PhysicsQuest 2025: Dancing matter

| **Title:** Dancing matter:  **Subtitle:** Mapping the quantum world with light  Developed by: Elisa Haber, Amy Yangyuxin Zou, Jessica Jenick, Adam Rubinstein, Rachel Stromswold - University of Rochester | | | |
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| **Total Time:** 45 minutes  **Audience:** Middle and High School Science Teachers  **Education Level:** Grades 6-10 | | | |
| **Content Area:**  Quantum  **Educational topic:**  Crystals, atoms, light, sound  **Objectives:** SWBAT   * Use a crystal model to explore how the atoms in solid matter are arranged * Model how scientists image matter using X-rays * Understand what sound waves look like as they move through a crystal material   **Key Question:**  How can we visualize the atoms that make up all of the matter in our universe? | | | |
| **Next Generation Science Standards:**  **MS-PS4-1**  Use mathematical representations to describe a simple model for waves that includes how the amplitude of a wave is related to the energy in a wave.  **MS-PS4-2**  Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials.  **HS-PS4-5**  Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy. | | | |
| **Materials** | This kit provides materials for one crystal structure and 3 “photons”. If your budget allows, teachers have said that having enough crystal structures for every 6 students to have a set up works best. See Figure 3 below for ideas on how to set up different crystal structures. Teachers find that hot glue works better than super glue when creating crystal structure and “photons”. Sanding the ping pong balls before glueing may help.  **Provided in kit:**   * Laser pointer * Compression springs of the same or similar length(s) (at least 28, less than 1mm width and at least 25mm long) * Ping-pong balls (at least 11) * Cardboard base plate or board * Thin black fabric * Graph paper (around 17 x 17in at least- okay to print out four 8.5 x 11in sheets and tape them together into a 17 x 22in rectangle)   + Teachers have noted that large chart paper can work as well * Two pieces of velcro * Small craft mirror piece (side lengths of 1 or 2in)   **Teacher provided:**   * Hot or super glue   **Optional (materials not included in kit):**   * Duct tape for quick fixes * Additional compression springs: one that is ∼20mm shorter than the ones used in the crystal model, and one that is ∼20mm longer (for additional photons, each spring will also require two ping-pong balls) * A clear container that is narrow and deep enough that when spare ping-pong (or other) balls are placed in it they settle into at least three layers * Cardboard, and tape for the measuring the width of a hair (extension activity 1) * [Any speaker system](https://www.amazon.com/gp/product/B0BRKPVZB4/ref=ppx_yo_dt_b_asin_title_o00_s00?ie=UTF8&th=1) where, when you turn the volume up, you can place your hands on it and feel it vibrating, and it can be connected to a phone/computer. This can be used for the generating pure Lissajous figures (extension activity 3) * One additional compression spring and mirror piece for modeling electron/superconductivity (extension activity 4) | | |
| **Overview:**  In this activity, students can simulate X-ray diffraction experiments using a crystal model made up of ping-pong balls connected by springs, and covered by a cloth. Students will explore how the atoms are the quantum building blocks that make up all of the matter in our world, but because they are too small to be seen directly, scientists use X-rays to reconstruct what objects look like on the smallest of scales. You will use a simple model of X-ray crystallography to uncover the structure of an unknown crystal model. | | | |
| **Teacher Background:**  Over the past century, crystallography has been fundamental to the development of many scientific fields, and 14 Nobel prizes have been given for work in this area. It is also notable that unlike in most of the physical sciences, which women were often systematically excluded from, many of the foundational contributions to crystallography [came from women](https://doi.org/10.1021/acs.cgd.5b00457) (credit, however, continued to largely be given to male collaborators).  Kathleen Lonsdale and Isabel Knaggs used X-ray diffraction to study the structure of benzene. Isabella Karle and her husband pioneered a novel method for analyzing crystals, and helped revolutionize drug design. Elizabeth Wood looked at crystals with interesting electric, magnetic and superconductive properties, and worked hard to make science accessible to the public. Dorothy Hodgkin was a Nobel Prize-winning chemist who used X-ray crystallography to determine the molecular structure of penicillin, vitamin B12, and insulin. Perhaps most famously, Rosalind Franklin’s X-ray diffraction work demonstrated the double helix structure of DNA.  **Crystallography**  In X-ray diffraction experiments, scientists study the atomic structure of crystals, which are any materials where the atoms are arranged in orderly, repeating patterns. Beams of X-rays are shone on a crystal sample, which causes the beam to change direction and split into many smaller beams as it passes through the sample (see Figure 1). By studying the pattern the scattered beams make on a detector scientists can work out the atomic structure of the sample.  