Name: ______________________

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C.1 Simple Harmonic Motion

Understandings

- Conditions that lead to simple harmonic motion.
- The defining equation of simple harmonic motion as given by $a = -\omega^2 x$.
- A particle undergoing simple harmonic motion can be described using time period *T*, frequency *f*, angular frequency ω, amplitude, equilibrium position, and displacement.
- The time period in terms of frequency of oscillation and angular frequency as given by $T = \frac{1}{f} = \frac{2\pi}{\omega}$.
- The time period of a mass-spring system as given by $T = 2\pi\sqrt{\frac{m}{k}}$.
- The time period of a simple pendulum as given by $T = 2\pi\sqrt{\frac{l}{g}}$.
- A qualitative approach to energy changes during one cycle of an oscillation.

Equations

$$a = -\omega^2 x$$

$$T = \frac{1}{f} = \frac{2\pi}{\omega}$$

$$T = 2\pi\sqrt{\frac{m}{k}}$$

$$T = 2\pi\sqrt{\frac{l}{g}}$$

Additional HL Understandings

- A particle undergoing simple harmonic motion can be described using phase angle.
- Problems can be solved using the equations for simple harmonic motion as given by
  - $x = x_0 \sin(\omega t + \phi)$
  - $v = \omega x_0 \cos(\omega t + \phi)$
  - $v = \pm\omega\sqrt{{x_0}^2 - x^2}$
  - $E_{\mathrm{T}} = \frac{1}{2}m\omega^2{x_0}^2$
  - $E_{\mathrm{p}} = \frac{1}{2}m\omega^2 x^2$

Additional HL Equations

$x = x_0 \sin(\omega t + \phi)$

$v = \omega x_0 \cos(\omega t + \phi)$

$v = \pm\omega\sqrt{{x_0}^2 - x^2}$

$E_{\mathrm{T}} = \frac{1}{2}m\omega^2{x_0}^2$

$E_{\mathrm{p}} = \frac{1}{2}m\omega^2 x^2$

If you are interested in learning more about waves then please read the book *Vibrations and Waves* by George C. King.

The solutions can be found on the YouTube channel Go Physics Go:

https://www.youtube.com/@gophysicsgo/playlists

Part 1: Use your favorite sources to answer the following questions

1. Define *oscillation.*

2. Give three examples of oscillations.

3. Define *periodic.*

4. Define *period.* Units?

   The *period* is the time it takes for an oscillating object to complete one oscillation (or revolution). *Period* is given in seconds.

5. Define *amplitude.* Units?

6. Define *frequency*. Units?

7. What is the mathematical relationship between the *frequency* and *period* of a wave?

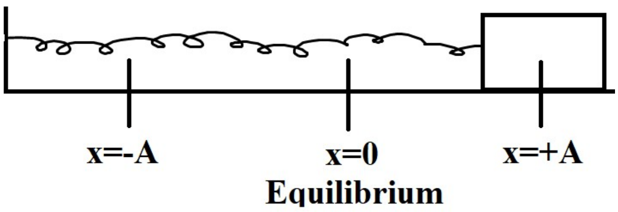
8. State the equation for the angular frequency for an object undergoing simple harmonic motion.

9. Topic A.1 Review: The slope of a displacement vs. time graph tells us the ___________ of an object while the slope of a velocity vs. time graph tells us the ___________ of an object.

10. Topic A.2 Review: Define *equilibrium.*

11. Give the name, define, and give the units of each variable from Hooke's Law $\vec{F} = -k \times \Delta\vec{x}$.

12. A mass lying on a smooth horizontal surface is attached to a spring and is stretched from its equilibrium position. It is then released. Label the forces on the mass.



13. **Use a pencil and ruler!** Draw and label an *acceleration vs. displacement* graph for simple harmonic motion.

