PHYSICS 102N
Spring 2022

Week 6

Oscillations, Vibrations, Waves, Sound and Music

Oscillations

- Any process that repeats itself after fixed time period *T*
- Examples:
  - Pendulum, spring and weight, orbits, vibrations (musical instruments, loudspeakers, jackhammer, quartz crystal, atoms, molecules…)
- Characterized by **two** quantities:
  - Frequency: $f = 1/T$, unit Hertz (1 Hz = 1/sec)
  - Amplitude: Maximum excursion from resting/reference position
    - Depends on initial conditions (“push”)

Harmonic oscillator

- 2 ingredients:
  - Restoring force $\propto$ excursion
    - Elasticity -> mass and spring
    - Opposing forces out of balance -> pendulum
  - Inertia: Keep overshooting equilibrium
  - Excursion follows sinusoidal shape with time
- **Important**: Frequency is intrinsic property of system, independent of amplitude
- Amplitude is due to “initial condition”, not fundamental
- Examples
    - Pendula: Frequency depends only on length: $$f = \frac{1}{2\pi}\sqrt{g/l}$$
    - Mass on string: Frequency depends on mass and spring constant: $$f = \frac{1}{2\pi}\sqrt{k/m}$$

Resonance

- Harmonic oscillator has its own, intrinsic frequency (“eigen”frequency)
- If we try to wiggle at a different frequency, have to put more effort and get little result
- If we wiggle exactly at the right frequency, we get huge response - RESONANCE!
- Examples: Swings, glass (singing to break it!), bridges, pendulum clock, radio receiver…

Waves

- What happens if restoring force of harmonic oscillator is due to (elastic) connection with next neighbor?
  - Disturbance/excursion will be passed on to neighbor
  - This neighbor will pass it on to its neighbor…
  - …and so on: disturbance travels along medium!
- Important parameter: How fast does it travel? => Wave velocity v_{wave}!

Depends on elasticity, tension, mass density etc.

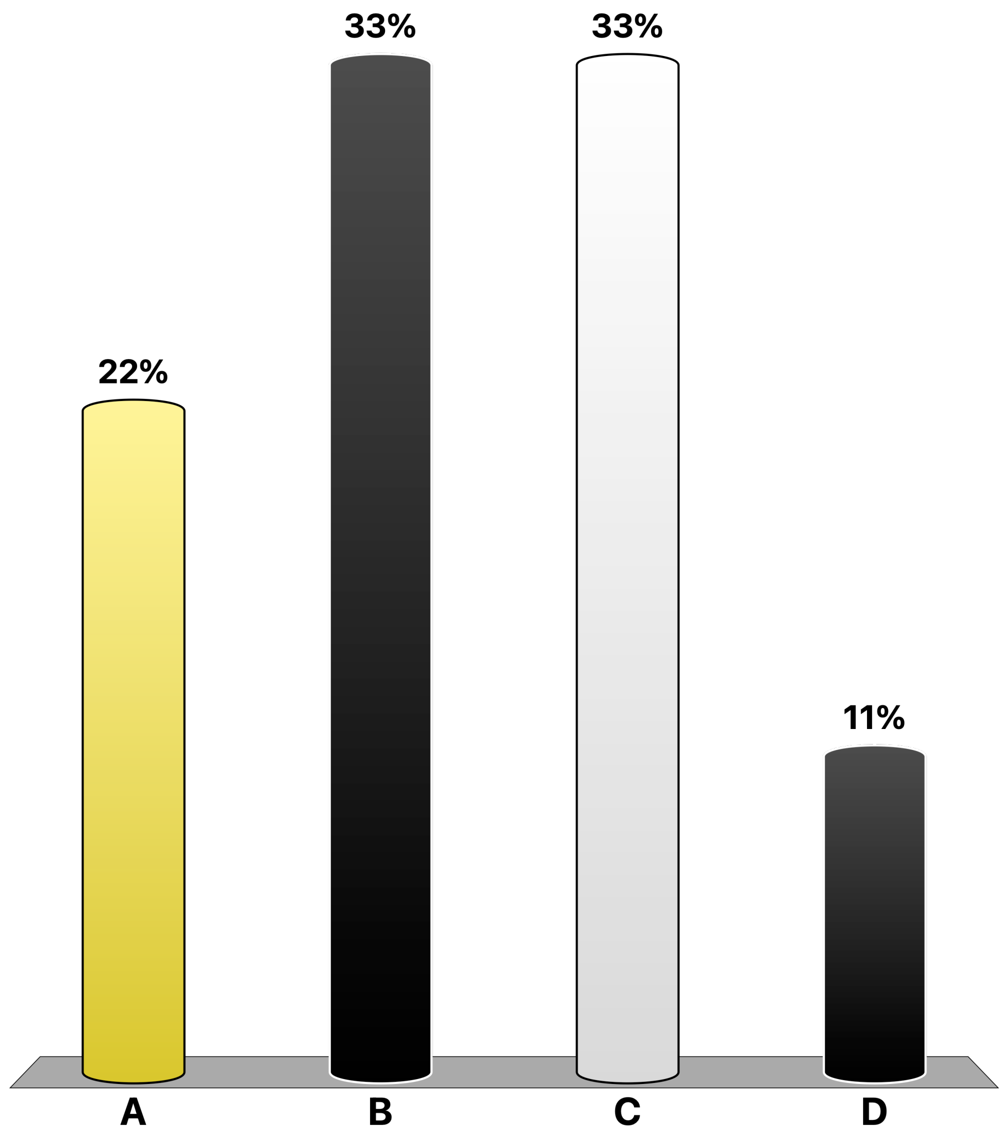
Examples: Water waves, string, slinky, sound, radio, light, “the wave” -> Transverse and longitudinal

