about what happens has been limited to envisioning what happens after incoming light rays bounce off the dot in many directions as shown in Fig. 1.37.

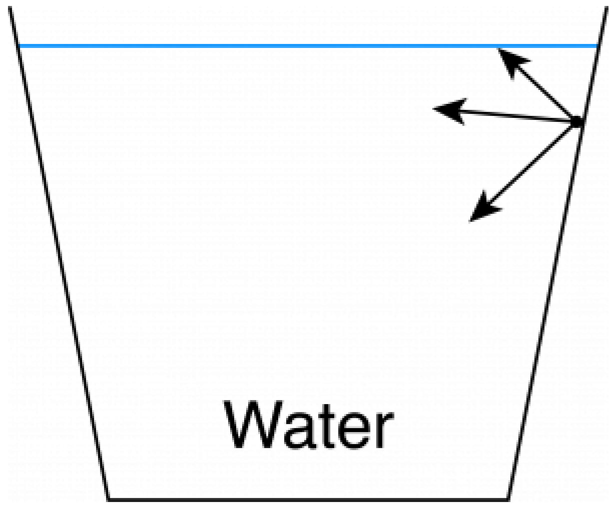

FIG. 1.37 Light rays bouncing in many directions off the real dot in the water.

Envision many light rays, after bouncing off the dot, traveling at many different angles to the surface of the water. Choose to focus only on those light rays that happen to be traveling at an angle in the water such that when they bend at the surface of the water they are headed in the direction of the observer's eye.

The phrase *bend at the surface of the water* does not refer to a curving path for the rays of light from the dot to the eye; this phrase refers instead to a path represented by one straight line, from the dot to a point on the surface, that changes direction at that point, and continues as another straight line, representing light rays traveling from that point on the surface of the water to the eye.

A ruler can provide a physical model of how light rays appear to be moving in a straight line from the apparent dot to the eye as shown in Fig. 1.38.

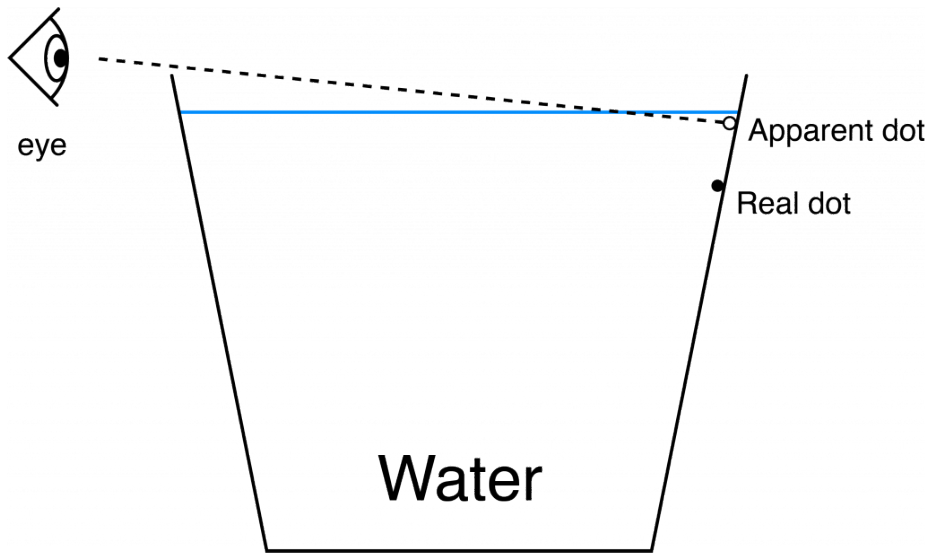

FIG. 1.38. Dashed line representing a ruler modeling the apparent straight path that light rays are traveling from the apparent dot to the eye.

This ruler represents, however, both the actual path of light rays that get to the eye and an apparent path from the apparent dot.

Where does the apparent path of light rays from the apparent dot turn into the actual path of light rays to the eye?

Consider the point that represents envisioning where light from the apparent dot crosses the surface of the water. A solid line from the real dot to this point represents some light rays bouncing off the real dot and traveling straight to this point in the water as shown in Fig. 1.39 where the point is labeled as the location that "Refraction" occurs.

Making the dashed line into a solid line from this point on the surface of the water to the eye represents envisioning light rays bending at this point and traveling to the eye. The dotted dot at the end of the dotted line represents the illusion of where the dot is.

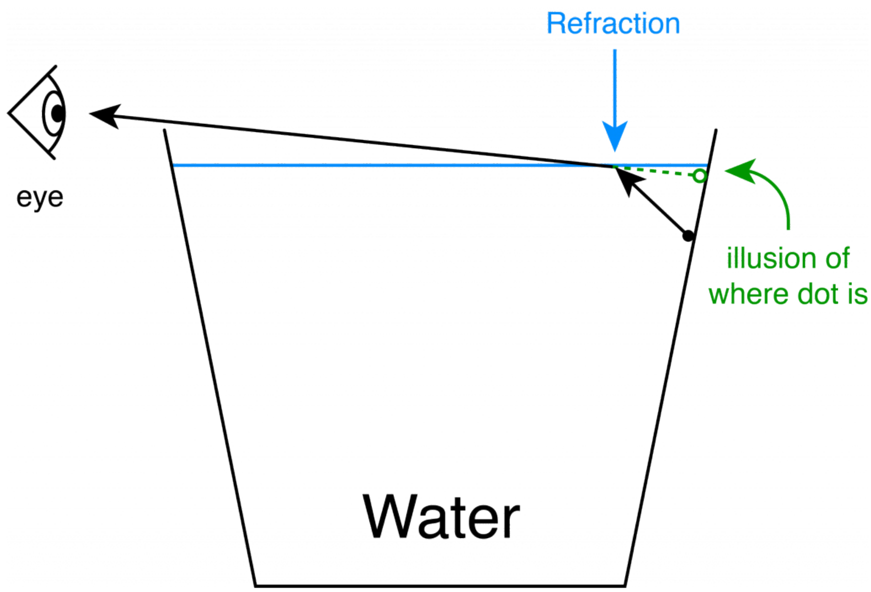

FIG. 1.39 Dashed and solid lines represent envisioning apparent and actual paths for light rays traveling from the apparent and real dots to the eye.

The dotted line on this ray diagram represents envisioning the apparent path of light rays from the apparent dot to the point where the actual light rays bend at the surface.

The solid line with arrows on this ray diagram represents envisioning the actual path of light rays from the dot to the surface of the water, the sharp bend at the surface, and the solid line from that point at the surface to the eye.

It is helpful to think about examples of refraction in a variety of contexts. In some positions, for example, a pencil or a stick looks like it is bending at the surface of the water as in Fig. 1.40. Why does it look bent?

As shown in Fig 1.40, light is envisioned as shining on a pencil in the water and bouncing off in many directions. Some of the rays are envisioned as bouncing off the pencil and traveling in straight lines toward the surface of the water. At the surface, these rays are envisioned as bending as they move into air. Some of the rays are envisioned to be bending in such a way that they travel straight to the observer's eye. The observer perceives the rays as if they had traveled in a straight line from a location different from where the actual pencil is located so the person perceives the pencil to be bent.

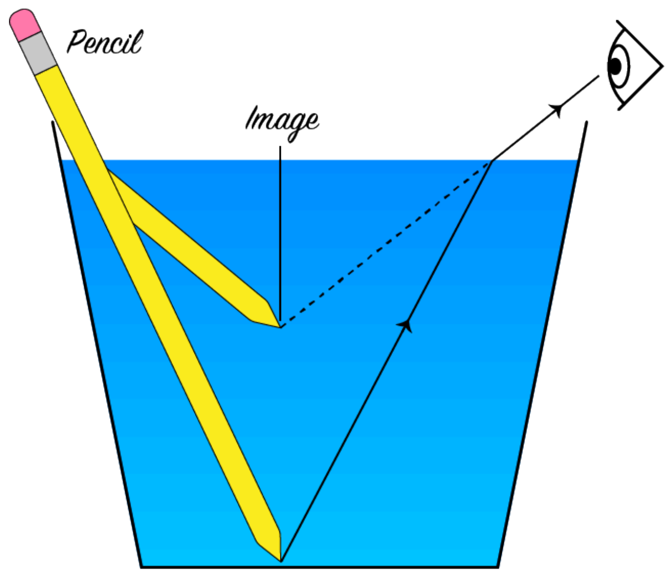

FIG. 1.40 Ray of light envisioned as bouncing off the tip of a pencil and bending at the surface of the water on way to the eye.

Another example of refraction occurs in a different context, spear fishing, as shown in Fig. 1.41. Where should you aim when spear fishing? (See: http://www.schoolphysics.co.uk/age14-16/Light/text/Refraction_and_fishermen/index.html)

FIG. 1.41 Spear fishing depicted in a wall painting from the tomb of Usheret in Thebes, 18 Dynasty around 1430 BC
https://commons.wikimedia.org/wiki/File:Tomb_of_Usheret_01.jpg

Question 1.22 What happens when exploring refraction with friends and/or family members?

3. Exploring refraction phenomena with a friend or family member

After class, our students have explored refraction phenomena with friends and/or family members and reflected upon this experience by describing details about what their learners ask, say, do, and find. They also have commented upon what they learn about learning and teaching science through this experience. A student, for example, wrote:

> *When I originally showed the phenomena to my roommate L, she said "whoa, when did you start doing magic tricks!" I laughed and told her that I was not doing magic but merely working with the phenomena of refractions.*
>
> *She asked "what is refraction?" I told her it was what allowed her to see the dot. I then showed her the experiment again. Afterwards I had her stand and asked if she could see the dot, she said "yes." I asked why, and she said because she was standing high enough. So, I turned off the lights and asked if she could see it. She said "No!" I turned back on the*

lights and asked what she must have to see the dot and she said "I need light to see the dot." So I kept the lights on and covered the dot so only I could look into the cup and see it. I asked if she could see the dot, the light was there so she should be able to. L then told me that the "light needs to hit the dot and then come to my eyes, I can't see it if you block the light from getting to my eyes."

So I asked L what must have happened for the light to travel from the dot, which was below her line of sight and go to her eyes. "Well," said L "the dot didn't move, cause that is impossible. So the light must have moved in the water to get to my eyes. Cause I only saw the dot look like it moved up after the water covered it."

At this point L was so close that it was very hard for me to not just tell her the answer. I refrained, but only barely. I asked L how she thought the light was moving; she said she didn't know.

So I drew out the flat ray diagram with the image of the dot on the side of the cup and her eye where it could not see the dot, but I did not draw the rays of light. I asked L to draw what she thought was happening. L drew a curved line from the dot to her eye.

Once again L was so close that it was hard not to give the answer away. So I asked L how light travels, she said "in rays, like the rays of the sun". I was surprised that she knew this but I was glad. So I asked her to show me a ray, a straight line leaving the dot and going to the surface of the water. She did so.

I asked if she thought this was how the light might have moved; she said, "well maybe, because the water going over the dot was what bent the light, so maybe the light only bends when it leaves the surface of the water." I was thrilled! She had figured it out! I then showed L the ray diagram of how light refracts and bends towards our eyes when leaving the surface of the water and going into the air.

The experience was hard for me. It was difficult for me to try and explain a concept to someone that was a new concept for me as well. However, it was rewarding to see that if I was patient, and continued to ask questions and only give small supplementary bits of information that L was able to understand the phenomena.

It was hard to try and think in a way that would foster L's own thinking about how the light rays traveled and to try and form questions that would help L to think in a certain way about light. I believe this will be much of what I feel as a teacher later. I will need to think of many different approaches for my students. Not all of them will understand instantly why a phenomena works; they will need more guidance or more questions, they may even need to experiment on their own to see if they can understand. I as a teacher must learn not to rush this process and to allow them to learn about the *subjects themselves. This is in the hopes that the students will remember more about the information as well as be more interested in the learning process.*

Physics student, Fall 2015

4. Thoughts about the nature of science exemplified by these explorations

The explorations of light phenomena so far exemplify the nature of science in that students developed central ideas based on evidence and modified those ideas as necessary after observing new phenomena. Initially, for example, explorations of light and shadow phenomena provided the basis for development of a conceptual model of light that included the central ideas that (a) *light leaves a source in all directions*, which, after discussion and additional exploration, was modified to *light leaves a point on most sources in many directions.* Additional explorations provided evidence for the central ideas that (b) l*ight can be envisioned as rays traveling in straight lines*, and (c) f*or someone to see something, light has to get to the person's eye*. A ray diagram representing how rays seemed to travel in straight lines was useful in developing an explanation of an intriguing observation, that the projection of an object in a pinhole camera was upside down. A straight meter or yard stick provided a physical model for thinking about light as behaving like rays traveling in straight lines.

Additional explorations of reflection and refraction phenomena, however, provided evidence that this conceptual model needed further revision. Observations of these phenomena provided evidence for development of three additional central ideas that refer to what happens when light shines on surfaces: c) that *light rays can be envisioned as being reflected from smooth surfaces with the angle of reflection equaling the angle of incidence*, d) that *light rays can be envisioned as bouncing off of rough surfaces in many directions*, and e) that *light rays can be envisioned as refracting (bending, changing direction) at the surface when traveling through a surface from one medium to another*. These are examples of the on-going nature of scientific knowledge, which is *open to revision in light of new evidence* and *can change when new information is found* (NGSS, *Lead States*, 2013, Appendix H).https://www.nextgenscience.org/resources/ngss-appendices

A bouncing ball also provided an elaborated physical model for light as rays composed of particles (photons) traveling in straight lines until interacting with a surface. More complex ray diagrams were useful in explaining another intriguing phenomenon, the apparent upward movement of a dot on the inside of a cup as water is poured into the cup. Additional modifications of this conceptual model for light may become necessary after exploring more phenomena. Meanwhile we turn next to elaborating experience with refraction phenomena in a new context.