14. Derive the defining equation of simple harmonic motion $a = -\omega^2 x$.

15. What are the main characteristics of simple harmonic motion?

16. Derive the equation for the time period of a mass-spring system $T = 2\pi\sqrt{\frac{m}{k}}$.

17. State the equation for the time period of a simple pendulum.

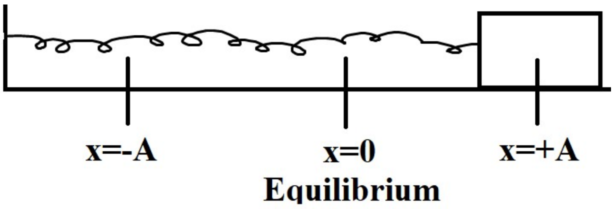
18. **Use a pencil and ruler!** Draw two waves which are *in phase*.

19. **Use a pencil and ruler!** Draw two waves which are *out of phase by* 180^{o}.

20. **Use a pencil and ruler!** Draw two waves which are *out of phase by* 90^{o}.

21. **Use a pencil!** The total energy of a simple harmonic oscillator is given by the equation $E_{\mathrm{T}} = E_{\mathrm{k}} + E_{\mathrm{p}} = \frac{1}{2}mv^2 + \frac{1}{2}k\Delta x^2 = \text{constant}$. In the figure below label the locations of

$E_{\mathrm{k,max}}$	$E_{\mathrm{k,min}} = 0\ \mathrm{J}$	$E_{\mathrm{p,max}}$	$E_{\mathrm{p,min}} = 0\ \mathrm{J}$
a_{max}	$a_{\mathrm{min}} = 0\,\frac{\mathrm{m}}{\mathrm{s}^2}$	v_{max}	$v_{\mathrm{min}} = 0\ \frac{\mathrm{m}}{\mathrm{s}}$



22. What is the mathematical relationship between the energy and amplitude of an object in simple harmonic motion?

23. **Use a pencil and ruler!** Draw an energy vs. displacement graph for a mass on a spring with three curves: a potential energy vs. displacement curve, a kinetic energy vs. displacement curve, and a total energy vs. displacement curve.

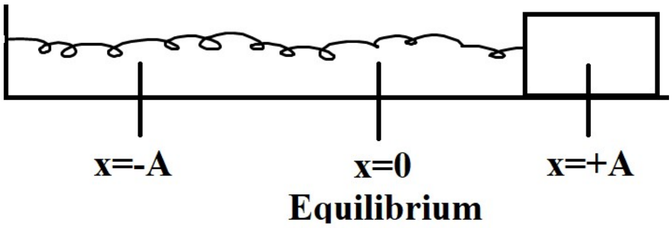
24. **Use a pencil and ruler!** Draw an energy vs. time graph during one oscillation for a mass on a spring with three curves: a potential energy vs. displacement curve, a kinetic energy vs. displacement curve, and a total energy vs. displacement curve.

Additional HL Understandings

25. Math review: Describe the significance of the variables *A*, *B*, *C*, and *D* in the equation $y = A\sin(Bx + C) + D$.

26.Derive the equations of motion, energy, and speed for simple harmonic motion.

For a mass on a spring:



Optional for math lovers

The small angle approximation ($\theta < 10°$) for the period of a pendulum is given in the physics data booklet: $T = 2\pi\sqrt{\frac{l}{g}}$

The exact solution is given from the video below:

Exact Solution of the Nonlinear Pendulum
Flammable Maths
https://www.youtube.com/watch?v=efvT2iUSjaA

Watch and take notes from the video above.

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C.2 Wave Model

Understandings

- Transverse and longitudinal traveling waves.
- Wavelength λ, frequency *f*, time period *T*, and wave speed *v* applied to wave motion as given by $v = f\lambda = \frac{\lambda}{T}$.
- The nature of sound waves.
- The nature of electromagnetic waves.
- The differences between mechanical waves and electromagnetic waves.

Equations

$v = f\lambda = \frac{\lambda}{T}$

The solutions can be found on the YouTube channel Go Physics Go:

https://www.youtube.com/@gophysicsgo/playlists

Use your favorite sources to answer the following questions

1. What is a *wave*? What do waves transfer? What do waves not transfer?

2. How are all waves created?

3. Define *medium*. Give three examples.

4. Define *vacuum*.

5. Define *mechanical wave.* Give an example.

6. Define *electromagnetic waves*.

7. List the seven electromagnetic waves in order of decreasing wavelength λ, increasing frequency f, and increasing energy $E = hf$.

