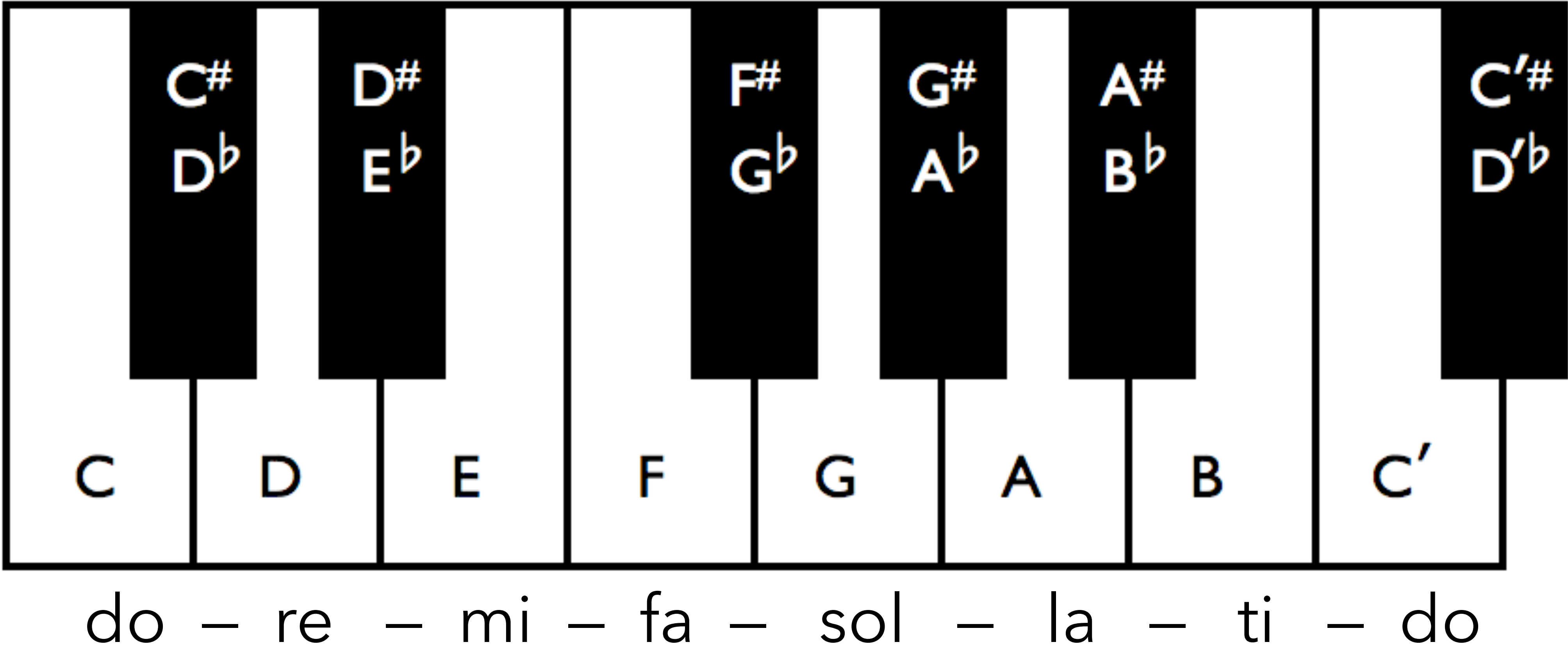


Music terminology

- 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 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/s², 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/m² or lb/in² = psi; 1 atm = 10⁵ N/m² = 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.

