Lesson Title	12. & 13. Medical Scans (Problems and Learning Tasks)
Lesson Designer	Peter Dufner
Standards	☐ CCSS ☑ NGSS ☐ ASCA ☐ Other HS-PS2-6 Motion and Stability: Forces and Interactions Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials. HS-PS4-1 Waves and their Applications in Technologies for Information Transfer Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media. HS-PS4-4 Waves and their Applications in Technologies for Information Transfer Evaluate the validity and reliability of claims in published materials of the effects that different frequencies of electromagnetic radiation have when absorbed by matter.
Learning Objectives	Students will explain basic wave properties and how waves can be used to create useful images of the human body through medical scans such as ultrasounds and X-rays.

Timeline	Duration
Day 1: Wave properties notes and worksheet (45 minutes) Day 2: Medical scans activity (45 minutes) Day 3: Medical imaging worksheet (30 minutes)	2-3 days

Teaching Strategies/Student Actions	Monitoring
Students can be given the notes sheet to read for information, or the instructor can use the notes as a basis for necessary information. The waves worksheet will be used to assess students understanding of wave properties. The wave activity uses an online simulation to help show reflection and transmission of waves, along with linking the information to x-rays and ultrasounds. Students will examine x-rays and connect their previous understandings of wave properties to the images they are seeing. The final worksheet has students perform the wave calculations in the context of medical imaging. This can be done as a class, or individually as either homework or classwork.	• Teacher monitors student progress • Teacher facilitates discussion • Teacher questioning

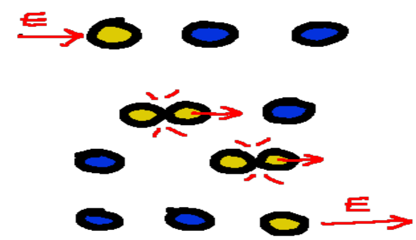
Product Description	
Evaluation	Students should be able to describe the differences between electromagnetic waves based off their properties such as wavelength and frequency. Students should be able to describe different uses of waves, and how the wave's unique properties are utilized for that purpose through the completion of the activities and worksheets.

Resources and Materials	Additional Notes
• Wave properties notes • Wave properties worksheet • Medical scans activity • Medical imaging worksheet	

Wave Properties Notes

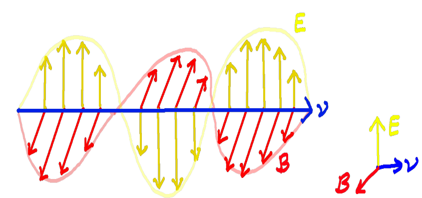
Waves are a travelling disturbance of energy. In physics a wave is not a physical object, but is instead a disturbance seen due to energy travelling from one place to another. These waves can be sorted into two broad categories, **mechanical** and **electromagnetic** waves.

Mechanical waves are seen as a travelling disturbance in a medium, such as air or water. A mechanical wave cannot travel through a vacuum, because they rely on the atoms of the medium knocking against each other to transfer the kinetic energy brought by the wave. An example of a mechanical wave is sound. **Sound** is created when the molecules in the air vibrate, sending shockwaves through the air (or whatever other medium the sound is created in). The molecules don't really move from their original position, but instead just ripple and push the molecules next to them.



Atoms collide in a mechanical wave, transferring energy between them.

Electromagnetic waves are different from mechanical waves in that they do not need a medium. Electromagnetic waves are created through a cycling effect created from the intimate relationship of electricity and magnetism. A moving electric field generates a magnetic field, and that moving magnetic field then creates an electric field. These fields continue to propagate, sending a wave out into the space around them. Since these waves do not need the vibration of any other atoms around them, they can successfully travel through a vacuum on their own. Light and x-rays are examples of electromagnetic waves.



An electromagnetic wave is propagated by the magnetic field (B) and electric field (E) moving through space

No matter the type of wave, they all have the same basic wave properties. Each wave will have a certain **frequency** (f). The frequency of a wave is the amount of wave cycles per second that it creates. Frequency is measured most often in Hertz (Hz), but is sometimes written with the unit $\frac{1}{second}$ or s^{-1}.