At an atomic level, the photons that make up the X-ray beam are scattering (deflecting or bouncing) off the atoms that make up the crystal. In the ocean, water is displaced and moves up and down in a repeating pattern--an oscillation. For light, the intensity is what is oscillating. Light intensity turns on and off 500 trillion times per second (which is a little too fast for us to see it happening!).    Figure 1. Constructive and destructive interference of two identical X-ray waves in two different crystals.  When X-ray beams (which are waves) are scattered from two nearby atoms and overlap they may interfere constructively, which means the peaks of the two waves align (see Figure 1). When this occurs they will combine to form an even brighter/bigger wave and will create a bright spot on the detector. If the two beams combine and interfere destructively (the peaks of one wave overlap with the low points of the other) they will cancel each other out and no light will reach the detector. How the waves interfere (and thus whether a bright spot appears on the detector) is determined by the spacing between the atoms, the wavelength of the X-ray beams, and the angle between the X-ray beams and the atoms in the sample. In Figure 1, X-rays with the same wavelength are shown hitting two crystals that differ only by the spacing between the atoms. In one case the scattered waves from nearby atoms line up and you get constructive interference, while in the other case the scattered waves interfere destructively. By directing X-rays from many different angles scientists can record when bright and dark spots are seen, and thereby work out the locations of the atoms in the crystal.  **Sound waves**  A sound wave [in a solid](https://www.popularmechanics.com/science/a45433537/soundwaves-crystal-xfel/) pushes the atoms back-and-forth, and the repulsive electric force between atoms leads each atom to push on its neighbor when it’s moved, causing the wave to propagate through the material. A crystal will have certain natural frequencies (like a musical instrument), and if a sound wave matches one of these natural frequencies then the amplitude of the wave will grow greatly. In a 2D crystal, these sound waves will shake each atom in [Lissajous patterns](https://resources.pcb.cadence.com/blog/how-to-read-lissajous-curves-on-oscilloscopes), which are figures with different numbers of loops like ovals, figure-eights, etc.  Just like light waves are made up of particles (photons), sound waves are also made up of quasiparticles called phonons. Quasiparticles are not true particles, they are collections of particles (in this case, collections of atoms) that collectively act like a single particle. One important application of phonons is [quantum computers](https://ionq.com/technology), which can be built using crystal arrays of atoms/ions like in the crystal model, and computations can be performed by shaking pairs of atoms. Quantum computers are of interest because they could one day solve problems that would be impossible to do even on the world’s most powerful supercomputer. There is an [extension activity](https://docs.google.com/document/d/1gZDmfMB6jSiwS-mhvxibzS-Z3OfQ2AQ_JrH-Hijm8iw/edit?usp=sharing) where students can learn about the quantum properties of electrons (and how this leads to [superconductivity](https://www.energy.gov/science/doe-explainssuperconductivity)!) using the crystal model. **Teacher Tips:**  1. Suggested [STEP UP Everyday Actions](https://engage.aps.org/stepup/curriculum/everyday) to incorporate into activity    1. When pairing students, try not to isolate students that aren’t as forthcoming with their ideas    2. As you put students into groups, consider assigning students to take the leadership role.    3. Take note of participation from students that don’t usually participate. If they seem to be taking direction and following along, elevate their voice by asking them a question about their experiment. 2. Consider using white boards, so students have time to work through their ideas and brainstorms before saying them out loud. 3. As students experiment, roam around the room to listen in on discussion and notice experiment techniques. If needed, stop the class and call over to a certain group that has hit on an important concept. 4. Consider these [responsive tools and strategies](https://www.nciea.org/blog/a-culturally-responsive-classroom-assessment-framework/) and/or [open ended reflection questions](https://www.cde.state.co.us/standardsandinstruction/es-student-reflections-mc) to help push student thinking, have students track their thinking during the activity, connect to their lives, and create opportunities to develop STEM identity. 5. Allow the work of physicists to come alive by signing up for a virtual visit from a working physicist using [APS’ Physicist To-Go](https://www.aps.org/initiatives/physics-education/k-12/physicists-to-go) program. You can request a plasma scientist to talk about the concepts students learned in this activity! | | | |