C. Exploring dispersion phenomena

In this section, we explore light phenomena known as dispersion.

Question 1.23 What happens when light from the Sun passes from air into a prism or water droplet?

Equipment: To explore dispersion phenomena on a sunny day, use a piece of white paper and a prism, a glass or quartz crystal, or a hose and sprinkles of water; inside use a prism or crystal with a bright lamp.

- What have you seen when light from the Sun passes through a glass or quartz crystal? Old-fashioned window panes? A prism? Water droplets when sprinkling with a hose?

  Note some of these experiences in the ***Before*** section of the physics notebook page documenting your exploration of dispersion phenomena.

- On a sunny day, take a prism or crystal outside and enjoy displaying what you see against a white wall or a piece of white paper on the ground. (Do not look directly at the Sun!)
- Or spray water with a hose and stand in such a way that you can admire making your own rainbow.
- Or play with a prism or crystal near a very bright light inside. What do you see? (Do not look directly at the bright light.)
- In the ***During*** section of your physics notebook page, record your findings. Draw a picture of what you did and saw. Note any vocabulary that is new to you.
- Discuss your findings and formulate a relevant central idea. In the ***After*** section of

the physics notebook page, report this idea and the evidence on which is based.

- Write a rationale that explains how the evidence supports the central idea and why this is important.
- Also reflect upon what you have learned during this exploration
- What are you still wondering?
- Add this central idea about dispersion to Table I.1:

TABLE I.1 (continued) Explorations of Light Phenomena: Dispersion

TABLE I.1 (continued) Explorations of light phenomena: Dispersion			
Sketch of set up Ray diagram	Evidence	Central Idea	Vocabulary
		White light disperses into its component colors when moving from one medium to another such as from air into a glass prism or water	Dispersion

Complete your entries on your physics notebook page and Table I.1. Summarize what you have learned about dispersion phenomena before reading an example of student work and nuances about exploring dispersion phenomena.

1. *Example of student work about exploring dispersion phenomena*

As shown in Fig. 1.42, a student added to Table 1.1 about explorations of light phenomena and stated as evidence, “White light from the Sun hit the prism and was broken up into its different colors.”

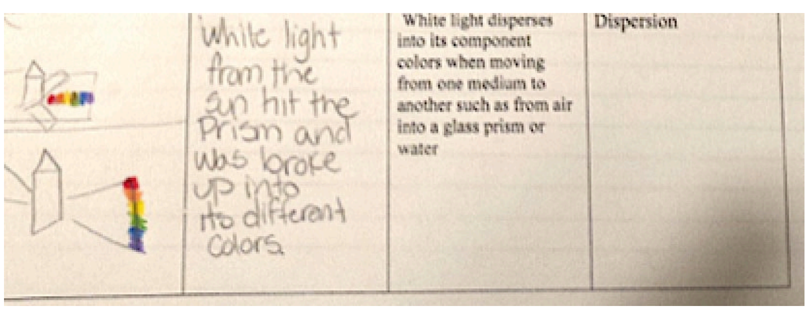

FIG. 1.42 Student’s addition to Table 1.1 about exploring dispersion phenomena:

The student summarized this new central idea about dispersion phenomena as follows:

> ***White light disperses into its component colors when moving from one medium into another such as from air into a prism or water.*** *For this experiment, students were given triangular prisms made of a clear material that may have been glass. We were then taken outside into the sunshine and told to move our prisms around and see what happened.*
>
> *It took a moment before someone exclaimed, "Hey I see a rainbow!" Soon many students began to really watch what happened when they tilted the prisms one way or another. Some students placed a piece of white paper on the ground and tried to project the "rainbows" onto the paper. When students set the prisms onto the paper facing the sun we were able to see two figures that looked like shadows but much lighter. It was light being dispersed through the prism onto the paper.*
>
> *When we moved the prism slightly we were able to see the light on the paper change from a slight white color to the rainbow of colors Red Orange Yellow Green Blue and Violet (ROYGBIV).*
>
> *The students then talked about what must be happening and our TA's told us that the sun sends out a kind of light called white light that holds all of the colors of the rainbow in it. The students decided that what must happen is that as the light passes through the prism it is broken up into the different colors when it is sent back out of the prism. This experiment is represented in a picture on (Fig. 1.41) as well as a ray diagram. In the ray diagram light goes into one side of the prism, where it is broken up into the many colors, and then dispersed on the other side into the different colors that were seen by the students.*
>
> Physics student, Fall 2015

2. Nuances about exploring dispersion phenomena

Figure 1.43 shows red and violet rays bending as they move from air into a prism and bending again as they move from the prism back into air. The violet rays bend more than the red rays and this difference separates the white light into its component colors. The colors between red and violet bend intermediate amounts.

Note that the orientation of the two surfaces of the prism differ, one side slants toward the left, the other side slants toward the right. If one draws a line perpendicular to the surface of the prism (a normal line) at the point where the white light enters the prism, the rays bend *toward* this normal as they move from air into the prism.

If one draws a line perpendicular to the surface of the prism at the point where each ray leaves the prism, the rays are bending *away* from the normal as they move from the prism back out to the air. The result of the different orientations of these surfaces is that the rays keep bending "down" as they enter and then leave the prism.

The drawing shows rays of light as they are inferred to be traveling. One can not actually "see" these colored rays as represented in the drawing. What one sees is the spectrum of colors when the rays land on some kind of screen such as a wall or piece of paper, or in the case of a rainbow, on the retina of an eye. This is a *model* of what seems to be happening. The next section uses this model to develop an explanation for an amazing natural event, the formation of a rainbow.

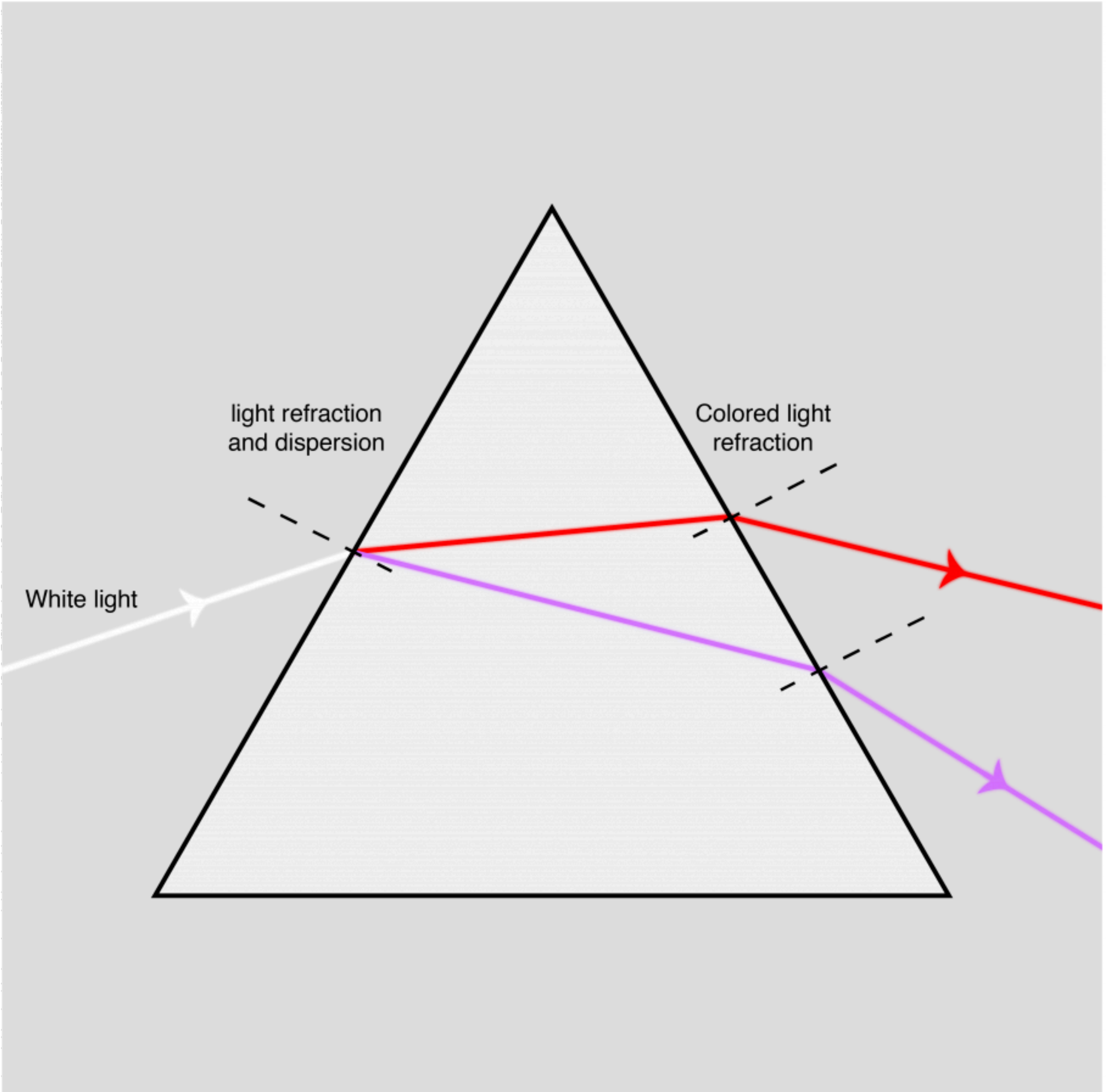

FIG. 1.43 Dispersion of white light into its spectrum of colors. The spectrum ranges from red to violet as shown here. Modified from https://wikivisually.com/wiki/File:Prism_rainbow_schema.png CC 3.0

VIII. Using Additional Central Ideas about Light to Explain an Intriguing Phenomenon

We can use these additional central ideas about reflection, refraction, and dispersion to explain a beautiful phenomenon: a rainbow.

Question 1.24 How are rainbows formed?

- When you see a rainbow, where are you standing with respect to where the sun and rain are?
  - Is the sun behind you, high above you, or in front of you?
  - Is the rain behind you, raining straight down on you, or some distance away in front of you?
  - Make a sketch that shows where you are with respect to the sun and rain.
- What happens when light from the sun enters a water drop?
  - What happens when light rays move from one medium into another such as from air into water?
  - Make a ray diagram showing white rays from the sun entering a water drop. Show only one color as rays of that color move from air into the drop.
- What happens when light rays reflect off a smooth surface?
  - Continue your ray diagram showing rays of one color reflecting off of the inner surface of the drop, back into the drop.
- What happens when light rays move from one medium into another, such as from water into air?
  - Continue your ray diagram showing rays of one color leaving the water drop and traveling through the air.
- Will colors from the same drop reach the observer's eye?
  - Continue your ray diagram showing rays of one color traveling to the observer's

eye.
    - Consider whether rays of another color would exit this drop in a direction toward the observer's eye.
    - Add another drop at a different height from which a different color reaches the observer's eye.
- Summarize how light from the sun sometimes forms a rainbow in the sky.

Complete your ray diagram and summary before looking at an example of student work and nuances about explaining rainbows.

1. *Example of student work explaining rainbows*

A student began explaining rainbows with a sketch of where someone is who is seeing a rainbow, with respect to the sun and the rain, and a ray diagram showing how one can envision what happens when light rays enter water drops in just the right way to form a rainbow as shown in Fig. 1.44.

(Figure 1.44) is a sketch of someone seeing a rainbow. The Sun is behind the person and the cloud with raindrops is in front of the person.

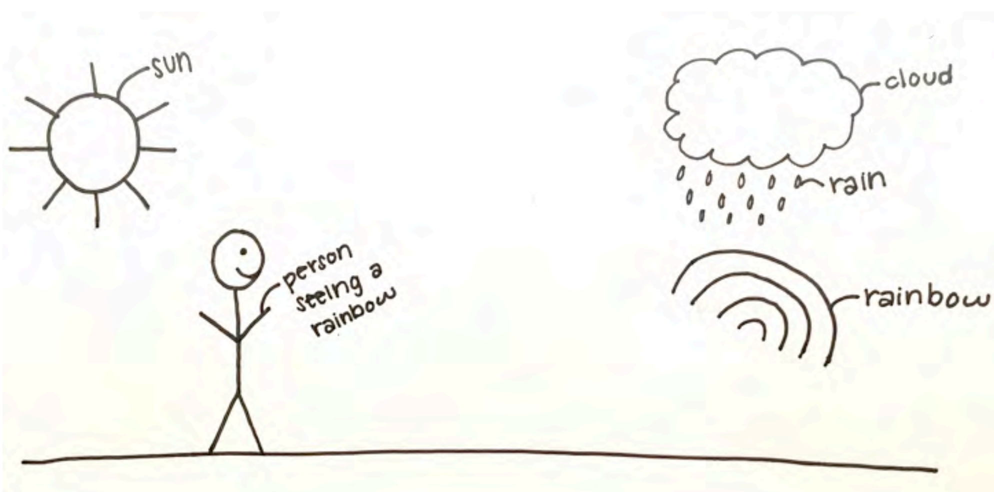

FIG. 1.44 *Sun, person, cloud, and rain when a person is seeing a rainbow.*

(Figure 1.45) is a ray diagram with the Sun, two rain drops, and a person's eye.

