How Do We Use Electromagnetic Waves to Cook Food?

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Electromagnetic (EM) waves are all around us, though we can only see a small range of them, they can be used to cook our food, allow cell phones to communicate with each other, and permit us to see inside the human body. This curriculum unit is designed to teach 9^{th}-grade students about EM waves using the microwave and conventional ovens as examples. In this two-week unit, students will learn the physics and chemistry behind how a microwave oven uses microwave radiation and a conventional oven uses infrared radiation to make their food hot.

In order to accomplish this, students will first become acquainted with the electromagnetic spectrum and the idea that the shorter the wavelength, the higher the energy of the EM wave. Next, students will be exposed to how a microwave oven creates and uses microwaves to heat water inside food. Following this will be a lesson on what exactly heat (or thermal energy) is and how heat is related to molecular motions.

The purpose of this unit is to make EM waves of different wavelengths apparent in students' everyday lives. This will be accomplished by using devices that students are already familiar with and most likely take for granted –microwave and conventional ovens. Students come into the classroom with the understanding that the microwave oven makes their food hot but without knowing why or how this happens at a molecular level. This unit will give the students real-world context for applications of microwaves and infrared waves.

Understanding wave properties and EM waves is relevant to students because EM waves are used for many purposes and surround us every day. These EM waves are used for technology. There are valid health and safety concerns with exposure to some higher frequency waves, such as ultraviolet radiation, x-rays, and gamma rays. This unit will explore why the microwaves in the microwave oven and infrared radiation from the conventional oven do not have the same safety concerns as the higher energy EM waves.

Wilbur Cross is a large high school with a diverse student body. Students come from a diverse range of socioeconomic backgrounds as well as many different races and ethnicities. Currently, there are three main instructional foci: HOTs or higher order thinking skills, students to student discourse, and using evidence to support claims. The schedule follows a block schedule with four periods a day and rotating A and B days. Thus, the curricular activities in this unit cater to an 80-minute period. The district's science sequence is that students begin with phychem, then biology and chemistry. After chemistry, there are science electives or advanced placement courses offered.

Students at Wilbur Cross High School are required to take three science courses with phychem as the first in the sequence. Phychem is an integrated science course that focuses on weather and climate, natural resources, wave properties, electricity and magnetism. The course focuses on electromagnetic and mechanical waves in the third marking period with an additional concentration on the application of electromagnetic (EM) waves. Following a unit on mechanical waves and general wave properties, students will be introduced to the EM spectrum.

Waves Background

Before beginning this unit on EM waves, students will have been exposed to the following vocabulary and concepts in a previous unit. What is a wave? A wave is a disturbance that transfers energy through matter or space. There are two types of waves: mechanical and electromagnetic (EM) waves. A mechanical wave is a type of wave that requires a medium for propagation while electromagnetic waves are a type of wave made of changing electric and magnetic fields and does not require a medium for propagation.[1] Examples of mechanical waves include earthquakes, water waves, and sound waves because each of these waves requires a medium or matter to travel through. There are two types of mechanical waves longitudinal and transverse waves. Transverse waves are waves in which the wave motion is perpendicular to particle motion while longitudinal waves are waves in which wave motion is parallel to the particle motion.[2] The difference between these two waves is nicely demonstrated with a slinky. Sound waves are examples of longitudinal while ripples on the surface of water are an example of transverse waves. All EM waves are transverse waves.

A transverse wave has the following properties and often looks like the following figure. The high point of a transverse wave known as the crest while the low point of a transverse wave is known as the trough. The amplitude of a wave is the greatest distance particles are displaced from their normal resting position. A wavelength is the distance between two identical parts of a wave. Frequency of a wave is the number of waves passing a given point in a given amount of time measured in the unit of hertz (Hz). A period is different from frequency because it is the time required for one full wavelength of a wave to pass a certain point.[3]

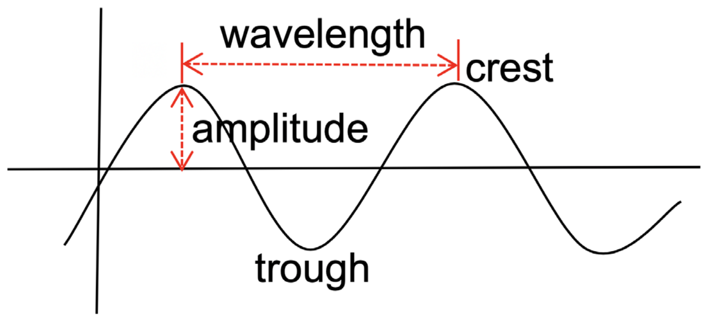

Figure 1: This diagram shows the characteristics of a transverse wave.