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

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

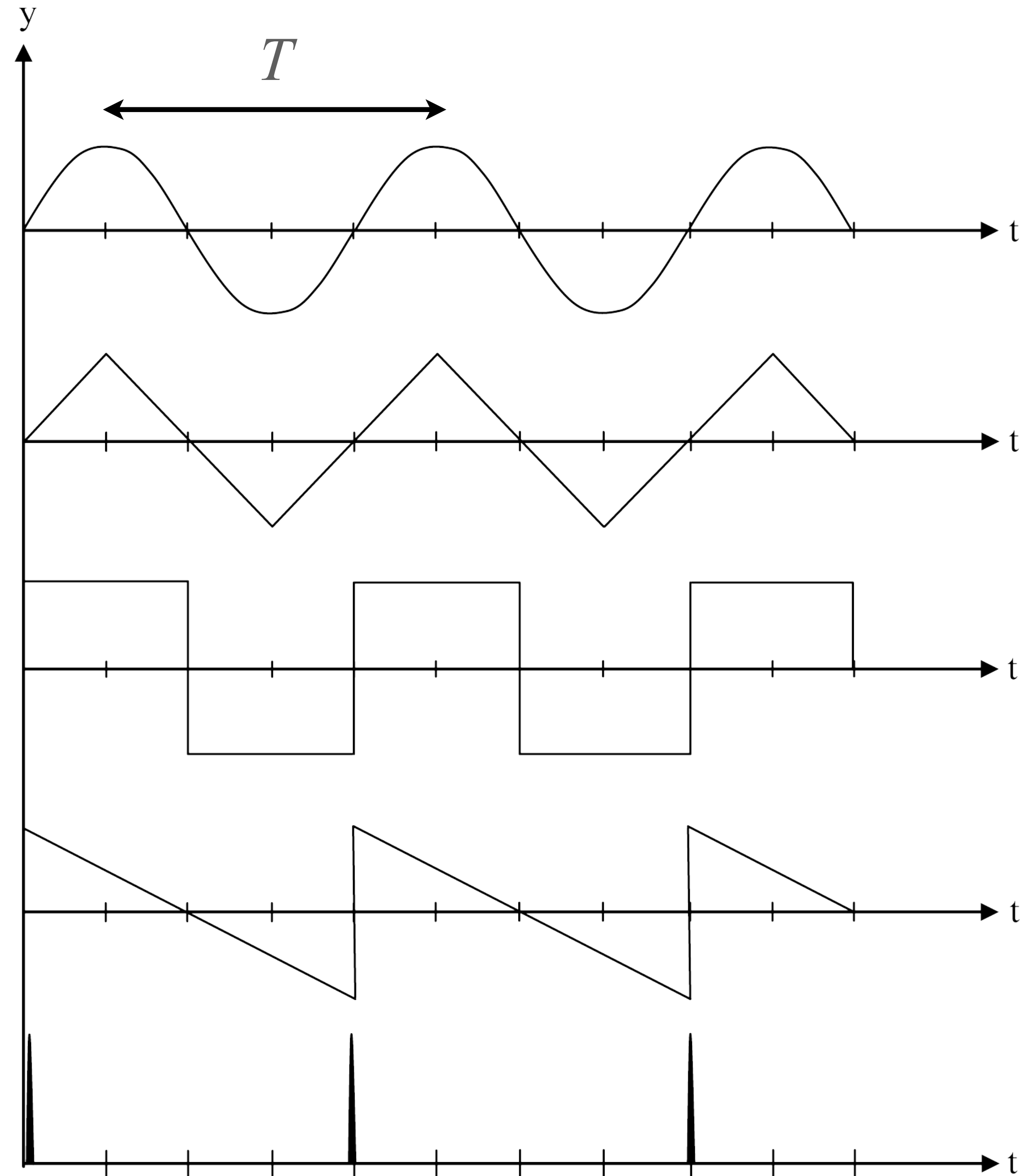
2. Oscillations

Periodic motion

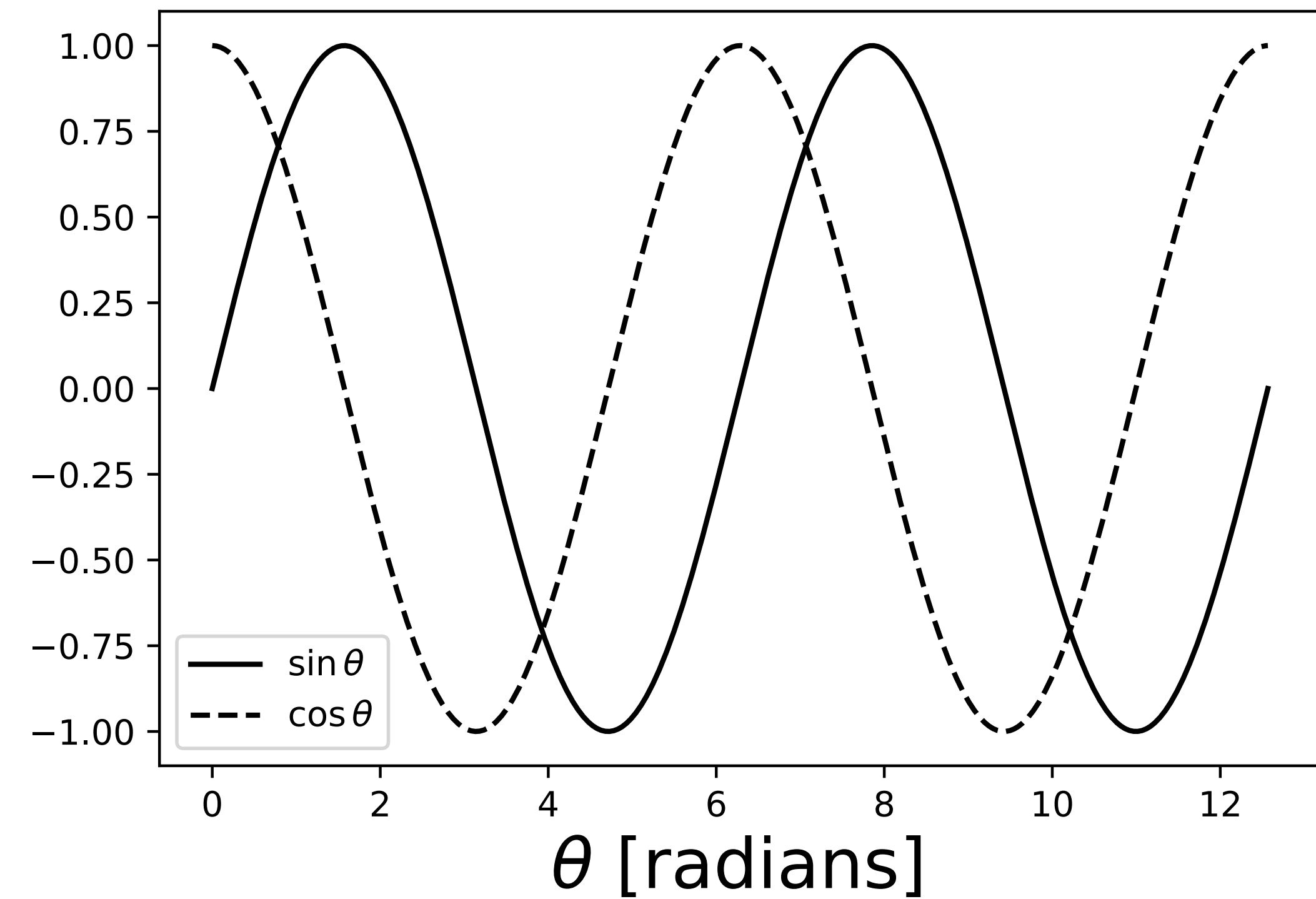
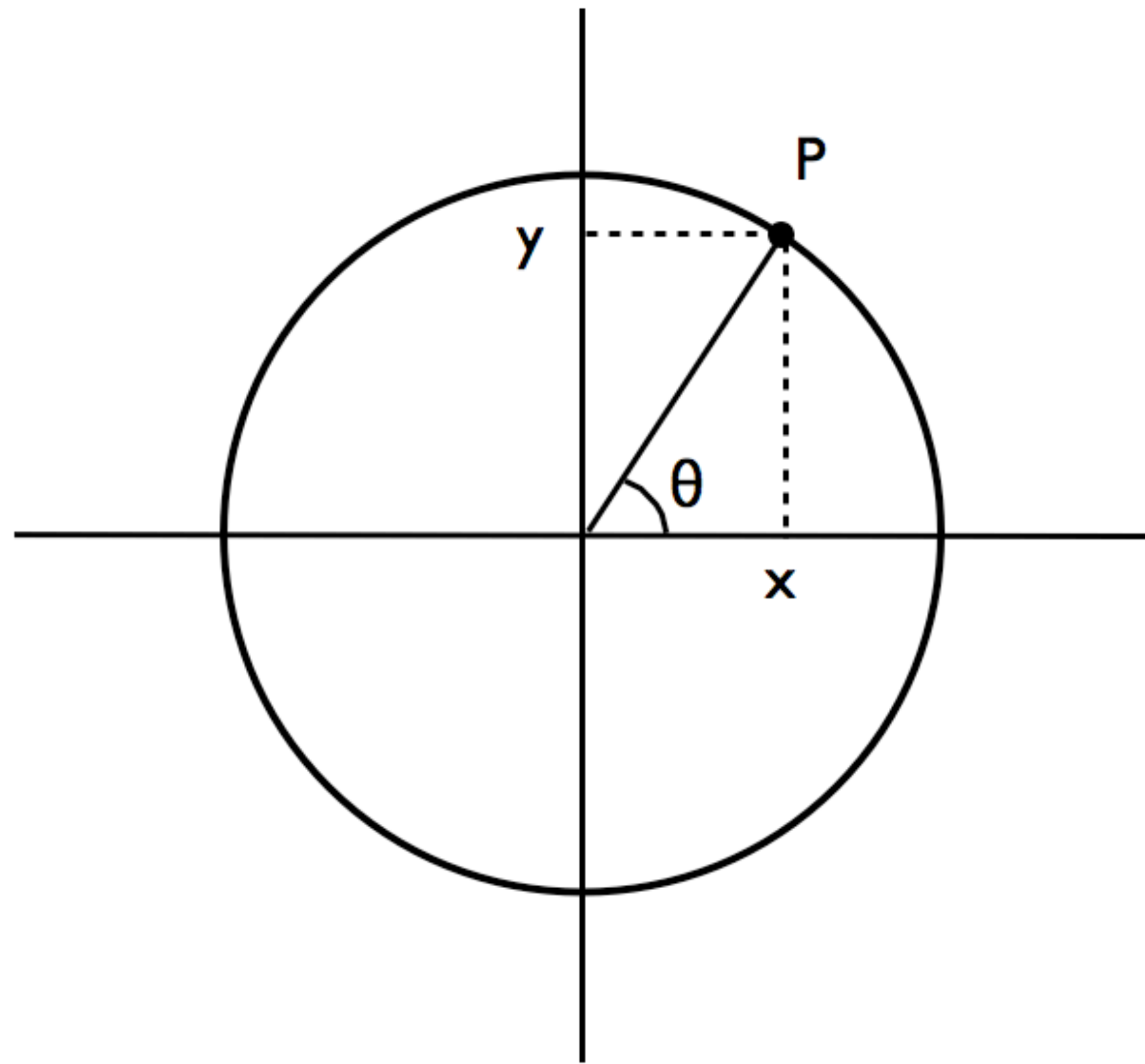
- Oscillation: any motion that repeats
- Examples: vibrating guitar string; vibrating reed of a bassoon; swinging pendulum bob; mass on a spring; yearly orbital motion of Earth around the Sun; beating heart; ...
- Period (T), frequency (f): period is the time for one complete oscillation; frequency is 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:** $f = 20$ 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)