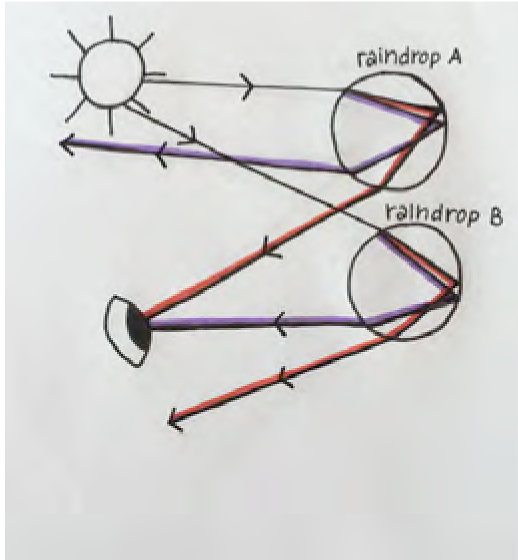

FIG. 1.45 Student ray diagram for two raindrops and person seeing a rainbow.

The ideas above can be used in tracing the two continuous rays in (Fig. 1.45), in order to explain how someone can see a rainbow.

First of all, white light disperses into its component colors when moving from one medium into another such as from air into a prism or water.

In Figure (1.45), the two light rays that are shown leaving the sun in the direction of the raindrops are white light. Once those white light rays hit the raindrops, which is a change in medium from air to water, it can be seen that the white light disperses into its component colors, which is represented by the red and violet rays seen inside of the raindrops. Next, light rays refract (bend, change direction) at the surface when light moves from one medium into another such as from air to water or from water to air. This refraction is first seen in Figure (1.45) in each of the raindrops directly when the light rays first hit the raindrops, since the rays are moving from the medium of air to the medium of water.

Next, light rays reflect from smooth surfaces in a regular way, where the angle of reflection equals the angle of incidence. This is seen in Figure (1.45) when both the red and the violet rays hit the back of the raindrops, which are smooth surfaces, and they reflect off in the same angles as which they came in, which are the angles of incidence.

Finally, refraction is seen again in Figure (1.45). The second time that refraction is seen is when the light rays are leaving the raindrops, since the rays are moving from *the medium of water to the medium of air. When the light rays leave the raindrops, the red rays bend less than the violet rays. So, in the raindrop on the top, only the red light rays exit at the correct angle to travel to the observer's eye. In the raindrop on the bottom, only the violet light rays exit at the correct angle to travel to the observer's eye. Since we only see one color from each raindrop, that is how a rainbow is seen.*

Physics student, Spring, 2016

2. Nuances in using central ideas about reflection, refraction, and dispersion to explain rainbows

A step by step view of the processes involved in forming rainbows can be helpful:

First the white light rays from the Sun are envisioned as being **refracted** on entering a water drop with different colors bending at different angles. Violet bends the most, red the least. The other colors bend in between. Figure 1.46 shows this first step of white light entering a raindrop and one of its component colors bending toward the normal at a particular angle at the surface of the drop.

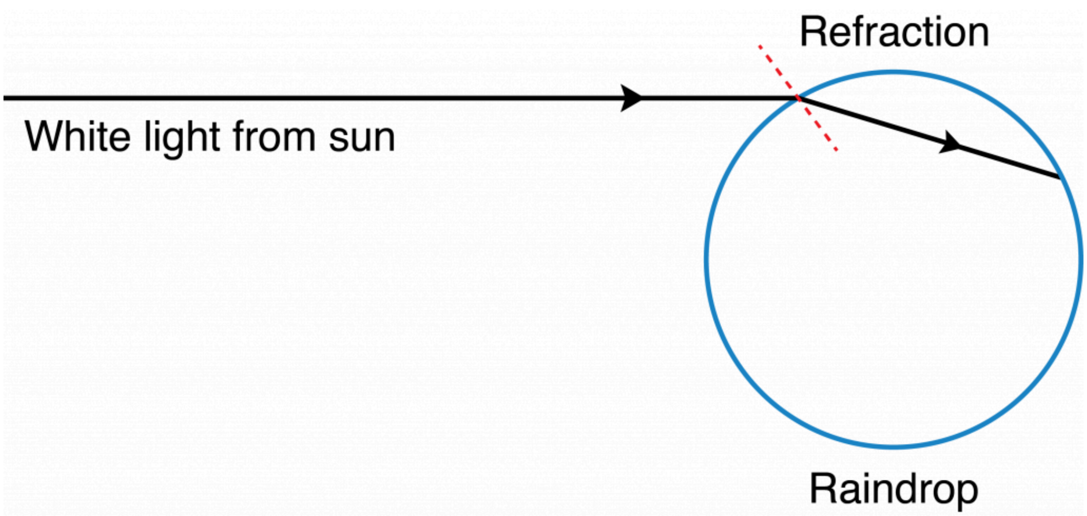

FIG. 1.46 White light ray from the Sun ***refracts*** *as it enters a raindrop.*

Next the colored light ray is envisioned as moving through the rain drop and encountering the inner surface of the other side of the raindrop. What happens there?

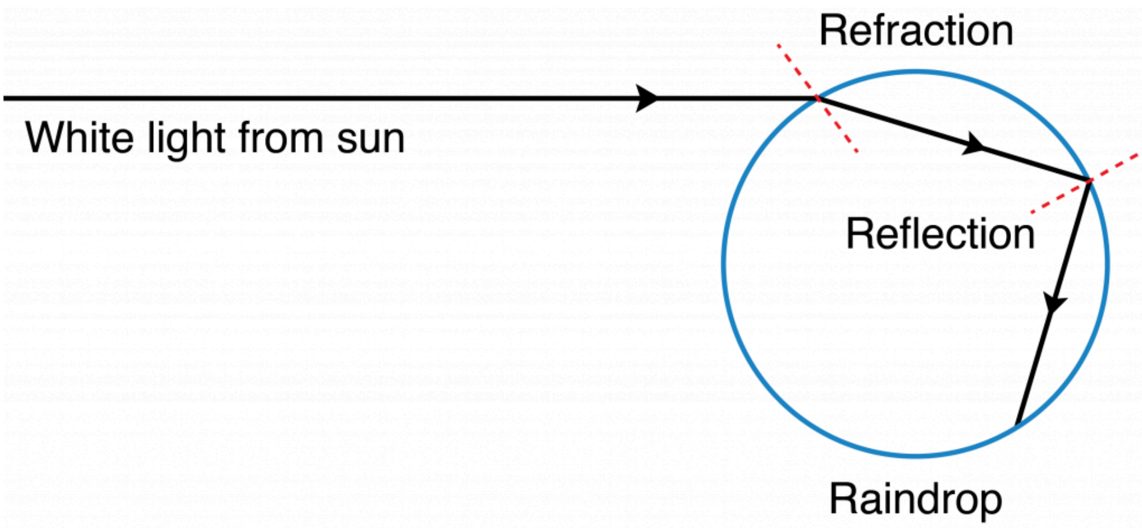

FIG. 1.47 Light ray of a particular color is ***reflected*** *at the smooth inner surface of the rain drop.*

As shown in Fig. 1.47, when rays of a particular color enter a drop, they are envisioned as bending and continuing to move in a straight line in a direction away from the observer until they reach the smooth inner surface of the raindrop. As shown in Fig. 1.47, some are envisioned as being **reflected** internally at the inside surface, where angle of reflection equals the angle of incidence for each color. These rays are envisioned as now heading back in a direction toward the observer.

Then the rays of all colors are envisioned as moving back through the raindrop to the original side they entered, but now traveling in the opposite direction. What happens there?

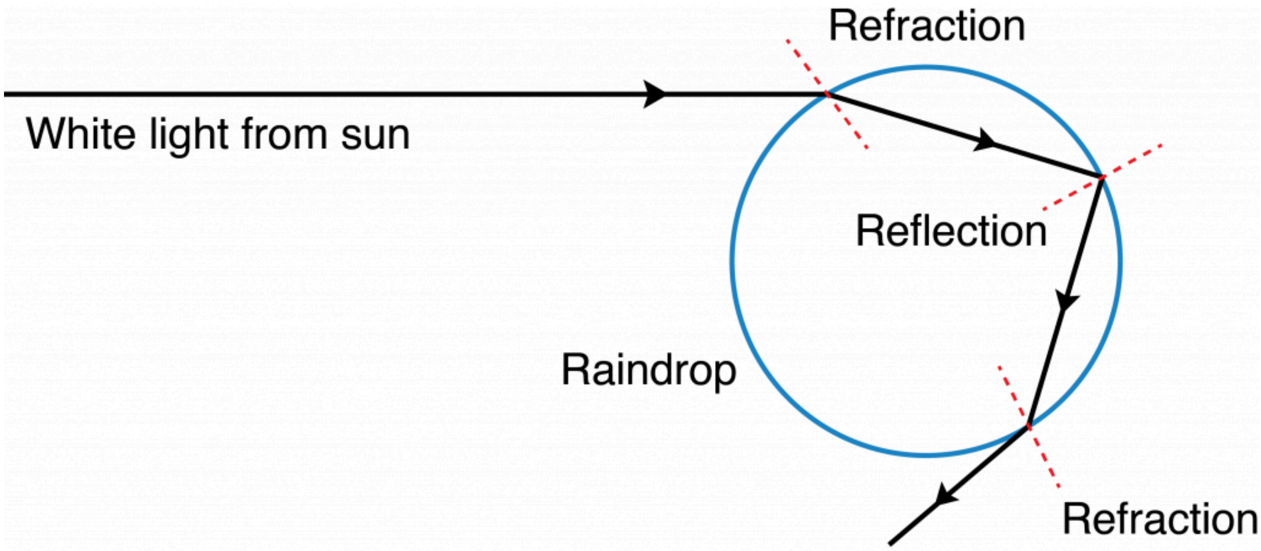

FIG. 1.48 Light ray of a particular color is ***refracted*** *again as it moves from water into air.*

As shown in Figure 1.48, rays of this color are envisioned as being **refracted** again as they leave the raindrop in the direction of the observer, bending again, but away from the normal at a particular angle for that color. The red rays leave the surface below the green rays, which are below the blue rays. This is the inverse order to colors seen in a rainbow.

As shown in Fig. 1.48, the entire trip through a rain drop is envisioned as involving a) **refraction** as white light enters the raindrop and separates into its component colors as each color bends at its own angle, b) **reflection** of each color at the opposite inner surface with color's angle of reflection equal to its angle of incidence, and then c) **refraction** again but in a direction toward the observer as the rays of each color leave the raindrop.

Note that if you see a rainbow you are seeing light from DIFFERENT raindrops. The red light is coming from drops high in the sky, the violet light from drops lower in the sky (See: http://science.howstuffworks.com/nature/climate-weather/atmospheric/question41.htm).

Figure 1.49 shows a ray diagram drawn by Rebecca McDowell when she was a second year Bachelor of Teaching student at the University of Melbourne, Victoria, Australia. She included many colors of the spectrum and represented someone seeing different colors from raindrops at different heights.

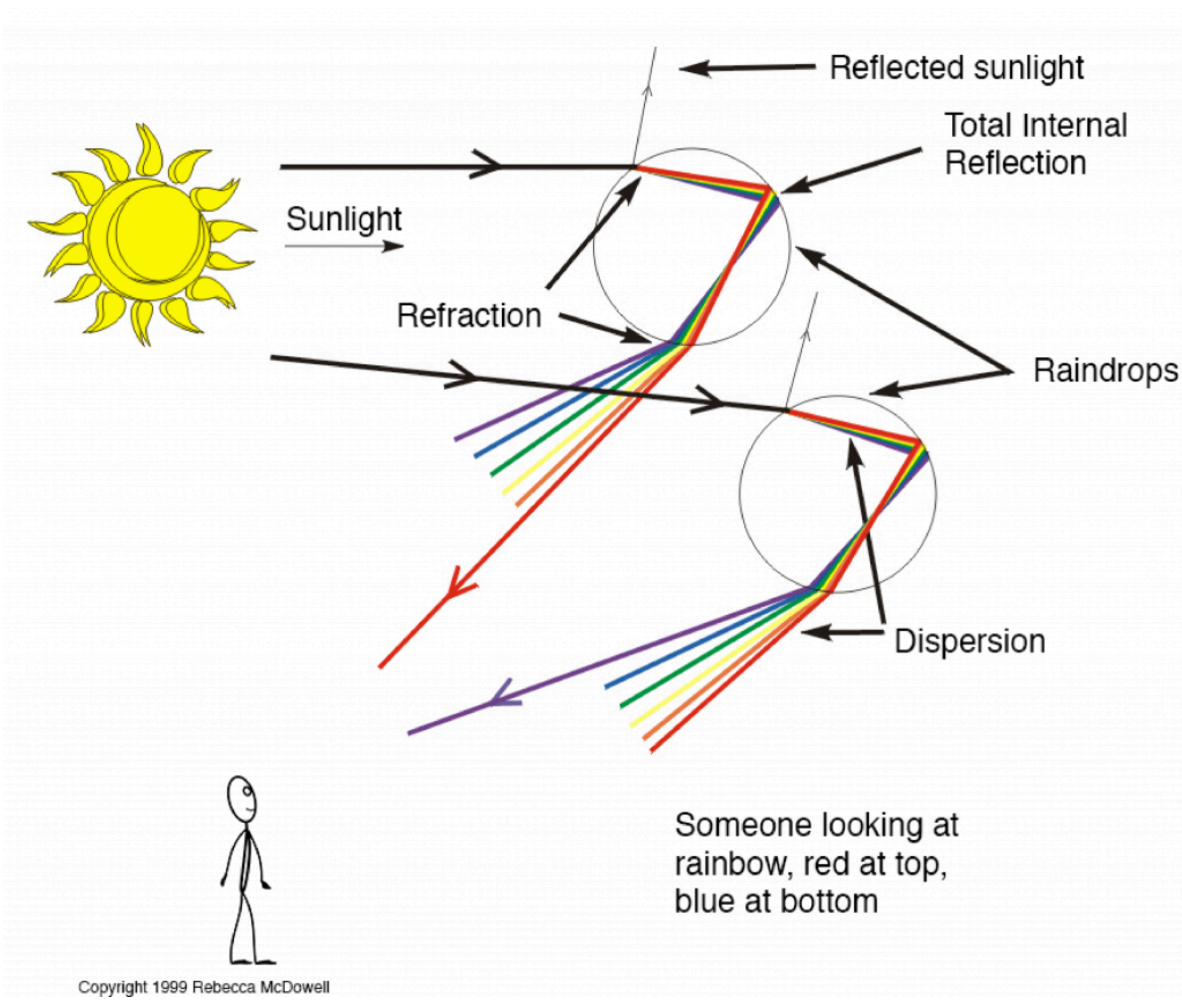

FIG. 1.49. Seeing different colors from different raindrops at different heights. Rebecca McDowell, How Rainbows Form, University of Melbourne (1999) [*http://www.rebeccapaton.net/rainbows/formatn.htm*](http://www.rebeccapaton.net/rainbows/formatn.htm) *accessed May 28, 2019.*

Next time you see a rainbow, enjoy!

