Sounds of Music • 2021 January 30

You may begin at any time within the testing period.

This test uses these conventions unless implied or stated otherwise:

- All frequencies are greater than 20 Hz.
- Sound sources are points emitting continuously in windless 20°C air at sea level.
- All strings and pipes are of very small, nonzero radius.
- An octave consists of twelve equally distant half steps referenced to A_4 = 440 Hz.

This test was written so that you'll be able to read every question, but not answer every question. Don't feel bad to make an educated guess even when you're not sure of your answer. The order of questions is multiple choice, short answer, and free response. Each multiple-choice question has only one answer and we won't deduct points for incorrect answers. For some short answer questions, you will get full credit even if you have a one-word answer. **With so many teams, ties are extremely likely this year, so each team will earn three free points for each tiebreaker question attempted.** Good luck!

School: _____ Team number: _____

Student names: _____

Test score: _____ Final score: _____ Rank: _____

Duke University Invitational

___ 1. Welcome to Duke University Science Olympiad! We're sorry you couldn't be here in person, but North Carolina's research triangle continues to buzz with new scientific discoveries, which overturn older pseudoscientific ideas. Which of the following hypotheses on sound and health is most scientifically meaningful?

(A) "Modern music's irrational frequency ratios has made humanity more irrational and restless."
(B) "Stressful events make the body accumulate bad energy, which is released when listening to music."
(C) "Exposure to high-intensity infrasound is correlated with reduced anxiety."
(D) "The body is its own musical instrument, and vibrations at the body's natural frequencies enhance balance."
(E) "Melodies surviving from ancient times to today are tried and true, and therefore have higher therapeutic benefits."

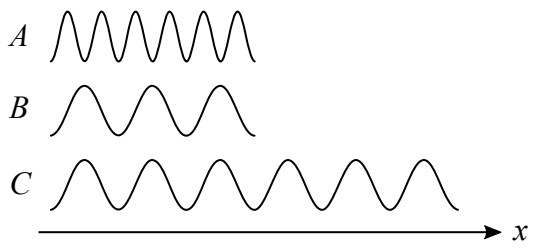
___ 2. Two loudspeakers play an identical tone. At a point between the loudspeakers, the intensity is greater than the intensity of the individual loudspeakers combined. This best exemplifies

(A) Transmission
(B) Rarefaction
(C) Diffraction
(D) Constructive interference
(E) Destructive interference

___ 3. Which of the following is NOT a property of transverse waves?

(A) Polarization
(B) Compression
(C) Frequency
(D) Wavelength
(E) Amplitude

Questions 4-5



Three waves A, B, and C move in the x-direction as illustrated in the figure above.

___ 4. Suppose that all waves travel at the same speed. Which of the following correctly ranks the frequency of each wave from least to greatest?

(A) $f_A < f_B < f_C$
(B) $f_C < f_A = f_B$
(C) $f_A = f_B < f_C$
(D) $f_A < f_B = f_C$
(E) $f_B = f_C < f_A$

___ 5. Now suppose instead that each wave travels in a different medium, but all have the same frequency. Which of the following correctly ranks the speed of each wave from slowest to fastest?

(A) $v_A < v_B < v_C$
(B) $v_C < v_A = v_B$
(C) $v_A = v_B < v_C$
(D) $v_A < v_B = v_C$
(E) $v_B = v_C < v_A$

___ 6. Which of the following pairs are synonyms?

(A) Harmonic .. overtone
(B) Compressional wave .. longitudinal wave
(C) Speed of sound .. particle speed
(D) Rarefaction .. Compression
(E) Wind instrument .. brass instrument

___ 7. Because standing waves do not travel, their frequency cannot always be defined as cycles per second passing a point. One alternative definition of the frequency of a standing sound wave in Hz is the number of times a particle returns to its maximum displacement per second. For which of the following locations on a standing wave is this definition always FALSE?