Frequency is also known as the inverse of the wave **period** (T), which is the time it takes for one wave cycle to complete. Period is measured in seconds, and can be calculated by using the formula $f = \frac{1}{T}$ where f is the frequency of the wave, and T is the period of the wave.

Each wave will also have a certain **wavelength** (λ) measured in meters. The wavelength is the length of one complete wave cycle. Waves with a larger wavelength tend to have smaller frequencies. This is because the **velocity** (v) of a wave is determined by the type of wave and the medium it travels through. Each wave will have a velocity that can be calculated using the equation $v = f\lambda$ where v is the velocity, f is the frequency of the wave, and λ is the wavelength of the wave.

Sample Calculation:	
A laser pointer is able to create a beam of red light with a wavelength of $685\ nm$ and travels through the air at a velocity of $3 * 10^8\ m/s$. What is the frequency of this light?	
Given Information:	**Known Formula:**
$\lambda = 685\ nm$ $v = 3 * 10^8\ m/s$ $f = ?$	$v = f\lambda$
Calculations:	

First we will want to make sure our units match. We have a wavelength in nm and a velocity in m. We will convert the wavelength to meters, since we know $1 * 10^9\ nm = 1\ m$

$$685\ nm * \frac{1\ m}{1 * 10^9\ nm} = 6.85 * 10^{-7} m$$

Now we use our velocity of a wave formula, but first we have to rearrange to solve for our wanted variable of f.

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

$$\frac{3 * 10^8}{6.85 * 10^{-7}} = \boldsymbol{f = 4.38 * 10^{14}\ Hz}$$

Knowing the frequency, wavelength, and velocity of a wave is important since it determines the properties of the wave. Electromagnetic waves are actually sorted into something called the **electromagnetic spectrum**, which is sorted by the frequency or wavelength of the wave. For all electromagnetic waves the velocity of the wave in a vacuum is the speed of light, $c = 3 * 10^8 \ \frac{m}{s}$. This means the defining property that differentiates different electromagnetic waves is their frequency or wavelength.

Radio	Microwave	Infrared	Visible Light	Ultraviolet	X-Ray	Gamma
Lowest f	→Increasing Frequency→					Highest f
Highest λ	→Decreasing Wavelength→					Lowest λ
Lowest Energy	→Increasing Energy→					Highest Energy

Radio waves are the largest wavelength and lowest energy waves on the electromagnetic spectrum. These are the generally considered any wave with a frequency of $3 * 10^9 \ Hz$ or lower. These are the same radio waves that are used for AM and FM radios, and because of their large wavelengths they can be reliably used to transmit information through the atmosphere.

Microwaves are another familiar name, and are the next highest frequency wave on the electromagnetic spectrum. Microwaves have a frequency between $3 * 10^9 \ Hz$ and $3 * 10^{12} \ Hz$. These microwaves are used to warm up your food in a microwave oven, but are also part of the larger cosmic background radiation left over from the big bang.

Infrared is also sometimes called *heat rays*, and are the next higher frequency wavelength. Infrared is categorized as between $3 * 10^{12} Hz$ and $4 * 10^{14} \ Hz$. When night vision goggles are used, they are visualizing the infrared waves emitted by a hot object.

Visible light ranges from $4 * 10^{14} \ Hz$ and $7 * 10^{14} \ Hz$. The colors we know as the colors of the rainbow are arranged within this band of frequencies. Red light has the largest wavelength of the visible lights. An easy way to remember this is that *infra*red is placed right below red light when the electromagnetic spectrum is organized by frequency. Red, orange, yellow, blue, indigo, and violet divide up the visible spectrum with each color being higher frequency and higher energy.

Ultraviolet is the electromagnetic wave with the next highest frequency after the color violet. Ultraviolet waves are sometimes called UV rays, and are responsible for getting sunburnt in the sunlight. These waves have a frequency range of $7 * 10^{14} \ Hz$ to $3 * 10^{16} \ Hz$.

X-Rays are the next highest frequency after UV light, and have a frequency of $3 * 10^{16} \ Hz$ to $3 * 10^{17} \ Hz$. These electromagnetic waves are used to visualize body tissues and bones, along with performing security scans at airports and other checkpoints.