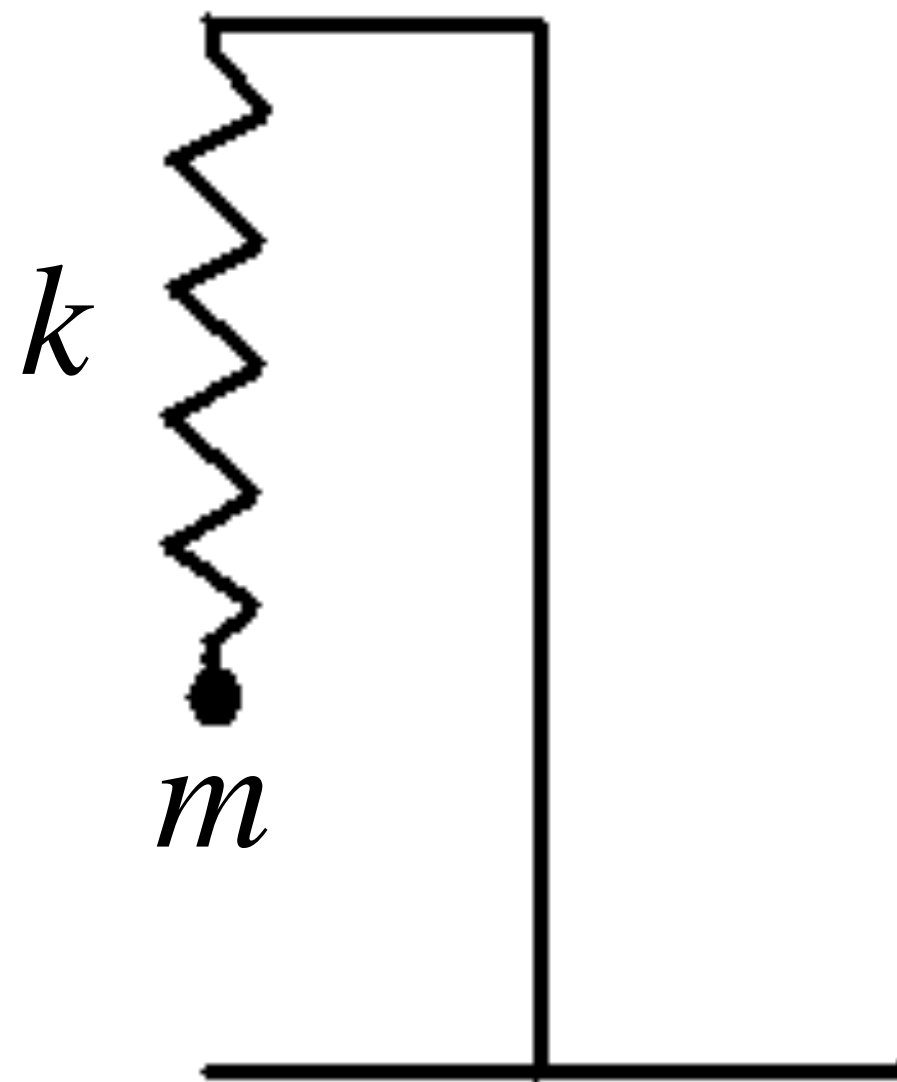


Examples of SHM

- SHM is 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.)

