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Investigation of Students' Understanding of Light Matter Interactions in a Chemistry Context

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Investigation of Students' Understanding of Light Matter Interactions in a Chemistry Context

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Abstract

Students' have varying levels of understanding of light matter interactions in chemistry contexts. This study investigated students' understanding through the use of semi-structured interviews and PhEt simulations of both the single slit and double slit experiments. Coding qualitative analysis and construct maps were used to assign students to specific levels of sophistication. It was found that students' carry differing levels of understanding of light and light matter interactions where low level learners struggled to connect ideas in their explanations while high level learners had strong connections between their knowledge and explanations.

Key Words: Undergraduate Students, Light, Light Matter Interactions, Double Slit Experiment

Introduction

Chemists recognize the central role light plays in their field of study. Advanced classes such as Organic Chemistry and Physical Chemistry call on prior knowledge regarding light for uses in spectroscopy, synthesis, NMR, and quantum mechanics. Without a fundamental understanding of light and its properties, students will likely be limited in learning these topics. Light is a concept that is first introduced to many STEM majors in introductory classes, such as general chemistry, introductory biology, and general physics. However, in beginning STEM courses, light is often taught at only the surface level and as a result this can leave gaps in students' understanding.

Relatively little research has been conducted in chemistry investigating students' understanding of the double-slit experiment. A few prior studies have been conducted in physics education in which they identified difficulties physics students had when discussing the double-slit experiment, specifically regarding their conceptual understanding, and understanding of light as photons and electrons as waves (Ambrose et al. 1998). A recent study by Susac et al. (2021) also showed the difficulty that high school and undergraduate students had with interference and diffraction for the single and double-slit experiment using eye-tracking. These difficulties ranged from understanding basic wave behaviors, to interference, to understanding duality. Another recent physics education qualitative and quantitative study revealed students often showed fragmented knowledge structures in their explanations of light interference (DAI et al. 2019). Dai et al. found that higher level students had integrated knowledge structures and were able to apply them to questions, where as lower level students were often unable to make connections with knowledge and lacked a dedicated path for answers. With these findings in physics contexts, its increasingly important to investigate how students understand light in chemistry contexts as chemistry instruction approaches light differently.

This study is part of a larger project on developing a learning progression for light-matter interactions. The goal of this study was to explore students' conceptions regarding wave-particle duality – a concept introduced in general chemistry showing students the relationship between particle and wave properties. A second study was conducted, part of the overall project, investigating students' concepts about the photoelectric effect. The results from the photoelectric effect study demonstrated that students' ideas varied in sophistication regarding wave-particle duality. It was noted that many lower-level students' explanations stemmed from observations in the real world, relying on intuitive explanations. This illustrated the issue that students may not be appreciating the actual takeaways from the PE experiment (Balabanoff, Al Fulaiti, Bhusal, Harrold, & Moon, 2020). The cumulative results of both studies will be used to develop a tool to measure students' understanding of both the photoelectric effect and the double slit experiment. This will offer instructors, other researchers, and curriculum developers data to inform facilitating learning of the photoelectric effect and double slit experiment. This study was guided by the following research questions:

Research Questions:

1. How do students from different levels of chemistry understand the wave nature of light?
2. How do chemistry students understand light-matter interactions in the context of the double slit experiment.

Construct Maps

One way to display students' understanding light and matter interactions is through the construct modeling approach. Construct modeling views students' understanding as varying in sophistication as opposed to a dichotomous model where students are correct or incorrect. Students' levels of understanding are described by a construct map within the construct modelling approach (Brown & Wilson, 2011). The construct modeling approach is used over other models of cognition because it allows for a continuum to be built which varies from intuition to expertise. This shifts the analysis from individual knowledge elements to more cohesive and detailed knowledge structures. A key part of this framework is the assumption that students' knowledge is malleable and develops in sophistication over time. This allows the focus to move from what students know as correct and incorrect to what knowledge students have and how it can be built upon.

The development of the construct maps used for analysis in this study stemmed from the first study's investigation into students' understanding of particle nature of light, and the second study's investigation of students' understanding of the wave nature of light. The first study involved semi-structured interviews where the interviewer asked students to consider a series of figures regarding the photoelectric effect and draw predictions and conclusions about light behavior. The second study involved semi-structured interviews utilizing PhEt simulations (Reid et al., n.d.) which showed animated demonstrations of the single and double slit experiment. Students were asked to predict and draw conclusions about light behavior based on their observations.