Gamma rays are the highest frequency electromagnetic waves, claiming any wave with a frequency of $3 * 10^{17} \ Hz$ or greater. These rays can be very dangerous to living cells, and are used to sterilize medical equipment.

With increasing frequency, these electromagnetic waves become more energetic. To quantify how much energy each wave is able to transmit, we use the term **photon energy** (E). This photon energy expresses how much energy is carried by a single photon and is measured in either Joules (J) or electronvolts (eV). The photon energy of an electromagnetic wave can be calculated using the formula $E = \frac{hc}{\lambda}$ where E is the photon energy, h is the Planck constant of $6.62 * 10^{-34} Js$, c is the speed of light in a vacuum which is $3 * 10^8 \ m/s$, and f is the frequency of the electromagnetic wave.

Sample Calculation:

What is the most energy that infrared light can transmit through a vacuum? Infrared light ranges from a frequency of $3 * 10^{12} Hz$ to $4 * 10^{14}\ Hz$.

Given Information:	Known Formula:
$3 * 10^{12}\ Hz < f < 4 * 10^{14}\ Hz$ $E = ?$	$v = f\lambda$ $E = \frac{hc}{\lambda}$

Calculations:

We know that the highest energy will occur at the highest frequency possible, so we will make the frequency of this light $4 * 10^{14}\ Hz$. *We know that all electromagnetic waves travel through a vacuum at the speed of light, so* $v = c = 3 * 10^{8}\ m/s$..

Rearrange the $v = f\lambda$ *equation to solve for* λ *so it can be plugged into the photon energy equation.*

$$v = f\lambda$$
$$\frac{v}{f} = \frac{f\lambda}{f}$$
$$\frac{v}{f} = \lambda$$
$$\frac{3 * 10^{8}}{4 * 10^{14}} = 7.5 * 10^{-7}\ m = \lambda$$

Plug our wavelength, Planck constant, and velocity into the photon energy equation to solve.

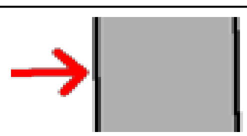
$$E = \frac{hc}{\lambda}$$
$$E = \frac{(6.6.2 * 10^{-34})(3 * 10^{8})}{(7.5 * 10^{-7})} = 2.65 * 10^{-19}\ J$$

Each photon of red light can transfer $2.65 * 10^{-19}\ J$ of energy.

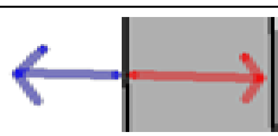
When electromagnetic waves hit a surface, there is chance that the surface will **<u>absorb</u>** some of the energy from the wave. This is similar to the reason why a black shirt will feel warmer than a white shirt in the sunlight, since the black shirt is able to *absorb* more energy from the infrared radiation from the sun than the white shirt. This is a reason why the higher energy electromagnetic waves are more dangerous than the low energy electromagnetic waves on the electromagnetic spectrum. Beginning with higher energy ultraviolet light and above, electromagnetic waves with high enough energy to ionize atoms are called **<u>ionizing radiation</u>**. These radiations can cause harm to living tissue when the energy from the wave is absorbed by the atoms within a living cell. Below the ultraviolet spectrum is called **<u>nonionizing radiation</u>** since the waves do not carry enough energy to ionize cells on their own.
If an electromagnetic wave hits a surface and is not absorbed, it can be reflected off of the surface, transmitted through the surface, or diffracted around the surface. **<u>Transmission</u>** through the substance allows the waves to transmit through the new surface. This is normally not a 100% transmission, with some of the wave also being diffracted or reflected off the surface as the wave crosses the boundary between the mediums.

Some of the waves will **<u>reflect</u>** off the surface, bouncing as the wave hits the boundary between the medium. The reflected wave will reflect from the surface at the same incident angle that the incoming wave had as it hits the surface.