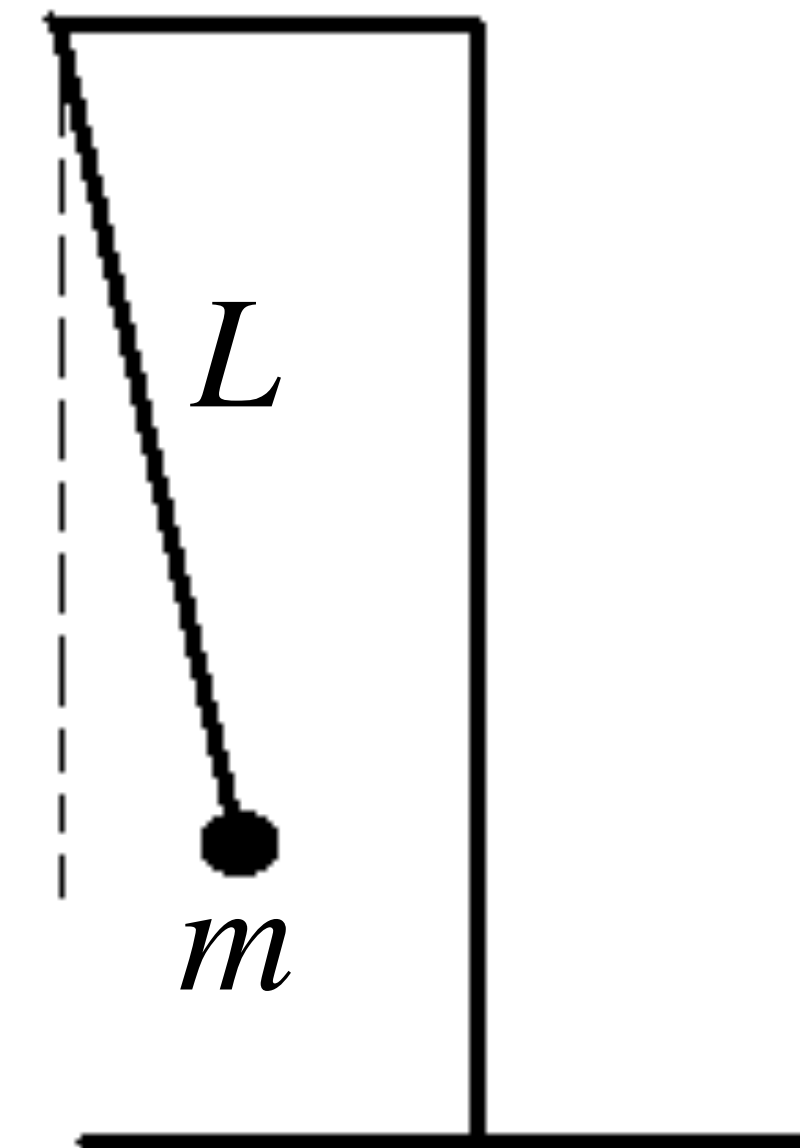
- **Mass on a spring**

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



- **Swinging pendulum bob**

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



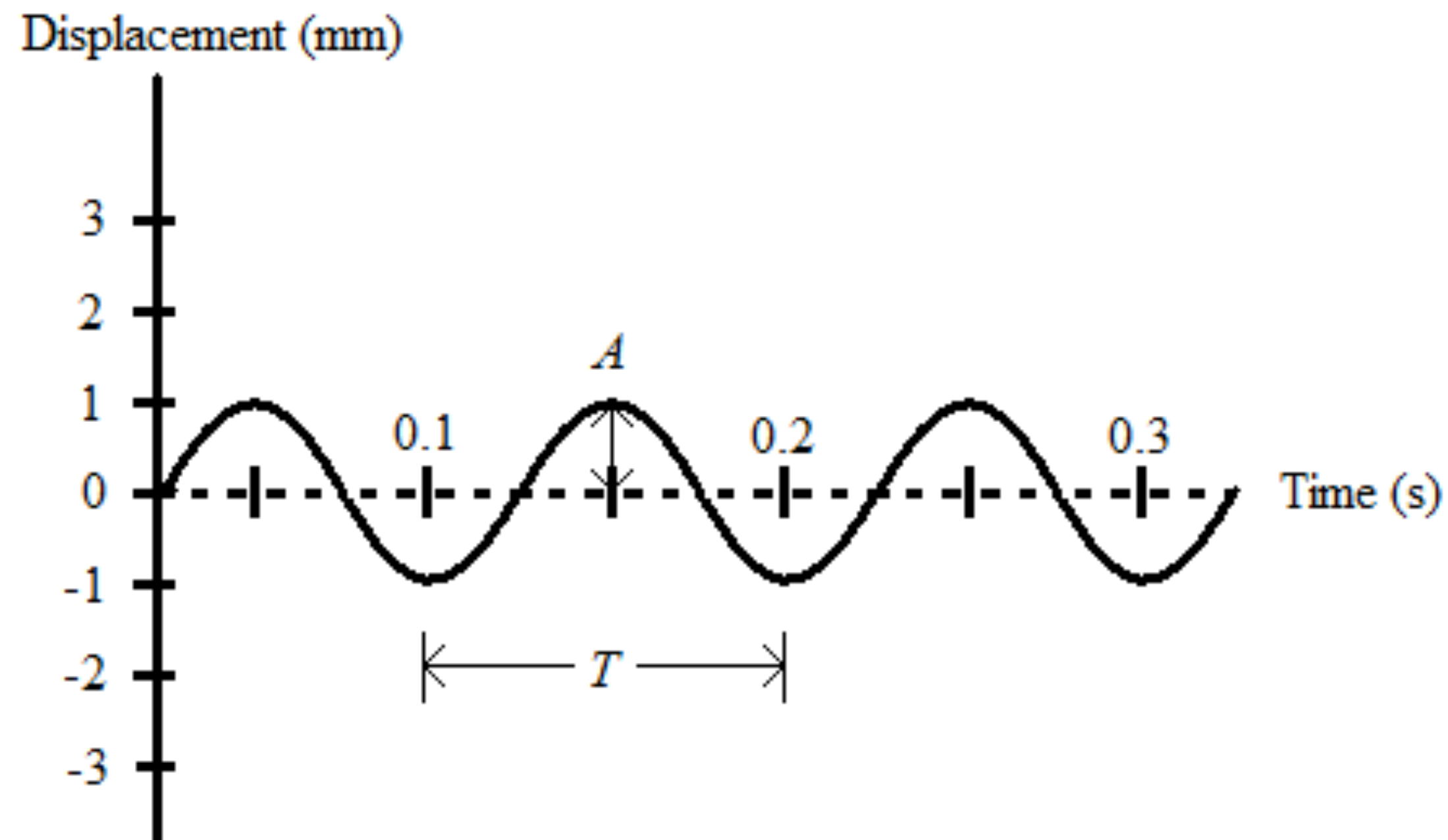
Damping and resonance

- Demo with swinging pendulum

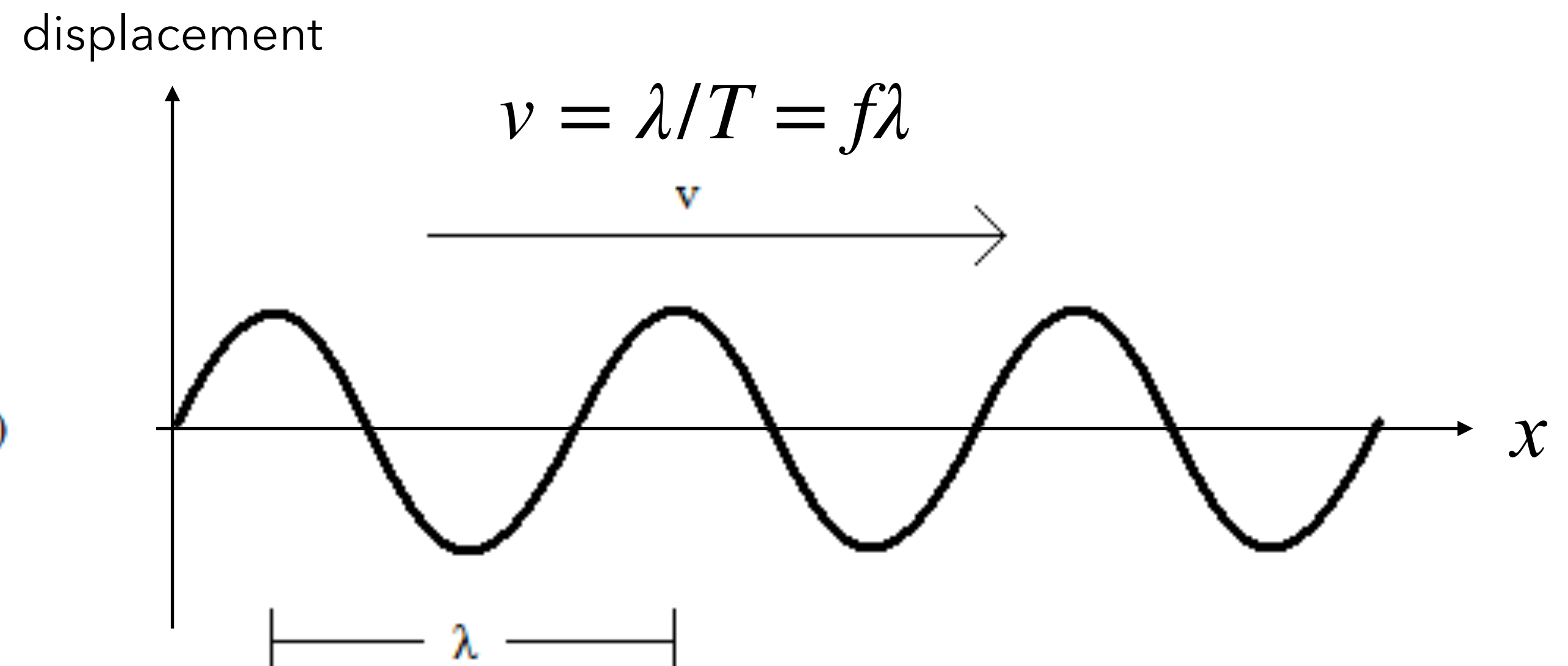
3. Waves & sound

Wave motion, wave velocity

- Wave: a “disturbance” of a medium that transports energy from one location to another without the transport of matter
- Examples?
- Transverse vs longitudinal; wave pulse; periodic waves; wavelength; wave velocity; $v = 346 \text{ m/s}$ (speed of sound in air at room temp)