Methods

The study took place at a large Midwest university (22,000 undergraduate students) during the fall 2019 and spring 2020 semesters. Students were recruited in class during the fall 2019 semester in General Chemistry 109 for non-majors ($n = 10$), General Chemistry 113 for majors ($n = 10$), Organic Chemistry 252 for non-majors ($n = 11$), and Physical Chemistry 481 ($n=1$). The total number of students interviewed was 32. During the spring 2020 semester students were sent a follow up email to schedule an interview.

Data Collection

Interviews were subsequently conducted in spring 2020 semester. Interviews are often one of the most utilized methods in data collection for misconceptions (Kaltakci-Gurel et al., 2016). Semi-structured interviews are utilized in this study to allow the interviewer to prompt questions where students can speak what is on their mind without consequence and the interviewer can follow up to elicit how they are thinking about or how they feel about something. This is important for gaining a deeper understanding of how students think about conceptions they have with light and light matter interactions. All interviews were captured on video using an overhead view to capture gestures from the students, and on an audio recorder. Paper was provided during the interview for students to help draw out or articulate ideas they had. All material was scanned and uploaded into a secured drive for later analysis. Interviews were semi-structured that followed an interview protocol which can be found in the supplemental information.

Interview Protocol

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During the interviews, students were first prompted to discuss any prior knowledge they may have concerning light and light matter interactions, this included physical applications. After, students were asked to make predictions about various PhEt simulations. First, they were shown a simulation of basic wave behavior. This was to get students familiar with how the simulation looked and grab their basic understanding of how waves worked. Students were then asked to predict what would happen during a single slit simulation. These predictions proved useful in seeing the amount of prior knowledge students had concerning properties of light and wave interactions such as interference, collectively analyzed by qualitative coding. Qualitative coding can be defined by the summarizing of ideas, or text into codes (single words or phrases). These ideas and codes are compiled into an overall general code list which is then used to code all the transcripts. To create this general code list, two researchers independently coded two transcripts in a process described as open coding. During open coding any content or reasoning by the student was assigned a code. Both researchers then compared their codes and created a general code list. Another transcript was then analyzed by both researchers independently using the general code list, and compared for consistency between the researchers. An example of coding is below, take a quote from a transcript.

> *'the energy that is able to go through would be like parts of the light, basically it kinda likes fades out again, it goes through from that small part and then it kind of like becomes larger as it goes, uh, further to the right. Kind of like a cone.'*

During open coding, specific codes were generated:

- Light post slit will have the shape of a cone

A 'screen' was then added to the simulation which displayed the light intensity. After the single slit, students were prompted to make conclusions about light properties and interactions. This protocol was then repeated for the double slit simulation.

Data Analysis

Interviews were transcribed through an online transcription service. These transcripts were then checked for accuracy by the main researchers and gestures and drawings were added to the transcript. Transcripts were

- Light is energy
- Light expands/Light is radial

These codes correlate with what was said in this piece of text. Light is energy correlates to the *'the energy that is able to go through would be like parts of the light'* Open coding is about generalizing student statements into codes that can then be compared across transcripts. After open coding has finished these codes may be changed to condense/simplify across transcripts. For example, instead of saying post slit the shape of light will be in the shape of a cone (correlating to *'it goes through from that small part (the slit) and then it kind of like becomes larger as it goes, uh, further to the right. Kind of like a cone')*, it would be easier to say – Post slit, light changes shape. This encompasses all examples of student predictions and explanations for what they see. This code in general was used frequently, after seeing the first simulations students often bring up that the light has changed shape. More often, their explanations contain more specific codes that describe why or how (i.e light is radial). Going from open coding to a well refined codebook helps us narrow the scope for what we want to analyze based on patterns we saw during open coding.

All transcripts were coded with the final coding list and the codes were compiled into an excel sheet for comparison.