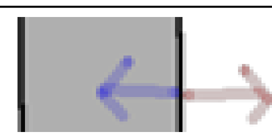
Waves can also **<u>diffract</u>** or bend around an object. **<u>Diffraction</u>** allows the waves to bend around the edges of an object, spreading the wave into the shadow region behind the object and changing the direction of the wave. The amount of diffraction increases with higher wavelength, causing a smaller wavelength wave to change direction during diffraction less than a higher wavelength wave.



<u>Step 1</u> : The incoming wave strikes the surface.



<u>Step 2:</u> Some of the incoming wave reflects off the surface, while the rest is transmitted into the object or absorbed.



<u>Step 3</u>: Some of the wave reflects off the other side, while the rest is transmitted out of the object or absorbed.

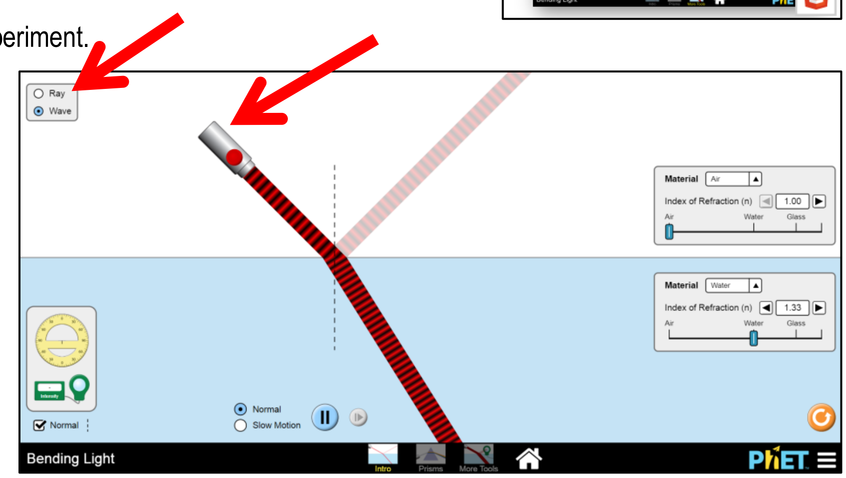
Ultrasound Learning Task

The human ear can hear sounds generally between 20 Hz and 200,000 Hz. Above that range, sounds are called ultrasonic. These sounds can be heard by certain animals such as dogs and bats, but are undetectable to most humans. Ultrasound transmitters can be used to release sounds of varying frequency about the 200,000 Hz mark, and can be used to create an ultrasound image. Sound waves are released into the human body, where they will transmit through until they hit a boundary between materials such as the walls of an organ or the surface of a bone. At that boundary the ultrasonic waves will split, some of the wave reflects back to the transmitter and some transmitting through the new medium. This process will repeat across every boundary along the way.

The transmitter is able to record the time it takes for each wave pulse to return back to the transmitter, and using the known frequency of the wave calculate how far the wave had to travel before it reflected backward. This allows the machine to create a virtual “map” of the body boundaries encountered.

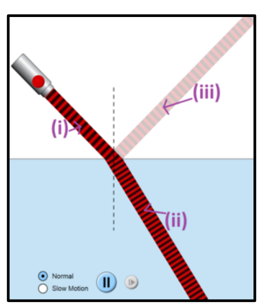
In order to see how waves, such as the sound waves used in ultrasounds interact with surfaces in the body we will use a simulation on the bending of light.

1. Go to: https://phet.colorado.edu/en/simulation/bending-light or search for “PhET Bending Light Simulation”
2. Click on the play button shown here to start the simulation.
3. Click on the “Intro” button to begin the simulation experiment.
4. Click the “Wave” button in the top left and then the red button on the laser pointer to fire the beam.
    a. What happens to the wave when it hits the surface of the water?
    b. Why is the beam below the water darker than the outgoing beam above the water?



    c. Measure the intensity of the beam at each point (i), (ii), and (iii).