Properties of Waves

- If we "shake" one point in harmonic oscillator pattern, each point further down the line will repeat same pattern - just a bit later: $\Delta t = \Delta x / v_{wave}$
- If we go far enough away, point at $\Delta x = \lambda$ will be in sync with point at origin Δx=0!
  - Really, a full period T of the oscillation behind
  - We call the distance between any 2 adjacent points in sync the wave length λ of the wave
  - Since it took time T for disturbance to travel distance λ, we have $v_{wave} = \lambda / T = \lambda f$! True for **all** kinds of waves!!
- Excursions can be perpendicular to wave motion (transverse) or along motion (longitudinal)

Q1 What happens if I increase the frequency of an oscillation?

A. The period increases.
B. The oscillator wiggles faster
C. The amplitude increases
D. None of the above



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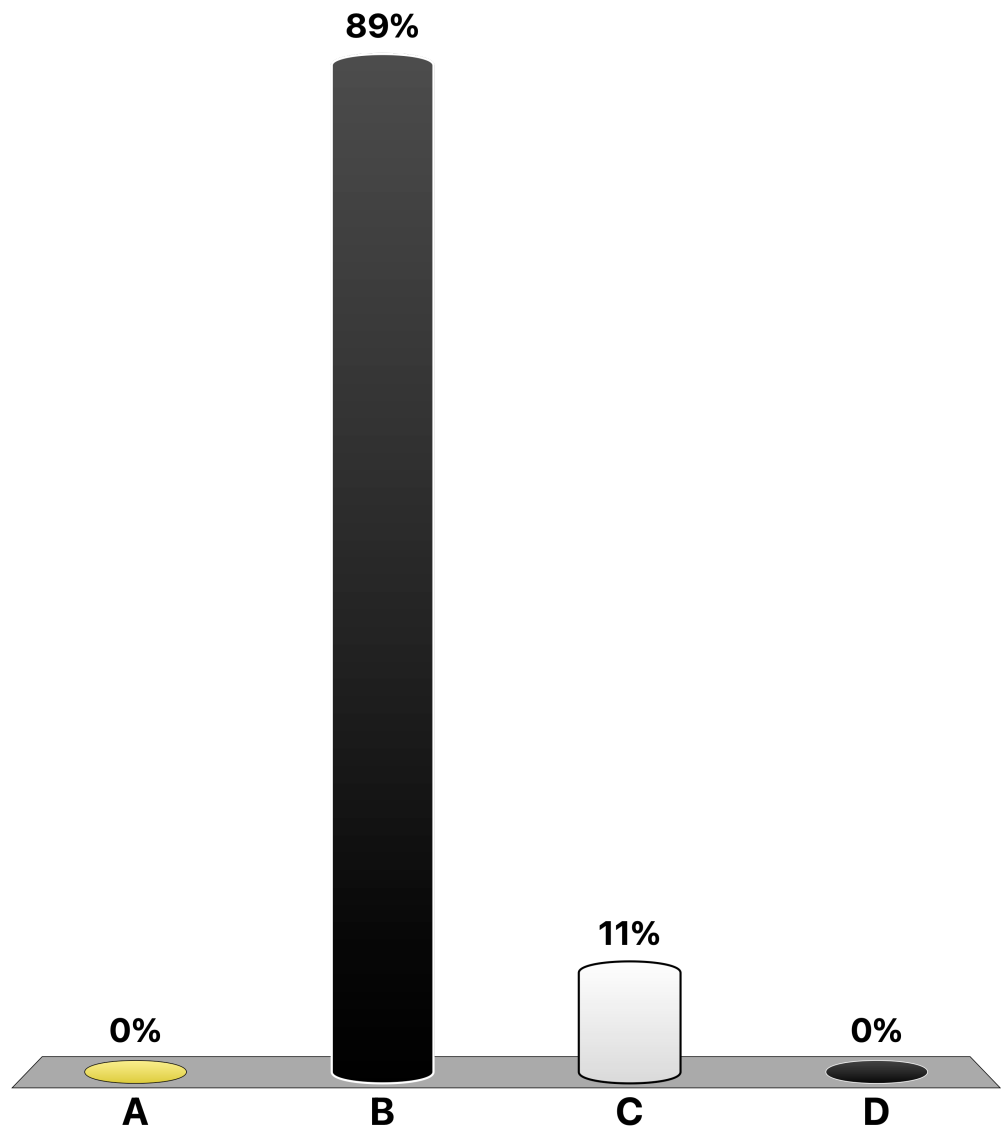
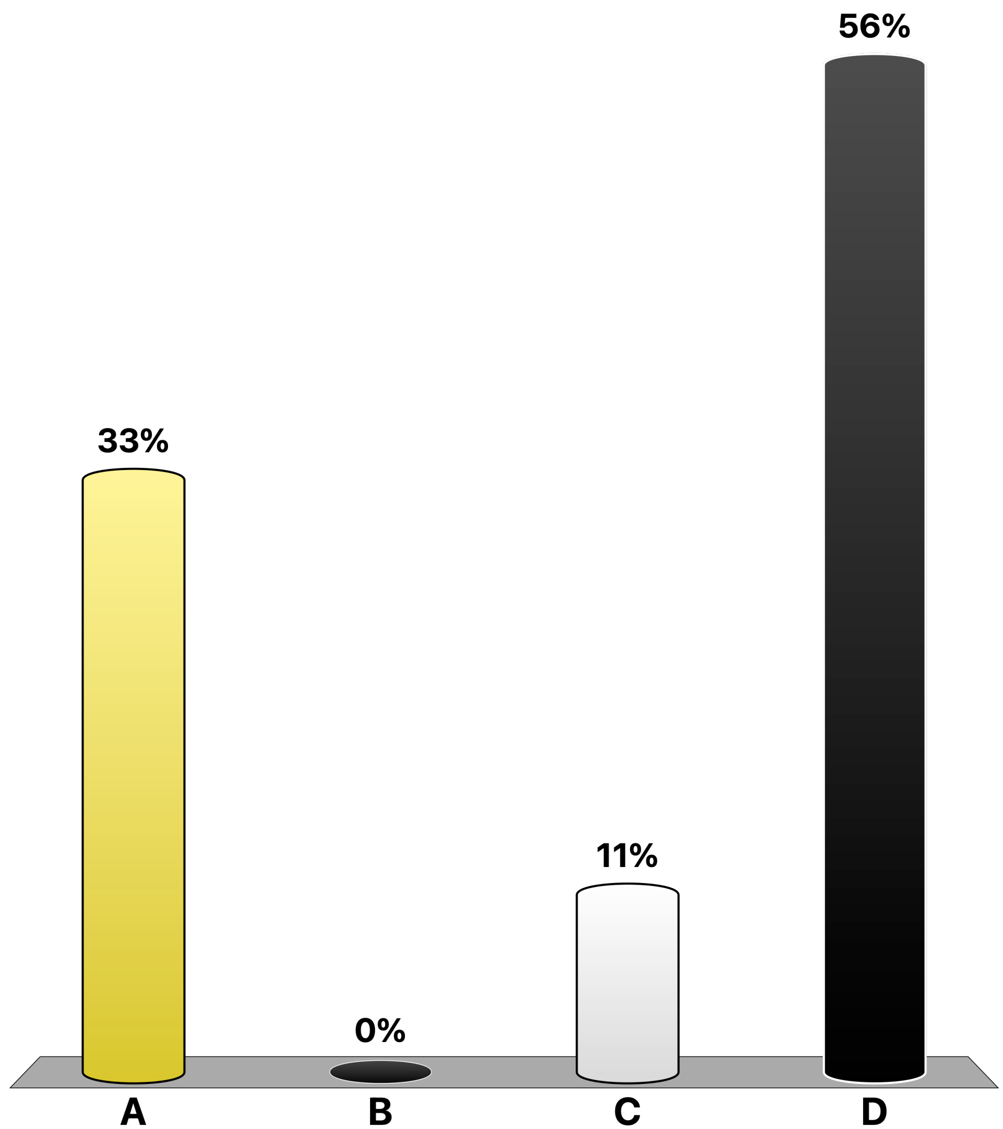