| **Key Terms (used or presented after the activities - see Forward for details)**  **Quantum:** The smallest amount of a physical quantity that can exist. A quantized quantity can only exist in discrete amounts. Particles are the quantum of a substance; they cannot be divided or split into smaller quantities.  **Electron:** A negatively charged particle that is the quantum of electricity (no smaller charge has ever been observed).  **Atom:** The fundamental building block of matter, it is made up of a positively charged core called the nucleus, which is surrounded by a negatively charged cloud of electrons.  **Photon:** An elementary, massless particle that is the quantum of electromagnetic radiation (e.x. light, X-rays).  **Phonon:** The quantum of sound waves in a periodic arrangement of atoms.  **Crystallography:** The scientific study of solids where the atoms repeat in an orderly pattern. A primary example is X-ray crystallography, where a beam of X-rays is used to determine the positions of the atoms and electrons in a material. | | | |
| **Teacher’s Guide** | | | |
| **Objectives:**  Students will use a crystal model to explore how atoms, the quantum building blocks that make up all of the matter in our world. Because they are too small to be seen directly, scientists use X-rays to reconstruct what objects look like on the smallest of scales. Teachers and students can also use lasers to visualize sound waves at the atomic level as they travel through a material.\*  \*It is important to understand that student goals may be different and unique from the lesson goals. We recommend leaving room for students to set their own goals for each activity. | | | |
| **Engage:** | | 1. We invite you to watch a [brief video demonstration](https://www.youtube.com/watch?v=qO-2KZfL4q0&t=4s) of the developer conducting the experiment you’ll be facilitating with your students. 2. Consider exploring XXX’s narrative using the lessons ideas detailed on the Introduction found in your materials kits. 3. Have students build or observe a common atomic structure (like glucose) using a molecule set (not included). Ask students    1. How do you think scientists figure out the atomic structure of objects, like you just created?    2. Let students know that the upcoming experiments will help them understand the atomic structure of much of the matter that makes up our universe. | |
| **Setting Up** | | Figure 2. Crystal model setup for the X-ray crystallography activity.   1. **This step can take up to an hour and should be done in advance of the lesson**. Before the students arrive, prepare one or more experimental setups (see Figure 2) using the following steps:  * Glue a spring to one of the ping-pong balls, and the other end of the spring to the base plate * Glue a second spring to the ball so that the spring is pointing horizontally across the base plate * Glue another ping-pong ball to the other end of the horizontal spring * Connect the second ball to the baseplate using a spring * Repeat the previous three steps until you like the size of your crystal (we suggest making it with at least 3x3 ping-pong balls as in Figure 2, arranged in any pattern you like as shown in Figure 3 below     Figure 3. Crystal lattice puzzle pieces.   * Glue velcro to one of the balls and then glue a mirror piece to another piece of velcro so that the mirror can be easily added to and removed from the setup * Finally, print or tape graph paper together to create a sheet that is at least 16 x 16in and center it underneath the base plate, and label different positions/angles around the fabric covered sheet with as shown in Figure 4 below  1. To create model photons for each setup, pairs of ping-pong balls should be connected with springs. Each pair of balls is one model photon, and the length of the spring is each photon’s wavelength. If springs with multiple lengths are available then photons with different wavelengths can be used in the experiment. At least one photon should have the same length spring as was used in the crystal model. | |
| **Explore/Experiment** | | **-Collecting Data**  **Modeling X-ray crystallography:**   1. After the student discussions of the “before experiment” questions, ensure that each student understands that atoms in solids tend to form periodic lattices (repeating, orderly patterns) because the system tries to minimize the energy. 2. Optional (see materials list above): You can demonstrate crystal patterns forming by throwing unused balls into a small clear container and gently shaking it (i.e. adding thermal energy) until the balls settle into a lattice.      1. Present the students with the crystal model covered by the sheet of fabric. Have students individually volunteer to gently toss photons at the covered model (Figure 3) at different angles (i.e. from different heights above the model and from different positions around the model - Figure 4).   Figure 3. X-ray crystallography setup.   1. Have another student record the height above the structure and the position from which the photon is thrown and record it in the table below (see Figure 4).     Figure 4. X-ray diffraction experiment using the crystal model (left), and in an actual X-ray diffraction experiment adapted from [Cornell](https://www.cs.cornell.edu/boom/2004sp/ProjectArch/AppofNeuralNetworkCrystallography/ProteinDiffraction.htm) (right).   | Wavelength of photon (spring length) | Angle (0°-330°) | Height above the structure (high, medium, low) | Distance the photon was displaced | | --- | --- | --- | --- | |  |  |  |  | |  |  |  |  | |  |  |  |  | |  |  |  |  | |  |  |  |  | |  |  |  |  |  1. The goal is for students to use the photons to try and determine what the crystal model looks like underneath the sheet, similar to how scientists use X-ray photons to determine the atomic structure of crystal samples, as they’ll learn more about in the next activity. They should use the bounce (constructive) or remaining (destructive) pattern of the photon to determine where the atoms and empty spaces of the model are located. Continue for a few rounds (if available with photons of different wavelengths). 2. Students should be encouraged to avoid looking at the sheet to try and determine where the balls beneath the sheet are located. Instead, they should try to figure out what the crystal model looks like only from the data they put in the table: the initial height of their throw, the angle at which they threw the photon, and how it scattered off the crystal. In a real experiment, the information in the table is the only thing scientists have to determine what a sample’s crystal structure is. 3. Share with the students that when both ping-pong balls that make up a photon collide with atoms in the crystal model then the photon will scatter the farthest from the model. Whether this occurs depends on both the photon wavelength, and the angle at which the photon is tossed at the model. When the wavelength is the same as the distance between two atoms, the angle can be chosen so that both of the photon’s balls line up with atoms, which should lead the photon to scatter farthest. 4. The connection between this experiment and X-ray diffraction experiments should be discussed: when the angle and wavelength of X-ray beams are correct, then constructive interference between the scattered beams will produce a bright spot on the detector, while incorrect combinations will produce a dark spot (see Figure 4). In X-ray diffraction experiments, scientists shine many different wavelengths of light at a sample at many different angles. By determining which wavelengths and orientations produce bright and dark spots, scientists can determine the atom spacing and structure of the sample. 5. Group students using best practices from the [STEP UP Everyday Actions Guide](https://engage.aps.org/stepup/curriculum/everyday).    1. Have them discuss the results of the experiment amongst themselves.    2. Determine which combinations of angles and wavelengths lead to the largest scattering distances.    3. Based on their data and observations, have student groups draw a proposed structure on their white boards.    4. Conduct a class discussion where each group presents their proposed structure using evidence and reasoning from the activity to support their drawing.    5. Reveal the crystal structure to the class. Have them rate their theories.   **Sound waves (teacher led portion):**    Figure 5. Crystal model setup for the sound waves activity.   1. Sound waves in matter can be visualized using the crystal model and a laser pointer    1. Velcro the mirror onto the crystal model, and shine the laser onto the mirror (see Figure 5) (make sure students do not look directly into the laser!)    2. If you keep your hand as still as possible, the laser light should reflect off the mirror and hit either the ceiling or one of the walls of the room (the farther away the laser point is from the crystal model the better).    3. Have students gently shake either the ping-pong balls or the base of the model.    4. As the balls (and the mirror) shake back and forth the laser dot on the wall should dance around.    5. Students should have fun and see what different shapes they can create by changing the speed and manner in which they shake the balls.      1. These patterns the laser is tracing out are called [Lissajous figures](https://resources.pcb.cadence.com/blog/how-to-read-lissajous-curves-on-oscilloscopes). In a real crystal, sound waves (and thermal noise) cause the atoms to jiggle and bounce around just like in the crystal model. These Lissajous patterns are one way to visualize what these sound waves look like as they bounce back and forth. In optional Extension Activity 3, a speaker can be used to create pure and controlled sound waves (and stable Lissajous curves) in the crystal model. 2. Just like light is made up of photons, these sound waves are made up of (quasi)particles called phonons, and these quasiparticles can actually be used to build quantum computers. This is a type of computer that could one day be used to solve certain problems that even the world’s fastest supercomputer would never be able to accomplish!   You can imagine that the ping-pong balls in the crystal model are the quantum bits (a bit is where the information in a computer is stored), and the sound waves are how the computer does operations on the bits to solve a problem. Students can learn more about this type of quantum computer [here](https://ionq.com/technology). | |