8. State the meaning of ROY G BIV

9. Define *longitudinal wave*. Give an example.

10. Define *compression.*

11. Define *rarefaction.* Do not confuse *rarefaction* with *refraction*!

12. **Use a pencil and ruler!** Draw a *longitudinal wave*. Label the *compression* and *rarefaction*.

13. Define *transverse wave.* Give an example.

14. Define *crest.*

15. Define *trough.*

16. **Use a pencil and ruler!** Draw a *transverse wave*. Label the *crest* and *trough*.

17. Define *wavelength* λ. Units?

18. Define *period* T. Units?

19. Define *frequency* f. Units?

20. State the equation which relates the *speed*, *wavelength*, and *frequency* of a wave.

21. What information can we obtain from a *displacement vs. distance* graph?

22. What information can we obtain from a *displacement vs. time* graph?

23. Define *intensity*. Units?

24. What is the mathematical relationship between the *intensity* and *amplitude* of a wave? What about the *energy* and *amplitude* of a wave?

25. What is the mathematical relationship between the *intensity* and *distance* from a wave source?

26. Imagine a boat which is in the middle of the ocean. A water wave passes under it. What happens to the boat? Does it travel vertically (up and down)? Does it travel horizontally (left and right)? Both? Neither?

27. What is the speed of sound in a vacuum? In air? In a metal?

28. What is the speed of an electromagnetic wave in a vacuum? In air? In a metal?

29. For sound waves pitch is directly proportional to ___________ and loudness is directly proportional to ___________.

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C.3 Wave Phenomena

Understandings

- Waves traveling in two and three dimensions can be described through the concepts of wavefronts and rays.
- Wave behavior at boundaries in terms of reflection, refraction, and transmission.
- Wave diffraction around a body and through an aperture.
- Wavefront-ray diagrams showing refraction and diffraction.
- Snell's law, critical angle, and total internal reflection.
- Snell's law as given by $\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$ where *n* is the refractive index and θ is the angle between the normal and the ray.
- Superposition of waves and wave pulses.
- Double-source interference requires coherent sources.
- The condition for constructive interference as given by path difference $= n\lambda$.
- The condition for destructive interference as given by path difference $= \left(n + \frac{1}{2}\right)\lambda$.
- Young's double-slit interference as given by $s = \frac{\lambda D}{d}$ where *s* is the separation of fringes, *d* is the separation of the slits, and *D* is the distance from the slits to the screen.

Equations

$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$$

Constructive interference: path difference $= n\lambda$

Destructive interference: path difference $= \left(n + \frac{1}{2}\right)\lambda$

$s = \frac{\lambda D}{d}$

Additional HL Understandings

- Single-slit diffraction including intensity patterns as given by $\theta = \frac{\lambda}{b}$ where b is the slit width.
- The single-slit pattern modulates the double slit interference pattern.
- Interference patterns from multiple slits and diffraction gratings as given by $n\lambda = d \sin\theta$.

Additional HL Equations

$\theta = \frac{\lambda}{b}$

$n\lambda = d \sin\theta$

The solutions can be found on the YouTube channel Go Physics Go:

https://www.youtube.com/@gophysicsgo/playlists

Use your favorite sources to answer the following questions

1. Define *wavefront.*

2. Define *ray.*

3. **Use a pencil and ruler!** Draw 3 wavefronts and 6 rays after a small rock falls vertically and hits water.

4. **Use a pencil and ruler!** Draw 2 wavefronts and 8 rays after a long thin rod falls horizontally and hits water.

5. Define *superposition.*

6. **Use a pencil and ruler!** Draw a before, during, and after image of two pulses on a rope traveling in opposite directions which go through constructive interference.

7. **Use a pencil and ruler!** Draw a before, during, and after image of two pulses on a rope traveling in opposite directions which go through destructive interference.