(A) Antinodes
(B) Nodes
(C) Root-mean-square values
(D) Midpoints
(E) Nonlinear Bessel points

___ 8. Which of the following best describes the purpose of a tuning fork in music?

(A) To initiate sound production in instruments prior to a performance
(B) To play a note of known frequency as a reference for tuning
(C) To tighten and loosen pegs and screws in string instruments
(D) To reduce unwanted noise caused when an instrument is touched
(E) To increase the perceptual sensitivity of listeners during a performance

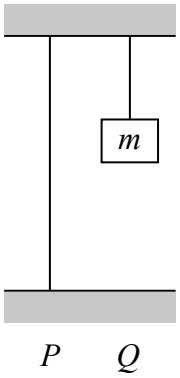
___ 9. A string of mass m and length L and under tension T is v. What is the wave speed on a different string of mass $5m$ and length $5L$, and under tension $3T$?

(A) $\sqrt{\frac{3}{5}}\,v$
(B) $\sqrt{3}\,v$
(C) $3v$
(D) $\frac{3}{5}v$
(E) $15v$

___ 10. Five sine waves of frequencies $1.0f$, $1.5f$, $2.0f$, $2.5f$, and $3.0f$ are played together. A human observer would hear a pitch closest in frequency to

(A) $0.50f$
(B) $0.71f$
(C) $1.00f$
(D) $5.00f$
(E) The resultant wave would have indefinite pitch

Questions 11-12



Two strings P and Q are suspended from the ceiling of a room. String P is attached to the floor, while string Q is held down by a box of mass m, as shown in the figure above. Both strings are held rigid under tension.

___ 11. Waves travel faster on which string?

(A) String P
(B) String Q
(C) The wave speed is equal on both strings
(D) It cannot be determined without additional information

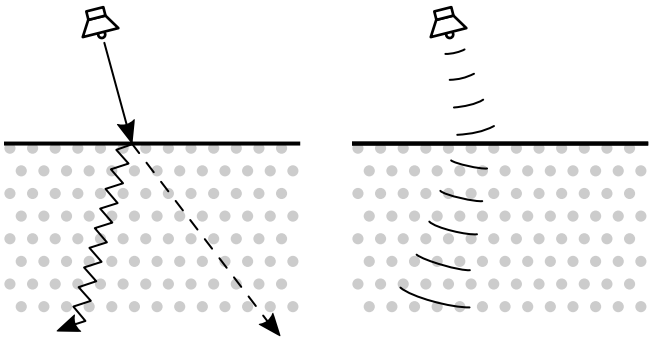
___ 12. The temperature in the room is raised. How does the tension in each string change?

	String P	String Q
(A)	Increase	Decrease
(B)	Increase	Increase
(C)	Decrease	Decrease
(D)	Decrease	No change
(E)	No change	Increase

___ 13. Which of the following phenomena accounts for a decrease in frequency measured by an observer moving away from a sound?

(A) Intensity dropoff
(B) Comoving distances
(C) Doppler Effect
(D) Superposition
(E) Lenition

Questions 14-15



Direction view Wave view

When sound moves from air into another medium, it typically changes direction only slightly, as represented by the dashed line in the figure above. However, some special materials have an internal geometry that reflects sound back and forth, as shown by the zigzag line. As a result, sound waves traveling left-to-right will flip direction to right-to-left upon entering the special material.

___ 14. If air has a refractive index of 1.00, which of the following is a possible value of the effective refractive index of the special material?

(A) −1.00
(B) 0.50
(C) 1.00
(D) 1.50
(E) 2.00

___ 15. The special material best exemplifies the class of substances known as

(A) metamaterials
(B) smart materials
(C) aerogels
(D) acoustically birefringent crystals
(E) condensed matter

___ 16. Two identical strings are sent to the International Space Station. Both are placed under tension T, but one string is inside the space station, while the other is outside the space station. Which of the following best describes the strings after both are plucked at their midpoints with equal energy?