Another concept important to this unit about EM waves is wave interference. Interference occurs when multiple waves in the same location combine to create a single new wave that is different from the original waves.[4] Two types of interference include constructive interference and destructive interference. When the crest of one wave overlaps the crest of another wave they reinforce each other and the amplitude increases. This type of interference is known as constructive interference. Destructive interference decreases the amplitude when the crest of one wave meets the trough of another. The resulting wave has an amplitude smaller than the amplitude of the larger of the two original waves. A third type of wave interference is the creation of a standing wave. A standing wave is the result of interference between a wave and its reflected wave. The result of a standing wave is that the medium vibrates in a stationary pattern that looks like a loop or a set of loops.[5] These are all the vocabulary and concepts that students will need to learn before the unit on EM waves presented here.

Electromagnetic Waves Background

Electromagnetic waves are able to travel through empty space and do not require a medium. They are made up of oscillating electric and magnetic fields.[6] These fields are travelling perpendicular to one another.

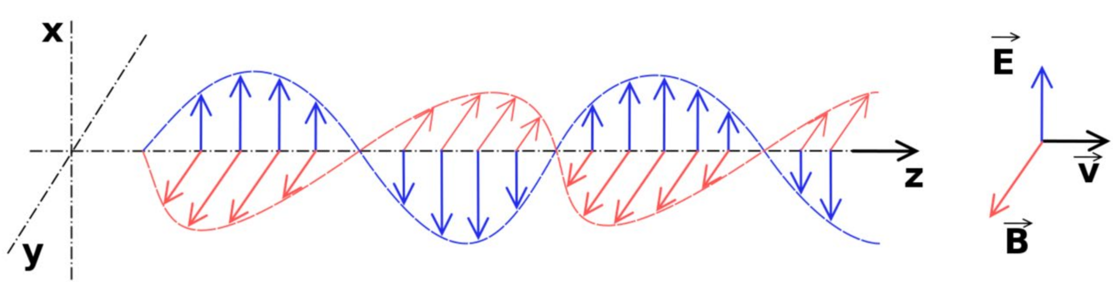

Figure 2: Electromagnetic waves are made of oscillating electric and magnetic fields at right angles to one another (https://en.wikipedia.org/wiki/File:Onde_electromagnetique.svg).

The energy of EM waves is determined by the wavelength and frequency of these transverse waves. A wavelength is the distance between two identical points on a wave, e.g., two neighboring crests or troughs. Frequency is the number of complete waves passing a given point in a given amount of time measured in hertz (Hz).

Regions of the electromagnetic spectrum from lowest energy, lowest frequency and longest wavelength to highest energy, highest frequency and shortest wavelength are radio waves, microwaves, infrared radiation, visible light, ultraviolet light, x-rays and gamma rays. Each region has its applications.

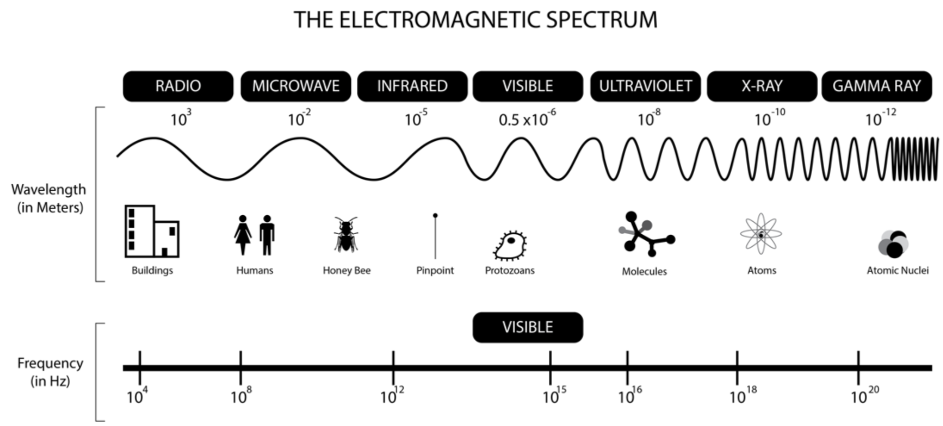

Figure 3: The electromagnetic (EM) spectrum with the seven regions in the order from the longest wavelength to the shortest wavelength with examples of applications. Also included are the frequency ranges for each region of the spectrum.[7]