Coding

Once a final coding list was achieved, common codes were synthesized into themes which would later become the construct map groups. For example, a high number of students (n = 11) attributed the peaks of waves to visible light and the troughs of waves to the absence of light or dark regions. This response was outlined as level two in the light properties construct map – Peaks of waves correspond to visible light and troughs of waves correspond to absence of light. Other common codes were grouped and organized hierarchically according to sophistication, which was informed by experts and canonical texts. Table one and Table two show the sophistication of students' explanations regarding single wave behavior of light and the double slit experiment.

Table 1. Construct map describing distinct levels of students' understanding about the Single Wave Behaviour of light.

Level	*Description*	*Common errors*
4	Waves have nodes and antinodes that correspond to the intensity of the light. Energy is dependent on wavelength. Light diffracts and waves bend when they encounter an obstacle.	
3	Alternating pattern represents density of photons. When light hits an object, it reflects and collides with other particles of light.	• Reflection causes light to spread out • Particles of light "bounce back" and collide with other particles
2	A single light source shows interference through alternating pattern. When light collides with an object, it disturbs the trajectory.	• Black regions correspond to destructive interference • Green regions = constructive • Light collides with objects and spreads out/disperses
1	Peaks of waves correspond to visible light and troughs of waves correspond to darkness. The energy of the light dictates how far and how light travels. Correct understanding of the relationship between frequency and wavelength.	• When light hits an object, how it spreads out depends on its energy
0	Varying intensities of light are described through shadows and visible light. Light travels in a straight line. Incorrect understanding of the relationship between frequency and wavelength.	• Light with zero intensity is described as shadow

Table 2. Construct map describing distinct levels of students' understanding about the double slit experiment.

Level	*Description*	*Common errors*
3	Light waves constructively and destructively interfere. Interference gives rise to a specific repeating interference pattern. Frequency determines instances of interference.	
2	Light waves can constructively and destructively interfere. Interference only explains some regions	• Illuminated regions are from constructive interference and

	of light collected on a screen. Frequency is related to the amount of time associated with interference.	unobstructed light passing through slits • Larger frequencies result in longer interference times, and larger regions on the screen.
1	Light can interact and add together or cancel out. This interaction is caused by attraction and repulsion of light. The distance between peaks is based on wavelength and determines the size of illuminated regions on the screen.	• Illuminated regions are a result of light being "attracted" and adding together • Dark regions are a result of repulsion of light • The larger the distance between peaks, the larger the illuminated regions.
0	Light can interact and add together. When light meets a barrier, it creates a shadow. Shadows correspond to dark regions. Size of wavelength determines how much space the light takes up on the screen.	• Waves "crash" together where light is illuminated • The remainder of the shadow from the barrier causes dark regions • Colliding with barrier edges causes light to bend • Larger wavelengths physically take up more space than smaller wavelengths.

Results

Based on the construct maps generated from the studies and displayed in table 1 and 2, students were placed into each level based on their responses. This section will encapsulate the progression of a couple of students through the single light source and single slit simulation. The remaining levels and the double slit simulation will be summarized at the end.

Single Light Source

Few students were placed into level four for the single wave behavior map. These students showed some understanding of nodes and anti-nodes and were able to connect them to the simulation.

Level four students used nodes and anti-nodes in their explanations of the single light source. The full description for level four, for the single wave behavior can be found in table 1. Using Ellen, an organic chemistry student, as our first example, their progression through the interview can be tracked through the following examples. Ellen was placed into level four for the following explanation they gave after viewing the first simulation (Figure 1).

> ***Ellen: I*** *think this is the idea that it is a wave. You are hitting, you have nodes and anti-nodes I believe. And the black parts represent one or the other. I think it is anti-nodes. No. Or is it nodes? I am not quite sure but, I know there's anti nodes and nodes that reflects the wavelength like the the wave like property, I guess.*
>
> ***Interviewer 1:*** *Okay so what is node and anti-node?*
>
> ***Ellen:*** *I believe the node is either on the top or the bottom of the wave, and the anti-node is in the middle, like between them.*

Here, Ellen uses her knowledge about node and anti-nodes to describe the single light source simulation, this would be characterized as level four knowledge using the level description from the construct map:

> **'Waves have nodes and anti-nodes that correspond to the intensity of the light'**

Despite not having a concrete definition of nodes, Ellen was able to use their prior knowledge 'I know there's anti nodes and nodes that reflects the wavelength like the wave like property, I guess' to make a conclusion on the location of the nodes. Another student, Maggie who is a general chemistry student, was placed into level four for their prior knowledge of nodes and anti-nodes for single wave behavior.