(A) Both strings will immediately return to their initial position
(B) The *in*side string will vibrate, but the *out*side string will immediately return to its initial position
(C) The *out*side string will vibrate, but the *in*side string will immediately return to its initial position
(D) The *in*side string vibrates for a longer time than the *out*side string
(E) The *in*side string vibrates for a shorter time than the *out*side string

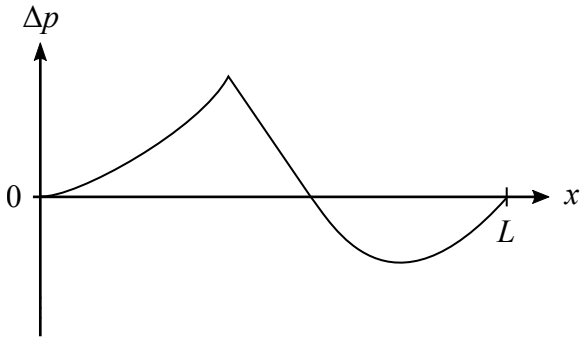
___ 17. A small wave packet in an unknown medium takes a duration of Δt_A to completely pass an observer A, and a duration of Δt_B to completely pass observer B. However, $\Delta t_A < \Delta t_B$. Which of the following could be true?

I. The medium is dispersive, and the observers are stationary.
II. The wave has zero wavelength.
III. Observers A and B are moving, and the medium is non-dispersive.

(A) I only
(B) II only
(C) III only
(D) I and II
(E) I and III

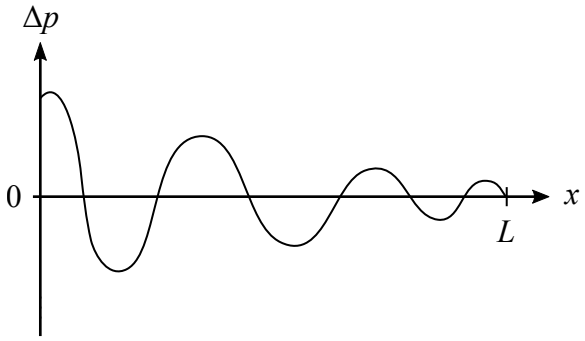
Questions 18-22

A special resonance machine can cause an open pipe of length L to play any of its harmonics at the same time. Each harmonic may have any possible pressure amplitude, not necessarily all the same.



___ 18. Is it possible for the machine to create a wave within the pipe of the form shown above?

(A) Yes, it is possible for the wave to exist
(B) No, because the wave is not symmetrical about the center of the pipe
(C) No, because the wave is not symmetrical with respect to both positive and negative amplitude
(D) No, because the wave has a sharp peak
(E) No, because an infinite amount of energy is required to form this wave



___ 19. Is it possible for the machine to create a wave within the pipe of the form shown above?

(A) Yes, it is possible for the wave to exist
(B) No, because the wave does not intersect the x-axis in equal intervals
(C) No, because the wave shown is transverse
(D) No, because both ends of the pipe must be at ambient pressure
(E) No, because damping does not occur within pipes

___ 20. The machine is set so that the *pressure amplitude* of the nth harmonic is p_1/n, where p_1 is the pressure amplitude of the first harmonic. If the intensity of the first harmonic alone is I_1, then what is the intensity of all harmonics together?

(A) $\frac{\pi^2}{6} I_1$
(B) $\frac{16}{15} I_1$
(C) $(\ln 2)\, I_1$
(D) $\frac{1+\sqrt{5}}{2} I_1$
(E) None of these answers are possible

___ 21. Now suppose that the machine is set so that the *intensity* of the nth harmonic is I_1/n, where I_1 is the intensity of the first harmonic. What is the intensity of all harmonics together?

(A) $\frac{\pi^2}{6} I_1$
(B) $\frac{16}{15} I_1$
(C) $(\ln 2)\, I_1$
(D) $\frac{1+\sqrt{5}}{2} I_1$
(E) None of these answers are possible

___ 22. The machine only operates on open pipes and will fail for instruments that do not consist of open pipes. This machine can successfully operate on which of the following?

(A) Clarinet
(B) Ocarina
(C) Piccolo
(D) Bassoon
(E) The machine is capable of successfully operating on any of these instruments

___ 23. A musician requires the LEAST amount of training to play microtonal pitches for a typical one of which of the following instruments?