Name of Region	**Range of Frequency (20)**	**Applications**	**Length Scale**
Radio waves[8]	$< 3 \times 10^{9}$ Hz	Radios, television and radar signals.	From about the length of a football to larger than the statue of liberty
Microwaves[9]	$3 \times 10^{9} - 3 \times 10^{11}$ Hz	Microwave ovens to cook food	A baseball
Infrared[10]	$3 \times 10^{9} - 4 \times 10^{14}$ Hz	TV remote	Diameter of a human hair.

Visible Light[11]	$4x10^{14}$- $7.5x10^{14}$Hz	Only range we can see	Thickness of a soap bubble membrane
Ultraviolet[12]	$7.5x10^{14}$- $3x10^{16}$	Causing a sunburn and killing bacteria	Diameter of the rhinovirus.
X-Rays[13]	$3x10^{16}$ - $3x10^{19}$Hz	Making images of bones	Diameter of an atom
Gamma Rays[14]	>$3x10^{19}$Hz	Released during nuclear reactions	Nucleus of an atom

Energy of an Electromagnetic Wave

As one moves along the electromagnetic (EM) spectrum from longer wavelengths, such as radio waves, to shorter ones, such as gamma rays, both frequency and energy increase. But why is this? All EM waves travel at the speed of light, which is about 3 x 10^8 m/s in vacuum. To calculate the speed of a wave, Equation 1 is used.

$$c = \nu\lambda \quad \text{Equation 1,}$$

where c is the speed of light in the unit of m/s, ν frequency in hertz, and λ is the wavelength in meters. The unit hertz (Hz) is equal to the number of complete waves passing a given point per second. For any wavelength on the EM spectrum, the wavelength multiplied by its frequency is equal to the speed of light. Light or any other EM wave can be considered as photons which carry a discrete amount of energy. It is possible to calculate the energy of a photon based on the EM waves' frequency and Planck's constant using the following equation.

$$E = h\nu \quad \text{Equation 2,}$$

where E is equal to energy, h is Planck's constant, and ν is frequency. Planck's constant is 6.626 x 10^{-34} J▪s. Energy in Joules is equal to Planck's constant in the unit of J▪s times the frequency in Hz (Equation 2). With this equation, it is possible to observe that as frequency increases, so does the energy. Because Planck's constant is a very small number, the amount of energy carried by a single photon is also very small.

How can infrared radiation and microwaves be used to heat food?

Two regions of the EM spectrum that will be focused on in this unit are the infrared and microwave regions. A conventional oven heats food using infrared radiation while a microwave oven uses microwaves to do the same job. In order to discuss how these types of radiation heat food, the unit will first need to discuss what heat is.

Heat can be described as an increase in temperature but one can take this a step further. Increasing the temperature of a system is an increase in the average kinetic energy of a system. Kinetic energy is the energy of molecular motions. This means that to increase the temperature, molecules and atoms in the system need to move faster. There are three types of molecular motion: translational, rotational and vibrational motions.[15] Microwaves are able to excite rotational motion of water while infrared radiation excites the vibrational motion. It is due to the resonance effect that this excitation is possible. The resonance effect is when the frequency of radiation matches the frequency of the molecular motions. This allows the radiation's energy to be absorbed and transferred to the molecules, further exciting the molecular motions.

To explain the resonance effect, one can consider an analogy. When a child on a swing, the back and forth movement of the swing is at a natural frequency of the swing, determined by the length and weight of the swing. If the child wants to swing higher you need to push at the right time or frequency to make that happen. In this analogy, the swinging motion of the child already happening before you push is at the natural frequency. You pushing the child at a particular frequency making the child swing higher is the resonance effect.[16] Each object has a natural frequency of motion and when a small periodic force synchronizes with this frequency the motion can be excited to a greater degree or larger amplitude.

