



A construct modeling approach to characterize chemistry students' understanding of the nature of light

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Abstract

Across science disciplines, light is a common tool for measuring, characterizing, and catalysing molecules and molecular processes. Despite the ubiquity of light-based tools, little research has been done to investigate how students understand light and light-matter interactions (LMI). This topic is typically first introduced in first-year undergraduate chemistry courses where students initially encounter the quantum nature of light and matter. How students make sense of this content and transition from classical concepts to quantum concepts is relatively unknown. To gain further insight on how students develop quantum-level conceptions about light, we use a construct modelling approach. This approach is best suited to capture progressions in student understanding. In this study, we begin to model students understanding of LMI by first developing a model for the nature of light. Two sets of qualitative interviews were conducted about the particulate nature of light and the wave nature of light. Analysis of interviews resulted in four construct maps, which can provide information to instructors and researchers about the variation in student understanding of the nature of light. Findings from this study have implications for how quantum chemistry is introduced at the postsecondary level.

Graphical abstract

Background

Across chemistry education, curriculum developers are seeking to narrow down the broad scope of material typically covered in introductory chemistry to the fundamental ideas learners are to master in chemistry (Cooper & Stowe, 2018; Sevia & Talanquer, 2014). In this article, we contribute to this discussion by asserting that one fundamental idea is light and matter interactions. Light and matter interactions (LMI), though ubiquitously used by chemists, is a relatively under-explored idea in chemistry education research. To support curricular development and research about this fundamental idea in chemistry, this article offers a model of cognition of a fundamental component of LMI—the nature of light—in the form of construct maps.

An undergraduate chemistry major will encounter LMI or an application of LMI (e.g., spectroscopy) in each chemistry class. This is affirmed by the American Chemical Society (ACS) Division of Chemical Education's

Committee on Professional Training, which includes spectroscopic competencies in all ACS-accredited major chemistry courses (*Undergraduate Professional Education in Chemistry: ACS Guidelines and Evaluation Procedures for Bachelor's Degree Programs*, 2015). Further, the ACS Examination Institute's anchoring concept maps include topics and concepts related to light and its interaction with matter in each chemistry course map (T. A. Holme, Reed, Raker, & Murphy, 2018; Murphy, Holme, Zenisky, Caruthers, & Knaus, 2012; Raker, Holme, & Murphy, 2013). Further, the ACS Examination Institute's anchoring concept maps include topics and concepts related to light and its interaction with matter in each chemistry course map (T. A. Holme et al., 2018; Murphy et al., 2012; Raker et al., 2013). A robust understanding of LMI hinges on the quantum mechanical nature of light and matter, which is first introduced in general chemistry (Murphy et al., 2012). While it may be assumed that learners build on this introduction to the quantum level in subsequent courses (e.g., as they encounter infrared spectroscopy to characterize molecules in organic chemistry), there exists very little evidence to support this assumption or explain how students reason and subsequently apply this fundamental idea. Additionally, there is little documented discussion or coordination across course boundaries, with the notable exception of a few institutions (Cooper & Klymkowsky, 2019; Garoutte & Mahoney, 2015; McGill et al., 2019; Shepherd & Grushow, 2013). Emory University's complete overhaul of the four-year chemistry curriculum resulted in a full-semester class targeting light-matter interactions (McGill et al., 2019). Michigan State's CLUE curriculum coordinates LMI between general chemistry and organic chemistry (Cooper & Klymkowsky, 2019) and POGIL curriculum addresses LMI from general chemistry to physical chemistry (Garoutte & Mahoney, 2015; Shepherd & Grushow, 2013).

What we do know about students' understanding of the quantum nature of light and matter and their interactions is primarily based on undergraduate students in introductory courses (Dangur, Avargil, Peskin, & Dori, 2014; Didiş, 2015; Didiş, Eryılmaz, & Erkoç, 2014; McKagan, Handley, Perkins, & Wieman, 2007; Ozcan, 2015; Stefani & Tsapalis, 2009; Steinberg, Oberem, & McDermott, 2005; Taber, 2005), where students' explanations of quantum phenomena were most often rooted in classical views (Mannila, Koponen, & Niskanen, 2002). Regarding the quantum nature of matter, through interviews with second-year students, Stefani and Tsapalis (2009) uncovered a host of alternative conceptions centring around the definition of an atomic orbital, atomic structure, molecular orbitals, and hybrid orbitals. Importantly, the alternative conceptions were organized into levels according to sophistication (Stefani & Tsapalis, 2009). Additionally, a study by Dangur et al. (2014)