Q2 What happens if I double the frequency of a **wave**?

A. The wave velocity doubles
B. The wave velocity halves
C. The wave length doubles
D. The wave length halves



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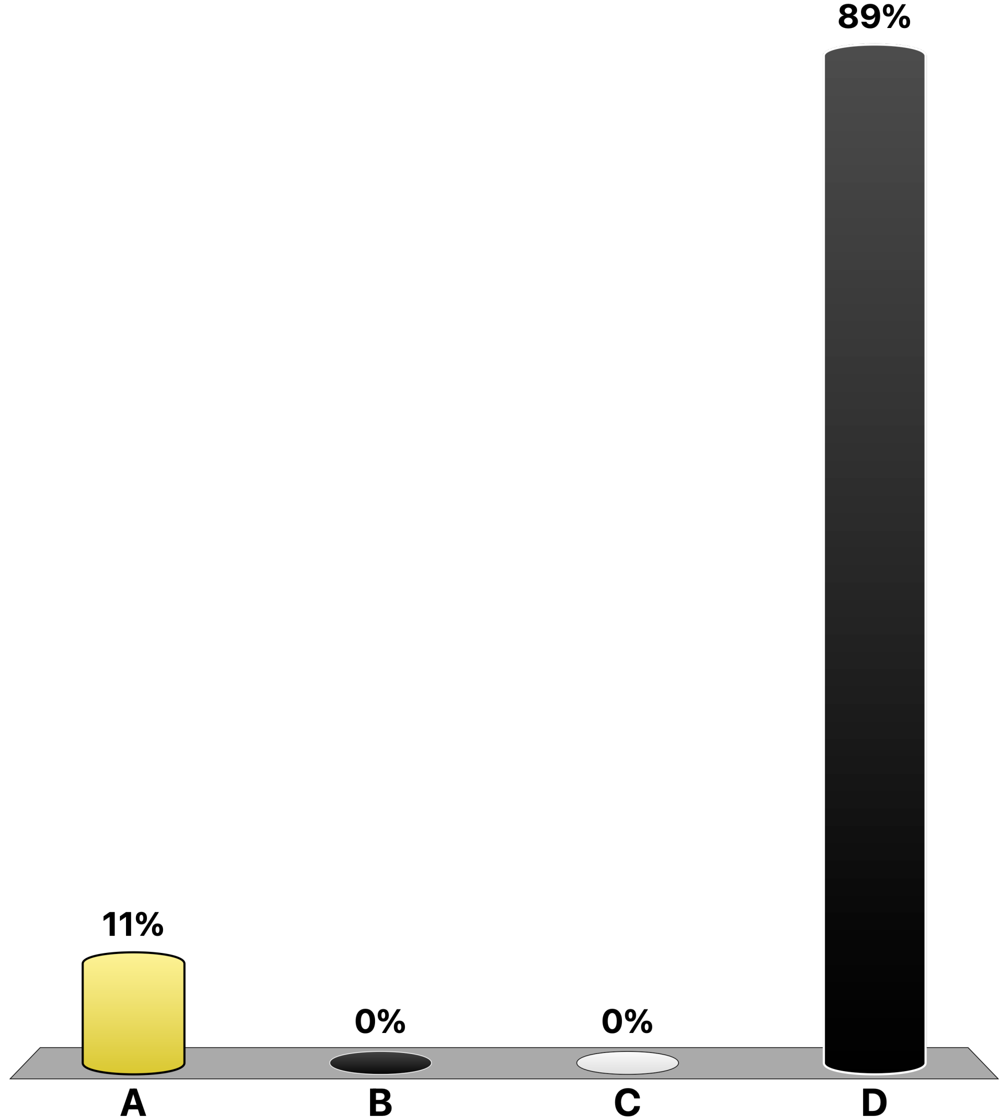


The strange life of waves 1: Interference

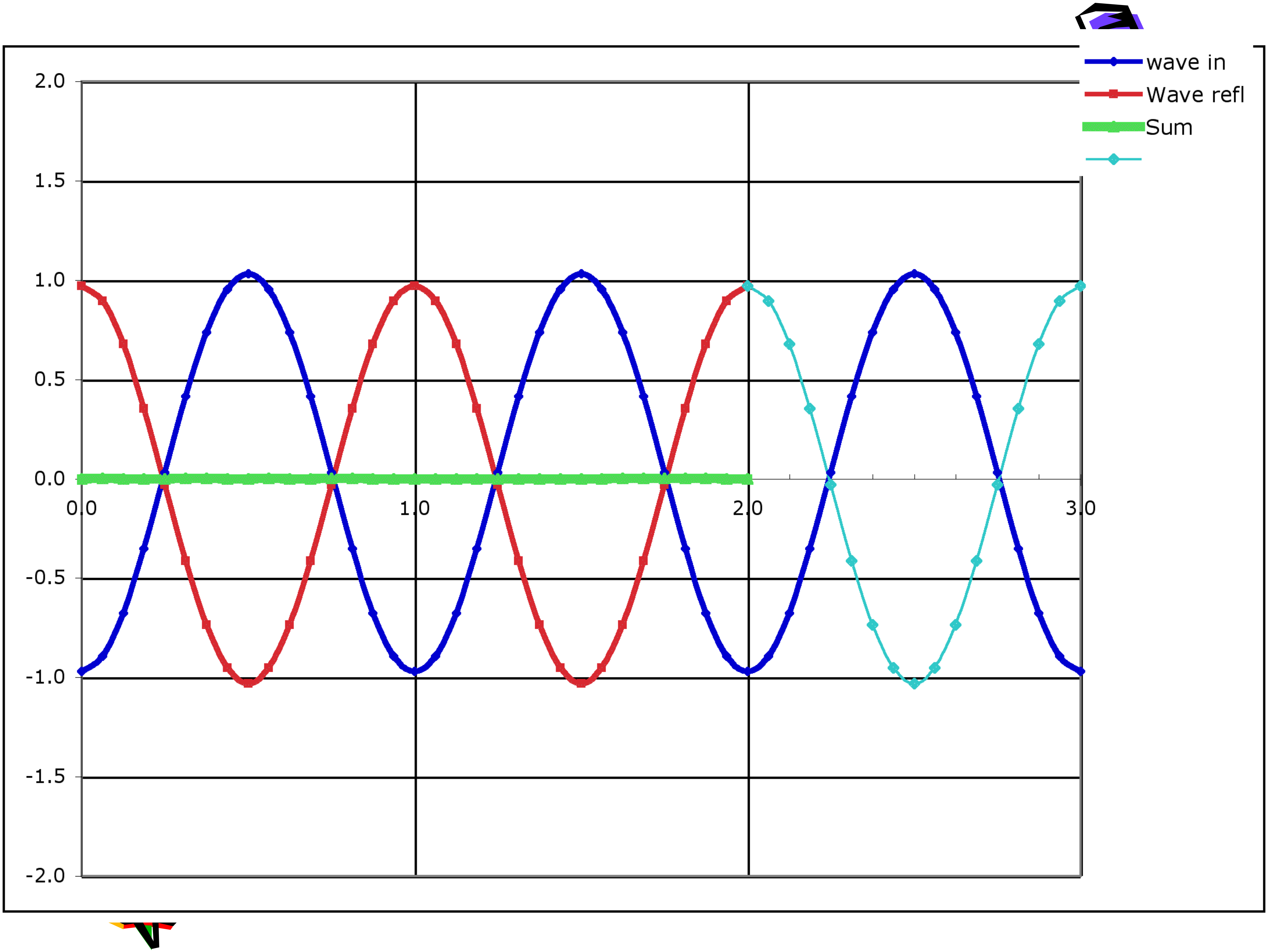
- Normally, no material travels in wave, just the information “swing up now!”
- Therefore, when 2 waves overlap, the “information” can simply be added (superposition): Do what the first wave says PLUS what the second wave says
- Constructive interference: Amplitudes add up (wave information **in** phase)
- Destructive interference: Amplitudes **cancel** (wave information 180 degrees out of phase)