Fig. 1.50 Rainbows!
Images by Katrina van Zee from a sailboat in Loch Nevis, Scotland.

As shown on the right in Fig. 1.50, the order of the colors in the faint secondary bow of a double rainbow is reversed with red light forming the inner arc. The explanation involves a similar model of envisioning light rays from the Sun refracting, reflecting, and refracting as they enter and leave raindrops. In a secondary bow of a double rainbow, however, the incoming refracted light rays are envisioned as reflecting twice within a raindrop rather than once, with violet light coming from higher drops and red light from lower ones. (See https://www.metoffice.gov.uk/weather/learn-about/weather/optical-effects/rainbows/double-rainbows and http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/rbowpri.html#c2.)

The process of using models to develop explanations of complex phenomena is an example of an aspect of the nature of science articulated in the US *Next Generation Science Standards* that *science models, laws, mechanisms, and theories explain natural phenomena* (NGSS, Lead States, 2013, Appendix H) (See: https://www.nextgenscience.org/resources/ngss-appendices.)

IX. Historical and Current Perspectives on the Nature of Light

Historical interpretations of the spectrum of colors dispersed by a prism

Archeologists have found glass prisms in ancient Roman ruins as well as natural prisms such as rock crystals in Pompeii (Rossi & Russo, 2017, p. 335). These findings suggest that people have been seeing a spectrum of colors displayed when white light shines through a prism since ancient times. Greek and Roman writers also discussed optical phenomena. Euclid (325 BC-265 BC), for example, envisioned light as rays moving in straight lines, formulated a law of reflection, and knew about refraction effects (Mach, 1926/2003, p. 3-4).

People also have pondered the nature of light and colors for a long time. The Greek philosopher Aristotle (384 BC-322 BC), for example, wrote that colors were mixtures of light (white) and darkness (black). This became widely accepted and led to the view that light from the Sun was a single form of light, white, and that a prism modified pure white light into the different colors as the white light moved through the prism.

This view of white light persisted until the publication of a letter to the Royal Society of London in 1671/72 by Isaac Newton. He stated and supported a different view, that white light was already a mixture of colors, with each color bending as it entered a prism at its own angle of refraction.

Newton (1671/72) referred to refraction as "refrangibility" and stated that:

> *As the Rays of light differ in degrees of Refrangibility, so they also differ in their disposition to exhibit this or that particular colour…The least Refrangible Rays are all disposed to exhibit red colour, and contrarily those Rays, which are disposed to exhibit a Red colour, are all the least refrangible: So, the most refrangible Rays are all disposed to exhibit a deep* Violet Colour, *and contrarily those which are apt to exhibit such a violet colour, are all the most Refrangible. And so to all the intermediate colours in a continued series belong intermediate degrees of refrangibility. (p. 3081, #1 and #2)* https://royalsocietypublishing.org/doi/abs/10.1098/rstl.1671.0072

In addition, Newton noted that when we perceive an object to have a particular color, that effect is due to the object primarily reflecting light of that color to our eyes:

> *…the Colours of all natural Bodies have no other origin than this, that they are variously qualified to reflect one sort of light in greater plenty than another. And this I have experimented in a dark Room by illuminating those bodies with uncompounded light of divers colours…and consequently when illuminated with day-light, that is, with all sorts of Rays of any colour promiseuously blended, those qualified with red shall abound most in the reflect light, and by their prevalence cause it to appear of that colour (ibid, p.* 3084-3085, #13)

Newton claimed that the colored rays already existed within the white light and that these rays separate as they bend at different angles within the prism (p. 3083, #7). To support this claim, Newton showed that not only did a prism disperse white light into separate colors but also that a lens could converge these colored rays back into white light like that that comes from the Sun. He presented evidence for this claim by describing his experimental setup and findings:

> *In a darkened room make a hole in the shut of a window, whose diameter may conveniently be about third part of an inch, to admit a convenient quantity of the Suns light: And there place a clear and colourless Prisme, to refract the entering light towards the further part of the Room, which, as I said, will thereby be diffused into an oblong coloured Image. Then place a Lens of about three-foot radius (suppose a broad Object-glass of a three foot Telescope,) at the distance of about four or five foot from thence, through which all those colours may at once be transmitted, and made by its Refraction to convene at a further distance of about ten or twelve feet. If at that distance you intercept this light with a sheet of white paper, you will see the colours converted into whiteness again by being mingled.*

He provided some details of how to do this and suggestions of what to observe:

> *But it is requisite, that the Prisme and Lens be placed steddy, and that the paper, on which the colours are cast, be moved to and fro; for, by such motion, you will not only find, at what distance the whiteness is most perfect, but also see, how the colours gradually convene, and vanish into whiteness, and afterwards having crossed one another in that place where they compound Whiteness, are again dissipated, and*

severed, and in an inverted order retain the same colours, which they had before they entered the composition…(ibid., p. 3086)

Newton also provided the ray diagram reproduced in Figure 1.51 to illustrate this experiment. In Figure 1.51, rays of white light from the sun (SF) enter a hole in a window (EG), pass through an equilateral prism (ABC), and are dispersed, with example rays FP bent more than FR. Lens (mn) converges these rays so that they meet at point Q on paper HI as white light, although they are seen as colored spots before and after Q if the paper HI is moved back and forth. (This excerpt from the letter also includes some of the text, in which the font for s looks like an f.)

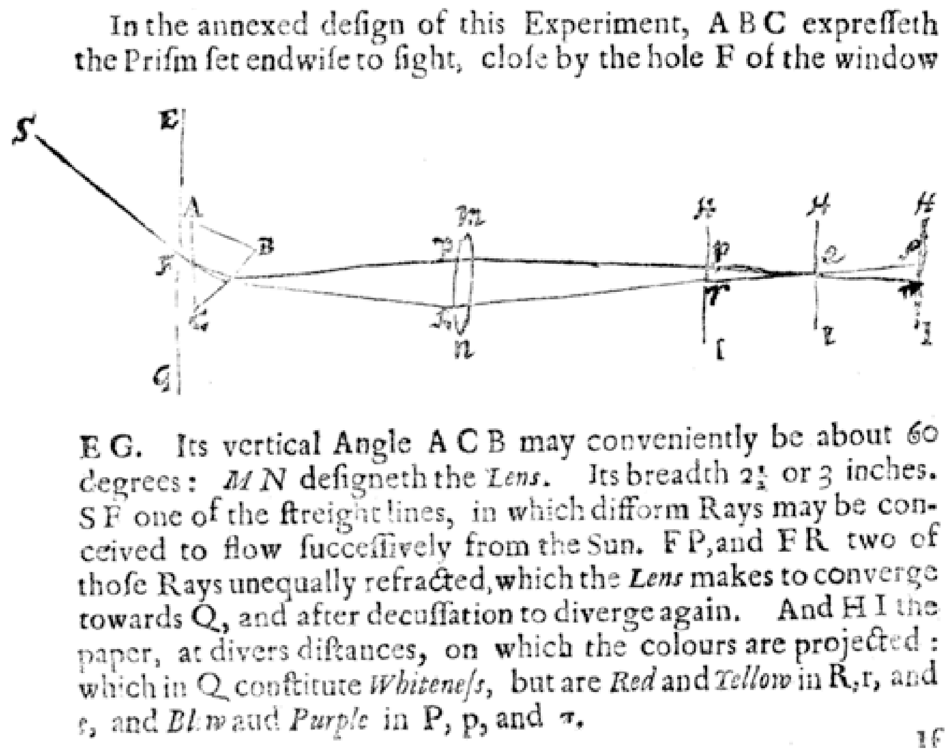
In the annexed defign of this Experiment, A B C expreffeth the Prifm fet endwife to fight, clofe by the hole F of the window E G. Its vertical Angle A C B may conveniently be about 60 degrees: *M N* defigneth the *Lens*. Its breadth 2½ or 3 inches. S F one of the ftreight lines, in which difform Rays may be conceived to flow fucceffively from the Sun. F P, and F R two of thofe Rays unequally refracted, which the *Lens* makes to converge towards Q, and after decuffation to diverge again. And H I the paper, at divers diftances, on which the colours are projected: which in Q conftitute *Whitenefs*, but are *Red* and *Yellow* in R, r, and ϱ, and *Blew* and *Purple* in P, p, and π.

FIG. 1.51. Excerpt from Newton (1671/72) showing white light (SF) dispersed by prism (ABC) into rays that are converged by lens (mn) back into white light on a piece of paper (HI) at Q. (p. 3086)
https://royalsocietypublishing.org/doi/abs/10.1098/rstl.1671.0072

Newton also applied this understanding to explain the colors in the rainbow (#10 on pages 3083-3084). We too can use what we now know about reflection, refraction, and dispersion to make sense of why we sometimes can see beautiful rainbows in the sky.

References in this section:

Newton, I. (1671/72). A letter of Mr. Isaac Newton, Professor of the Mathematics in the University

of Cambrdige; Containing his new theory about light and colors: Sent by the author to the publisher from Cambridge, Febr. 1671/72; in order to be communicated to the R. Society. *Philosophical transactions of the Royal Society of London*, 6, (60-80) 3075-3087. https://royalsocietypublishing.org/doi/abs/10.1098/rstl.1671.0072

For information about this letter and its problematic reception at the time, see Patricia Fara's article celebrating the 350th anniversary of the journal *Philosophical Transactions of the Royal Society*:

Fara, P. (2015). Newton shows the light: a commentary on Newton (1672) 'A letter…containing his new theory about light and colors…' *Philosophical Transactions of the Royal Society*, *http://rsta.royalsocietypublishing.org/content/373/2039/20140213*.

Other references mentioned in this section:

Ernst Mach, *The principles of physical optics: an historical and philosophical treatment*. Trans. J. S. Anderson and A.F.A. Young. (Methuen & Co, London; Dover, Mineola, NY, 1926/2003).

Cesare Rossi and Flavio Russo, *Ancient Engineers' Inventions: Precursors of the Present*. (2nd ed.) Cham, Switzerland: Springer International, p. 335. (2017). ISBN 978-3-319-44476-5

Library of Universal Knowledge, A Reprint of the Last (1880) Edinburgh and London Edition of Chambers's Encyclopaedia, p. 731
https://play.google.com/store/books/details?id=ichZAAAAYAAJ&rdid=book-ichZAAAAYAAJ&rdot=1
https://play.google.com/books/reader?id=ichZAAAAYAAJ&printsec=frontcover&output=reader&hl=en&pg=GBS.PA731 p. 731

In addition to referring to light as rays, Newton envisioned rays as composed of "small particles". In a later major document summarizing his exploration of light phenomena, the book *Opticks*, he wrote:

> *Are not the Rays of Light very small Bodies emitted from shining Substances? (p.* 371, Question 29)

Newton, I. (1730). *Opticks: Treatise of the Reflections, Refractions, Inflections and Colours of Light*. (4th ed.) London: William Innys at the Westend of St. Paul's . http://www.gutenberg.org/ebooks/33504

Christiaan Huygens (1690), a Dutch contemporary of Newton, however, proposed an alternative way of envisioning light, as analogous to sound, traveling outward in all directions from a source like a wave formed when a pebble drops into a puddle of water:

> *It (light) spreads, as Sound does, by spherical surfaces and waves: for I call them waves from their resemblance to those which are seen to be formed in water when a stone is thrown into it, and which present a successive spreading as circles, though these arise from another cause, and are only in a flat surface.*(p. 4)

Christiaan Huygens, *Treatise on Light*. (Translated from French by Silvanus P Thompson). Macmillan, London, 1690/1912). http://www.gutenberg.org/ebooks/14725

Figure 1.52 shows examples of successive spreading of circles from raindrops falling on water.

FIG. 1.52. Example of circular waves formed by rain falling on water. Image by Ruth Hartnup CC by 2.0 https://www.flickr.com/photos/ruthanddave/5713878850

Envisioning light as such successive spreading of circular waves also occurs today. Light waves can be represented as shown in Figure 1.53, which presents the primary colors of the spectrum of light from the sun. Red light has the largest wavelength, violet the smallest.

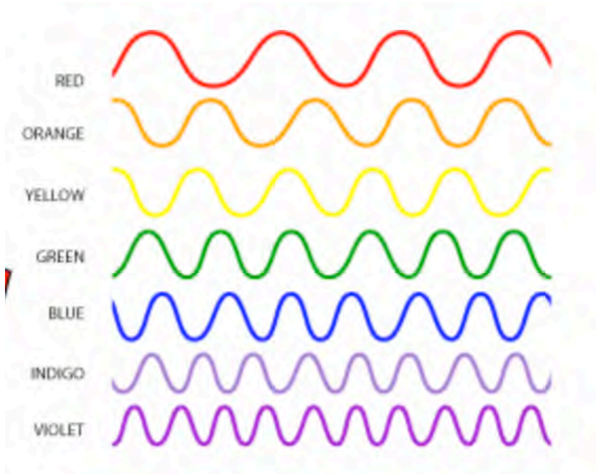

FIG. 1.53 Primary colors of the spectrum of light from the Sun as represented by waves with different wavelengths. [National Aeronautics and Space Administration, Science Mission Directorate. (2010). Visible Light. http://science.nasa.gov/ems/09_visiblelight , accessed May 28, 2019.]