(A) Trombone
(B) Trumpet
(C) Tuba
(D) Euphonium
(E) French horn

___ 24. All of the following are generally considered to be brass instruments EXCEPT

(A) saxophone
(B) trombone
(C) sousaphone
(D) Wagner tuba
(E) alto horn

___ 25. Which of the following is an example of sound localization?

(A) Binaural search tree
(B) Otoacoustic emission
(C) Echolocation
(D) Tritone paradox
(E) Palatalization

___ 26. Some music boxes play notes when inserted with a piece of paper with holes. Which of the following most accurately describes how the pitch of the note is determined?

(A) Hole location on the paper corresponds to different bars which play when struck
(B) The rate at which the handle is turned correlates to the number of times a gear is struck per second
(C) All notes play by default, and holes in certain locations suppress a note
(D) Holes shaped like different regular polygons trigger a note determined by the number of sides in the polygon

___ 27. Which of the following uses a single reed?

(A) Bass clarinet
(B) Bass oboe
(C) Contrabassoon
(D) English horn
(E) Didgeridoo

___ 28. Which of the following is true of an electric guitar?

(A) It cannot produce sound without being plugged into a loudspeaker
(B) It only produces sound through strings, and the loudspeaker is only for display
(C) Only the strings produce sound when unplugged, and *only* the loudspeaker produces sound when plugged in
(D) Only the strings produce sound when unplugged, and *both* the loudspeaker and strings produce sound when plugged in

___ 29. Which of the following sequences of solfège form a pentatonic major scale?

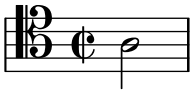
(A) *do re mi sol la*
(B) *do re mi fa sol*
(C) *re mi do ti fa*
(D) *do re mi fa sol la ti*

___ 30. A piece has a tempo of ♩ = 120. What is the duration of each half note?

(A) 0.50 s
(B) 0.60 s
(C) 0.83 s
(D) 1.00 s
(E) 1.20 s

___ 31. In the Hornsbostel-Sachs system, a castanet is classified as which of the following types of instruments?

(A) Aerophone
(B) Membranophone
(C) Chordophone
(D) Electrophone
(E) Idiophone

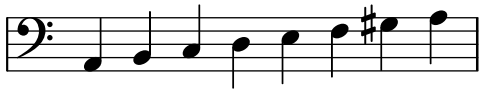


___ 32. What is the note shown in the staff above?

(A) B_3
(B) D_3
(C) A_3
(D) A_4
(E) D_4

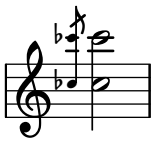
___ 33. In four-part voice leading, the second highest voice is known as

(A) alto
(B) baritone
(C) bass
(D) soprano
(E) treble



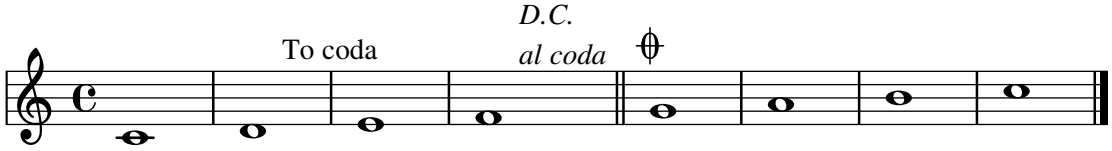
___ 34. The scale above is

(A) diatonic major
(B) melodic minor
(C) natural minor
(D) harmonic minor
(E) in the Ionian mode