> ***Interviewer 1****: So what are we seeing here [*playing wave simulation]*? What is giving you pause?*
>
> ***Maggie:*** *It's just, I'm thinking about, um, nodes and that's not at all anything to do with that. It just looks like nodes*
>
> ***Maggie:*** *nodes are like, um, that has to do with, uh, what's it called? Um, the models that we've been going over lately where you can't find any electrons. And so as there gets more orbitals there's more nodes and it's just like the end value minus one, okay. To get the number of nodes. So like it's like the probability of finding electrons in that given area. And so a node is an area you wouldn't find it at, which again has nothing to do with light.*

Maggie gave a distinct definition for nodes, despite the uncertainty in their original statement. Their first visual perception led them to consider nodes – in later simulation explanations Maggie comes back to the node explanation for other tangible explanations for the physical phenomena they are seeing.

Single Slit Simulation

Both students generated explanations that placed them into lower levels for the single slit simulation. For Maggie, they were placed into level one for the single slit simulation because they struggled to reason through the simulation. When asked about the shape of the light post slit for the single slit experiment Maggie responded:

> ***Maggie:*** *Where it's more rounded versus straight [inaudible] I have no idea why that would be, but I guess it's because like maybe it's taking more time for the light to pass through the barrier then with the middle and so around off a little bit.*

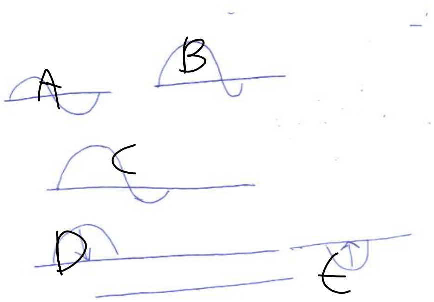
The first thing to note is that Maggie did not bring up nodes or anti-nodes for the rest of the interview, and instead introduced other concepts for each simulation, such as intensity = light interaction, and time. Because Maggie attributed the phenomena of the single slit to physical behaviors with the barriers, she was placed into level one. Noted in table 1 is the common errors associated with each level's explanations, most common in level one explanations was the physical explanation with light hitting an object. Maggie relied on intuition viewing the simulation first before utilizing concepts previously discussed. Below is an excerpt from the single slit simulation section where Maggie explains their thinking of the simulation utilizing intensity. The interviewer pushes Maggie to explain further their thinking on intensity, eliciting a definition and reasoning.

> ***Maggie:*** *Like when I think about it in real life. Yeah, that's kind of what I see it as. But I guess [inaudible] more of it probably is through the new thing, but I also don't know why it's like cloudy green on the outside, but it's probably just because the intensity is greater towards the middle where there's*

actually a hole. Well [inaudible] but yeah, I don't know.

Interviewer 1: *How do we observe intensity?*

Maggie: *Well, I know that like in light has to be, when I think of that, I just think of the metals, how you have to have a certain intensity in order to eject an electron when the like, yeah, but that's the only thing I can think of. I don't really know. Again, I did the math.*



Interviewer 1*: What about the sort of shape that light takes on the right hand side of the barrier.*

Maggie: *Where it's more rounded versus straight [inaudible] I have no idea why that would be, but I guess it's because like maybe it's taking more time for the light to pass through the barrier then with the middle and so around off a little bit.*

Maggie references tangible examples to help understand the simulation and goes from using definitions to help describe or explain to using intuition ("it's probably just because the intensity is greater towards the middle") due to her understanding breaking down.

Ellen placed level two after placing level four in the single light source. Ellen originally predicted for the single light source a particle explanation that there would be one straight line of light from the slit, a common misconception. After seeing the simulation, she changed from particle to wave explanation.

Ellen: *I think that's cause it's not acting as a particle it's acting as a wave, and so you're going to have reflection around these sides (top and bottom of screen) rather than just (the center screen), I don't know, if it was just a particle I think it would just if you looked at it as a particle it would just go straight across (points pen towards the slit of the barrier and drags it to the center screen) where if it was a wave it would be reflected (use pen to draw outside of the screen how big the wave would continue to get with curves) throughout like the cone, I guess.*

Ellen was able to shift her explanation based upon what she saw happen in the simulation, however, once the screen was added she added interference to her explanation. When prompted about the top and bottom regions of the screen, Ellen used interference and light interaction to describe the areas.