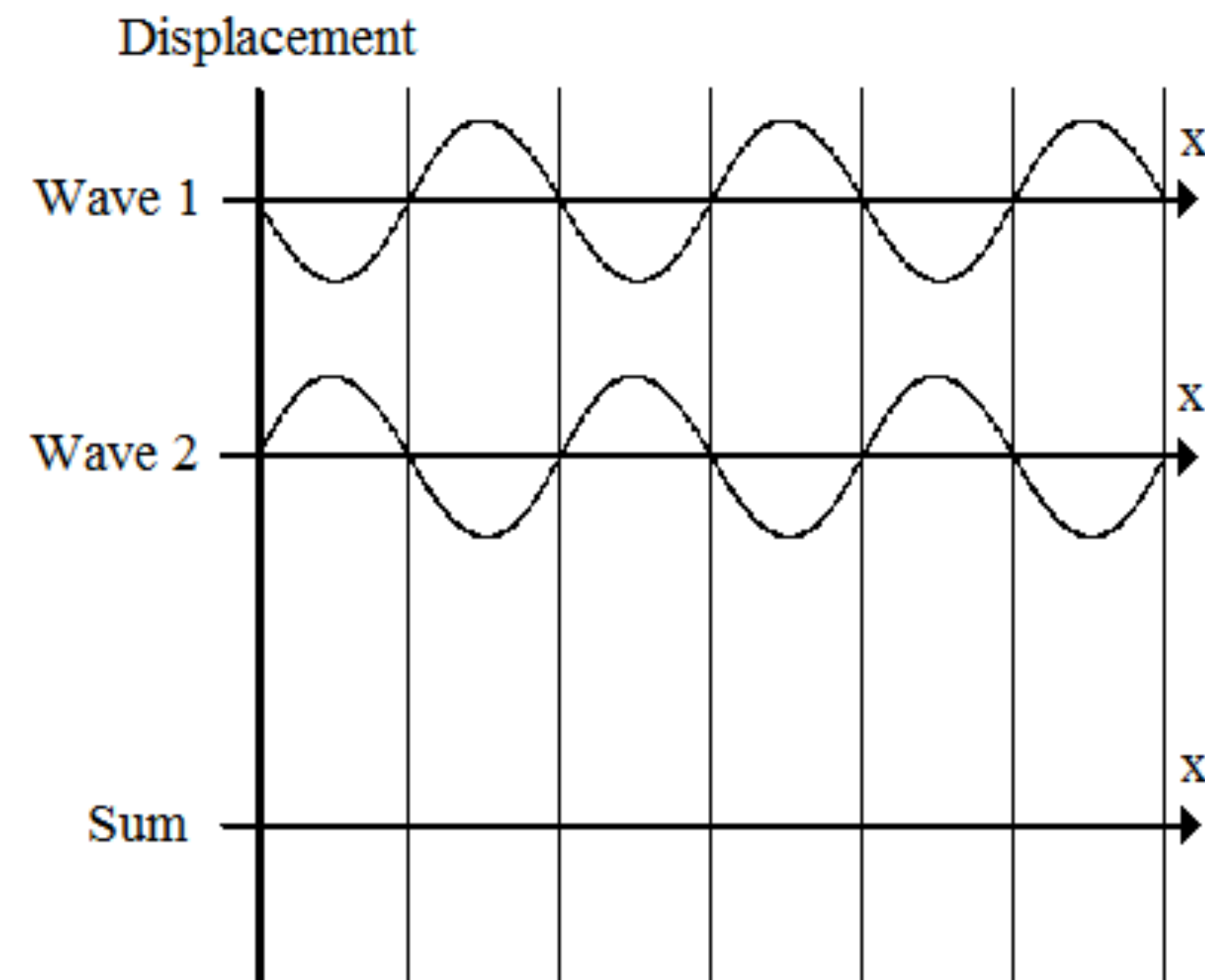
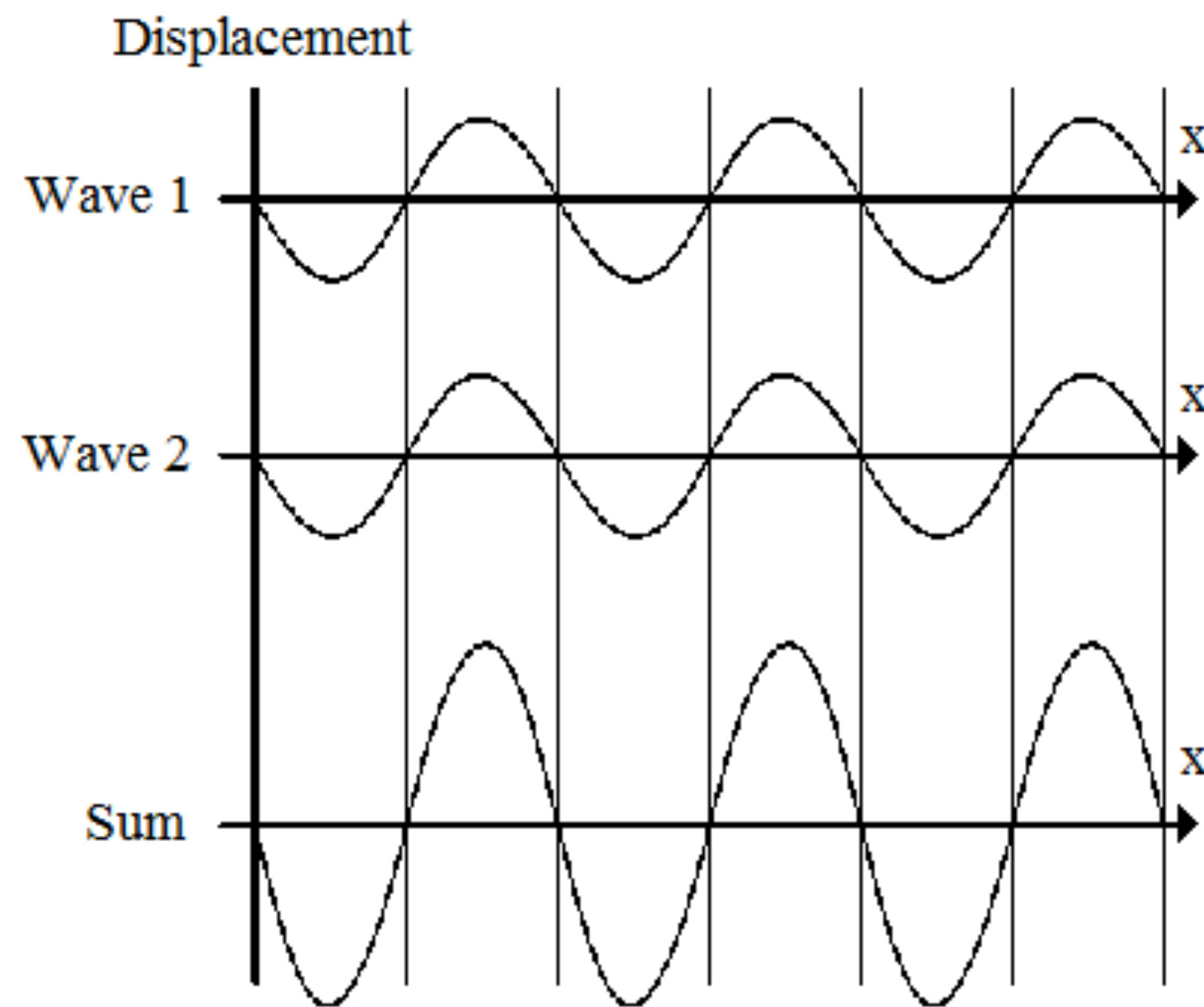
fixed location, showing how the displacement varies with time