8. **Use a pencil and ruler!** Draw a before and after image of a single pulse wave on a string striking and being reflected from a vertical pole with a fixed end.

9. **Use a pencil and ruler!** Draw a before and after image of a single pulse wave on a string striking and being reflected from a vertical pole with a free/loose end.

10. What is the equation, units, and meaning of *index of refraction n*? What is the range of values for the *refractive index* of an object? What is the *refractive index* for a vacuum?

11. **Use a pencil and ruler!** Define *reflection* and draw a labeled figure.

12. State the equation for the *law of reflection*.

13. **Use a pencil and ruler!** Define *refraction* and draw a labeled figure. (Do not confuse *refraction* with *rarefaction*!)

14. State the equation for refraction: *Snell's law*.

15. **Use a pencil and ruler!** Define *dispersion* and draw a labeled figure.

16. **Use a pencil and ruler!** Define *total internal reflection* and *critical angle*. Draw a labeled figure.

17. Define *diffraction*. Give two examples.

18. What is the relationship between the slit width and wavelength of the wave which gives maximum diffraction?

19. What is the relationship between the slit width and wavelength of the wave which gives minimum diffraction?

20. Light passes through a slit which is equal to the lights wavelength. What happens to the intensity of the central maximum as the slit width decreases?

21. **Use a pencil and ruler!** Draw an intensity vs. displacement graph for *single source interference*.

22. For double source interference state the equations and define each variable for

   a. constructive interference:

   b. for destructive interference:

23. The equation for double slit wave interference is $s = \frac{\lambda D}{d}$. Define the following variables and draw a neat and detailed *intensity vs. displacement* graph for double slit interference:

   a. s: distance between maximum intensities (or bright spots)

   b. λ: wavelength of wave entering the double slit

   c. D: distance from double slit to screen

   d. d: distance between two slits

Additional HL Content

24. **Use a pencil!** Draw the lab setup and the intensity vs. distance graph for single slit diffraction.

25. Derive the equation $\theta = \frac{\lambda}{b}$. Define each variable.

26. What will happen to the thickness of the central maximum $2\theta = \frac{2\lambda}{b}$ if
    a. the wavelength λ of a wave passing through a single slit is increased?

    b. the wavelength λ of a wave passing through a single slit is decreased?

    c. the opening of a single slit b is increased?

    d. the opening of a single slit b is decreased?

27. What happens when white light passes through a single slit?

28. **Use a pencil!** Draw the lab setup and the intensity vs. displacement graph for Young's double slit experiment.

29. State the equation for double slit **constructive interference** and define each variable.

30. State the equation for double slit **destructive interference** and define each variable.

31. What happens to the intensity pattern as the number of slits increases?
https://www.geogebra.org/m/g6fsxcyn

32. **Use a pencil and ruler!** Carefully draw an *intensity vs. distance* graph for the following number of slits:

One slit
Two slits

Three slits
Four slits
Five slits

Six slits

33. What is a *diffraction grating*? What is its purpose?
https://www.geogebra.org/m/g6fsxcyn

34. Describe the equation $n\lambda = d\sin\theta$ for multiple slit diffraction.
https://www.geogebra.org/m/g6fsxcyn

35.Describe the meaning of the single slit *envelope*.

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C.4 Standing Waves and Resonance

Understandings

- The nature and formation of standing waves in terms of superposition of two identical waves traveling in opposite directions.
- Nodes and antinodes, relative amplitude, and phase difference of points along a standing wave.
- Standing waves patterns in strings and pipes.
- The nature of resonance including natural frequency and amplitude of oscillation based on driving frequency.
- The effect of damping on the maximum amplitude and resonant frequency of oscillation.
- The effects of light, critical, and heavy damping on the system.

You need to watch animations on ***standing waves*** to perfectly understand it!:

https://www.acs.psu.edu/drussell/Demos/StandingWaves/StandingWaves.html

Topics C.1-C.3 dealt with **traveling waves**.
Topic C.4 deals with **standing waves**.
Please treat **standing waves** and **traveling waves** differently!