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3 with advanced secondary and introductory postsecondary students uncovered developmental stages
4 characterizing a learner's understanding of quantum mechanics. The initial developmental stage was
5 characterized primarily by macroscopic understanding and termed a naïve model. Students proceed to a hybrid
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7 model, which incorporates terminology and ideas from quantum mechanics into the naïve model. Students can
8
9 60 build on this hybrid model to develop a visual-conceptual quantum mechanical model, which includes qualitative
10 references to quantum theory. Ultimately, the target level of understanding is a mathematical quantum
11
12 mechanical model (Dangur et al., 2014).
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17 In a qualitative exploration of the nature of light, Özcan (2015) identified three different ways of reasoning
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19 65 about the nature of light across the contexts of blackbody radiation, photoelectric effect, and Compton effect.
20 Students tended to use a hybrid model, a beam ray model, or a particle model. However, in varying contexts
21 students switched models or inconsistently invoked multiple models (Körhasan & Miller, 2020; Özcan, 2015).
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23 Students have also had difficulty discriminating between quantum and classical ideas (Körhasan & Miller, 2020)
24 and were more likely to prefer classical interpretations of quantum mechanical ideas (Ayene, Kriek, & Damtie,
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26 70 2011). Because of students' reliance on classical ideas even in quantum contexts, it is difficult for students to
27 develop a robust quantum model that they can apply consistently (Ayene et al., 2011). Because of students'
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29 reliance on classical ideas even in quantum contexts, it is difficult for students to develop a robust quantum model
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31 that they can apply consistently.
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37 In addition to inconsistently applying models and relying heavily on classical ideas, it is difficult for students to
38 75 draw conclusions about the nature of light, even with a reformed physics curriculum (Carr & McKagan, 2009).
39 Implementing a reformed curriculum targeting the photoelectric effect resulted in an improvement in making
40 correct predictions about the outcome of modifying variables such as frequency and intensity (McKagan et al.,
41
42 2007). However, students still struggled to use these predictions to draw conclusions about the nature of light.
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44 Furthermore, upper-level physics students found it difficult to apply duality to electrons. For example, in one study
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46 80 upper-level physics students considered a single electron traveling through two slits and struggled to
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48 conceptualize the electron as a wave when going through the slits but as a particle when it lands on the screen
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50 (Singh & Marshman, 2015). In a cross-sectional interview study with students from general chemistry, organic
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52 chemistry, biophysical chemistry, and physical chemistry, we uncovered levels of reasoning about the
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54 photoelectric effect, where only the highest level of reasoning was able to generate a mechanistic explanation of
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the photoelectric effect (Authors, 2020). Further, this highest level of reasoning was characterized by an understanding of wave-particle duality and facility with distinction between continuous and discrete variables.

The results of the above-mentioned studies suggest that learners may progress through conceptual stages as they learn the quantum nature of light and matter. When it comes to investigating students' understanding of the interaction of light and matter, the primary focus has been about atomic absorption and emission (Ivanjek, Shaffer, McDermott, Planinic, & Veza, 2015; Körhasan & Wang, 2016; Savall-Alemany, Domènech-Blanco, Guisasola, & Martínez-Torregrosa, 2016). Both chemistry and physics students had a tendency to associate spectral lines with energy levels, rather than electronic transitions, which limited their ability to explain the spectra (Ivanjek et al., 2015; Körhasan & Wang, 2016; Savall-Alemany et al., 2016). A cross-sectional qualitative study with physics students ranging from high school through advanced undergraduate physics about atomic emission revealed that students did progress when reasoning about atomic energy diagrams and energy in general (Savall-Alemany et al., 2016). However, a difficulty with connecting their model of the atom with radiation phenomena persisted.