- Waves can **reflect** and even interfere with their reflected “selves”!

The strange life of waves 2): Standing waves (Huh?)

- 1 wave moving one way, 2nd equal (reflected) wave moving opposite way
- Get fixed points where the interference is **always** destructive - nodes (every 1/2 wave length λ!)
- Points halfway in between nodes: interference is always **constructive** - oscillation “in place”
- If medium is finite (length L) and fixed at both ends, there have to be 0, 1, 2 … nodes in between => only if 1/2 wavelength is equal to L, $L/2$, $L/3$…

Resonance! Explains musical instruments (see later):
$f = v_{wave}/\lambda = v_{wave}/2L$, $v_{wave}/2(L/2)$, $v_{wave}/2(L/3)$,…



wave in
Wave refl
Sum
2.0
1.5
1.0
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-2.0
0.0
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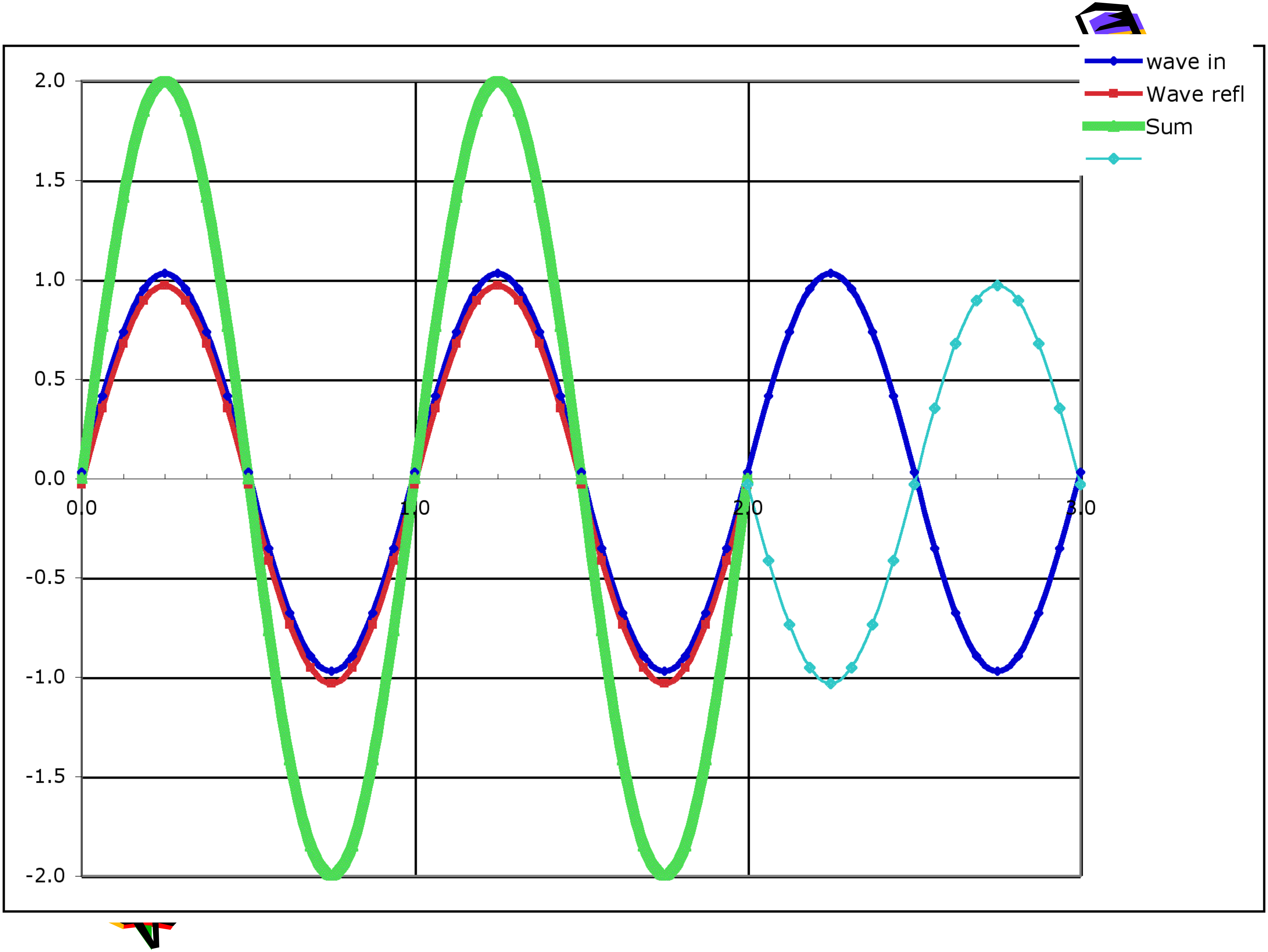
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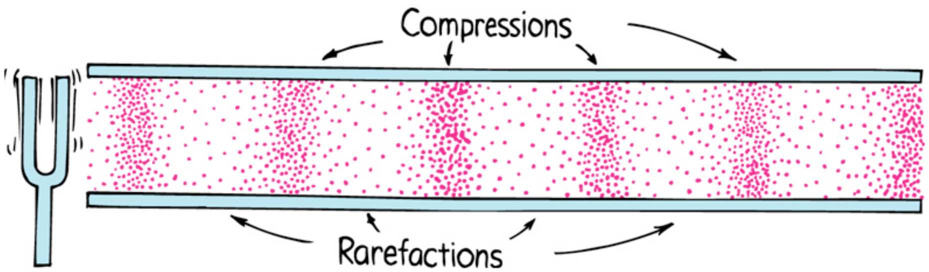
The strange life of waves 3): Refraction and Diffraction