| **Explain** | | 1. Give students the opportunity to discuss the key terms, and make sure each student understands them. Allow students to define the key terms in reference to the experiments and evidence they collected during this activity. 2. The experiment you just performed is similar to X-ray diffraction studies (see Figure 4). In these experiments, scientists shine X-ray beams, which are made up of particles called photons, on a material. By detecting how the beams scatter off of the crystal sample they can determine what the atomic structure of the object is. The wavelength of the X-rays is similar to the length of your photon’s spring. Consider the results of your experiment:    * Describe in your own words what happens when a photon hits an atom in the crystal? Bonus points if you use the word constructive or destructive.    * Describe in your own words what happens when a photon hits the molecule in between the atoms of the crystal? Bonus points if you use the word constructive or destructive.    * How would they have come out differently if you were using a crystal model where the springs connecting the atoms together had a different length than the photon wavelength?    * Would the same angles have produced the same scattering distances? 3. Was your personal essential question answered? If so, what is the answer? If not, what additional information would you need to answer it? 4. Explain, in your own words, what a sound wave looks like as it travels through a crystal. 5. Make sure each student understands the important concepts the experiment was meant to help elucidate. | |
| **Student’s Guide** | | | |
| **Intro:**  All matter in the universe, from your shoes to the most distant stars, is made up of atoms. But how are atoms packed together to form all of the structure of our world? In this activity we will explore several techniques that are used in the field of X-ray crystallography, many pioneered by women, to see inside matter and take pictures of the atoms themselves. Inside the atom   Figure 1. Structure of the atom.  Figure 1 shows two different pictures of what an atom looks like. The central region is called the nucleus of the atom. It has a positive electric charge and is thousands of times heavier than the electrons that make up the outer part of the atom. Electrons are negatively charged particles (particles are the smallest amount of a thing that can exist, no matter how hard you try they cannot be cut into smaller amounts). The Bohr model of the atom (shown on the left side of Figure 1) was one of the first models of the atom. It was developed in 1911 and it shows the electrons orbiting around the nucleus of the atom much like the planets in our solar system orbit around the sun. This simple model explains many of the properties of atoms, but it is incomplete.  A better model, the Schrodinger picture, is shown to the right in Figure 1. In this (quantum) model the electrons are like a cloud that spreads out and surrounds the nucleus. The electron has a probability of being found at each location in the cloud. In quantum physics, the electrons only appear to be particles when we take a picture of them, or observe them. If we leave them alone they will spread out like a wave. If you are interested you can learn more about the quantum properties of electrons in the [extension activity 4](https://docs.google.com/document/d/1gZDmfMB6jSiwS-mhvxibzS-Z3OfQ2AQ_JrH-Hijm8iw/edit?usp=sharing); in this activity we will instead study the atom as a whole. X-ray crystallography In order to study how atoms are arranged in a material, scientists can shine an X-ray beam on a sample of that material. When the beam passes through the sample it will scatter (deflect or bounce) off of the atoms. By studying the pattern the scattered beams make on a detector scientists can work out how the atoms are arranged in the sample. For this to work the atoms must be arranged in a periodic/repeating pattern (as you’ll see during the activity).  When the atoms are arranged in a repeating pattern, the sample is called a crystal, **and the technique of shining X-rays on it to determine its atomic structure is called X-ray crystallography**. This technique has many applications, for instance biologists use it to design more effective drugs, and engineers use it to develop new materials, technology and sources of renewable energy! Wave interference To understand how crystallography works we first need to talk about the fact that light (X-rays are one type of light) is a wave. You may be more familiar with ocean waves, where water moves up and down in a repeating pattern (in physics we would say that the water is oscillating up and down). This is generally true: in all types of waves something is oscillating up and down or back and forth.    Figure 2. Constructive and destructive interference of two identical X-ray waves in two different crystals.  To see what happens when we shine X-ray photons (which are waves) on atoms look at Figure 2. In the picture, the X-rays are the dark lines that are going up and down repeatedly, similar to what an ocean wave looks like. The distance between the peaks of the wave is called the wavelength. For ocean waves it’s about 160 ft, and in the figure the X-ray photons have a wavelength of about 1.1 inches (in reality X-ray photons have a wavelength of around one millionth of a millimeter, but this is just a model).  In Figure 2 you can see the waves are scattering off of two atoms (the red and blue balls) in the sample. When the scattered waves reach the detector they will interfere (combine with each other). This means that at each point in space the heights of the two waves are added together. On the left side of Figure 2, the peaks of the two waves add together, which creates an extra large wave, and this is called constructive interference. On the right side of Figure 2, however, the peaks of the first wave overlap with the low points of the second wave, so when they’re added together you just get a flat line (this is called destructive interference).  **In X-ray crystallography, the conditions for constructive and destructive interference are determined by the wavelength of the X-rays, the angle the X-ray beam hits the sample, and by the spacing between the atoms in the sample.** In Figure 2, the only difference between the constructive and destructive interference examples is that the atoms in the crystal on the right are closer together than the atoms in the crystal on the left. This is also why we can’t use visible light to do crystallography: the distance between atoms in most solids is similar to the wavelength of X-rays, but visible light has a wavelength that is usually thousands of times longer, so the interference pattern you’d see with visible light wouldn’t tell you anything about the arrangement of the atoms. Scientists observe what X-ray wavelengths and beam angles lead to constructive or destructive interference, and from that data determine how the atoms are arranged in the sample. | | | |
| **Objective:**  By the end of this activity, you will be able to   1. Use a crystal model to explore how the atoms in solid matter are arranged 2. Model how scientists image matter using X-rays 3. Understand what sound waves look like as they move through a crystal material | | | |
| **Before the experiment** | | 1. Your teacher will give you a molecule set.    1. Build the model    2. How do you think scientists figure out the atomic structure of a material, like the one you just created? | |
| **Setting Up** | | 1. Read the Introduction and Objective with your class. Write your own objective for this activity. 2. Get all of the materials required to perform these experiments from your teacher. | |
| **Explore/Experiment** | | **-Collecting Data**    Figure 3. X-ray crystallography setup.   1. Your teacher will provide a model covered by a sheet. Take turns gently tossing photons (the pairs of ping-pong balls connected by springs) at the model from different heights above the model, and different angles or positions around the model (see Figure 3). For each trial:    1. Measure the wavelength of the photon you’re using (the length of the spring), the initial angle you’re going to throw the photon from (one of the numbers between 0° and 330° marked on your paper). Estimate the height above the model you’re throwing from (high, medium or low). Record all of these in the table below.    2. Throw the photon and observe how it bounces off the model.    3. One student should measure how far away from the model the photon lands and record the number in the table.  | Wavelength of photon (spring length) | Angle (0°-330°) | Height above structure (high, medium, low) | Distance the photon was displaced | | --- | --- | --- | --- | |  |  |  |  | |  |  |  |  | |  |  |  |  | |  |  |  |  | |  |  |  |  | |  |  |  |  |  1. Your teacher will put you into groups. Get a white board from your teachers. With your group, do the following:    1. Discuss the results of your experiment, including the data in the table.    2. Determine which combinations of angles and wavelengths lead to the largest scattering distances.    3. Underneath the sheet, your teacher has arranged the “atoms” (ping-pong balls) in an unknown pattern.    4. Based on your data, draw on your white board how you think they’re arranged beneath the sheet (see Figure 4 for an example pattern). How will the arrangement of atoms beneath the sheet affect the distance the photon scatters?    5. Present your proposed structure to the class using evidence and reasoning from the activity to support their drawing.    6. Look at the crystal structure that your teacher uncovers. How well does your theory match the actual structure?     Figure 4. X-ray diffraction experiment using the crystal model (left), and in an actual X-ray diffraction experiment adapted from [Cornell](https://www.cs.cornell.edu/boom/2004sp/ProjectArch/AppofNeuralNetworkCrystallography/ProteinDiffraction.htm) (right).   1. To wrap up the activity, your teacher will place a mirror on one of the ping-pong balls and shine a laser on it. Do the following:    1. One at a time, you can go up to the model (make sure not to look directly into the laser pointer!) and gently shake one or more of the balls or the base of the model.    2. Try shaking the balls or the base at different speeds and see if the shapes the laser is tracing out on the wall/ceiling change. | |
| **Explain** | | 1. Discuss each of the key terms listed below in your group, and write down your group’s definition of each:  * Quantum * Atom * Photon * Crystallography  1. The experiment you just performed is similar to X-ray diffraction studies (see Figure 4). In these experiments, scientists shine X-ray beams, which are made up of particles called photons, on a material. By detecting how the beams scatter off of the crystal sample they can determine what the atomic structure of the object is. The wavelength of the X-rays is similar to the length of your photon’s spring. Consider the results of your experiment:    1. Describe in your own words what happens when a photon hits an atom in the crystal? Bonus points if you use the word constructive or destructive.    2. Describe in your own words what happens when a photon hits the molecule in between the atoms of the crystal? Bonus points if you use the word constructive or destructive.    3. How would they have come out differently if you were using a crystal model where the springs connecting the atoms together had a different length than the photon wavelength?    4. Would the same angles have produced the same scattering distances? 2. Was your personal essential question answered? If so, what is the answer? If not, what additional information would you need to answer it? | |