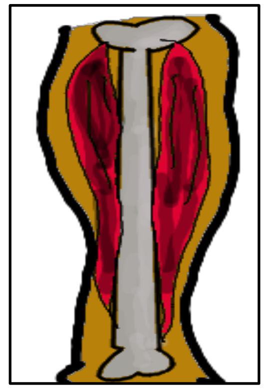
Location	Intensity
(i)	
(ii)	
(iii)	



    d. The beam below the water underwent:
        a. Transmission
        b. Reflection
        c. Absorption
        d. Diffusion

    e. The outgoing beam above the water underwent:
        a. Transmission
        b. Reflection
        c. Absorption
        d. Diffusion

5. Change the angle of incident (the angle that the beam hits the water with).
    a. What happens to the intensity of the reflected beam as you increase the angle to $90°$ above the horizontal?
    b. What happens to the intensity of the reflected beam as you decrease the angle to $0°$ above the horizontal?
    c. What happens to the beam below the surface as the incident angle approaches $0°$?
6. Increase the index of refraction for the lower substance while keeping the top substance the same.
    a. What happens to the intensity of the reflected beam?
    b. Explain why this may happen.
7. Decrease the index of refraction for the lower substance while keeping the top substance the same.
    a. What happens to the intensity of the reflected beam?
    b. Explain why this may happen.
8. Higher index of refraction substances often also have higher densities. Order the substances from least dense to most dense.
9. What would happen to the ultrasonic sound waves used during an ultrasound as they hit a barrier between an organ and a body cavity?



10. Look at the cartoon image of a leg shown. Imagine a transmitter is placed directly on the left side of the leg, touching the skin.
    a. What will reflect sound back to the transmitter of the ultrasound before the sound waves leave the other side of the person?

    b. Which part do you believe will cause the most reflection of sound? Explain your answer.

    c. How many times will the transmitter record sound bouncing back before it leaves the body?

    d. Mark on the image where the beams will reflect backward with an X.

11. Ultrasounds are used to image fetus because the waves are low enough energy that they do not cause harm to the living cells in the body.
    a. A gel is spread across the skin, and then the probe (transmitter) is placed directly on the skin. Why would you not want to hold the transmitter off the skin when using an ultrasound?

    b. Will an empty cavity show up on an ultrasound? Why or why not?

    c. What is one use other than imaging a baby that an ultrasound could be used for?

X-Rays Learning Task

X-Rays are another type of medical imaging that is done using waves. X-rays are created and sent into the body, where they collide with tissue and cells along the way. Some of the x-rays are absorbed as they collide with the cells, causing the intensity of the x-ray to weaken. The x-rays that manage to pass through the object will hit a screen placed behind the subject, working similar to exposed camera film. Areas of the film with high exposure to x-rays appear dark, while areas of low exposure appear bright. The denser the tissue or substance, the more x-rays are absorbed. This is why most people commonly think of broken bones as being the reason to get an x-ray. X-rays are considered dangerous, as they are able to ionize tissues within the human body. X-rays are normally only done when necessary, and a lead vest is used to protect vital areas that do not need the exposure.

1. Order the following substances from least dense to most dense.

Substances (not in order)	Steel	Bone	Air	Soft Tissues	Fat

Ordered Substances	**Least Dense**	→			**Most Dense**

2. On an x-ray, which of the substances above would show up as a dark region on the film?

3. On an x-ray, which of the substances above would show up as a bright white region on the film?

4. A thicker material will also absorb more x-rays, since there are more cells to absorb as the wave travels through the body. How might this complicate reading an x-ray?

5. Why would a lead vest be able to protect the tissue underneath from the x-rays?

6. Look at the image provided.
   a. Which region of this x-ray film received the highest exposure to x-rays?

   b. Why did the other regions of this x-ray film receive lower exposure to x-rays?

   c. Which part of this x-ray is the densest?

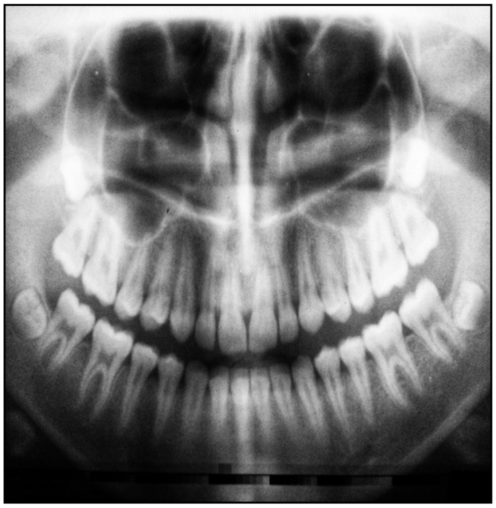
   d. What types of materials are seen here?

   e. Why does the x-ray not show clean, crisp lines for the edge of the skin like it does for the bones?