In the microwave oven, the electric and magnetic fields of microwaves oscillate at the frequency matching the natural frequency of rotational motion of water in food. Hence, the microwave radiation can be absorbed by exciting the rotational motions and thereby heating up food. Similarly, the EM wave of infrared radiation of the conventional oven oscillates at the frequency matching the vibrational motions of molecules in food. Thus, energy of infrared radiation can be absorbed by food, leading to excitation of vibrational motions and thus increasing the temperature of foods[17]

History of the Microwave Oven

The microwave oven was invented by Percy Spencer who worked for Raytheon. Raytheon was a technology company at the forefront of its field. It all began with a candy bar melting in Percy's pocket while he was working with a magnetron, leading him to question the possibilities for its use in the kitchen. More experiments were performed with eggs and popcorn kernels. Then, the focus was to enclose a magnetron to generate electromagnetic waves at the microwave region to create a microwave oven. Raytheon patented the invention in 1945 calling it the *Radar Range*, which was sold in 1946 for

$5,000 each but by 1994 the size and price of microwave ovens had come down enough that they were found in 90 percent of homes. Originally, the microwave oven was 6 feet tall and 700 pounds.[18]

A Microwave Oven

Microwave ovens contain a magnetron which creates microwaves at a wavelength of about 12 centimeters. A microwave oven uses the microwaves created by the magnetron to heat the water inside food and thereby heating food.[19] A magnetron inside a microwave oven is a source of microwaves because electrons released by a hot cathode travel past resonant cavities at speeds that create microwave energy. The microwave radiation is sent through a waveguide to the oven.[20]

Water

Water with a chemical formula of H_2O is a special molecule made up of one oxygen atom covalently bonded with two hydrogen atoms in a bent shape. This shape comes from the two pairs of lone-pair electrons on the oxygen atom. Water is also a polar molecule. This means that the electrons are not evenly shared among the oxygen and the two hydrogen atoms. Oxygen is more electronegative, meaning that electrons are drawn closer to the oxygen atom. This gives the oxygen atom a partial negative charge and the two hydrogen atoms partial positive charges. Thus, water is a polar molecule made of covalent bonds but the uneven sharing of electrons results in a positive and a negative end of water. It is due to this polar nature of water that a microwave oven is able to heat the water in our food.

Why Does a Microwave Oven Work?

Another important piece of information to show how a microwave oven works is that electromagnetic waves are made up of oscillating electric and magnetic fields. Hence, they are able to excite rotational motion in water molecules. Because water is a polar molecule it orients itself within the electric field like the needle of a compass within a magnetic field; the negative end of the water molecule aligns with the positive part of the electric field and vice versa.[21] In an electromagnetic wave like a microwave, there are many oscillations per second and these oscillations induce rotational movement of the water molecule. This rotational motion of the water molecule is then converted into other types of motions (translation and vibration) of water and other molecules in food. Thus, the kinetic energy of molecular motions increases, resulting in an increase in temperature and higher heat energy.[22]

Molecular Motion

During the first quarter, phases and phase changes are covered in the phychem curriculum. Discussions are focused on phase changes among solids, liquids and gases also whether energy is increasing or decreasing during the phase change. Students are asked to learn not just phases and phase changes but molecular spacing and molecular motion in the three phases. In solid, molecules are close together and do not move relative to one another. In liquid, molecules are moderately close with limited motion, while in gas, molecules have the largest distance between each other and with the most molecular motion of the three phases. For the six phase changes there is either an increase or decrease in thermal energy between the starting and ending phase. Melting, evaporation and sublimation require an increase in molecular motions. Freezing, condensation and deposition require a decrease in molecular motions. The idea here is that all matter fundamentally carries some motion explained by the Kinetic Theory of Motion. This theory states that all matter (solid, liquid, or gas) is composed of small particles that are in constant motions