There are three popular examples of standing waves:

- Waves on a string (guitar) (closed closed)
- Sound waves in a pipe (flute) (open closed or open open)
- A vertical pipe with the top end open and the bottom end in water. The vertical pipe can be raised and lowered to change its length. A tuning fork is placed on top of the vertical pipe. (open closed)

The solutions can be found on the YouTube channel Go Physics Go:

https://www.youtube.com/@gophysicsgo/playlists

1. List some observations which can be made from standing waves but not traveling waves.

2. Define the following terms:

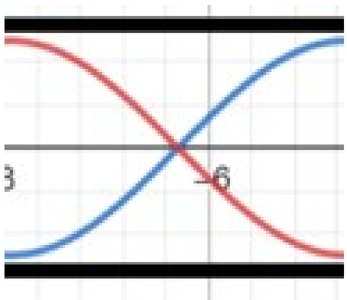
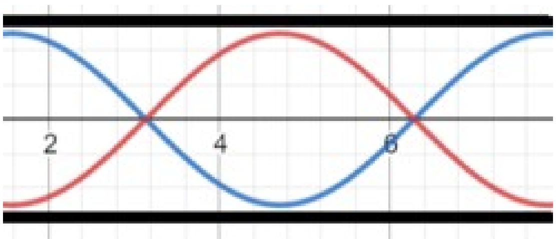
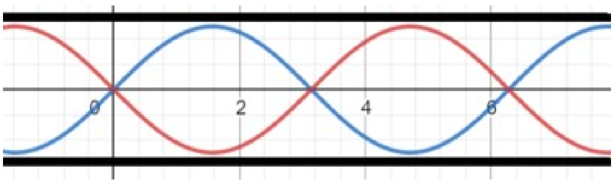
    a. Node:

    b. Anti-node:

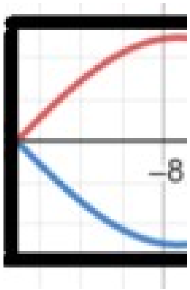
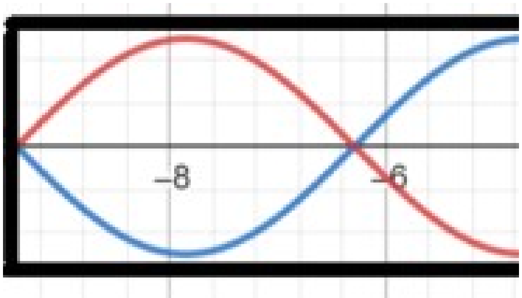
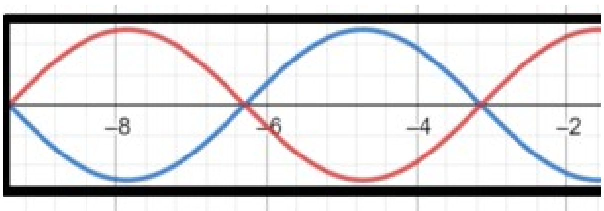
    c. First harmonic:

    d. Fundamental frequency:

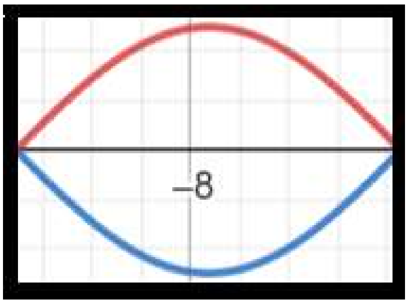
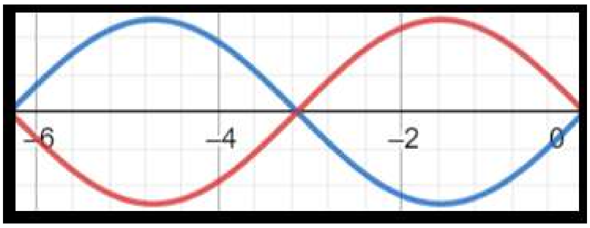
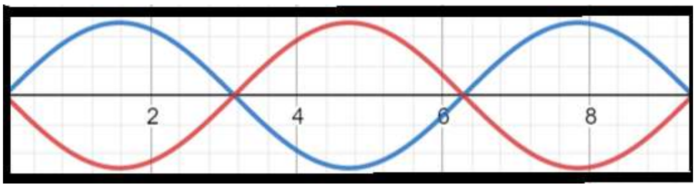
3. **Use a pencil and ruler!** Below are the first three harmonics of a tube with both ends open. The frequencies of the first three harmonics are derived for you. Draw and solve for the next three frequencies on the next page.