“snap shot” at a fixed time, showing how the displacement varies with position

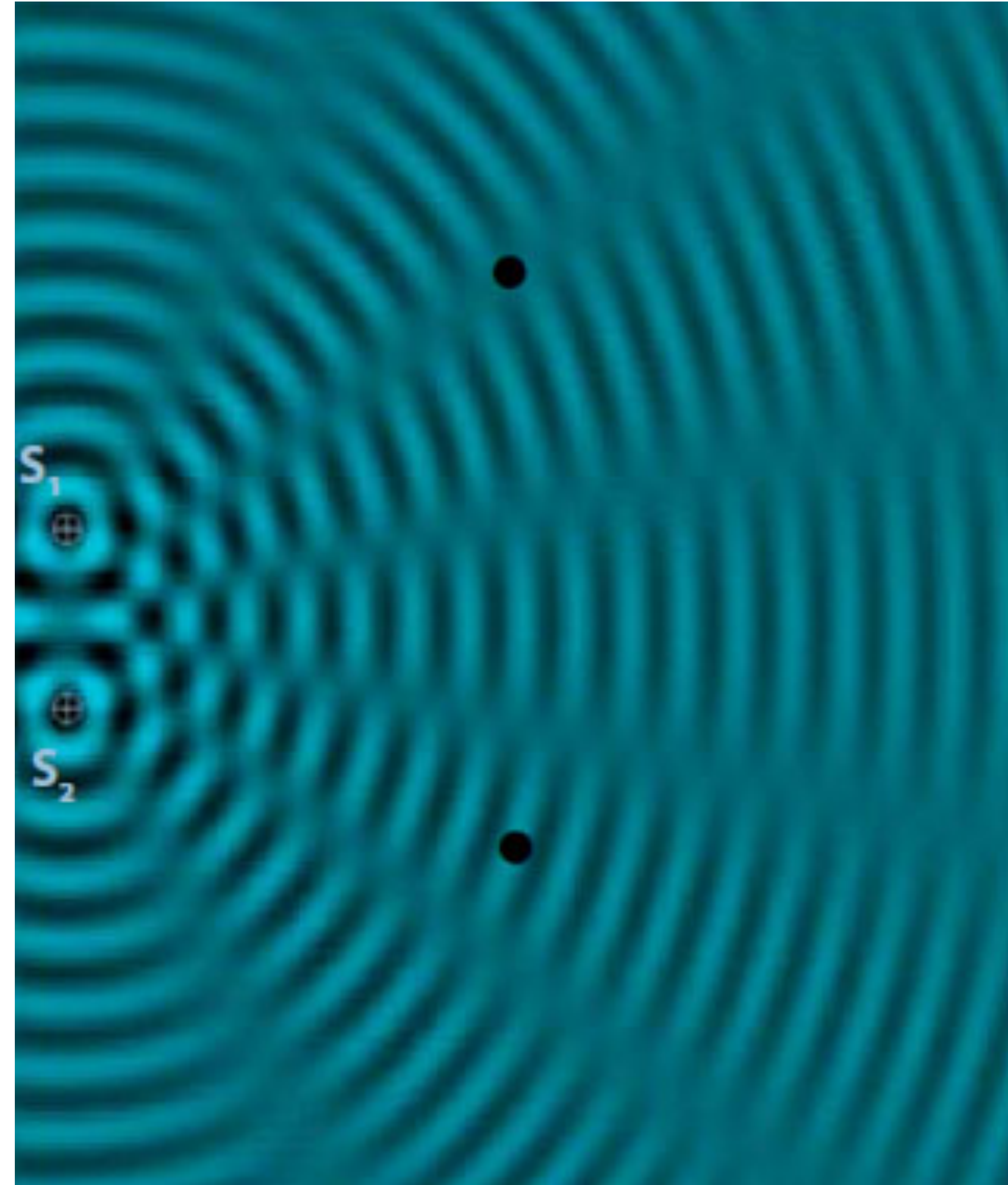
Superposition

- the combination of two waves is another wave; constructive & destructive interference (matlab demo)



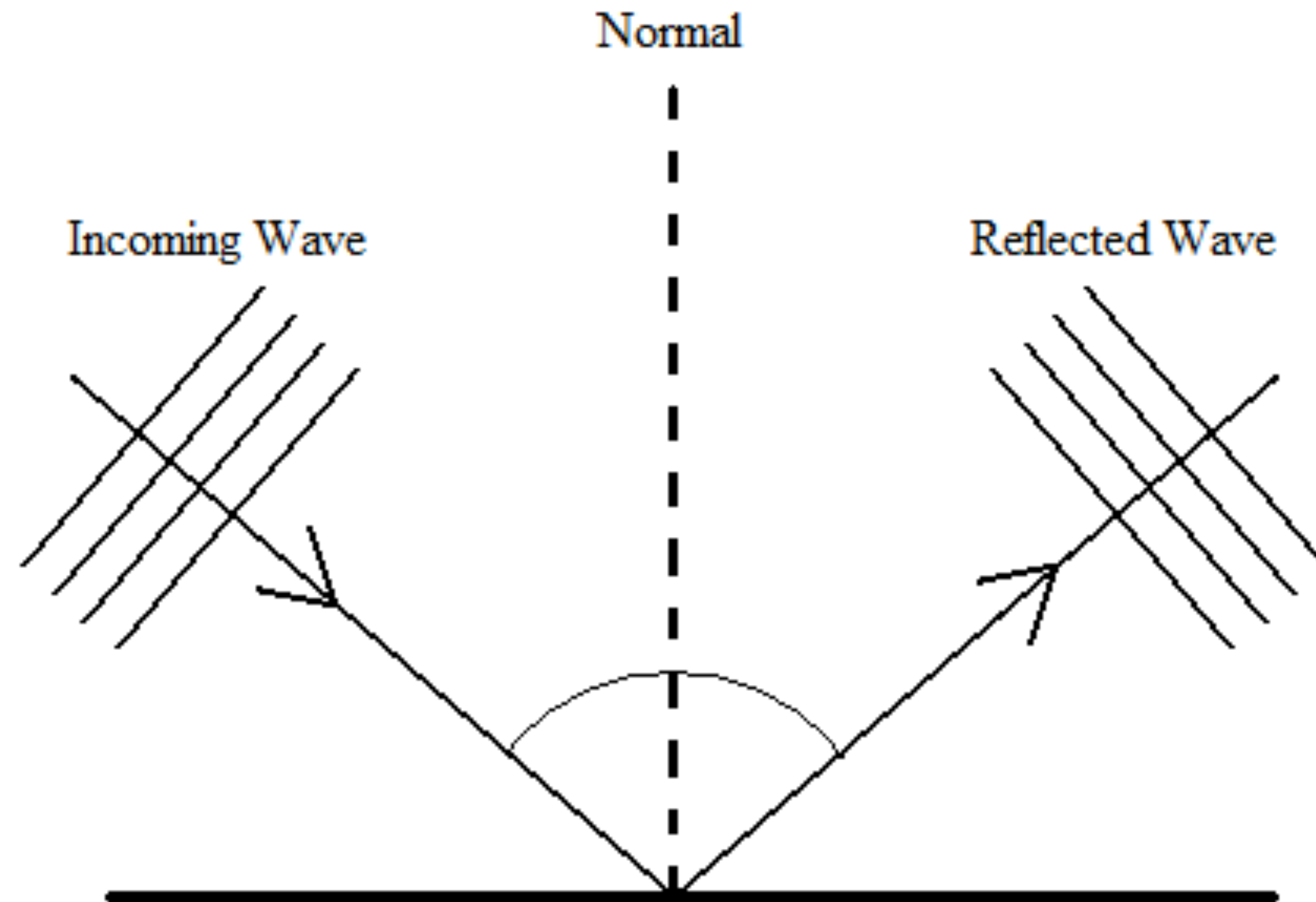
Interference

- Interference in space and time
- Beats (matlab demo, and using signal generators)