Ellen: *Cause it's interacting with other waves. So, if you had two waves and you had one like this (A) and then you had one maybe like this. If they combine, they might go, it is going to be in between the two. Whereas if you had one just like this and then you would have one just like this. Then they would cancel each other out (draws D and E), that is the interference that I am talking about.*

For this reason, Ellen was placed into level two of the light property construct map: In comparison to Maggie, Ellen sticks to using definitions she knows are associated with wave and light properties, while Maggie began to use intuition to describe and explain what she was saying.

‘A single light source shows interference through alternating pattern’

Both students approached the simulation in different ways, Maggie relied on intuition, as shown in the previous quotes, to describe what was happening during the simulation while Ellen relied on prior knowledge such as anti-node and nodes and wave interference to explain what was happening during the simulations. Though Ellen was able to connect the simulations to interference, she was unable to correctly describe the single slit simulation. Her ideas in the original single light simulation were correct, but she dropped the ideas once the single slit simulation was viewed. Ellen may have limited prior knowledge on nodes and anti-nodes and felt more comfortable describing the future simulations with her knowledge of interference and wave interaction.

The remaining level zero, three, and four of the single wave behavior was characteristic of more sophisticated responses. Like in Maggie’s original explanation of the single light source, many level four explanations were characterized by identifying nodes and antinodes. Level three students were characterized by their identification of particles and collisions in their explanations. One common error many level three students made in their explanations was the use of reflection, often mentioning particles

And later when asked about the blurry regions on the top and bottom of the simulation:

Interviewer: *And then what about the blurriness on top and bottom here?*

Brianna: *That was seen as well with the other ones it's just behind the barrier. So it's blurry cause the light, I cannot see through it.*

Commonly, students placed in level one had physical light interactions or physical visual explanations for the phenomenon they were seeing during the simulation. Students also used shadows to explain dark/blurry regions of the

colliding with or reflecting off of other particles or objects. The lowest level responses contained intuitive responses in relation to the real world. For example, many students included the use of shadows in their explanations. One student responded:

> *“So the green would be the light that the sources giving out. And the black would just be like the shadowing… like that's the contrast there… Obviously the green is the light source.”*

Table 1 captures the full variation between levels.

Double Slit Simulation

Level zero for the double slit consisted of explanations with the context ‘Light can interact and add together’ and ‘when light meets a barrier, it creates a shadow.’ Students that were characteristic of this explanation had explanations where light was interacting with the barrier in the simulation or the edges of the barrier. For instance, Brianna when prompted about the blurry regions in the middle post slit answered:

Brianna: *I mean it was just... Okay. Blurry is only behind the barrier and what's coming through obviously is the light that I can see. So what's causing the blurriness is the barrier.*

simulation. Ramona is a good example where she explains the blurry regions behind the slits with shadows:

Ramona: *That's cause, um, since the waves still move out like that. Um, but meet in the middle, that's kind of like the remainder of the shadow that's able to like be there from that middle part. It's sorta like, yeah. I don't know if they, if the waves didn't move like the way they would, that whole part [region 3 of DSE (shown in figure 1e)] would be shadow. But since they still like move out and hit each*

Many students who fell into the level one category for the double slit were unable to connect higher ideas of wave interaction with the simulation. Students used ideas that were tangible to what they were seeing (i.e shadows or physical interactions). This provided a roadblock where they could not advance their level of thought past these set ideas and explanations.

Level two students were able to develop more sophisticated explanations involving interference. For example, Arthur explained that light had particle characteristics and was able to collide with each other creating the pattern on the simulation:

Arthur: *"So as the light exits both of those openings, it collides. And I suppose when it collides it, they kind of push off each other and start going in that forward direction instead of going straight outward."*

After the addition of the screen (Figure 1), Arthur reaffirms his explanation with prior knowledge from a high school experiment:

Arthur: *"I'm starting to think back to like high school when we did some experiment like this where we had those two slits in a sheet of paper. It makes sense that of course we get two light sources on that screen from each of the openings. But then those waves are colliding in the middle and kind of combining to organize themselves into a third [region]."*