___ 35. In the excerpt above, what are the small notes before the half notes called?

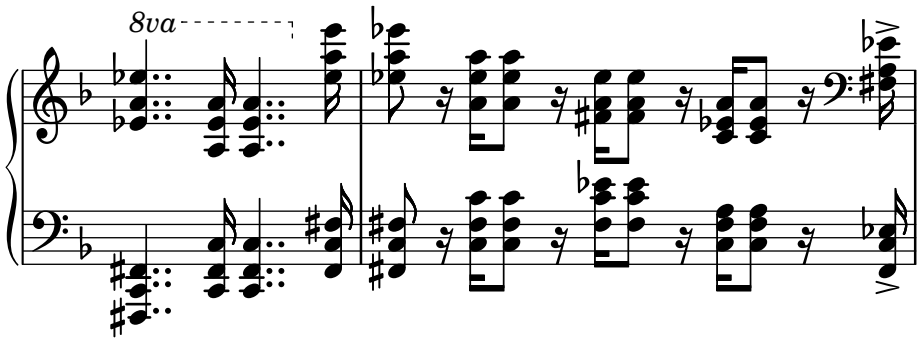
(A) *Fermata*
(B) *Sostenuto*
(C) Tied notes
(D) Ghost notes
(E) Grace notes



___ 36. In the musical passage above, what sequence of notes will be played?

(A) C – D – G – A – B – C
(B) C – D – E – F – G – A – B – C
(C) C – D – E – F – C – D – E – F – C – D – G – A – B – C
(D) C – D – E – F – C – D – G – A – B – C
(E) C – D – E – F – G – A – B – C – C – D

Questions 37-38



___ 37. The passage above is an excerpt from a piano sonata by Franz Liszt. What is a valid time signature for these two measures?

(A) $\frac{3}{4}$

(B) $\frac{4}{4}$

(C) $\frac{5}{4}$

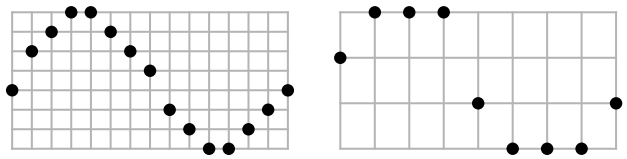
(D) $\frac{7}{8}$

(E) $\frac{9}{8}$

___ 38. In comparison to other notes, the musician should play the final notes of the second measure

(A) more loudly
(B) less loudly
(C) with greater precision on pitch
(D) with faster tempo
(E) with slower tempo

Questions 39-40



High fidelity Low fidelity

Computers cannot store sound waves with infinite accuracy, or *fidelity*. Instead, they take samples of the wave, and they store each sampled data point at fixed values. These fixed values are represented by the tick marks in the figure above. While both the high- and low-fidelity grids in the figure could be derived from the same sound wave, the high-fidelity sample represents the original sound wave more closely than the low-fidelity sample.

___ 39. Which of the following determines the number of tick marks per unit of time on the horizontal axis (*x*-axis)?

(A) Sampling rate
(B) Slew rate
(C) Bit depth
(D) Square approximation frequency
(E) Anti-aliasing filter

___ 40. Which of the following determines the number of tick marks on the vertical axis (*y*-axis)?

(A) Sampling rate
(B) Amplitude rate
(C) Bit depth
(D) Square approximation frequency
(E) Anti-aliasing filter

Short answer questions

No questions need more than a sentence for you to answer for full credit. One-word answers are okay.

41. A wave has frequency of 654 Hz and has a wavelength of 0.0883 m. What is the wave speed?

42. A human observer perceives a pitch of frequency 345 Hz with beats of 5 Hz. If the beats consist of two sine waves of equal intensity, what are the frequencies of the two individual tones?

43. A sound source has intensity of 7.125×10^{-5} W/m^2 at a distance of 8.00 m. What is the intensity at a distance of 3.00 m from the source?

44. A cone of length 0.35 m has an open base. What is the fundamental frequency of the air column of the cone?

45. At a temperature of 1.82×10^2 K, the speed of sound in an ideal gas is 2.37×10^3 m/s. Its speed of sound is equal to 4.00×10^3 m/s at what temperature?

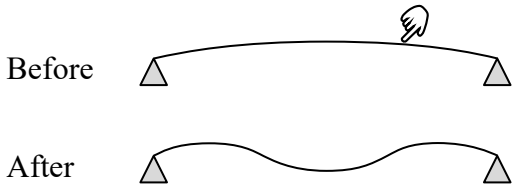
46. A *quarter tone* is an interval where one note has a frequency $\sqrt[24]{2}$ times the frequency of the other. A *schisma* is an interval of approximately 1.954 cents. How many schismas are in a quarter tone? Write your answer to the nearest hundredth.