As shown in Fig. 1.54, a *wave length*, often represented by the Greek letter *lambda* can be measured from crest to crest, midpoint to midpoint, or trough to trough. The wave's *amplitude* is the distance from the midpoint to the crest or trough.

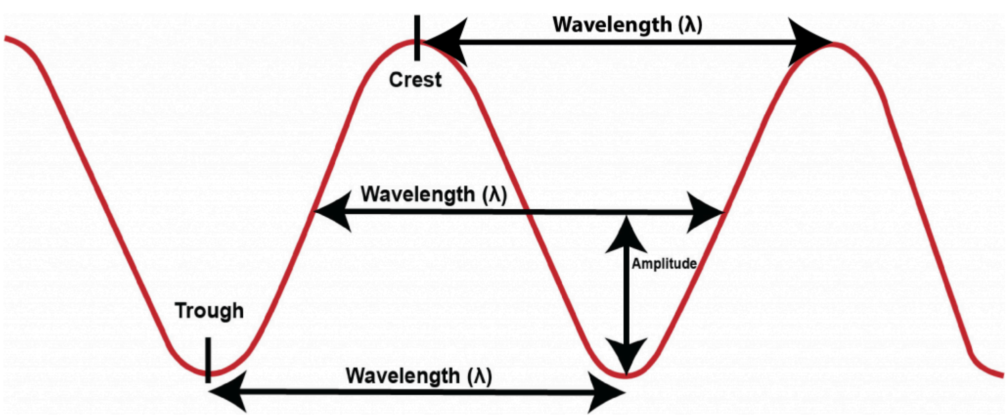

FIG. 1.54 Wave diagram showing wave length and amplitude. Modified from Phil Stoffer http://geologycafe.com/images/wavelength.jpg

The light's *frequency*, often represented by f or the Greek letter *nu* is the number of waves that pass a point each second. The *speed* of a wave depends on both the wavelength and the frequency: $(\text{speed}) = (\text{wavelength})(\text{frequency})$.

These two perspectives on what light IS, whether particles or waves, were evident in the writings of Newton and Huygens in the 17th century. They continue today in the "wave-particle duality" to which physicists refer. Sometimes it is helpful to think of light as a stream of particles, sometimes as a spreading wave. Each perspective is useful, depending upon the context within which one is asking questions about light.

X. Making Connections to Educational Policies

What does it mean *to do* science? What should every person know about science? How should science be taught? These are questions that every community decides by what and how children learn science, or not, in its schools.

This section completes this unit. As an informed citizen, you should become aware of your community's standards for teaching science, particularly if you are a teacher, preparing to become a teacher, or a parent advocating for more science to be taught in elementary schools.

Question 1.25 What are the current standards for teaching science at various grade levels in your community?

- Contact the department of education in your community to find out about the current standards for teaching science at various grade levels. The Oregon Department of Education's announcement, for example, is at https://www.oregon.gov/ode/educator-resources/standards/science/Pages/Science-Standards.aspx . This state adopted the US *Next Generation Science Standards* (NGSS Lead States, 2013) in 2014.

A. Learning about the US *Next Generation Science Standards: Science and engineering practices*

The *Next Generation Science Standards* (NGSS) website is at https://www.nextgenscience.org . This website describes three dimensions of what it means to be proficient in science and engineering. These dimensions are *science and engineering practices, crosscutting concepts, and disciplinary core ideas* that NGSS recommends for students to learn at various grade levels.

This unit began, for example, with the scientific practice of *asking questions* about the nature of light such as *How does light seem to travel from a source to a screen*? By exploring light and shadows, students developed a model for thinking about light, that *light can be envisioned as rays traveling in straight lines*. Students next used that model to explain the *cause* of a surprising *effect*, that the projection on the screen of a pinhole camera is upside down. Searching for the *cause of an effect* is a *crosscutting concept* characteristic of the many domains of science and engineering. During explorations in this unit, students inferred and used a *disciplinary core idea* that *objects can be seen when light reflected from their surfaces enters our eyes.*

Development of the *Next Generation Science Standards* was based on an earlier document, A *Framework for K-12 Education: Practices, Crosscutting Concepts, and Core Ideas* (https://www.nap.edu/read/13165/chapter/1). The NGSS website includes a series of appendices that discuss various aspects of the *Framework*'s recommendations.

- NGSS Appendix F describes eight scientific and engineering practices at https://www.nextgenscience.org/resources/ngss-appendices . Scan these to see what they are and read about any that you find particularly interesting.
- Complete Table I.4 by indicating with a check mark your perception of participating in some way in some of the eight NGSS science and engineering practices during your exploration of light phenomena.

Table I.4. Science and engineering practices (NGSS Lead States, 2013)

Table I.4. Science and engineering practices (NGSS Lead States, 2013)

Practices	Exploring light and shadows	Exploring pinhole phenomena and estimating the size of an object	Exploring reflection, refraction, dispersion and explaining rainbows
1. Asking questions (for science) and defining problems (for engineering			
2. Developing and using models			
3. Planning and carrying out investigations			
4. Analyzing and interpreting data			
5. Using mathematics and computational thinking			
6. Constructing explanations (for science) and designing solutions (for engineering)			
7. Engaging in argument from evidence			
8. Obtaining, evaluating, and communicating information			

- Provide an example by choosing one of the practices and describe how you did this.

Complete your entries into Table I.4 and description of participating in one of the practices before reading an example of student work.

1. Example of student work about relevant educational policies

As shown in Fig. 1.55, a student indicated that many of the NGSS science and engineering practices had been used during this unit.

Science and Engineering Practices (NGSS, 2013)

Practices	Exploring light and shadows	Exploring pinhole phenomena and estimating the size of an object	Exploring reflection, refraction, dispersion and explaining rainbows
1. Asking questions (for science) and defining problems (for engineering	✓	✓	✓
2. Developing and using models	✓	✓	✓
3. Planning and carrying out investigations	✓	✓	✓
4. Analyzing and interpreting data		✓	
5. Using mathematics and computational thinking		✓	
6. Constructing explanations (for science) and designing solutions (for engineering)	✓	✓	✓
7. Engaging in argument from evidence	✓	✓	✓
8. Obtaining, evaluating, and communicating information	✓	✓	✓

FIG. 1.55 Student's response indicating use of science and engineering practices in this unit.

(The table) indicates with a check mark my perception of participating in some way in some of the eight practices specified during my exploration of light phenomena…One of the practices that we have participated in during class is developing and using models and we did this when we developed the idea that light can be envisioned as rays traveling in straight lines. In order to do this, we used a lamp, a barrier, a white piece of paper, and a meter stick. The light shined directly on the barrier, so the barrier made a shadow on the white paper. The meter stick was placed at the edge of the lamp and it went straight past the edge of the barrier. The meter stick represents a ray of light traveling from the lamp. The shadow of the meter stick was lined up with the edge of the barrier's shadow on the paper, which we inferred means that the light travels in a straight line because the shadows lined up perfectly in relation to the actual objects, so we assume that light can

always be envisioned as rays traveling in straight lines. Developing and using a model allowed us to develop a very important idea.

Physics student, Spring 2016

B. Reflecting upon this exploration of light phenomena

This unit began with exploring light and shadows in order to develop ways to think and talk about the nature of light. The first demonstration involved turning on a lamp in a dark room and observing light shining all around on the ceiling, the floor, and people's faces. The first central idea to emerge from discussing this demonstration likely seemed obvious, that *light leaves a source in all directions*. This central idea needed refinement, however, to acknowledge that directional sources like lasers exist and that not all directions might occur. The refined central idea became *light leaves most sources in many directions*. Small group explorations with a light source, barrier, and screen included using a meter stick (or ruler) to serve as a physical model representing the central idea that *light can be envisioned as rays traveling in straight line*s.

These two central ideas formed a conceptual model useful in explaining an intriguing phenomenon: if one looks at a light bulb through a pinhole camera, the projection of the light bulb is upside down! A good way to start thinking about such puzzling phenomena is to make a sketch of the situation, in this case, to draw a picture of the light bulb and a picture of its upside-down projection. The next step is to think about what one knows that is relevant to the situation shown in the sketch. For example, how can envisioning light as rays leaving a source in straight lines help here? In particular, how can the physical model, the meter stick (or ruler), help to think about how light from the top of the light bulb can travel through the pinhole toward the bottom of the screen?

Laying one end of the meter stick (or ruler) near the sketch of the top of the bulb and the other end of the meter stick (or ruler) near the sketch of the bottom of the projection suggests a useful insight: that if light rays from any <u>point</u> on the bulb can be envisioned as leaving the source in many directions, some rays from the top of the bulb can be thought of as traveling straight through the pinhole toward the bottom of the screen; some rays from the middle of the bulb can be thought of as traveling straight through the pinhole to the middle of the screen; and some rays from the bottom of the bulb can be thought of as traveling straight through the pinhole toward the top of the screen. This insight implies that an alternative explanation is not needed, that something happens to the rays to "flip" the projection. The physical model of the meter stick (or ruler) suggests that nothing happens to the rays forming the projection; they just keep traveling in the same direction they happen to be going, straight through the pinhole. The aluminum foil around the pinhole blocks other rays from the source from shining on the screen.

Simplifying a sketch can help make important aspects of a situation more prominent. Drawing a vertical line representing the bulb and a parallel vertical line representing an upside-down projection, for example, provides a useful visual model for pinhole phenomena, the *ray diagram*. Tracing the rays with one's finger while telling the story represented by a ray diagram can be a compelling way to communicate to others what one is envisioning to be happening.

The ray diagram for pinhole phenomena consists of two similar triangles. Interpreting these geometrically leads to a mathematical model for pinhole phenomena, an algebraic equation that expresses the direct relationship between ratios of the corresponding lengths of the similar triangles. This mathematical model made possible estimating a quantity that could not be directly measured. Students held a pinhole in a sheet of aluminum foil one meter away from a screen, traced the Sun's projection on the screen, measured the diameter of the projection, and used the equal ratios of corresponding lengths of similar triangles as well as information about the distance from the Earth to the Sun to estimate the Sun's diameter.

Exploring reflection phenomena with a mirror and two meter sticks or rulers in a dark room prompted a refinement of this ray model for light. *Light rays can be envisioned as traveling in straight lines until they hit a mirror and bounce away, with the angle of reflection equaling the angle of incidence*. Balls also bounce off walls and floors in this way, which suggests an elaboration of this model for light, that *rays can be envisioned as an on-going flow of particles, called photons, in straight lines*. An alternative model, representing light as waves, also can be helpful in explaining complex phenomena, as discussed in Unit 4.

Exploring refraction and dispersion phenomena prompted an additional refinement of this conceptual ray model for light. *When light rays move from one medium into another, such as from air into water or from water into air, the rays can be envisioned as traveling in straight lines that bend at the point of entering or leaving a medium. White light from the Sun can be envisioned as composed of many colors, with the degree of bending related to the color of the ray*. This refined conceptual model of light was powerful in explaining a complex phenomenon: rainbows!

C. Making connections to NGSS understandings about the nature of science

This unit has provided many examples of the nature of science as articulated in Appendix H of the *Next Generation Science Standards* (NGSS, Lead States, 2013) https://www.nextgenscience.org/resources/ngss-appendices . Appendix H includes tables that provide insights about the development of these understandings about the nature of science across grade spans of K-2, 3-5 (elementary), 6-8 (middle school), and 9-12 (high school). Four NGSS understandings about the nature of science are related to the science and engineering practices.

One NGSS understanding about the nature of science, for example, is that s*cientific investigations use a variety of methods.* Children in grades K-2, for example, should understand that *scientists use different ways to study the world.* In this unit, for example, students have made observations using lamps, barriers, pinhole cameras, mirrors, cups of water, and prisms to explore what happens when light moves from one place to another.

Another NGSS understanding is that s*cientific knowledge is based on empirical evidence.* Students in grades 3-5, for example, should learn that *science findings are based on recognizing patterns.* In this unit, for example, students have explored patterns in what happens to shadows when someone moves a barrier closer or farther away from a light source.

Students experience in several ways the NGSS understanding that s*cientific knowledge is open to revision in light of new evidence.* Students in grades 6-8 (middle school), for example, should learn that *science explanations are subject to revision and improvement in light of new evidence.* In this unit, the central idea that *light can be envisioned as rays traveling in straight lines*, for example,was modified as the students explored what happens when light reflects from a mirror, refracts when entering and leaving a new material, and disperses if the light is composed of more than one color

K-8 development of the NGSS understanding that s*cience models, laws, mechanisms, and theories explain natural phenomena* ranges, for example, *from* s*cientists use drawings, sketches, and models as a way to communicate ideas* (K-2) to s*cience theories are based on a body of evidence developed over time (*middle school). In this unit, for example, students have learned how to use ray diagrams and central ideas based on evidence to explain a variety of phenomena. They also have had access to original descriptions of investigations of light conducted over several centuries.