Light-matter interactions encompass many concepts. We begin modelling LMI by exploring students' understanding of the nature of light and wave-particle duality. Wave particle duality is a central component of quantum mechanics (Krijtenburg-Lewerissa, Pol, Brinkman, & van Joolingen, 2019) and has been suggested as a "gateway to quantum theory" (Hobson, 2005; Müller & Wiesner, 2002). The dual nature of light is a uniquely quantum mechanical concept that is commonly introduced in introductory chemistry to introduce the dual nature of matter. Further, an understanding of the photon, including its wavelike properties (i.e., frequency and wavelength), is crucial to understanding many LMI applications (e.g., spectroscopy or photochemistry). Targeting a quantum mechanical concept introduced early in the postsecondary curriculum has the potential to offer two important insights. First, because students are encountering this concept very early in their undergraduate careers, it is likely to offer insight into the conceptions that students are bringing into their transition from classical to quantum mechanics. Second, the complexity of wave-particle duality (i.e., that it draws on ideas about wave behaviour and particle behaviour) make it likely to elicit a range of student conceptions varying in sophistication. For these reasons, the study presented herein was guided by the following research question:

In what ways do chemistry students reason about the nature of light?

Multiple cross-sectional qualitative investigations were used to develop construct maps that describe how students' reasoning about light can develop in sophistication over time. These construct maps offer cognitive models that can inform assessment, curriculum, and instruction about this topic (Brown & Wilson, 2011). One of the difficulties with teaching wave-particle duality is the ontological assumptions that affect interpretations and reasoning (Henriksen, Angell, Vistnes, & Bungum, 2018). Indeed, in the development of a conceptual quantum mechanics survey, faculty struggled to agree on the correct answer when defining wave-particle duality (McKagan, Perkins, & Wieman, 2010). For this reason, some science educators have argued for explicitly embedding a historical-philosophical perspective in instruction about quantum physics, specifically wave-particle duality (Cheong & Song, 2014; Henriksen et al., 2018). We do not consider ontological assumptions in this work. Rather, we take more of a pragmatic perspective and treat a first-level meaning of duality, as conceptualized by Cheong and Song (2014), as a target understanding that is appropriate for chemistry students. Cheong and Song (2014) summarize first-level meaning as follows: "Light (or electrons) behave like particles or waves according to the context of the experiment, however, it is impossible to measure simultaneously both particle properties and wave properties."

Theoretical and Methodological Framework: Construct Modelling

The construct modelling approach is grounded in a developmental perspective, which characterizes student understanding as varying in sophistication. Because of this, student understanding can be modelled on a continuum. The developmental perspective contrasts with a dichotomous model, which characterizes student understanding as correct or incorrect. In this way, the developmental perspective moves away from a deficit model of student understanding (Cooper & Stowe, 2018). That is, it shifts the focus from what learners do not know to what they do know, which can then be built upon. The developmental perspective is captured via construct maps within the construct modelling approach (Brown & Wilson, 2011). A construct map is a model that describes the continuum for a progress variable, a single variable for which student reasoning can vary in sophistication. It is important to note that while construct maps outline a potential development trajectory of reasoning, there is no single correct trajectory (Smith, Wiser, Anderson, & Krajcik, 2006). Prior experience, instruction, and individual differences shape the potential learning pathways a student may experience. That is also to say that students may be simultaneously engaging with multiple pathways at one time as many progress variables within a fundamental idea are interconnected (Smith et al., 2006). Modelling student understanding in

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3 140 this fashion aligns with the idea that learners continuously build upon prior knowledge and students'
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5 understanding continues to grow in sophistication.
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7 Construct maps