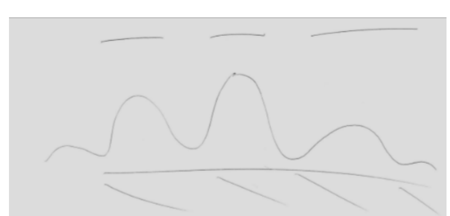
Arthur was able to develop a more sophisticated explanation for the phenomena he viewed, but was unable to explain all regions of light on the screen. Despite not mentioning interference as a term, Arthur was able to provide an analogy that led him to his conclusion. Arthurs mentions:

Arthur: *"If you have two sound sources, they kind of collide and then merge into one. Um, and I guess it's kind of the same thought process as if you had two pool balls and you were to push them toward each other. They're going to collide and then start moving forward because when they collide, they cancel out the side-to-side motion, if you will. And the only thing that's left is that forward motion."*

This excerpt demonstrates Arthurs attempt to connect both particle and wave behavior into what he was seeing on the simulation, one with sound waves, and two with pool balls. Arthur was able to connect prior knowledge in both academic settings and real world settings to explain the double-slit simulation. In the end of the interview when asked to make a conclusion about light behavior, Arthur stuck with his explanation and concluded that the light behavior displayed by the simulation was the result of light acting as a particle, and that light particles then organize themselves into waves. Though Arthur's explanation of the double slit interference is not correct, he was able to transition prior knowledge and experiences into an explanation regarding collisions and particles. Compared to level zero and one students, Arthur was able to be productive in thinking about his observations of the simulations.

Level three students were able to think about light cohesively, generating explanations with constructive and destructive interference, and light-wave behavior. For example, Destiny prior to seeing the double slit simulation provided a strong prediction and drawing:

Destiny: *That's where I expect a little bit more, little bit over for some two slits Um, but yeah, I just kind of, I guess the same thing that I drew before (draws picture below without the wave) of behind like the region between the two slits.*



Um, whatever you would call that you would get kind of your biggest or your brightest area of light right there. And then just kind of working outward, (Adds the wave below) getting bright spots and dark spots intermittently as the lights interact and to have constructive or destructive interference with the two different waves that come from the individual slits.

Destiny pulled on their prior explanation for the single slit simulation and was able to generate an accurate prediction for the double slit. Destiny was able to describe the constructive and destructive interference pattern that would arise in the simulation, as well as describing the bright and dark regions. The drawing above also shows the pattern that arose on the screen of the simulation. Destiny's prediction aligned with her prior explanations and understanding of interference in the explanations. After seeing the simulation, Destiny confirmed her prediction. Collectively, Destiny was able to explain the simulations using her robust understanding of light and wave properties.

Conclusions

Overall, this study was able to demonstrate the ways that introductory STEM students' understanding of light matter interactions can differ. With this variation in student understanding, construct maps were created based on student responses and organized hierarchically according to sophistication informed by experts and canonical texts. It was displayed starting with the lowest level of the construct maps, that these students often used intuition to inform their explanations. Their explanations were also characteristic of fragmented understanding and limited knowledge on light and wave behavior. Higher level students were able to connect knowledge to explanations they were more comfortable with. For example, double slit students level two and three students were able to comfortably explain interference connecting their ideas with particle or wave behavior. Highest level students were able to put particle and wave behavior together and create coherent explanations to the double and single slit experiment. These students often displayed prior knowledge with many key definitions for interference or wave behavior.

By utilizing students' knowledge structures through construct maps, we can help instructors at the undergraduate level create more informed curriculum for instruction. Through helping curriculum develop, students will have more support transitioning from high school to undergraduate introductory STEM courses and beyond. Creating a solid learning progression from the beginning for students that supports their undergraduate journey learning light and light matter interactions. These improvements can only benefit students in later courses and students who wish to enter industry post-graduation by filling any gaps in students' knowledge,