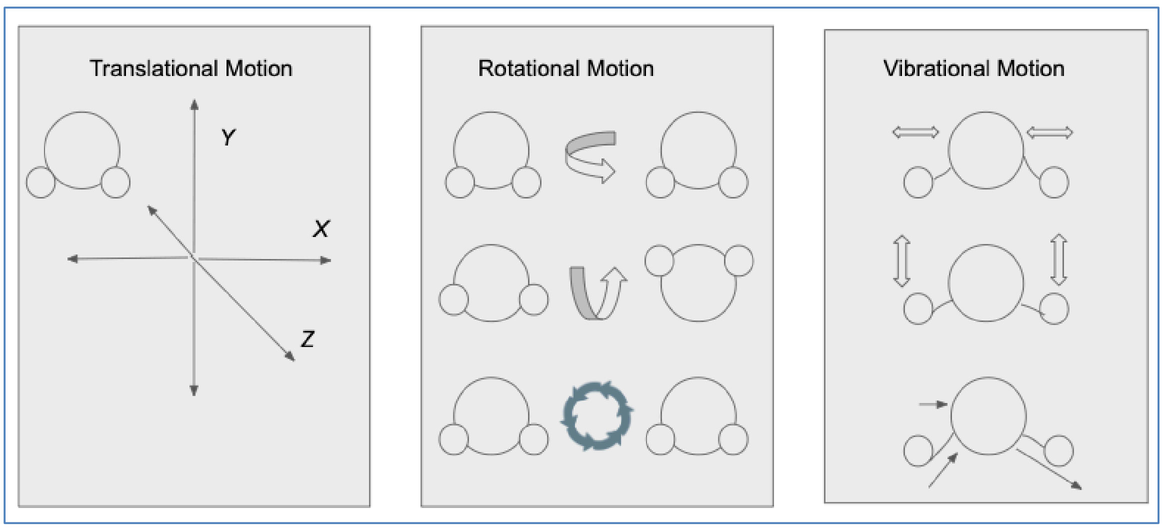

Figure 4: The translational, rotational and vibrational motion for a water molecule are depicted in this figure. [23]

Translational, rotational, and vibrational motion are the three types of motions that molecules can exhibit. Translational motion is the movement of an atom or molecule along the x, y, or z coordinates. Rotational motion is when the whole molecule rotates on an axis. Moreover, vibrational motion is the repetitive motions that change the bond lengths or angles in a molecule.

Molecules are limited in the types of motion exhibited by the number of atoms in the molecule. One example is diatomic molecules that are molecules with only two atoms. These molecules can display translational, rotational, and vibrational motion. The translational motion may be experienced along the x, y, or z axis and this means that there are three degrees of freedom for translation in a diatomic molecule.[24] Rotation has two degrees of freedom and vibration for a diatomic molecule is one. If all of these are possible ways that a diatomic molecule can move are added together we get a total of 6 degrees of freedom. Another way to calculate the degrees of freedom is by multiplying three with N, where N is the number of atoms in the molecule.[25]

We can apply all of our wave, kinetics, and phase change knowledge to a real-world experience making popcorn. Inside each kernel, there is a small amount of water. When the water in the kernel absorbs the microwave radiation, the frequency of the radiation is in resonance with the natural rotational frequency of water molecules. Thus, the rotational motion of the water molecules can be excited with higher kinetic energy. The increase in kinetic energy heats up the water at a temperature that turns liquid water into steam. Steam takes up more space than liquid water and thus the popcorn kernel pops.

Interaction of Electromagnetic Waves with Matter

If some EM waves can cook our food and others, e.g., x-rays and gamma rays, are hazardous, are microwaves generated by microwave ovens dangerous? In order to explore this question, we first need to answer the question of what happens when EM waves interact with matter? There are three ways that EM radiation can interact with matter. It can be transmitted, reflected, or absorbed. When the EM radiation passes through matter, if the matter is transparent and remains unchanged, then the EM radiation has been transmitted through the matter. If the matter is a very good reflector, then the EM radiation will not change except in the direction that it is travelling. In this case, the radiation is reflected. Absorption occurs when the electromagnetic radiation is absorbed by the matter and the EM radiation is transferred to the matter.[26] This absorption can transfer energy from the radiation to the matter, resulting in an increase in molecular motions, such as the vibrational energy of particles in a solid, and translation, rotation, and vibration of molecules in liquids and gases. If the energy is high enough, chemical bonds may be broken and electrons can be excited to higher energy levels. Overall, absorption of EM waves results in an increase in the temperature of the absorbing medium.[27]