8 Construct maps describe the continuum of understanding for a single concept, or progress variable. A
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10 significant step in utilizing a construct modelling approach is to deconstruct a "big idea" into a set of specific
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12 145 progress variables, which enables both modelling and measurement. To describe these continua, the construct
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14 maps provide qualitatively distinct levels of understanding for one progress variable, with levels organized
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16 hierarchically from lower levels describing less sophisticated understanding to higher levels describing more
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18 sophisticated understanding. Levels can also include common errors or heuristics specific to that level, which tend
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20 to be resolved as students move to a higher level. The development of construct map levels can be informed by a
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22 150 variety of exploratory qualitative methods including interviews or open-ended surveys. Development is further
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24 supported with existing research studies and knowledge of student understanding as well as instructional
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26 expertise (Wilson, 2005). Construct maps serve as a model of cognition when designing assessment items,
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28 specifically ordered multiple-choice (OMC) items, which is the long-term goal of the larger project that produced
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30 the findings presented herein (Authors, 2021).
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32 155 Construct maps directly inform OMC items. Because of this, OMC items differ from traditional multiple-choice
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34 items by the structure and design of response options. In traditional multiple-choice items, the response options
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36 include a scientifically accurate option and inaccurate distractors, whereas in an OMC item, the response options
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38 correspond to levels in the construct map. In this way, item response options differ by conceptual sophistication,
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40 rather than scientific accuracy. OMC items were designed in this way to support valid and reliable inferences
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42 160 about students' knowledge when modelled as a progression (Alonzo & Steedle, 2009; Briggs, Alonzo, Schwab, &
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44 Wilson, 2006; Hadenfeldt, Bernholt, Liu, Neumann, & Parchmann, 2013). OMC assessments provide a means for
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46 instructors to track students' progress over time easily and efficiently. For an in-depth discussion of construct
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48 modelling and OMC items in chemistry education research, readers are encouraged to read the primer on this
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50 topic published in the *Journal of Chemical Education* (Authors, 2021).
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52 165 Based on the literature presented above, we assert that a construct modelling approach is appropriate to
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54 model chemistry students' learning about the nature of light due to its capacity to capture the ways students'
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56 reasoning can vary in sophistication, as was shown in many of the studies. Importantly, a construct modelling
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3 approach equips us to deconstruct the fundamental idea of the nature of light into a specific set of progress
4 variables, which we can then model and measure through the development and use of ordered multiple-choice
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7 170 (OMC) assessment items (Authors, 2021).
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10 **Methods**

11 The development of construct maps and OMC items are based on two qualitative investigations of students'
12 understanding of light: (1) the particle nature of light (Authors, 2020) and (2) the wave nature of light.
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15 Participants and Setting

16 175 Participants in this study were recruited from multiple chemistry classes during the Fall 2018, Spring 2019,
17 and Fall 2019 semesters (Table 1). All participants provided consent prior to conducting interviews.
18 Representation from multiple levels (introductory chemistry through advanced chemistry) was important for
19 capturing the diversity and variation of students' knowledge. For interviews targeting the photoelectric effect
20 (Particle Interviews), students were recruited from general chemistry (N=14), organic chemistry (N=3), physical
21 chemistry with biological applications (N=7), and a physical chemistry quantum mechanics course (N=2). For
22 180 interviews targeting the double slit experiment (Wave Interviews), students were recruited from general chemistry
23 (N=11), general chemistry for chemistry majors (N=10), organic chemistry (N=11), and a physical chemistry
24 quantum mechanics course (N=1).
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34 Data Collection

35 185 Two sets of qualitative semi-structured interviews were used to inform the development of construct maps
36 targeting students' understanding of wave-particle duality. Both sets of interviews were collected at the
37 corresponding author's home institution. The first set of interviews introduce the photoelectric effect experiment to
38 target students' understanding of the particle nature of light (Authors, 2020). The interviews lasted from 21 to 72
39 minutes. Students were shown figures (Figure 1) that displayed varying frequencies of light, with some
40 frequencies above the threshold frequency resulting in electron ejection (Figures 1b and 1c) and some
41 frequencies below the threshold frequency that did not result in electron ejection (Figure 1a). The interviews
42 190 consisted of three parts: (1) describe general understanding of light, (2) make predictions about the effect of
43 intensity and exposure length when shining varying frequencies of light on a metal surface, and (3) draw
44 conclusions about the nature of light including wave-particle duality. Each part of the interview was used to
45 generate the Particle Behaviour of Light construct map.
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The second set of interviews introduce the double slit experiment to target students' understanding of the wave nature of light. The interviews lasted from 25 to 73 minutes. Students were shown simulations that depicted light waves traveling without any barriers and through barriers with one and two slits with resulting interference patterns displayed on a screen (<https://phet.colorado.edu/en/simulation/wave-interference>) (Reid et al., n.d.). The interviews consisted of four parts: (1) describe the light behaviour from a single continuous light source, (2) make predictions and describe a single light source that is shining on a barrier with one slit, (3) make predictions and describe a single light source that is shining on a barrier with two slits, and (4) draw conclusions about the nature of light including wave-particle duality. During the interviews, students were shown simulations and then asked to make predictions or provide explanations for the phenomenon they were observing. The simulations involving a single light source (part 1) and a single light source shining through a barrier with one slit (part 2) were used to investigate students' general understanding of the wave behaviour of light. The simulations depicting a single light source passing through a barrier with two slits targeted interference in the context of the double slit experiment (part 3). Parts 1 and 2 were used to generate the Wave Behaviour of Light construct map, and part 3 was used to generate the Interference construct map. In both sets of interviews, flexibility was employed to follow veins of interest, which meant that the exact questions posed varied across interviews, in line with a phenomenographic approach (Marton, 1986).