47. What is the lowest note, with note number, on a cello?

48. A microphone detects two sounds of 120 dB SIL and 20 dB SIL. How many times more power does the microphone receive from the first sound than the second sound?

49. Sonar is a system that uses sound to detect underwater objects. What does "sonar" stand for?

Questions 50-51



One interesting technique for many string instruments is called *flageolet*, where the player taps a finger on the string, dividing the length of vibration to a fraction of the length of the string and exciting higher harmonics.

50. In the figure above, the player taps at one-third the length of the string. If the pitch of the string before tapping is C_4, then its pitch after tapping is closest to what note, including note number?

51. Is the frequency of the note in the previous problem after tapping greater than, less than, or equal to the frequency of the equivalent note in equal temperament?

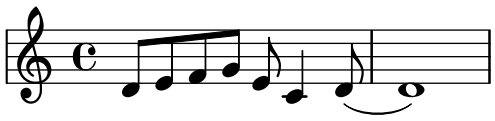
    _____ Greater

    _____ Equal

    _____ Less

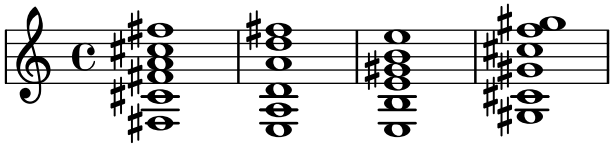
52. The leading tone is higher than the tonic of a scale by how many semitones?

53. Write the following tempo markings from slowest to fastest: *andantino*, *andante*, *lento*, *prestissimo*, *presto*, *allegro*.



54. The passage above is famously known as "the lick." Assuming a major key, write each note in order in movable *do* solfège. (2 points)

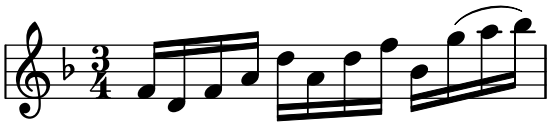
Questions 55-56



Gerudo Valley is a piece of video game music known for its chord progression. Its chord progression is provided above, with its key signature is intentionally left without sharps or flats.

55. What are each of the four chords in *Gerudo Valley*? You may use standard chord symbols or any other notation you'd like, as long as it is evident what your response is. (3 points)

56. How many sharps or flats should be on its key signature?



57. An excerpt of Bach's *Chaconne* is shown in the staff above. Assuming a minor key, write each note in order in movable *do* solfège, using **either** *la*-based or *do*-based. (3 points)

Because the number of teams make ties extremely likely this year, each team will earn **three free normal points** for each tiebreaker question attempted. In other words, don't leave any of these blank! Provide as much detail as you can in your responses.

58. (Serious tiebreaker) Lyle drops two balls of equal mass from the top of a gymnasium, then measures how high the objects will bounce after hitting the ground exactly once. By calculating the change in gravitational potential energy after the balls return to their peak height, Lyle plans to determine which object creates a louder sound upon hitting the ground. Describe ONE scientific reason why his plan is unlikely to succeed.[Note 1] (2 normal points, 8 tiebreaker points)

59. (Serious tiebreaker) Although the note would be inaudible to humans, what note letter name and number corresponds to the pitch of 2020^{2021} Hz? Explain the mathematical process you used to determine the answer. You don't have to use mathematical notation on Scilympiad if you don't want to; as long as we know what you mean, you can earn points. (2 normal points, 4 tiebreaker points)