Are microwaves dangerous? Just like microwaves can cook food, they can cause burns on human flesh.[28] The microwave oven door contains a metal mesh to prevent microwaves from exiting the oven but still allow light to escape.[29] However, microwaves are not high enough energy to ionize atoms. To ionize atoms means to have enough energy to knock and electron free. Thus, EM energy that is high enough is known as ionizing radiation.[30] Ionizing radiation includes higher frequency ultraviolet radiation, x - rays, and gamma rays. These types of radiation have enough energy to damage DNA and result in cancer.[31] Microwaves do not carry enough energy with their much lower frequency microwaves and do not cause cancer.[32]

Just like microwaves, infrared radiation is a non-ionizing form of energy; however, this does not mean that it cannot be dangerous. Exposure to near, mid, and far infrared radiation can be damaging to both the eyes and skin. Infrared radiation may be experienced as heat and result in premature skin ageing and damage to the cornea, iris and lenses of the eyes.[33]

Activities and Laboratory Experiments

Presented here are several suggested activities and laboratory experiments to go along with the science presented above.

Laboratory Experiment One

Objectives: Review and apply the equations that can be used to calculate the speed of a wave and then to review constructive and destructive interference, as well as standing waves.

Equipment Required: microwave oven, metric ruler, large plate that fits in the microwave, shredded cheese

The lab will show the actual wavelength of the waves used in the microwave oven. This lab may be performed as a demonstration or hands-on experiments if enough equipment is available. For a warm-up activity, the students will review the vocabulary: wavelength, frequency, wave speed, interference, constructive interference, and destructive interference. Student will also complete a few wave speed practice problems. Also recommended is a review of claim evidence and reasoning (CER).

To begin the lab, students will be asked what evidence they need to prove that it is possible to use the equation for wave speed to calculate the frequency of the microwaves in the microwave oven. Given the equation $c = \nu\lambda$ and the speed of light, wavelength of the microwaves will be needed to calculate the frequency. To measure the wavelength of microwave radiation from a microwave oven, students are first asked to remove the pieces of the microwave that rotate and place a large plate with a layer of shredded cheese in the microwave. For safety concerns, It is important to point out that the large plate cannot be made or contain any metal. The students will heat the cheese for about 20 seconds or not long enough for all the cheese to melt. During this time, the students are expected to see hotspots and cold spots created by wave interference both constructive (hot spots) and destructive (cold spots).[34] By measuring the distance between the hotspots, one can calculate the wavelength of the microwaves used in the microwave oven. [35]

This experiment works because a microwave oven generates microwaves using a magnetron. Microwaves inside the oven are reflected back by the metal mesh lining the oven, thereby creating a standing wave. The hot spots of the melted cheese represent the constructive interference and the cold spots the destructive interference. Therefore, the wavelength is equal two times the distance between two hotspots. This is because the hot spots correspond to the antinodes and the cold spots the nodes. In a standing wave each loop is separated from the next by points that have no vibration known as nodes. A node is a point of complete destructive interference where the crest of the original waves meets the troughs of the reflected waves. At the midpoint between nodes are points of maximum vibrations where complete constructive interference occurs. The measured wavelength can be validated by comparing the frequency calculated using Equation 1 ($c = \nu\lambda$) with the frequency of the microwave given by the manufacturer of the microwave oven, which can often be found at a label on the back of each microwave oven.[36]

Focusing on the school-wide instructional focus of supporting a claim with evidence, students will be asked to write a conclusion for the claim that one can use the equation for wave speed to calculate the frequency of the microwaves in the microwave oven.

Laboratory Experiment Two (two class periods)

Objective: Explain how microwaves heat food by increasing the rotational motion of water molecules in food.

Equipment Required: Microwave oven, 2 identical microwave-safe bowls, 6 paper towels (same size pieces), water, graduated cylinder, and an infrared thermometer.

For this laboratory experiment students will analyze data they collect to draw and support a conclusion. This experiment may also be completed as a demonstration or in lab groups.