- Two ways for waves to bend (change direction):
  - If traveling from one medium to another with slower wave speed, wave will bend such that it has less distance to go in slower medium - **Refraction**
    - Example: light rays in water - see later
  - Waves can bend around corners and spread out (Huygens’ principle: Each point along a wave generates a new wave) - **Diffraction**
    - Example: Water waves encountering a jetty, sound waves going around obstacles



Sound

- Sound = longitudinal compression-expansion wave within matter
  - Fluids: compression = higher pressure vs. rarefaction = lower pressure; generated by vibrating surfaces *)
  - Solids: molecules swing around their equilibrium position (back and forth)
  - Vacuum: No sound possible

*) like loudspeakers; or by oscillating resonant fluid columns (flute, organ pipe,… see later)

Properties of Sound Waves

- Wave velocity:
  - 330 m/s (0^oC) - 340 m/s (20^oC) in air (Mach 1)
  - 4 times faster in water
  - 15 times faster in steel
- Audible frequencies: 20 Hz - 20,000 Hz
- Audible wave lengths: 17 m - 1.7 cm in air; ultrasound much shorter
- Intensity (= amplitude^2)
  - ranges from 10^{-12} W/m^2 (0 decibel, threshold of hearing) to 1 W/m^2 (120 decibel, pain). Each additional 10 decibel = factor of 10 more intensity (20 decibel = factor 10 in amplitude)

Reflection and Refraction

- Reflection:
  - hard surfaces reflect better than soft ones
  - reflected wave has same angle with surface as incoming one
  - Can be used to measure distance: echo log, depth / fish finder, orientation for bats and whales, ultrasound imaging
  - acoustics, reverberation, echo,…
- Refraction:
  - Sound waves are bent by differences in temperature or by going through different substances with different wave speeds

Interference and standing waves

- Interference: Sound waves can add or subtract - increased sound or less
  - Example: Hooking one stereo speaker up backwards; noise-cancelling headphones
  - If frequencies are slightly different, get “beat” effect: hear average frequency fluctuate in loudness as interference goes from constructive to destructive and back
    - beat frequency = difference in frequencies
- Standing waves
  - Interference between incoming and reflected wave
  - Resonance at fundamental frequency (where wave length is 2x or 4x physical length) and multiples (harmonics)
    - Examples: Driving in car with windows down, flute, organ, all woodwinds, all brass instruments,…

Doppler Effect *)

- Object moving towards you:
  - Wave length gets “compressed”
  - Wave speed in medium stays the same
  - Apparent frequency goes up
  - Sound wave: higher pitch; Light: blue-shifted
- Object moving away from you:
  - Wave length gets “expanded”…frequency goes down; Sound wave: lower pitch; Light: red-shifted

*) Skip if time too short

Sound and Music

- Pitch = fundamental frequency of sound
  - Concert A = 440 Hz, middle C = 262 Hz
  - 1 Octave = factor 2 in frequency; 1 half tone is factor $2^{1/12} = 1.0595$ (equal tempering)
- Harmonics = multiples of fundamental frequency
- Timbre = relative loudness of various harmonics
- Loudness = amplitude (intensity)
- Envelope = change of loudness with time