XI. Exploring Physical Phenomena: Summary of Equipment and Supplies for Unit 1

Exploring Physical Phenomena: Summary of Equipment and Supplies for Unit 1

***Exploring Physical Phenomena*: Summary of Equipment and Supplies for Unit 1**			
When used	For instructors and demonstration	For each group of 3	For each student
Often	4 large whiteboards Set of white board markers and erasers 2 meter sticks Chart paper Masking tape Large whiteboard for class moon observations	1 large whiteboard, 1 meter stick, 1 plastic bin with set of magic markers; Example NSTA journal, NSTA newsletter, Children's books about light, thermal phenomena, weather, climate change (Need second meter stick for each group for exploring reflection in Unit 1)	Small whiteboard, Whiteboard marker; Whiteboard eraser Half of an old manila folder with which to make paper "tent' name plate _______ /______/\
Unit 1 **Week 1** Day 1 **Q1.1 Exploring ways to foster science learning**	2 sheets chart paper on which volunteers alternately record findings reported by small groups about ways to foster science learning	Bin with above materials 1 sheet of chart paper on which group members draw pictures and record ways that fostered their own science learning	U1H1 Welcome Handout U1H2 Student information Form
If weather permits, go on field trip outside to start sky journals	Sky journal (see Unit 5, Question 5.6)		Before field trip outside: U1H8 Diagnostic Questions about the Sun, Moon, and stars Sky Journal (See Unit 5, Question 5.6)
Q1.2 Diagnostic Question about Light	Bright lamp, no shade; Basketball with "stand" (masking tape roll)		U1H7 Diagnostic Questions about Light Handout

Exploring Physical Phenomena: Summary of Equipment and Supplies for Unit 1			
Q1.3 – Q1.7 Exploring light and shadows	Large whiteboard Sheet of chart paper to cover whiteboard to serve as opaque screen Lamp with clear bulb so can see filament if available; otherwise frosted LCD bulb	Large whiteboard Sheet of chart paper to cover whiteboard to serve as an opaque 'screen' Shaded table lamp with bendable stem Barrier (board, book, or hand) U1H3 Exit ticket	U1H4 Physics Notebook Page with Explanations 2 U1H5 Physics Notebook Pages U1H9 Table1.1, Light and Shadows (use near end of class) Near end of class: cardboard cutout to take home and use in exploring light and shadows with friend or family member
Day 2 **Q1.9 – Q1.2 Exploring pinhole phenomena**:	Bright lamp with bulb that is not a sphere, no shade	Pinhole Exploration Envelope: (2 paper cups, 1 paper towel roll; 1 Al foil square, 3 wax paper squares, 6 rubber bands, 1 pin) (paper cups replace previous use of empty toilet paper rolls – they are clean, only need one rather than 2 ends added, and provide a larger projection) U1H3 Exit ticket	U1H5 Physics notebook page If remote learning: paper cup, empty paper towel roll, cereal or snack box; translucent cover such as cereal box liner or plastic bag; Al foil square or Al from candy bar wrapper unless using a paper cup; 1 or 2 rubber bands, pin or needle U1H10 Table1.1cont; Table 1.2, Pinhole Phenomena (use near end of class)

Exploring Physical Phenomena: Summary of Equipment and Supplies for Unit 1			
Week 2 Day 3 **Q1.16 Using pinhole phenomena to estimate diameter of Sun:**	Sunny day If not a sunny day: Bright lamp with bulb that is not a sphere, no shade Extra physics notebook pages if students have not brought their own	Pinhole Math Envelope (White paper on cardboard screen, cardboard holder with Al foil with pinhole; cardboard holder with wax paper screen if not a sunny day) U1H3 Exit Ticket	U1H11 Sun Pinhole problem stated;for use if rainy day) U1H13 Solving Pinhole Math Problems U1H12 Diameter of the Sun Handout; Table 1.3 (Use near end of class)
Day 4 **Q1.18 – Q1.20 Exploring reflection phenomena**:	(If there is a holiday during the term, combine reflection and refraction explorations)	Flashlight 2 meter sticks, yard sticks, rulers, or pencils Mirror Computer (provided; or laptop brought in by group member) Logger lite software TI Light Probe or other light sensor* ($16) or cell phone APP: LUX meter Interface** ($61) Reflectivity Envelope (samples of Al foil, cardboard, wax paper, colored paper including black, paper towel, dark cloth) U1H3 Exit Ticket	U1H14 Reflection Phenomena (use near end of class)
Week 3 Day 5 **Q1.21 Exploring refraction phenomena**		2 paper cups, one with dot Tray, straw or wooden stirrer U1H3 Exit Ticket	U1H15 Refraction Phenomena (use near end of class)

Exploring Physical Phenomena: Summary of Equipment and Supplies for Unit 1			
Day 6 **Q1.23-1.24 Exploring dispersion phenomena and explaining rainbows**	Sunny day or bright lamp	Prism (note: CDs can make rainbows but this involves a different mechanism than dispersion) (sunny day or bright light) Red, blue, and black whiteboard markers U1H3 Exit Ticket	If remote learning: prism or some drinking glasses, glass plates or jewelry crystals, or access to hose and spray of water on a sunny day U1H16 Dispersion Phenomena (use near end of class) U1H17 NGSS Practices
*** https://www.vernier.com/products/sensors/tilt-bta/50/** ****For example: Go!Link https://www.vernier.com/products/interfaces/go-link/**			

UNIT 2: EXPLORING THE NATURE OF THERMAL PHENOMENA

Exploring Physical Phenomena: What happens when light from the Sun shines on the Earth?

Unit 2 Table of Contents

Figures

Tables

I. Introduction

When light from the Sun shines on the Earth, things often get hot. This unit explores the nature of such thermal phenomena. Why, for example, do some things feel hot or cold? What is the difference between heat and temperature? How is energy conserved when mixing hot and cold water? While exploring the nature of thermal phenomena, you will be:

- ***identifying resources*** such as relevant language you use and experiences you have had
- ***developing central ideas based on evidence*** that you record in exploring how energy flows from hot to cold objects
- ***explaining an intriguing phenomenon*** such as why you might prefer sitting on wooden rather than metal risers in watching a soccer game late in the fall
- ***developing mathematical representations*** of the transfer of energy in various contexts
- ***using mathematical representations to estimate a quantity of interest*** such as how much cold water to add to a cup of tea too hot to drink and
- ***making connections to educational policy***, such as the *Next Generation Science Standards* (NGSS Lead States, 2013), the science standards adopted by many US departments of education.

During this unit, you will be learning about learning processes as well as about physics as you summarize and reflect upon your explorations. Also important will be integrating science and literacy learning such as speaking clearly, listening closely, writing coherently, reading with comprehension, and creating and critiquing media.

The main sections of the text present questions with suggestions for exploring topics and for writing reflections about your findings. Text in gray font indicates that these are suggestions; you may think of other ways to explore the topic. You are encouraged to ask and explore your own questions about thermal phenomena as well as those posed here. Check with your instructor if you choose to devise an alternative approach.

Much of the learning will occur within small groups as you and your group members talk with one another about what you are thinking and why. Keeping track of what one is doing and thinking is important. This course uses a template for a physics notebook page on which to record notes during class. The physics notebook page can help you remember your thoughts *before*, *during*, and *after* an exploration. An experienced elementary teacher, Adam Devittt, designed this notebook page to mirror the structure of *before*, *during*, and *after* reading strategies.

Before starting an exploration, think about and discuss with your group members what you know already about the topic, what questions you are asking, how you plan to conduct the exploration, and what you think you might find out.

During your exploration, record what is happening, what you are observing, and what you are thinking about what you are observing. Include sketches of equipment and observations. Note any words that are new and their definitions.

After your exploration, record any central ideas that have emerged from your observations and discussions. Also note the evidence on which you have based these ideas. In addition, provide a rationale that states explicitly how the evidence is relevant and supports the claims you are making in stating the central ideas. Also explain why this result is important. Then write a reflection about whatever you want to remember about this experience. In addition, briefly state what you are still wondering in this context.

After class, use your physics notebook pages and any handouts to write a summary of your exploration and findings. Writing such a summary after every class is a good way to prepare for the midterm and final examinations.

Next, to be sure you have understood the physics involved, read this text and some examples of student work. The student authors first wrote drafts, received feedback for ways to enhance content and clarity, and submitted these final versions. Also read about some nuances to consider when explaining the phenomena explored.

You also may find helpful student reflections about teaching a friend or family member about what they had just learned in class, historical information about ways knowledge about the topic developed, and some relevant aspects of the nature of science in the context of the topic explored. These sections of the text may broaden your understanding of science and of science learning and teaching.

II. Identifying Student Resources

Young children learn to stay away from hot stoves, to get mittens when going outside to play in the snow, and to sip carefully before drinking from a cup of hot cocoa when they come back inside. Such experiences can serve as resources on which to build when studying about thermal phenomena.

A. Connecting to what one already knows about thermal phenomena

One way to begin learning about a topic is to consider relevant everyday experiences and the language used to describe them:

Question 2.1 What are some everyday experiences you have had with thermal phenomena?

- How do you keep things hot or cold for a picnic?
- Adjust the temperature of water for a bath?
- Cook dinner?

Like many English words, the adjective *thermal* derives from a Greek root, in this case: *thérme*, which refers to *heat*.

- What words with the root thérme do you know?
    - What do you use to measure temperatures?
    - How do you keep a liquid hot or cold?
    - What controls how much heat a furnace delivers to a room?
    - What is the medical condition in which a person loses heat faster than the body can produce heat?

Everyday experiences with thermal phenomena may include using *thermometers* to measure temperatures, storing hot or cold liquids in a *thermo*s, adjusting a *thermostat* to increase or decrease the amount of heat delivered to a room, and taking care to avoid *hypothermia* while hiking in cold and/or wet weather.

The formal name for the focus of this unit is *thermodynamics*. This is the study of energy in the form of heat (*thermo*) and ways such energy flows within a system (its *dynamics*). Thermodynamics is the study of what happens when things warm up or cool down.

- Record some of your experiences with thermal phenomena before reading examples of student work.

1. Examples of student work identifying everyday connections to thermal phenomena

A student reflected on relevant resources as follows:

> *The elementary students in my classroom will experience thermal phenomena in their everyday lives. They will experience the warmth of the sun on their faces, the coldness of metal handrails in the winter, and hot pavement in the summer. Students who take baths may also be aware of what happens when you combine a lot of hot water with some cold water – the water temperature lowers, but is still on the warmer side.*
>
> Physics Student, Spring 2015

Another student wrote about an early experience that she had had:

> *I can remember being a young child and running to be the first in my classroom so that I could get a good seat. The good seat was not only close to the front, but it was a wooden chair, so it did not feel as cold as some of the metal and plastic chairs in the room.*
>
> Physics student, Fall 2015

Such memories provide useful examples of thermal phenomena to be explained.

B. Documenting initial ideas with diagnostic questions about thermal phenomena

One way we make sense of the world is through observations, what we see, hear, smell, taste, and feel. These observations provide evidence that we can think about and interpret in different ways. The diagnostic questions below document some of your initial ideas about thermal phenomena and will not be graded.

Name________________________________ Date______________

Diagnostic Questions about Thermal Phenomena

1. Consider (without touching) materials you may have at home such as an aluminum pie pan, steel can opener, Styrofoam or paper cup, and wooden salad fork – or four blocks made of such materials: an aluminum block, a steel block, a Styrofoam block or pad of paper, and a wooden block.

   Rank these in order of temperature. Explain the reasoning for your predicted ranking.

2. Touch the four materials. Rank these in order of temperature.

   Explain the reasoning for your ranking.

III. Developing Central Ideas Based on Evidence

What does it mean to develop an idea based on *evidence*? This is a practice central to doing science, to observe phenomena closely, record findings, and make sense of these results in ways that explain what is happening. Why, for example, would a child seek as a "good seat" a chair made out of wood rather than metal?

A. Developing central ideas about thermal phenomena

Some things feel cool when you touch them; other things not so much. How do their temperatures compare when measured with a thermometer?

Question 2.2 How would you rank different materials in order of temperature?

- Without touching, consider different kinds of materials often found in kitchens:

FIG. 2.1 Examples of aluminum, steel, Styrofoam or paper, and wooden materials

Equipment: Kitchen items such as aluminum pie pans, steel can openers, Styrofoam or paper cups, and wooden salad forks are often accessible but all have difference sizes and shapes. To simplify thinking about these materials, also consider using four blocks of about the same size and shape made out of aluminum, steel, Styrofoam or paper, and wood. Also obtain a bulb and tube thermometer, digital temperature probe, or cell phone APP that measures everyday temperatures (rather than just human body temperatures) to measure the items' temperatures after you have ranked them.

- Rank these materials in order of temperature.
- Explain the reasoning for your predicted ranking.

When all of your group members are ready:

- Touch the materials. Rank them in order of temperature.
- Explain the reasoning for your ranking.
- Talk with your group members about your rankings and reasoning.

If you want to record some of their ideas or change yours, leave your initial responses unchanged on the front of your paper and write instead on the back

- Try to come to consensus for ranking these materials in order of their temperatures. How do you as a group explain these observations based on touching the blocks?

- Measure the temperature of all of the items with a thermometer.

There are several ways to measure the temperature of objects. One simple way is to place a thermometer on each object in turn. One also can use a set of objects made out of different materials with a hole drilled in each to hold a thermometer as shown in Fig. 2.2

In using a regular glass bulb and tube thermometer, it is important to hold on to the thermometer near the top so one's hand does not affect the reading. Also keep holding the thermometer while waiting for the reading to stabilize so that the thermometer does not fall over and break.

Fig. 2.2 Styrofoam, wood, and two kinds of metal blocks and a thermometer.

- What is your ranking in order of temperature reading?
- Explain the reasoning for your ranking.
- Talk with your group members about your rankings and reasonings.

If you want to record some of their ideas or change yours, leave your initial responses unchanged on the front of your paper and continue writing instead on the back.

- Try to come to consensus for ranking these materials in the order of their temperatures.
  How do you as a group explain these observations based on measurement with a thermometer?