To begin, students will fold the paper towel into quarters or so that it fits in the microwave safe bowl. Then, the students will microwave the dry paper towel, recording the starting and ending temperatures with the infrared thermometer. Next, they will repeat this experiment with a paper towel that has absorbed approximately 30 ml of water. The amount of water may be different depending on the type of paper towel used. Students will measure the increase in surface temperature for wet and dry paper towels three times each calculating the change in temperature for each trial. Then an average change in temperature for each type of paper towel will be calculated and graphed. Looking at their graphs, students will be asked which one has the greatest increase in temperature. The wet paper towel will be heated up more because of the interaction of the water molecules with the EM waves of the microwave oven. The interaction will excite the rotational motion of water. This excited rotational movement increases the other types of motion as well, thus increasing the overall kinetic energy of the water. The overall increase in the molecular motions results in heat energy, leading to an increase in temperature.

Increasing the temperature of water in food can have tasty results. One example is making popcorn. By discussing what happens to water in the microwave oven and phase change, students will be asked to explain why popcorn pops in the microwave and why steam comes out of the bag when it is done. Inside of each kernel of popcorn, there is a little bit of water. When placed in the microwave oven, this water is exposed to microwaves. Hence, the water is heated. The high temperature causes the water to expand and change into steam. Steam occupies much larger volume and thus causes the kernels to explode. Finally, when it is done, steam to come out of the bag.

In this lesson, the students can practice higher order thinking skills by analyzing data and applying knowledge to real world scenarios.

Activity One

<u>Objective:</u> Create a moving model of the motion of water molecules in food in a microwave oven compared to a conventional oven

<u>Equipment required:</u> Each student in the class will require one water molecule model made of one larger Styrofoam sphere and two smaller Styrofoam spheres connected by pipe cleaners bent in such a way that they resemble springs. Permanent markers may also be useful to label each atom. See figure below.

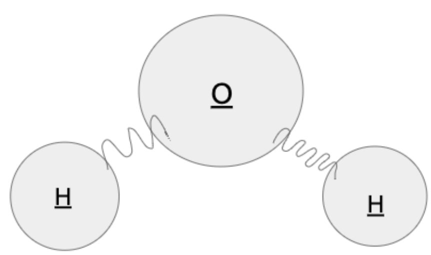

Figure 5: This figure shows the model each student will use for this activity made of labeled styrofoam spheres and bent pipe cleaners.

In a preceding lesson, it will be important to review the properties of water focusing on the polar nature of water and the partial positive and negative ends of the water molecule. It will also be important to review how opposite charges attract while same charges repel one another.

A good way to begin this activity is with a class discussion on what heat is, or what it means to heat something up. The discussion should cover heat is an increase in temperature and what causes this is that the molecules are moving faster. Kinetic energy is the energy of motions. An increase in molecular motion of molecules is equivalent to an increase in kinetic energy of the molecular system. The next question would be: what are the different ways that a water molecule can move? Here, students would use their water molecule models to demonstrate the different ways a water molecule can move including translational, vibrational and rotational motion.

Next, the student will use the water molecule model to demonstrate how a water molecule interacts with microwave radiation. With a generic graph of a wave on the board and the crests labeled with a plus sign ("+") and the troughs labeled with a minus sign ("-"), students will be asked to model how a water molecule will move as this wave passes. The oxygen atom has a partial negative charge while the hydrogen atoms have a partial positive charge. Hence, within the electric field of the EM wave, the water molecule will align itself so that the oxygen atom faces the crests and the hydrogen atom face the troughs, causing rotational motion as the wave passes.

Pairs or small groups would work here. They will be encouraged to address the following questions. What would happen if the frequency of the EM wave was high? Would the water move more or less? What is the effect of the water having increased motion? A closing question could be: How do microwave ovens heat up a glass of water?

This lesson targets multiple instructional foci, including student-to-student discourse and higher order thinking skills. By having students work in groups to figure out a problem, they must share ideas. Although their ideas do not have to be the same, the activity will allow for student-to-student discourse. By applying the material from the lesson to create the water model will encourage students to access the higher order thinking skills.

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Appendix on Implementing District Standards

HS-PS4-1 Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media.

During the third quarter the focus for the quarter is waves using the Next Generation Science Standards as guidelines. For this particular standard laboratory experiment, one provided in this units addresses the material.

HS-PS4-4 (Evaluate the validity and reliability of claims in published materials of the effects that different frequencies of electromagnetic radiation have when absorbed by matter.).

There is a lot of misconception around standing in front of a microwave and another possibility for an activity for this unit could be presenting something that argues for or against this claim addressing the NGSS standard above.

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