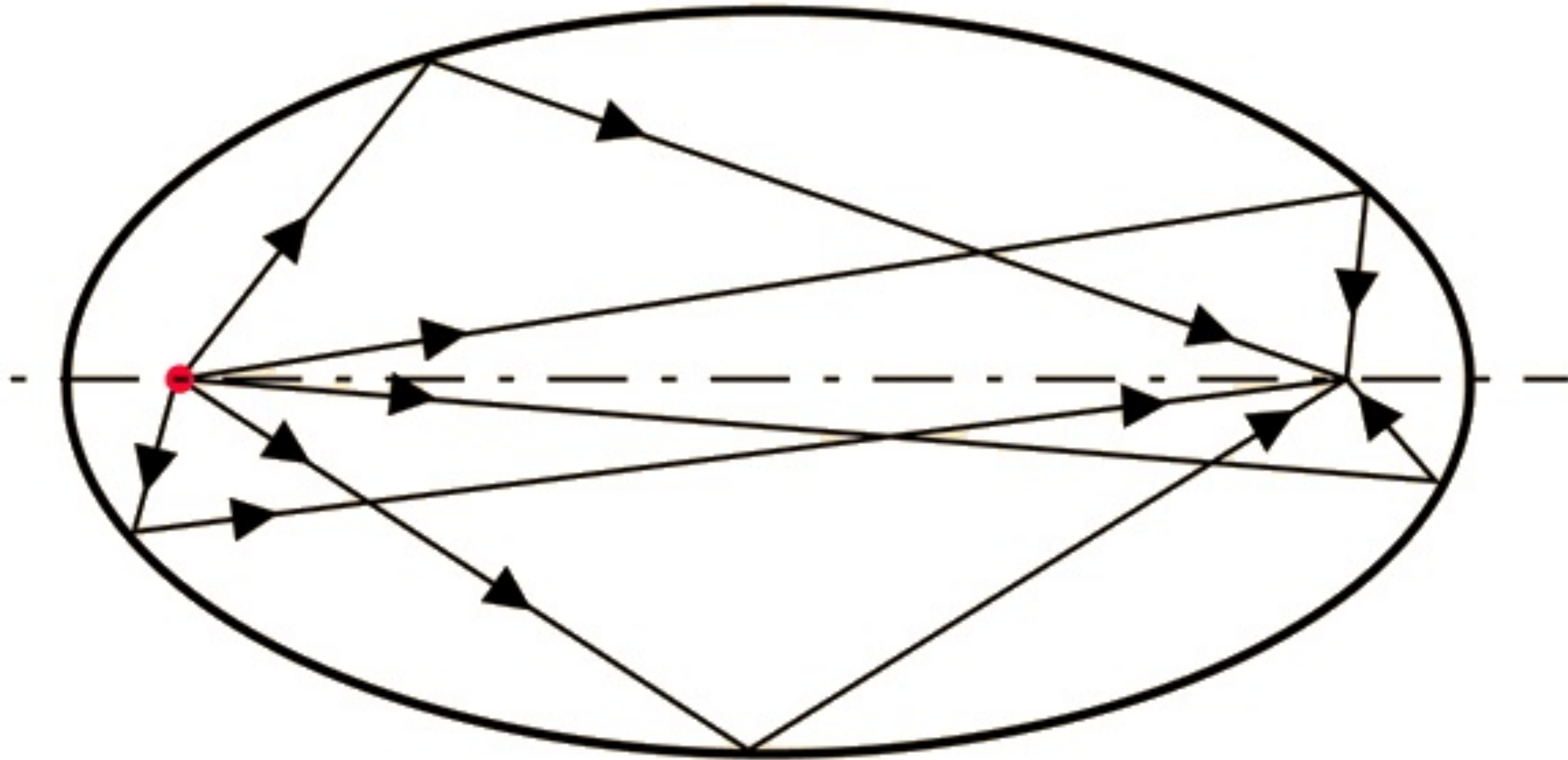


Reflection

- Demos with plane, concave, and convex mirrors

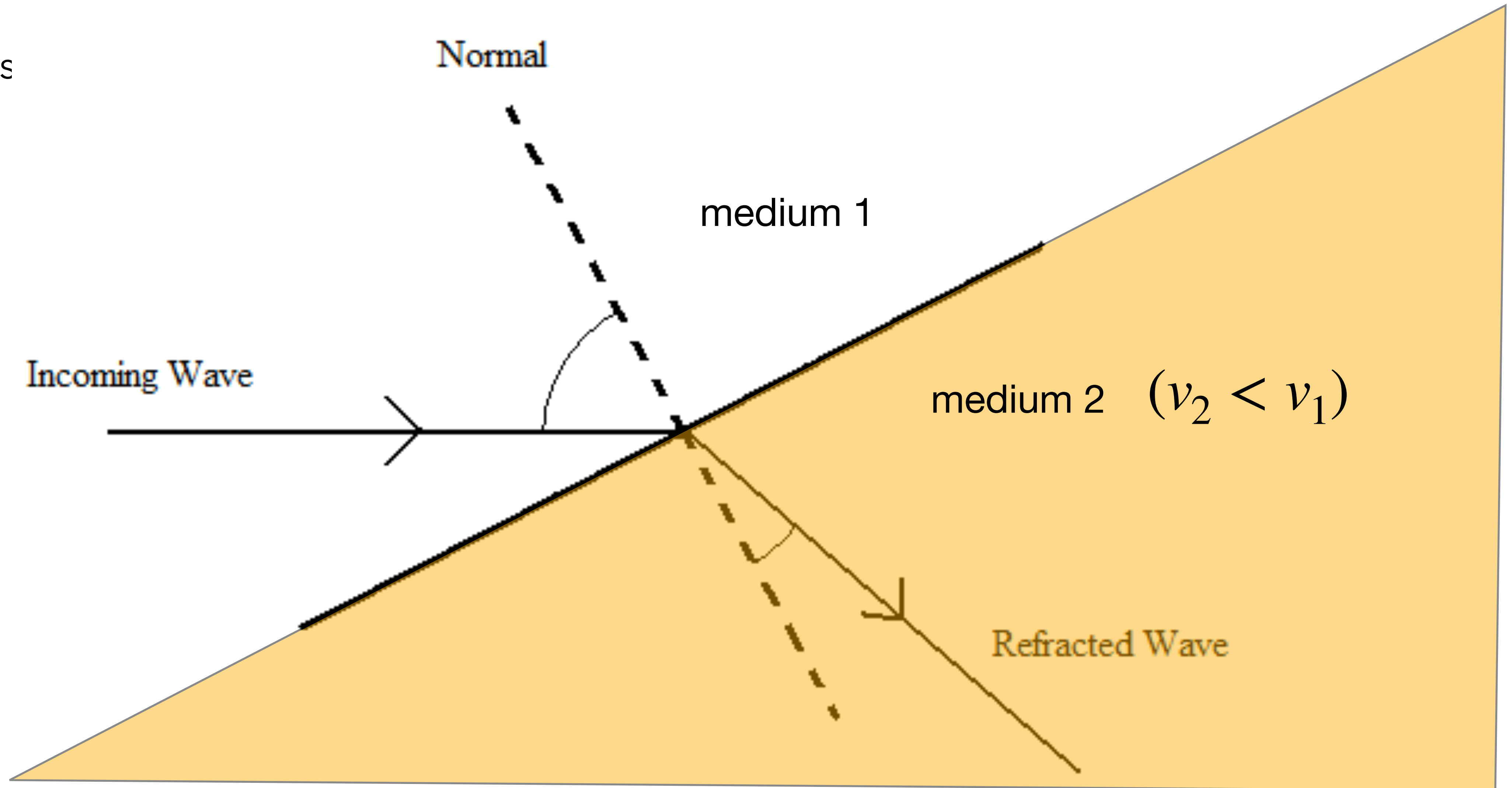


Reflections - whispering chamber



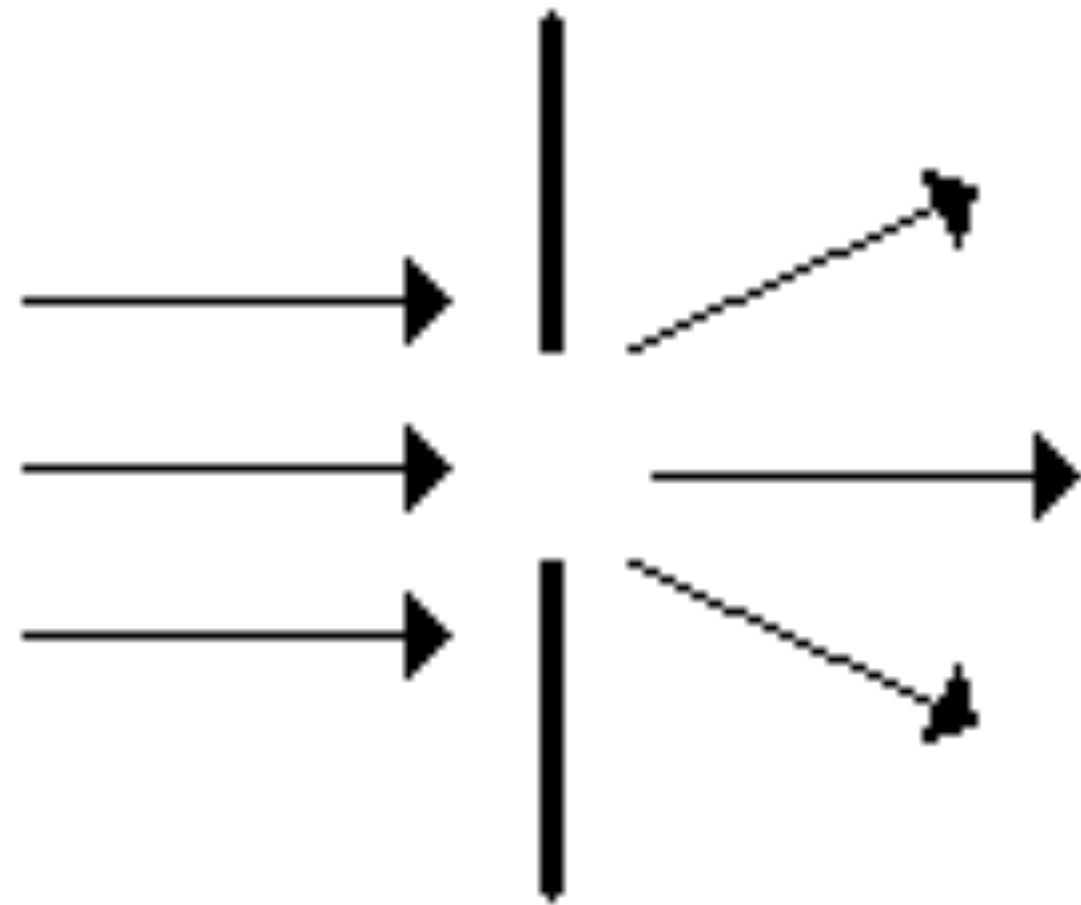
Refraction - change in direction of a wave due to change in velocity