Musical Instruments

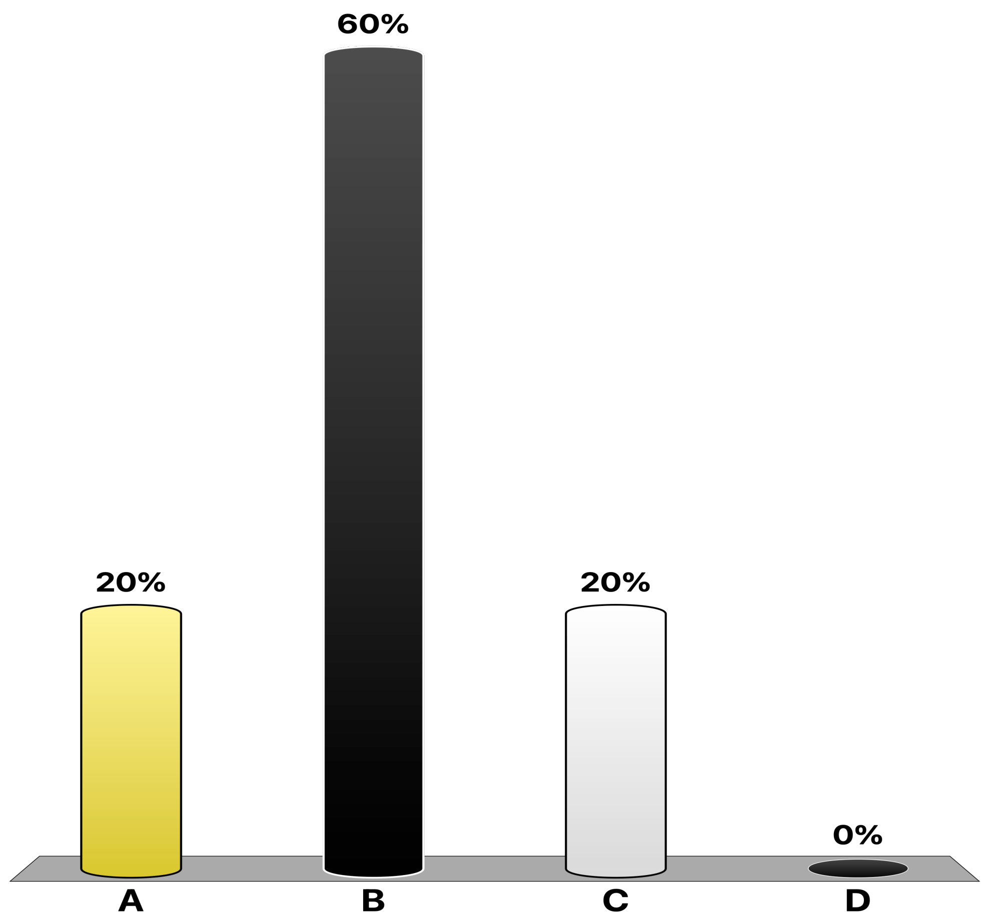
- Most based on standing wave resonance
- Examples:
  - string instruments (transverse standing wave on vibrating string): piano, violins, harps, guitars
  - woodwind, brass, organ: resonant air column (excited by reed, lips, or self-excitation)
  - 2-dimensional surfaces with resonant eigenfrequencies: drums, bells, vibraphone
  - electronic instruments (vibrating loudspeakers)

Music Reproduction

- Recording:
  - Use small membrane to “catch” air vibrations; motion of wire in magnetic field to convert into electrical signal (or pick up signal directly from oscillating string or electronic instrument)
  - Record on magnetic tape (varying magnetization of iron-oxide powder), record (oscillating groove), or
  - convert to string of numbers (excursion vs. time - digitization), store on computer, compact disc,…
- Reproduction: Reverse process
    - Magnetic reader, stylus plus magnet plus coil, digital-to-analog converter (DAC) -> electric currents -> loudspeaker -> air vibrations

Q1 What happens if I superimpose two waves going in the same direction, with exactly the same frequency, but out of phase by 1/2 wave length?

A. The resultant wave has double the amplitude of each individual wave
B. The resultant wave has zero amplitude
C. I get a standing wave
D. The wave speeds up