- Write a summary of your findings and explanation.

After completing your own summary, look at an example of student work

1. *Example of student work about how different materials feel to the touch*

Many students report feeling confident that the Styrofoam feels warmest and the metal feels coolest, based on prior experience with these materials as well with actually touching them now. There usually are some differences of opinion about how to rank the Styrofoam and wooden blocks and in what order to rank the steel and aluminum metal blocks.

One student described her experience in ranking the temperature of the four blocks after she touched them as follows:

> *Four blocks were laid out in front of me. I touched all four of the blocks and I noticed that they all felt like they were different temperatures. The two metal blocks felt the coldest, the wood block felt warmer than the metal blocks, and the Styrofoam block felt the warmest. Since these different materials all felt like they were different temperatures when I touched them, this is evidence that materials differ in how hot or cold they feel to the touch.*
>
> Physics Student, Spring 2016

Another student described what happened when her group used a thermometer to measure the temperatures of the four blocks. The scale of the thermometer was marked in degrees Celsius. This temperature scale is named after Anders Celsius (1701-1744), a Swedish scientist who defined a scale of a hundred degrees between the freezing and boiling points of water. On the current Celsius scale used world-wide, the freezing point of water is 0°C, room temperature is in the neighborhood of 20°C, human body temperature is about 37°C, and the boiling point of water is at 100°C at standard atmospheric pressure. For a summary of the history of measuring temperatures, see https://www.britannica.com/technology/thermometer#ref227799.

The student reported the following experience:

> *Students were then asked to flip over the plates and found that each one had a small hole drilled into it. Each table was then given a thermometer and asked to measure the temperature of the plates. Our table measured first the wood and Styrofoam and found both to be 24 °C. I thought that potentially there was something wrong with my thermometer, so I warmed it up to 30 °C and then placed it into a*

hole on one of the metal plates. The temperature went down and read 24 ^{O}C. I could not believe it. So I tried again with the thicker plate of metal and once again the temperature was measured to be 24 ^{O}C.

Physics Student, Fall 2015

Most groups are surprised to find that all the materials are at about the same temperature. The metal feels cool and the Styrofoam feels warm but the thermometer readings for the temperature of the metals, wood and Styrofoam are nearly or exactly the same! How can this be!

One possibility is that the thermometer is broken. That is readily tested by holding the thermometer's bulb in one's hand. The liquid in the thermometer's tube usually rises quickly with a warm hand on the bulb. Another possibility is that the thermometer is working properly and that the blocks are actually at or nearly at the same temperature.

Question 2.3 Why do some materials feel warmer or cooler than others?

- Talk with your group members about some possibilities for why the materials are all at the same temperature even though some feel warmer or cooler than others.
- Share your ideas with other groups. Listen closely to ideas that other groups are proposing.
- Talk with your group members about any suggestions from the other groups that seem helpful. Refine your group's ideas or pursue some new possibilities for explaining what was happening when you touched the different materials.
- Share your current ideas with the other groups. Listen closely to ideas that other groups are proposing now.
- Keep talking and refining ideas until your group and the other groups reach a consensus on some central ideas about what must be happening in order for the materials to have the same temperature but to feel so different when touched.
- Write a summary of the central ideas based on evidence that emerged from the small group conversations and whole group discussions.

After completing your own summary, look at an example of student work about thermal phenomena, nuances in exploring how hot or cold different materials feel to the touch, and some thoughts about the nature of science in this context.

1. Example of student work about developing central ideas based on evidence about thermal phenomena

A student interpreted the surprising finding that materials can feel different even if at the same temperature as follows:

> *…the thermometer did not read a different temperature for any of the four plates. This made students realize that since each of the plates was found to have the same temperature, that they were all at room temperature. Essentially each of the plates had been left for a long time untouched in the room and had not had a heat source or sink that would have affected them. This means that they all were the same temperature.*
>
> Physics Student, Fall 2015

Usually while discussing why the blocks are all at the same temperature, someone eventually utters the phrase *room temperature*. Occasionally someone will use the phrase *ambient temperature*. This has a more general meaning referring to the temperature of surroundings, sometimes used to refer to the temperature of the air surrounding a big computer. Once uttered, the phrase *room temperature* shifts most students from puzzlement to acceptance of the finding that the four blocks are all at the same temperature.

What remains is puzzlement about why the blocks feel so different even though they are all at room temperature.

The small group reports of current thinking may range from "I have no idea" to thoughts that hint at the next step. Someone, for example, may say something about hands being warmer than all of the blocks and someone else may struggle to express an idea about the materials of the different blocks being different in some way, hinting at the idea of a particular property of the materials that is making a difference.

Having heard these still-emerging ideas hesitatingly expressed, the small groups may make some progress if given another opportunity to talk with one another. Another round of reporting out may yield a well-articulated explanation that the class as a whole then adopts. This student, for example, continued with such an explanation:

> *Students were surprised to find that all of the plates were the same temperature, because when they placed their hands upon them, they could feel that the plates were colder or warmer than one another. What students came to realize is that what they were feeling was energy transfer by conduction. Essentially the metal objects are conductors of heat, which means that the energy from the students' hands was*

flowing from their palm into the metal…which left our hand feeling colder as the energy was leaving.

In this experiment, the students found that metal was a conductor, meaning that the metal transfers energy more quickly and has a high thermal conductivity. However, the Styrofoam, a substance often used for coolers, is an insulator, meaning that it has a low thermal conductivity, meaning that it transfers energy more slowly so it can keep hot things hot and cold things cold.

Physics Student, Fall 2015

The rounds of conversations that result in such a clear statement of what is happening take time, but they seem to help students make sense of what may have been a very puzzling experience. A goal of this course is to raise issues but to have students resolve these issues through small group conversations and whole group discussions. The intent is to create opportunities for students to experience science in ways similar to the ways that scientists experience science, as both interesting and comprehensible.

2. Nuances in exploring how hot or cold different materials feel to the touch

Students who held the bulb of their thermometer in their hands noted that the temperature indicated by the thermometer was higher than the temperature that the thermometer indicated for the four materials. They observed that there was a *temperature difference* between their hands and the blocks and inferred that *energy flowed from their hotter hands into the metal blocks*, which lowered the temperature of their hands.

The inference that energy flows only from hot to cold can be hard to accept because prior experiences may suggest a different direction. When one is sitting on a metal bleacher at a late fall soccer game, for example, the perception likely is that cold is seeping into one's body. However, the inference here is that what is actually happening is that one's body heat is flowing out into that entire metal bleacher!

The metal blocks felt cold; the Styrofoam felt warm. The inference is that the metal blocks differed from the Styrofoam in the *property of how easily the metal blocks conducted energy away from the students' hands*, the property of *thermal conductivity*.

The inference is that more energy flowed out of the students' hands into the metal blocks than into the Styrofoam block. The energy flowing into the metal blocks spread rapidly throughout the blocks; the metal blocks had a higher thermal conductivity. The students' hands lost more energy to the metal blocks and therefore felt cold when touching the metal blocks.

Another inference is that the energy flowing into the Styrofoam blocks did not spread throughout the Styrofoam blocks but stayed near where the hands were touching the blocks. The students' hands lost very little energy to the Styrofoam blocks and therefore their hands continued to feel warm

This introduces central ideas about the *transfer of energy* from hot to cold objects and the ease with which such energy transfer occurs. The inference is that energy flows quickly through materials that are *conductors*, which have a high *thermal conductivity*; energy flows slowly through materials that are *insulators*, which have low thermal conductivities.

Note that both judgments about the four blocks were based on evidence. Students produced rankings that differed based on observations made by touching the blocks. Students produced rankings that were the same based on observations made with a thermometer.

The usefulness of the rankings would depend upon the purpose. If one is choosing a material on which to sit on a cold day, rankings in terms of *thermal conductivities* would be helpful. If one is interested in the temperature of a room (without a heat source or sink), one could choose to use a thermometer to measure the temperature of an object made with any of these materials, the number obtained would be the same, or close to the same, for all. (Holding the object for a long time while making the measurement might change its temperature if the object has a high thermal conductivity.)

3. Some thoughts about the nature of science in this context

Science involves making judgments based on evidence. One needs to be aware, however, both of the nature of the evidence and its appropriateness for answering a question. When puzzlements occur, one may need to clarify ambiguities in formulating the question as well as in designing an exploration. Asking *How would you rank different materials in order of temperature*? turns out not be answerable by ranking materials by how they feel to the touch. Underlying the mismatch of that question with the suggested procedure is a conceptual distinction between heat and temperature.

B. Clarifying distinctions between closely related ideas

If something seems puzzling, one way to seek a better understanding is to ponder ideas that seem closely related, are they the same or different?

Question 2.4 What is the difference between the concepts of heat and temperature?

A useful way to organize outcomes is to review the set up, evidence, and relevant vocabulary for central ideas that emerge from explorations and discussions, as in Table II.1

- Clarify for yourself the difference in the meaning of the words *heat* and *temperature* in the context of physics by completing the following table:
  - Make a sketch of the set up with the four different materials
  - Note the evidence of how the materials felt when touched and what their temperatures were as measured by a thermometer
  - Define any relevant vocabulary.
  - Then write a summary of the central ideas about thermal phenomena developed so far in this unit.

TABLE II.1 Developing central ideas about thermal phenomena.

TABLE II.1 Explorations of Thermal phenomena			
Sketch of set up	Evidence	Central Ideas	Relevant Vocabulary
		Materials differ in how hot or cold they feel to the touch	
		Temperature is measured by a thermometer	
		Materials left for a long time without a heat source or sink in the room come to the same temperature, room temperature	Room temperature

		A temperature difference implies a flow of energy from hotter objects to colder objects. When the objects are touching, this process is called *energy transfer by conduction.*	Conduction
		Materials differ in their thermal properties such as how well they conduct energy throughout the material, their *thermal conductivity*. Conductors have high thermal conductivities. Insulators have low thermal conductivities.	Thermal Conductivity Conductors Insulators
		Heat and temperature are different ideas	

After completing the table above and summarizing your understanding of each central idea, look at an example of student work.

1. Example of student work clarifying the meaning of the words heat and temperature

Figure 2.3 shows one student's notes for the table above. Also presented is this student's summary of the central ideas about thermal phenomena developed so far in this unit.

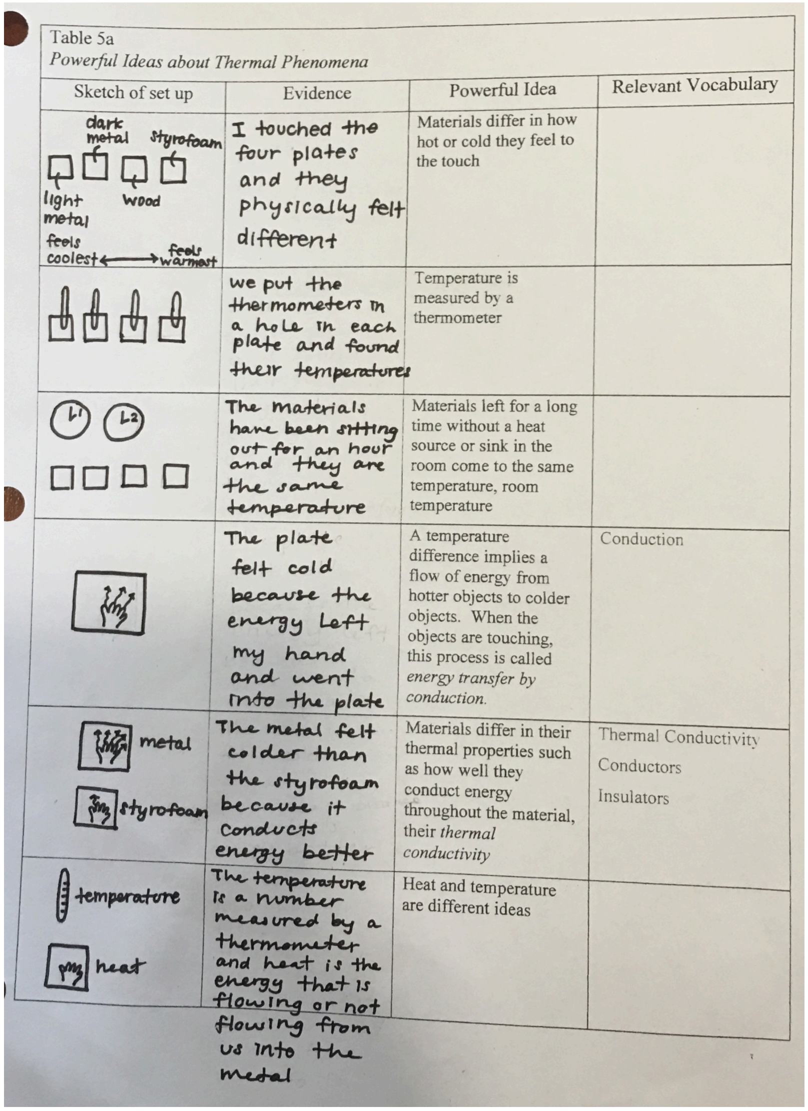

Table 5a
Powerful Ideas about Thermal Phenomena

Sketch of set up	Evidence	Powerful Idea	Relevant Vocabulary
dark metal, Styrofoam, light metal, wood; feels coolest ⟷ feels warmest	I touched the four plates and they physically felt different	Materials differ in how hot or cold they feel to the touch	
	we put the thermometers in a hole in each plate and found their temperatures	Temperature is measured by a thermometer	
L1, L2	The materials have been sitting out for an hour and they are the same temperature	Materials left for a long time without a heat source or sink in the room come to the same temperature, room temperature	
	The plate felt cold because the energy Left my hand and went into the plate	A temperature difference implies a flow of energy from hotter objects to colder objects. When the objects are touching, this process is called *energy transfer by conduction.*	Conduction
metal; styrofoam	The metal felt colder than the styrofoam because it conducts energy better	Materials differ in their thermal properties such as how well they conduct energy throughout the material, their *thermal conductivity*	Thermal Conductivity Conductors Insulators
temperature; heat	The temperature is a number measured by a thermometer and heat is the energy that is flowing or not flowing from us into the metal	Heat and temperature are different ideas	

FIG. 2.3 Student's entries describing the initial exploration of thermal phenomena.