Data Analysis

Interviews were transcribed verbatim using transcription services. Gestures captured from the interview videos were added to the transcript and images of student work were extracted from videos for the appropriate time in the transcript. The transcripts were analysed using a phenomenographic approach to identify the qualitatively different explanations and reasoning that varied in sophistication (Åkerlind, 2012; Marton, 1981). A phenomenographic approach relies on the idea there are various but finite ways of thinking about the same concept or experiencing the same phenomenon. Data analysis occurs in stages. In the first stage, meanings about the phenomenon of interest (in this case, particle behaviour, wave behaviour, and wave-particle duality) are extracted from individual interview transcripts. These meanings and ideas are then pooled together. From this "pool of meanings", the primary analyst (first author) iteratively began clustering meanings that had similarities to form categories. During this sorting process, the meanings and ideas are rearranged, and categories are modified. Rearranging and modification decisions were discussed with the second and final authors. The

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3 225 “completion” and trustworthiness of this analytical approach are characterized by stabilization. That is, categories
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5 of meanings and the organization of quotes illustrating those meanings remain unchanged (Marton, 1986). The
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7 result of a phenomenographic analysis is an outcome space, which shows the qualitatively different experiences
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9 of the phenomenon organized hierarchically to illustrate the relationships between the experiences (Marton,
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11 1981). In this case, the outcome space consisted of the construct maps (Brown & Wilson, 2011).

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13 230 To illustrate this process, we will describe a few examples in generating the Particle Behaviour of Light
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15 construct map (Table 4). The first step of the process was to identify recurring explanations that were qualitatively
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17 different. During interviews, some students explained that particles of light have a constant amount of energy and
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19 some students explained particles of light as discrete units of energy. For example, one student explained energy
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21 would be constant based off the equation $E=h\nu$. When asked why the energy of light is constant, they explained
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23 235 *“it’s not just sitting in the metal and building up the energy... Light or energy is always being transferred. It usually*
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25 *doesn’t stay in one spot for very long.”* This explanation shows that some students were comfortable with using
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27 equations to think about the energy of light not accumulating, however, did not exhibit an accurate conceptual
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29 understanding of why energy does not accumulate. Students whose explanations included discrete energy or
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31 constant energy could both accurately predict that an increase in intensity would not result in an energy increase,
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33 240 rather more electrons would be ejected if the light was above the threshold frequency. While both groups provided
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35 accurate predictions, each group provided qualitatively different explanations of their predictions. Students who
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37 explained that the energy of light is constant recognized the relationship between intensity and energy, however,
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39 they did not explain that each photon has a discrete amount of energy. This distinction indicated that these two
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41 explanations, while similar, were in fact differing in sophistication. Following the identification of recurring ideas,
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43 245 explanations were arranged hierarchically from least sophisticated to most sophisticated. Explanations that
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45 applied quantum concepts were considered the most sophisticated whereas explanations that applied entirely
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47 classical ideas to a quantum phenomenon were considered least sophisticated. The presence of quantum
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49 thinking served as the criteria for determining sophistication of students’ explanations where quantum-level
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51 250 thinking has been outlined as the most sophisticated developmental stage of chemistry understanding (Dangur et
52
53 al., 2014). The most sophisticated level of the Particle Behaviour Construct Map was determined by instructional
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55 expertise and included an explanation of the discrete nature of photons. This analysis resulted in organizing
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57 students’ explanations to generate a construct map describing students’ understanding of the particle behaviour.
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This same approach was used to generate each construct map with levels arranged hierarchically according to sophistication. Because construct maps may include any number of levels that correspond to reoccurring ideas observed from interview data, the number of levels for each construct map vary.

Following the initial development of the construct maps, both Particle and Wave interviews were revisited by the first and second authors to evaluate each construct map's capacity to capture the range of explanations across students. In this part of the analysis, the construct maps served as a codebook where each student explanation was assigned a specific level. The purpose of this step was to qualitatively investigate the validity of the construct maps as a model of students' understanding of light.