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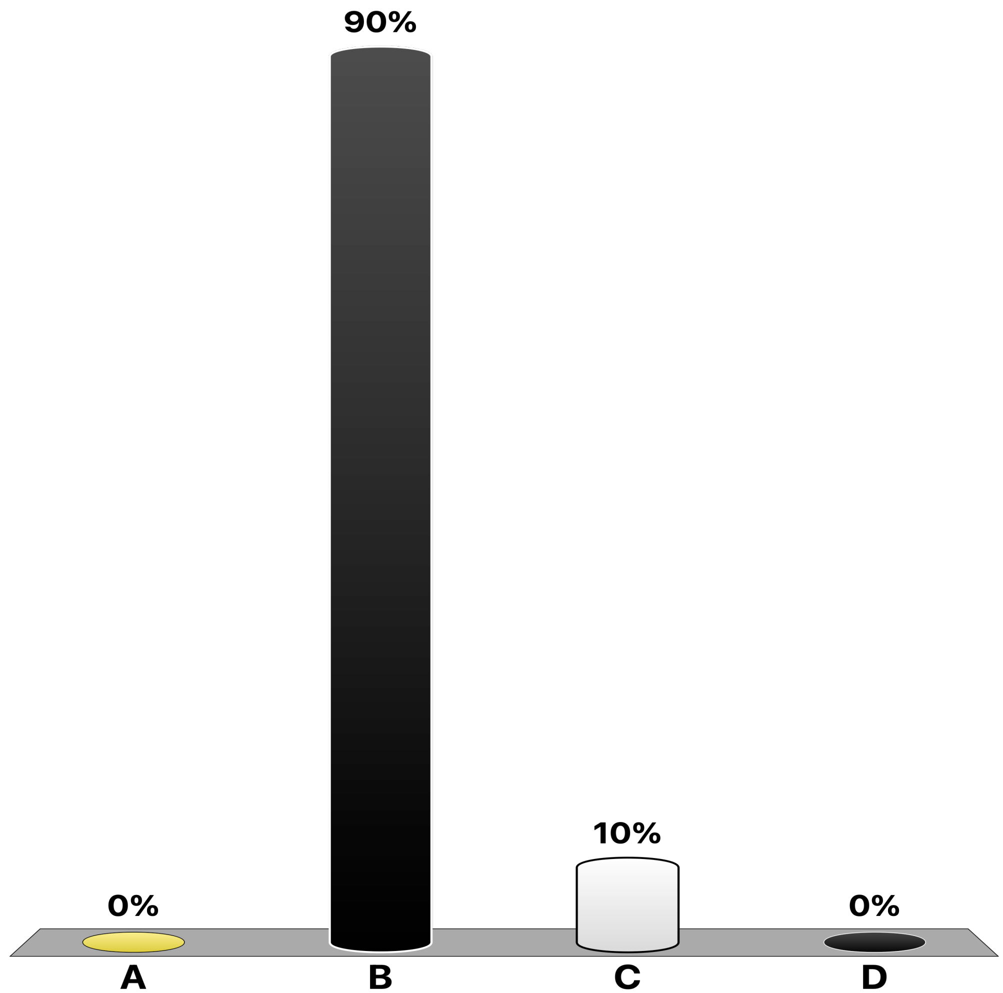
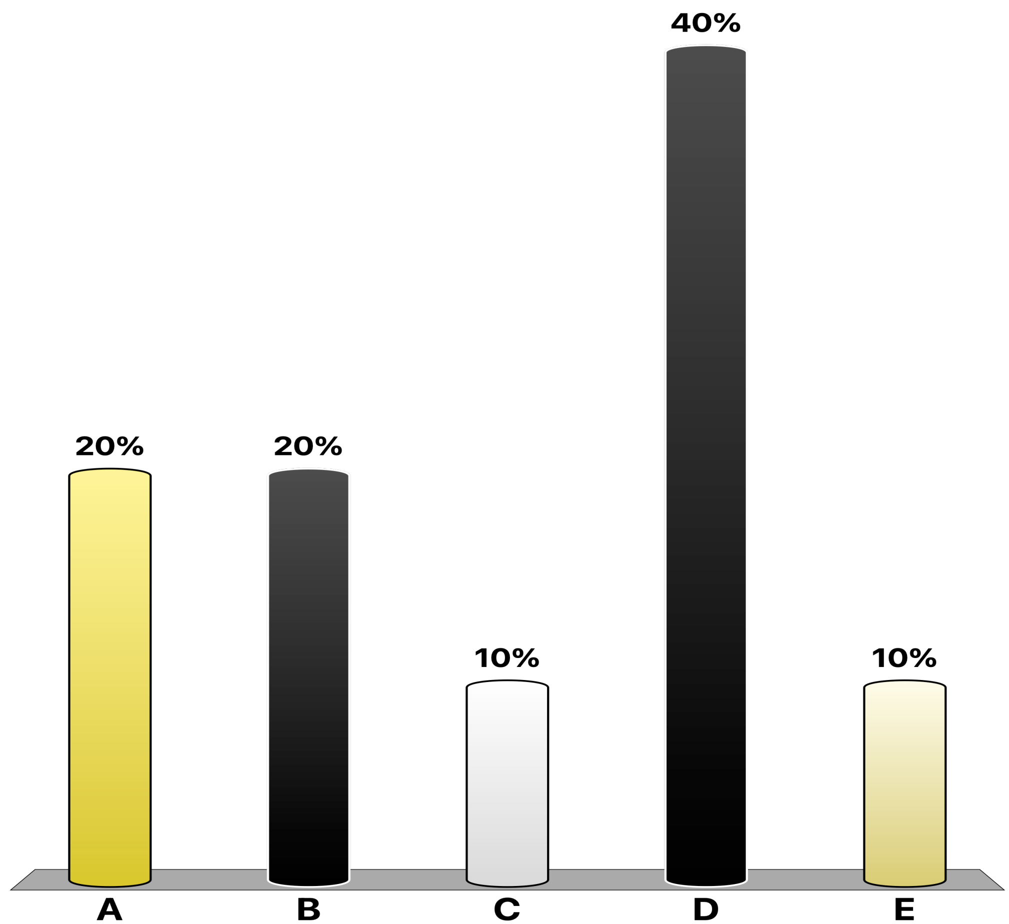


Q2 An organ pipe in a cold church (0^oC) has a length that will support a standing sound wave with a wave length of 1 m. Which musical note should I sing to get it to resonate?

A. A (440 Hz)
B. E (330 Hz)
C. E’ (660 Hz)
D. Either B or C, with B being louder
E. It will resonate at any frequency



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