 Image from https://www.geogebra.org/	$L = \frac{\lambda}{2}$ $\lambda = 2L$ $v = \lambda f$ $v = 2Lf$ $f = \frac{v}{2L}$
	$L = \lambda$ $\lambda = L$ $v = \lambda f$ $v = Lf$ $f = \frac{v}{L}$
	$L = \frac{3\lambda}{2}$ $\lambda = \frac{2L}{3}$ $v = \lambda f$ $v = \frac{2Lf}{3}$ $f = \frac{3v}{2L}$

4. **Use a pencil and ruler!** Below are the first three harmonics of a tube with one end open and one end closed. The frequencies of the first three harmonics are derived for you. Draw and solve for the next three frequencies on the next page.

 Image from https://www.geogebra.org/	$L = \frac{\lambda}{4}$ $\lambda = 4L$ $v = \lambda f$ $v = 4Lf$ $f = \frac{v}{4L}$
	$L = \frac{3\lambda}{4}$ $\lambda = \frac{4L}{3}$ $v = \lambda f$ $v = \frac{4Lf}{3}$ $f = \frac{3v}{4L}$
	$L = \frac{5\lambda}{4}$ $\lambda = \frac{4L}{5}$ $v = \lambda f$ $v = \frac{4Lf}{5}$ $f = \frac{5v}{4L}$

5. **Use a pencil and ruler!** Below are the first three harmonics of a tube with both ends closed. The frequencies of the first three harmonics are derived for you. Draw and solve for the next three frequencies on the next page.

 Image from https://www.geogebra.org/	$L = \frac{\lambda}{2}$ $\lambda = 2L$ $v = \lambda f$ $v = 2Lf$ $f = \frac{v}{2L}$
	$L = \lambda$ $\lambda = L$ $v = \lambda f$ $v = Lf$ $f = \frac{v}{L}$
	$L = \frac{3\lambda}{2}$ $\lambda = \frac{2L}{3}$ $v = \lambda f$ $v = \frac{2Lf}{3}$ $f = \frac{3v}{2L}$

6. What is a *restoring force*?

7. What are some characteristics for *simple harmonic motion?*

8. Define *free oscillation.*

9. **Use a pencil!** Label and draw a displacement vs. time graph for a *free oscillation.*

10. Define *damping.*

11. Define *underdamping* (or *light damping*).

12. **Use a pencil!** Label and draw a graph for an *underdamped system.*

13. Define *overdamped motion*.

14. **Use a pencil!** Label and draw a graph for *overdamped* motion.

15. Define *critically damped motion*.

16. **Use a pencil!** Label and draw a graph for a *critically damped system.*

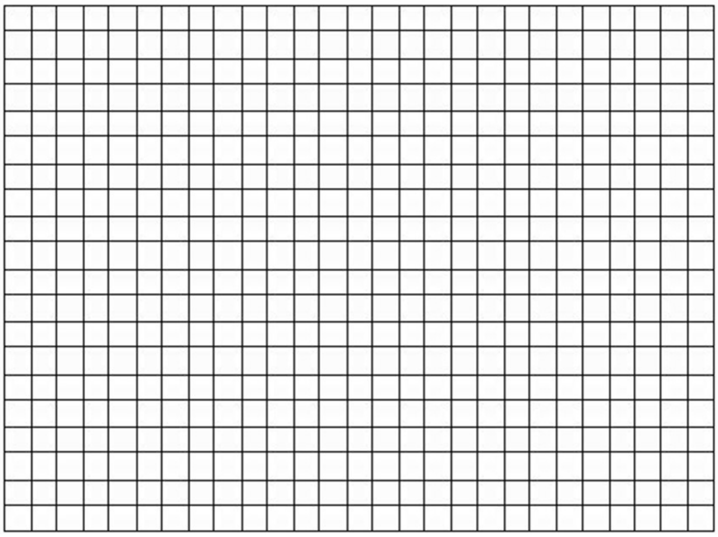
17. What is a *driving force?*

18. Define *natural frequency.*

19. What happens to the amplitude of an object when the *natural frequency* of the object is much lower or much higher than the *driving frequency*?