| **Additional Resources:**   * [History: Women in crystallography](https://doi.org/10.1038/505609a) * [Women who changed science: Dorothy Crowfoot Hodgkin](https://www.nobelprize.org/womenwhochangedscience/stories/dorothy-hodgkin) * [Broader impacts of women in crystallography](https://doi.org/10.1021/acs.cgd.5b00457) * [X-ray crystallography: Revealing our molecular world](https://www.sciencemuseum.org.uk/objects-and-stories/chemistry/x-ray-crystallography-revealing-our-molecular-world) * [X-ray interactions](https://howradiologyworks.com/x-ray-interactions/), illustrated summary * [For the very first time, we’ve actually filmed sound waves inside crystals](https://www.popularmechanics.com/science/a45433537/soundwaves-crystal-xfel/) * [Quantum computing](https://www.energy.gov/science/doe-explainsquantum-computing) | | | |
| **Evaluate/Elaborate activities\*\* (optional to extend thinking after the lesson):**   * Check out our [extension activity guide](https://docs.google.com/document/d/1z3KGghDzjYSQlxsE3hTlQV9xJ4hfA9Aa_JBM4uiEyBQ/edit?usp=sharing)! * Real world connections -   + Sign up for [Physicists To-Go](https://www.aps.org/programs/outreach/physiciststogo.cfm) to have a scientist talk to your students. * Suggestions for drawing, illustrating, and presenting content in creative ways -   + Kinesthetic activity: crystal model     - The entire class can act as a big 1D crystal where everyone stands in a line and holds hands.     - Each person in the line should stand in place, but whenever one of their neighbors pushes on them they are allowed to sway in response to the push, just like the balls in the crystal model (note that each person should sway both forwards and backwards in response to the push, as though connected to their neighbors by springs).     - A transverse wave can be created having one or both people on the ends raising their arms up, and their neighbors can raise their hands up and so on down the line (this is like the [waves people do at sports games](https://en.wikipedia.org/wiki/Wave_(audience))!)     - You can model a longitudinal sound wave by having one or both people on the ends gently lean in and push on their neighbors, who can then push on their neighbors and so on.     - If everyone sways forwards and back fast enough and in sync with one another the class can create a (resonant) standing wave! (Meaning that everyone in the line will eventually be swaying in sync with everyone else).     - Next, you can model the X-ray crystallography experiments! Instead of holding hands in the line, each person should hold up one hand at chest level with their palm facing away from themselves (as though to give someone a high five).     - A few people can start outside the line, they will be X-rays. They should raise both their hands at chest level with their palms facing away from themselves. They should separate their hands by any distance they desire and hold them still (this distance will be their wavelength).     - The X-rays should walk towards any part of the line, and when they reach it if their hands both line up with the hands of two of the atoms in the line then constructive interference occurs and the X-rays should “bounce” off the crystal. Once they bounce off they can approach a different part of the lattice.     - If an X-ray reaches the lattice and their hands don’t line up with the hands of the people in the lattice then destructive interference occurs and the X-ray should switch out with someone in the lattice line who then gets to play as an X-ray (everyone in the line should get a chance to be an X-ray)     - You can simulate thermal motion or sound waves in the lattice by having the students in the line move their hands around slightly as the X-rays approach, making it harder for the X-rays to line up their hands with those in the lattice (i.e. making it more difficult for perfect constructive or destructive interference to occur). * Engineering and design challenges connected to the content   + If engineering challenges have a time constraint, students are allowed to keep iterating and developing their ideas outside of class time and continue to participate in the challenge at a later date   + Growing sugar and salt crystals     - Using household materials like [sugar](https://crystalverse.com/sugar-crystals/) and [salt](https://www.sciencefun.org/kidszone/experiments/salt-crystals-science-experiment/) it is easy to grow your very own crystals; try using different solutions (salts, sugars, borax, etc.) and in different concentrations to create as large a crystal as possible!   + Build your own 3D crystal model   \*\*Real world situations/connections can be used as is, or changed to better fit a student’s own community and cultural context. | | | |