7. Look at the image provided:
   a. What is this an x-ray of?

   b. The background of this film is white instead of black; this is because the photo shown is the negative of an x-ray film. Knowing that, where is the densest part of this object?

8. Look at the image provided:



   a. How many teeth does this person have?
   b. Why are the teeth not one solid color?
   c. Why would your dentist take multiple x-rays instead of just using this one?
   d. The region above the teeth is dark. That means that the region is:
   e. What is likely seen as the dark region above the teeth in this image?

Waves Worksheet

Fill in the blanks in the following section using the words from the word bank provided. No term in the word bank should be used more than once.

Word Bank #1-#5		
Electromagnetic	Wavelength	Frequency
Photon Energy	Hertz	Ionizing
Electromagnetic Spectrum	Diffraction	Mechanical

16. ________________ waves require a medium, while ________________ waves can exist in a vacuum.
17. ________________ is the inverse of period and is measured in ________________.
18. The ________________ organizes electromagnetic waves by their frequency or ________________.
19. ________________ radiation has enough ________________ that it can ionize atoms that it collides with.
20. ________________ is when a wave bends around an object.

Mark each statement as either (T) true or (F) false. If the statement is false, correct the statement as best you can to make it true.

21. _____ A wave with a high frequency will have a small wavelength.

22. _____ Mechanical waves travel at the speed of light, $c = 3 * 10^8\ m/s$ through a vacuum.

23. _____ Visible light has a wavelength between $4 * 10^{14}\ Hz$ and $7 * 10^{14}\ Hz$.

24. _____ Gamma rays are the highest energy electromagnetic wave found on the electromagnetic spectrum.

25. _____ When a wave is absorbed by a surface the surface will gain energy proportional to the frequency of the incident wave.

Answer the following questions by choosing the one best answer to each.

11. Which of the following waves has the largest wavelength?
    a. Gamma
    b. X-ray
    c. Microwaves
    d. Infrared

12. Which of the following is not able to travel through a vacuum?
    a. Sound
    b. X-rays
    c. Visible light
    d. Radio

13. Which of the following is not a possible result of waves hitting a surface boundary?
    a. Reflection
    b. Transmission
    c. Absorption
    d. Relaxation

14. Which of the following types of electromagnetic wave is classified as ionizing radiation?
    a. Infrared
    b. Ultraviolet
    c. Microwave
    d. Radio

15. Which of the following waves is caused by molecules vibrating and pushing on other nearby particles?
    a. Sound
    b. Microwaves
    c. Visible light
    d. X-ra

Answer the following questions to the best of your ability, making sure to clearly mark your answer and appropriate unit.

16. The human eye is only able to see a light with a frequency greater than or equal to $4.0 * 10^{14}\ Hz$, and less than or equal to $7.9 * 10^{14}\ Hz$.
    a. What color is the lowest visible frequency?

    b. What color is the highest visible frequency?

    c. How fast does light travel through a vacuum?

    d. What is the smallest wavelength of light that is visible to the human eye?

    e. What is the largest wavelength of light that is visible to the human eye?

17. An incoming electromagnetic wave has photon energy of $2.32 * 10^{-17} J$ travelling through a vacuum.
    f. What is the wavelength of this electromagnetic wave?

    g. What is the frequency of this electromagnetic wave?

    h. What type of electromagnetic wave is this?

18. An unknown electromagnetic wave is measured to have a period of $2.67 * 10^{-14}\ s$.
    i. What is the frequency of this electromagnetic wave?

    j. What is the wavelength of this electromagnetic wave as it travels through a vacuum?

    k. How much photon energy does this wave have?

    l. What type of electromagnetic wave is this wave?