- Demos

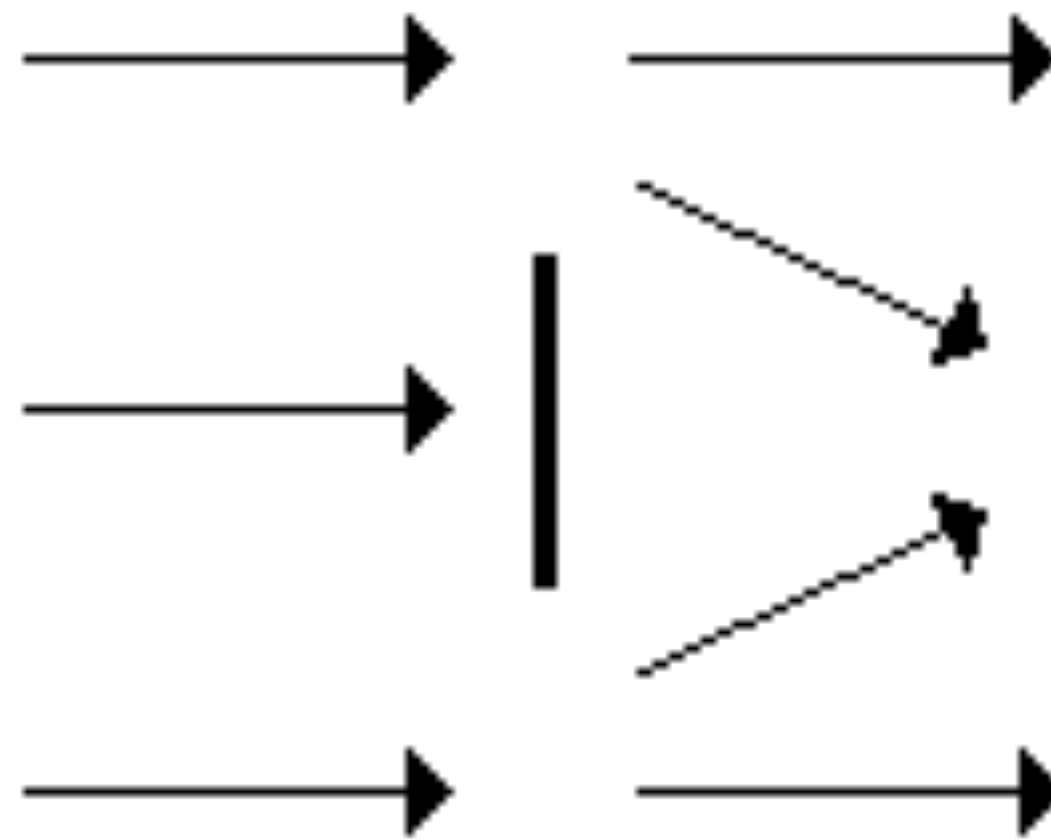


Diffraction – “spreading” of waves through openings, etc.

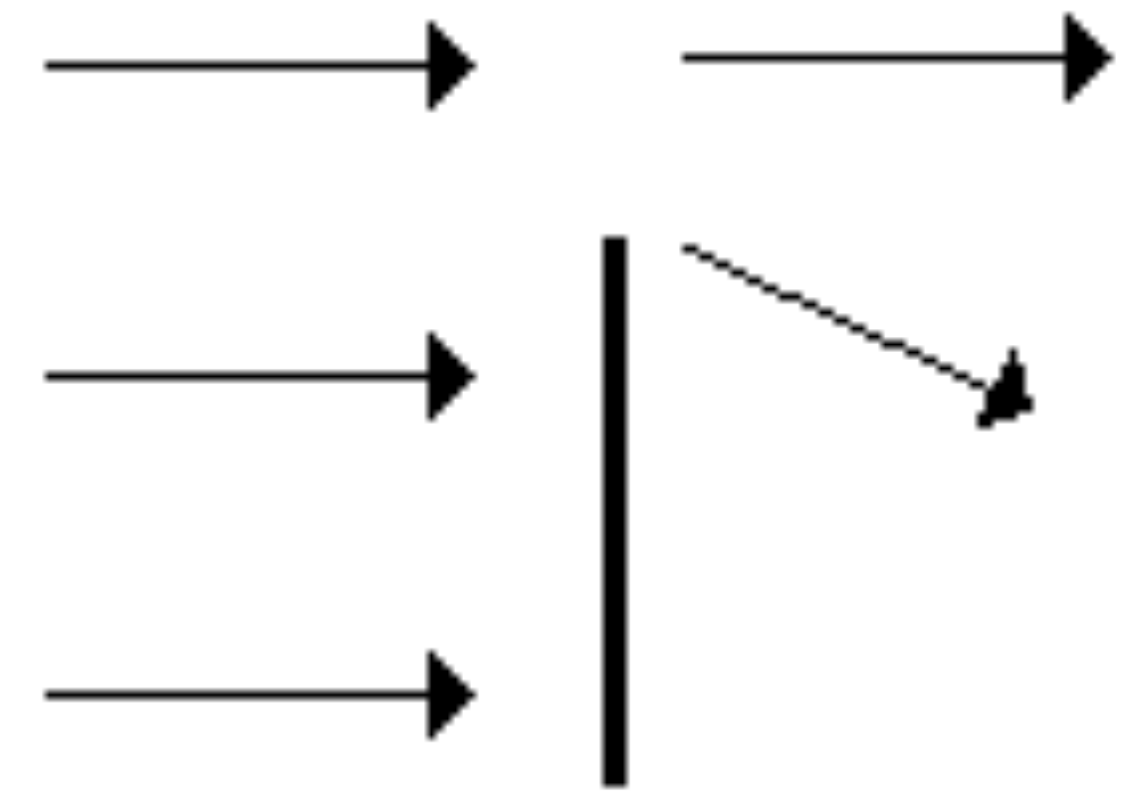
- amount of spreading depends on relative size of wavelength and opening, barrier, ...
- **Ques:** What is the wavelength of sound waves corresponding to the range of human hearing? Use $v = 346 \text{ m/s}$ for the speed of sound in air.



Opening



Barrier



Edge

Doppler effect

- Demo

Standing waves

- superposition of right-moving and left-moving waves on a string