For "sketch of the set up" in the first row, this student drew the four blocks in order from "*feels coolest*" on the left to "*feels warmest*" on the right and labeled the blocks "*light metal, dark metal, wood, Styrofoam.*" For evidence, the student wrote "*I touched the four plates and they physically felt different.*"

In the second row, the student drew four blocks with four thermometers and wrote "*We put the thermometer in a hole in each plate and found their temperatures.*"

In the third row, the student drew the four blocks and two wall clocks showing the times of 1 and 2 o'clock. The student wrote, "*The materials have been sitting out for an hour and they are the same temperature.*"

In the fourth row, the student drew a picture of a block and hand, with a representation of energy flowing out of three of the fingers of the hand into the block. The student wrote, "*The plate felt cold because the energy left my hand and went into the plate*."

In the fifth row, the student drew a picture of two blocks, each with a hand touching the block. The hand touching the metal block has a representation of energy flowing out of four fingers; the hand touching the Styrofoam block has a representation of energy flowing out of only one finger. The student wrote, "*The metal felt colder than the Styrofoam because it conducts energy better*."

In the sixth row, the student drew a picture of a thermometer and labeled it "*temperature*" and a picture of a block with a hand on it and labeled "*heat*". The student wrote : "*The temperature is a number measured by a thermometer and heat is the energy that is flowing or not flowing from us into the metal*."

The student wrote the following rationales for the central ideas claimed in the third column of the table:

> ***Materials differ in how hot or cold they feel to the touch***. *Four blocks were laid out in front of me. I touched all four of the blocks and I noticed that they all felt like they were different temperatures. The two metal blocks felt the coldest, the wood block felt warmer than the metal blocks, and the Styrofoam block felt the warmest. Since these different materials all felt like they were different temperatures when I touched them, this is evidence that materials differ in how hot or cold they feel to the touch.*
>
> ***Temperature is measured by a thermometer.*** *The thermometer that we used to measure the temperatures of the four blocks was long and narrow and had rounded edges. The thermometer was made out of glass and it measured the temperatures in degrees Celsius.*
>
> ***Materials left for a long time without a heat source or sink in the room come to the same temperature, room temperature***. *The four blocks of different materials were laid out for a long time without being touched at all. There were no heat sources or sinks in the room. This allowed the blocks time to sit in room temperature.*
>
> *Each of the four blocks had a small hole in it that allowed the thermometer to sit inside of the material. To measure the temperature of each of the blocks, I held the thermometer in the hole for a minute by holding it at the top so that my hand did not affect the temperature. After waiting for a minute for the thermometer to finish reading the temperature of the material, I recorded the temperature of each of the blocks.*
>
> *The light-colored metal block was 18°C, the dark-colored metal block was*

18.25-18.5°C, the wood block was 18.5-18.75°C, and the Styrofoam was 19°C. Even though the blocks differed in how hot or cold they felt to the touch, the readings are all within 1°C of each other. Because the readings on a thermometer for the four blocks of different materials were all relatively the same temperature, room temperature, this is evidence that materials left for a long time without a heat source or sink in the room come to the same temperature, room temperature.

A temperature difference implies energy is flowing from hot objects to colder objects. *Four blocks that are room temperature were laid out in front of me. We know that the blocks are room temperature because they were left for a long time without any heat source or sink in the room.*

When students touched the blocks, they noticed that some felt colder or warmer than others. Human body temperature is warmer than room temperature, so my hand is warmer than the blocks. When I touched the metal block it felt cold. There is a difference in temperature between my hand and the metal block, which is what allowed energy to flow from the warmer object, my hand, to the colder object, the metal block. Energy leaving from my hand to the metal block made my hand feel cold. Metal has high thermal conductivity, so energy is quickly transferred from my hand and I feel the temperature difference right away.

The wood and the Styrofoam are insulators, so they have lower thermal conductivity. Because the transfer of energy takes longer for these materials, there is less energy flowing, and as a result my hand does not feel as much of a temperature difference.

Energy transfer by conduction, in this context, refers to the rate that energy is transferred by touch between two objects, such as a hand and a metal block. Energy is transferring from my hand to the blocks, because they are different temperatures. My body temperature is warmer than the metal block and when I touch the metal block my hand feels cold, which is evidence that a temperature difference implies energy is flowing from hot objects to colder objects.

Materials differ in their thermal properties such as how well they conduct energy throughout the material*. Thermal conductivity is referring to the rate or speed that energy is transferring between two objects when they touch. First of all, metal is a conductor. When I felt the metal, it felt the coldest out of the four blocks. Since the metal has high thermal conductivity, it rapidly transfers energy. So, when I touch the metal, energy leaves my hand quickly, so there is a lot of energy flowing, therefore leaving me to feel a big temperature difference between the object and my hand.*

Next, the wood and the Styrofoam are insulators. The wood and the Styrofoam have low thermal conductivity, so they slowly transfer energy. Styrofoam transfers energy slowly so that it can keep hot things hot and cold things cold, which is why it is often used for coolers. Since it takes a while for all of the energy to transfer from my hand to those materials, there is less energy flowing and I feel less of a temperature difference between the object and my hand.

So, because metal which is a conductor and wood and Styrofoam which are insulators feel like they are different temperatures to the touch, this tells us that they conduct energy at different rates. This difference in rates for conducting energy is evidence that materials differ in their thermal properties such as how well they conduct energy throughout the material.

***Heat and temperature are different ideas.** …Temperature is a number measured in degrees. In class we used a thermometer to measure the temperature of the different blocks. According to the thermometer, the temperature of the light- colored metal block was 18°C, the dark colored metal block was 18.25–18.5°C, the wood block was 18.5–18.75°C, and the Styrofoam was 19°C. So, the numbers measured by the thermometer were the temperatures of the blocks.*

Heat can be thought of as a feeling, for instance the metal blocks felt colder than the other blocks, however what the students are feeling is the transfer of energy. Heat is the energy that is flowing or not flowing from us into the metal. So, when I touched the metal with my hand, the energy from my hand rapidly transferred to the metal because it is a conductor. The heat is what one feels because of the transfer of energy from one thing to another. Less energy was flowing from my hand to the wood, and even less to the Styrofoam, because they are insulators and are slower at conducting energy.

Because the different materials felt like they were different temperatures, the rate of the energy flow of each of the materials is different. Even though the rate of the energy flow of each material is different, the temperatures on the thermometer are all within 1°C of each other. So, since the thermal conductivity of the materials are different while the temperatures of the materials are about the same; this is evidence that heat and temperature are different ideas.

Physics student, Spring 2016

This student recognized that even though the measured temperatures were in the expected direction, with the Styrofoam block's temperature slightly higher than the light-colored metal block's temperature, a measured difference within 1°C could not explain the very large difference felt when touching these materials. The inference is that the large difference in how these materials felt to the touch was due to a large difference in a property of the materials, in how well they conducted energy from warm hands, their *thermal conductivities*.

Styrofoam is an insulator; it has a low thermal conductivity. Energy flowing from a warm hand to the Styrofoam stayed where the hand was touching the Styrofoam; therefore, energy stopped flowing from the hand to the Styrofoam when the hand and the small place where the hand was touching the Styrofoam became the same warm temperature. The rest of the Styrofoam remained near room temperature.

The metals, however, are conductors; they have high thermal conductivities. Energy flowing from a hand to the metal continued flowing and spreading throughout the metal block. Energy continued to flow from the hand, noticeably cooling the hand so the metal felt cool.

IV. Using Central Ideas about Thermal Phenomena to Explain an Intriguing Phenomenon

One aspect of the nature of science is its use of central ideas based on evidence in developing explanations of intriguing phenomena. The central idea that materials differ in the property of thermal conductivity can explain why some materials feel cooler than others even though they are the same temperature.

A. Applying the property of thermal conductivity in an everyday context

Question 2.5 Why do the metal legs of a chair feel cooler than its plastic seat?

- Use the central idea about thermal conductivity to explain this observation.
- Also engage a friend or family member in learning about such thermal phenomena.

Complete your responses before reading an example of student work.

1. Example of student work explaining an intriguing thermal phenomenon

After discussing the difference between heat and temperature, a student wrote:

> *The ideas above can help explain why metal parts of a chair feel colder than the plastic seat even though both parts of the chair have been in the same room for the same amount of time. One important idea to remember is that the metal part and the plastic part are the same temperature, regardless of how they feel. The metal part of the chair is a conductor so the heat from our bodies transfers quickly to the metal,*

leaving our hand feeling cold. However, plastic is not as conductive; the heat from our bodies takes longer to transfer to the plastic so our hand feels warmer.

I invited my friend to explore thermal phenomena with me. I engaged my friend in thinking about the difference between heat and temperature by adapting the activity we did in class with materials that I had in my house. I provided her with a metal spatula, a wooden spoon, and a Styrofoam coffee cup. I asked her to feel each of the objects and rank these materials by temperature and to roughly estimate what the temperature of each object was. She, like many of us in class, gave a clear ranking and suggested that the temperatures of each object were dramatically different.

I then explained, because I did not have a thermometer to prove it, that each of the materials was the same temperature. She looked at me puzzled and bluntly asked why they felt so obviously different. I explained to her, like it is stated above, that the materials act as conductors, some better than others, and that the rate the heat is transferred determines how it feels to us.

She then told me that she had learned about this before, but it had not stuck with her. So hopefully this will.

Physics student, Spring 2016

This is a typical report, that the friend or family member ranks the items by how hot or cold the items feel, expresses surprise when shown or told that the items are at the same temperature, recognizes the explanation that all are at room temperature but differ in how well they conduct energy throughout the material, and notes a lack of retaining learning that had occurred earlier.

V. Developing Additional Central Ideas about Thermal Phenomena

There are many ways to explore thermal phenomena. Thermometers are useful tools and come in many forms, based upon many different physical processes that depend upon how some change occurs with a change in temperature. This course uses digital temperature probes. Students can use regular bulb and tube thermometers that measure everyday temperatures (rather than only warm body temperatures), however, such as those that are typically available in schools.

A. Exploring thermal phenomena with technology

Students can see visually what is happening moment-by-moment on a graph of temperature versus time when using digital temperature probes connected to a computer. Students also can use regular bulb and tube thermometers in the explorations that begin with Question 2.7 below. Students using regular thermometers can become aware of what is happening moment-by-moment by viewing the figures below.

Equipment for each group:

• Provide two digital temperature probes that can be connected to a computer loaded with the relevant software, two regular bulb and tube thermometers and a stop watch, or a cell phone temperature app. Several technology companies such as pasco.com and vernier.com provide digital temperature probes. For example, we use Go!Temp probes (see https://www.vernier.com/products/sensors/temperature-sensors/go-temp/) that connect to a computer or other electronic device through free software, such as Logger Lite (http://www.vernier.com/products/software/logger-lite/#download).

•Provide a computer to use with the digital temperature probes. In our course, usually at least one student in a group can bring a laptop on days a computer is needed. We also have two netbooks that students can use or two groups can work together with one computer if necessary.

• To begin explorations, provide each group with a cup of cold water to cool the probe

quickly. The students can use their hands to warm up the probe or a cup of hot water. Place the cup(s) of water on a tray well away from the computer.
• Also provide a towel in case of spills.

The first exploration is very open-ended, in order to help students become familiar with using the temperature probes.

Question 2.6 What can you find out about thermal phenomena with a temperature probe connected to a computer?

This initial open-ended exploration provides time to learn how to set up the computer, download the software, plug in the temperature probe, and *play*. You and your group members have access to yourselves as heat sources and whatever is around you as materials.

- What questions can you ask and answer by playing in various ways with a temperature probe connected to a computer? Use a physics notebook page to keep track of what you are asking, doing, and thinking.

As shown in Fig. 2.4, the computer will be plotting a graph of temperature in degrees Celsius versus time in seconds. To start the computer program using Go Temp! probes, click on the little green box near the middle of the top of the screen.

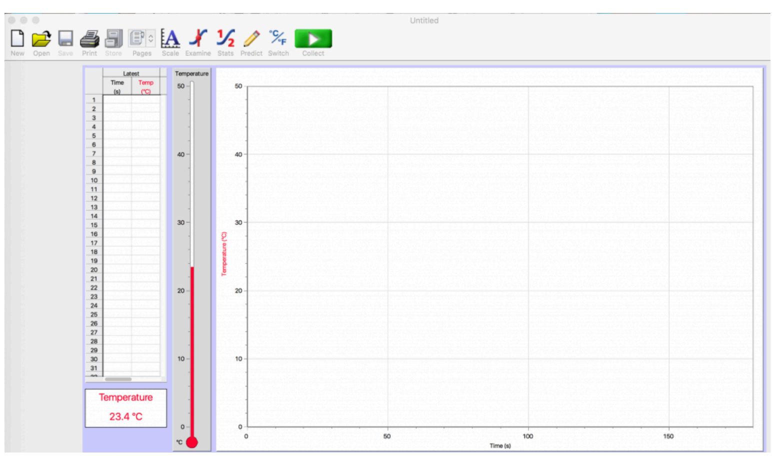

Fig. 2.4 Computer screen for displaying thermal explorations. ©Vernier Software & Technology-used with permission.