Deconstructing wave-particle duality

Analysis resulted in the identification of four progress variables: (1) Particle Behaviour, (2) Single Wave Behaviour, (3) Interference, and (4) Wave-Particle Duality. These four progress variables uniquely capture different concepts within light behaviour about which we observed variation in reasoning. The progress variables serve as smaller conceptual units to better describe the observed variance. Because light is a complex and big idea that involves independent understanding of concepts *and* coordination of concepts, identifying multiple progress variables provides a fine-grained and precise way to identify differences in student understanding. For instance, the wave behaviour of light has been split into two different progress variables, Single Wave Behaviour and Interference. The first progress variable targets the general behaviour of light in terms of one light source. The second focuses on wave behaviour in the context of the double slit experiment, which includes interference and the interaction between two sources of light. During interviews, it was apparent that understanding how a single light wave travelled was qualitatively different than understanding how two light waves interfered. For example, a student may have a productive understanding of how light waves bend around an object but may lack an understanding of the mechanism behind light interference. Had we treated wave behaviour as one progress variable, we would not have been able to capture and explain this difference. While both progress variables emerged from the interviews contextualized in the double slit experiment, the interviews were designed to elucidate students' understanding of a single light source prior to investigating their understanding of interference. In this way, targeting wave behaviour with two progress variables allowed us to capture differences in students' understanding between single and double light sources. Furthermore, a range of common errors and heuristics about light were identified that were context dependent. Depending on the light behaviour being targeted,

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3 students had varying ideas about light. This was apparent when students conflated photons and electrons in the
4 context of the photoelectric effect experiment. This common error was not observed in the context of wave
5 behaviour. Because we observed explanations that varied in sophistication and common errors that were context-
6 dependent, splitting light behaviour into four progress variables was warranted and necessary to capture and
7 model differences in student understanding.
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13 **Results**

14 This section will present one progress variable (i.e., Wave-Particle Duality) in full including an in-depth
15 discussion of the construct map, interview analysis, and corresponding OMC item development. The remainder of
16 the progress variables (Figure 2) will be summarized here, with full details and further discussion in the
17 Supporting Information.
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22 Wave-particle duality

23 Construct map

24 Both the double slit experiment and the photoelectric effect were used to explore students' understanding of
25 wave-particle duality because understanding wave-particle duality relies on understanding both particle and wave
26 behaviour. In addition to understanding these behaviours independently, students are expected to reason about
27 how these behaviours simultaneously exist in light. Often these experiments are used in instruction to showcase
28 how experimental setup can dictate the observed light behaviour. Explanations provided by students describing
29 295 duality were the basis for generating the construct map shown in Table 2.
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36 For the wave-particle duality construct map, the lowest level of reasoning is described as having no
37 understanding of duality. This came about in multiple forms where some students were unable to reconcile both
38 300 wave and particle behaviour. Other students remarked that they would expect light particles to behave differently
39 than light waves with the double slit experiment setup. One student explained that with light particles, they would
40 only expect to see two regions illuminated on a screen corresponding to the two slits in the barrier:
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46 *"It just makes the most sense [that] they're coming out in a straight line because there are only two ways*
47 *[for the particles] to get to the other side."* (Level 0)
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50 Based on this student's explanation, they predict that light particles and light waves behave differently with the
51 same experimental setup. This shows that this student does not perceive a relationship between wave-particle
52 duality and experimental observations. Instead, this student reasoned that some inherent particle nature of light
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entirely dictated its behaviour. The explanation aligns with Level 0 in the construct map (Table 2) because this student did not attempt to reconcile wave-particle duality.

To reconcile the two behaviours, some students generated models that included both behaviours. This student explained how they envisioned particles and waves existing together:

"What I'm thinking is maybe the wave is made up of the particles. If light is a wave, being compared to water or something that has waves, water is made up of particles and it's a wave so the light can be a wave but made up of particles." (Level 1)

Their description and understanding of wave-particle duality is that the particles are along the entire wave of light. This explanation aligns with a Level 1 explanation for wave-particle duality in the construct map.

Another model generated by students to describe wave-particle duality explains that particles travel in waves. To explain how particles and waves coexist, a student describes particles traveling sinusoidally:

"A [photon] has energy, and it travels in a wave form...that moves... in a sinusoidal pattern." (Level 2)

This explanation aligns with Level 2 in the construct map because the student describes how photons travel in a wave-like form. In contrast to a level 1 attempt at reconciliation, this explanation shows students are attempting to reconcile by assigning a wave-like property (i.e., trajectory) to the photons.