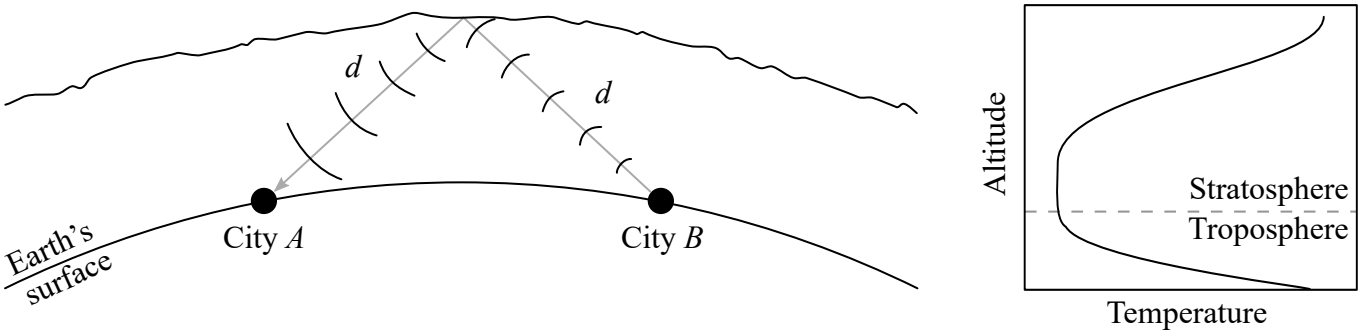
60. (Almost silly tiebreaker) Describe how the physics of sound influenced the historical development of quantum theory. In your response, include any one or more of the terms "box," "disgruntled house pet," or "mystery school blimp." (1 normal point, 2 tiebreaker points)

61. (Silly tiebreaker) If your spirit animal were a musical instrument, what instrument would it be? (0 normal points, 1 tiebreaker point)

[1] Do not try this for real without proper precautions. If you were standing below, it could injure you (and probably somebody else too), and you'd probably not be too happy about that.

Free-response question

The weight of each point on the free-response question will be multiplied by two when calculating test score.



62. A surprising effect can happen where people in city *A* can hear a sound originating in city *B*, but the sound cannot be heard in other cities located between *A* and *B*. A hypothesis in the early 1900s was that after sound left city *B*, it traveled a distance *d* and reflected in the stratosphere, before traveling another distance *d* to city *A*, as shown in the figure above.

The troposphere is the layer of Earth's atmosphere inhabited by humans, and it extends from Earth's surface to an altitude of approximately 10 km $\left(\text{or } 10^4 \text{ m}\right)$. The stratosphere is the layer directly above the troposphere. As the graph in the figure depicts, the temperature falls gradually with height in the troposphere, and is approximately constant at the bottom of the stratosphere, before rising sharply at higher stratospheric altitudes.

(a) Using your knowledge of acoustics and the provided information, explain why it was reasonable for early scientists to expect sound from city *B* to reflect from the stratosphere. (2 points)

(b) i. A loud sound in city *B* is observed 6.80×10^2 seconds later in city *A*. Calculate the total distance $2d$ traveled by the sound according to the hypothesis, assuming that the speed of sound is 343 m/s. (1 point)

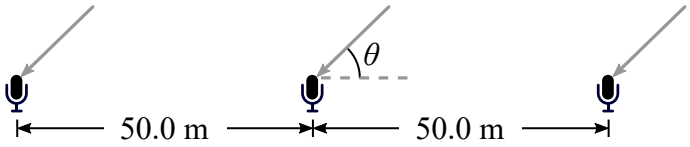
ii. Suppose that the cities are 2.0×10^2 km apart $\left(\text{or } 2.0 \times 10^5 \text{ m}\right)$. Using your answer in part (i), calculate the altitude at which the sound reflects. (1 point)

(c) The calculations in part (b) assume that sound travels at constant speed. Explain ONE reason why this assumption may lead to an error in the calculations. (1 point)

(d) Although modern scientists know that sound reflects in the stratosphere, they believe that atmospheric refraction, rather than reflection, better explains why sound travels from city *B* to city *A* without being heard along the ground between the cities.

i. Explain this effect by using refraction. (2 points)

ii. Explain ANOTHER scientific reason for why the calculations in part (b) may be in error. If you want, you may choose to repeat or refer to your response in part (d)(i), but do not repeat what you wrote in part (c). (1 point)



(e) An array of three microphones is arranged in city *A* as depicted in the figure above. Explain how the microphones may be used to determine the angle θ at which sound approaches the ground. (2 points)