20. What happens to the amplitude of an object when the *natural frequency* of the object is approximately equal to the *driving frequency*?

21. Draw an *amplitude vs. frequency* graph of an object oscillating with a driving force and a damping force.



22. Define *resonance.*

23. List some effects of resonance in the real world.

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C.5 Doppler Effect

Understandings

- The nature of the Doppler effect for sound waves and electromagnetic waves.
- The representation of the Doppler effect in terms of wavefront diagrams when either the source or the observer is moving.
- The relative change in frequency or wavelength observed for a light wave due to the Doppler effect where the speed of light is much larger than the relative speed between the source and the observer as given by $\frac{\Delta f}{f} = \frac{\Delta \lambda}{\lambda} \approx \frac{v}{c}$.
- Shifts in spectral lines provide information about the motion of bodies like stars and galaxies in space.

Equations

$$\frac{\Delta f}{f} = \frac{\Delta \lambda}{\lambda} \approx \frac{v}{c}$$

Additional HL Understandings

- The observed frequency for sound waves and mechanical waves due to the Doppler effect as given by:
  moving source $f' = f\left(\frac{v}{v \pm u_s}\right)$ where u_s is the velocity of the source
  moving observer $f' = f\left(\frac{v \pm u_o}{v}\right)$ where u_o is the velocity of the observer.

Additional HL Equations

Moving source: $f' = f\left(\frac{v}{v \pm u_s}\right)$

Moving observer: $f' = f\left(\frac{v \pm u_o}{v}\right)$

The solutions can be found on the YouTube channel Go Physics Go:

https://www.youtube.com/@gophysicsgo/playlists

1. Define the *Doppler effect*.

2. **Use a pencil!** Draw a wavefront diagram for a moving source and stationary observer in front of the source and behind the source.

3. **Use a pencil!** Draw a wavefront diagram for a stationary source and moving observer in front of the source and behind the source.

4. Describe the equation $\frac{\Delta f}{f} = \frac{\Delta \lambda}{\lambda} \approx \frac{v}{c}$ and define each variable.

5. Describe the term *red shift*.

6. Describe the term *blue shift*.

7. Describe the term *expanding universe*.

Additional HL Content

8. Describe the equations for the Doppler effect given in the IB physics data booklet.

9. Late to class! Usain Bolt runs towards his physics class with a constant speed of 9.58 m/s while blasting music from his boom box which emits a frequency of 440 Hz. What is the observed frequency and wavelength detected by the students in his physics classroom? The speed of sound in air at sea level is approximately 340.29 m/s.

10. Class ends! Usain Bolt runs away from his physics class towards the cafeteria with a constant speed of 9.58 m/s while blasting music from his boom box which emits a frequency of 440 Hz. What is the observed frequency and wavelength detected by the students in his physics classroom? The speed of sound in air at sea level is approximately 340.29 m/s.

11. Late to class! Usain Bolt runs towards his physics class with a constant speed of 9.58 m/s. He can hear his physics teacher lecturing with frequency of 440 Hz. What is the observed frequency and wavelength detected by Usain Bolt as he is running towards his physics class? The speed of sound in air at sea level is approximately 340.29 m/s.

12. Class ends! Usain Bolt runs away from his physics class to the cafeteria with a constant speed of 9.58 m/s. He can hear his teacher continue to lecture with frequency of 440 Hz. What is the observed frequency and wavelength detected by Usain Bolt as he is running towards the cafeteria? The speed of sound in air at sea level is approximately 340.29 m/s.