Appendix

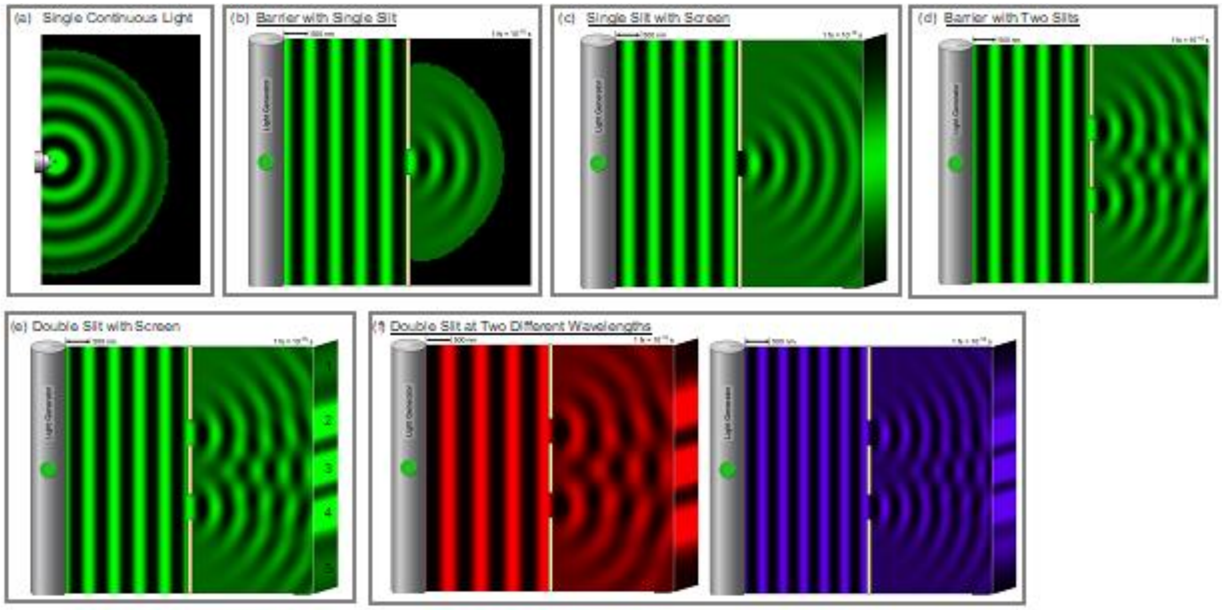


Figure 1 Shows the sequence of PhEt simulations that students observed during the interviews. (a) is a single light source, (b) is a single light source with a single slit, (c) is a single light source with a slit with the screen, (d) is the single light source with double slit. (e)is the single light source with double slit and screen, note the labeled 1-5 regions of light. (f) shows varying frequencies of the double slit.

Double slit interview guide

RQ 1: How do postsecondary chemistry students understand and apply the double slit experiment?

RQ 2: How do postsecondary chemistry students reason about light behavior in the context of the double slit?

Intro

1. How would you describe light?
    a. What can you say about the concept of light?
    b. What are some properties?

2. How are frequency and wavelength related? Are there any equations that you can use to help you describe the relationship?
    a. If unable to provide equation, show them $c=\nu\lambda$ and ask them to label/identify
    b. Relate back to energy, behavior of light
    c. ask them to define each term

    d. ask them to reason through this relationship

3. What is the relationship between energy and frequency? Are there any equations you can use?
    a. If unable to provide equation, show them $E=h\nu$ and ask them to label/identify

PHET predictions

Waves simulation

1. What do you predict to see on the screen?

Single slit - waves

No screen

1. What do you predict to see if there is one slit?
    a. Figure 1, followed by PhET simulation with one slit
2. Why is there this interference pattern?

Screen

3. What do you predict see on **the screen** with one slit?
    a. PhET simulation with screen
4. Why is this pattern created?
5. What conclusions can you draw about light behavior?

Double slit - waves

No screen

1. What do you predict to see if there is one slit?
2. Why is there this interference pattern?
    a. Why is the pattern slightly different where the waves meet?

Screen

3. What do you predict see on **the screen** with one slit?
4. How is your prediction different than what we see in the simulation?
5. Why is this pattern created?
6. What would you expect to happen if the frequency is increased?
    a. Why?
    b. Show Figure 2.
7. Why is this pattern different than a single slit pattern?
8. What conclusions can you draw about light behavior?

Double slit – photons

Show students Figure 3 and Figure 4 at the same time. Ask them to predict which student has depicted the most accurate outcome.

1. What is a photon?
2. What type of pattern would you expect to be on the screen?
3. Why are light particles producing the same pattern as waves?

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