There was also evidence of students demonstrating target understanding of wave-particle duality. For example, this student described wave-particle duality as the "smashing" of both behaviours together. They expressed that light could behave like a wave or a particle, and the dual nature describes two behaviours coexisting:

"There used to be like two like streams of the thought, light moves as a wave or light moves as like a particle and these two had different ... Some phenomena of light matched one like train of thought but then some other phenomena matched the other train of thought. So, then they go: 'Oh, well it must be like both then.' So, they kind of smashed the two together. So, they function as both a particle and wave." (Level 3)

This student explains that both wave behaviour and particle behaviour have been observed, but in the context of different phenomena. They go on to explain that because both behaviours are observed, light must be both a wave and a particle that can function either way depending upon the phenomena observed. The student

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3 recognizes the independent behaviours of light and alludes to scientists observing both wave and particle
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5 behaviour. This explanation aligns with Level 3 in the construct map.
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7 These explanations were arranged hierarchically, according to sophistication, into the Wave-Particle Duality
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9 construct map shown in Table 2. The first, and least sophisticated level (Level 0), is defined by having no
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11 340 understanding of duality, or attempt to reconcile the different behaviours. Beyond Level 0, two different models
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13 that students generated to explain duality were considered (Level 1 and Level 2) where both models are evidence
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15 of students' attempts to combine wave and particle behaviour. We considered Level 2 to be more sophisticated
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17 because Level 2 represents a more integrated understanding of light by assigning the motion of light waves (i.e.,
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19 wave properties) to photons. For Level 1, waves are comprised of particles similarly to water, where a wave
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21 345 represents macroscopic light and particles represent more fine-grained or smaller scale light. In this way, a Level
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23 1 understanding of duality does not really reconcile the different behaviours. Level 2 connects wave-like
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25 behaviour to particles by describing photons traveling in waves which is closer to a target understanding of wave-
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27 particle duality because it shows that students reason that light particles possess wave properties. While it is not
28
29 correct to describe particles traveling sinusoidally in Level 2, it is productive that students are beginning to assign
30
31 350 wave properties to light particles. Ultimately, quantum mechanics offers a paradigm for using wave properties
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33 (i.e., wave function) to describe particles (e.g., electrons). Finally, Level 3 was considered the highest level of the
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35 construct map because it represented the most sophisticated explanations produced by students. This level
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37 describes a robust understanding of duality and recognizes the key concept of observance while explaining the
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39 dual nature of light.

40 355 *Coding interviews using the construct map*
41 Following development of the Wave-Particle Duality construct map (Table 2) via a phenomenographic
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43 approach, a systematic analysis of the interview transcripts was done to ensure that the construct map captured
44
45 the entire range of understanding demonstrated in interviews. The explanations provided by students during the
46
47 interviews were assigned to a corresponding construct map level. This systematic analysis of interview transcripts
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49 360 revealed that the Wave-Particle Duality construct map captured the variation in student explanations. That is,
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51 each level had examples of student explanations as support, including some aligned with the highest level (Level
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53 3), the expected understanding of Wave-Particle Duality. In line with a phenomenographic approach, this stage
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was considered a test of the categories of explanations against the data. This stage reached completion when description of categories and organization of data samples reached stabilization (Marton, 1986).

The distribution of student explanations for each level of the Wave-Particle Duality construct map can be found in Table 3 organized by course, where both the photoelectric effect interviews (N=26) and the double slit interviews (N=33) are included. Because of the nature of semi-structured interviews, not every student explicitly discussed the dual nature of light when asked to draw conclusions about the nature of light thus the total number of students listed in Table 3 is less than the total number of interviews for this specific progress variable (Marton, 1986). For most, if not all, of the interviews in which wave-particle duality was not discussed explicitly, the target phenomenon in the interview posed to be so difficult for the participant to reason about that the interviews decided in real time to not pursue the dual nature of light. These decisions were based on how students described wave or particle behaviour independently and the conclusions that students drew about the way light behaves.

This coding process also provided a means to identify common errors associated with each level, or to refine the language used to describe each level of the construct map. Considering Level 2 (Table 2), students who explain that particles travelled sinusoidally tended to focus on the way light travels:

"[Light] is described as both a particle and a wave, I assume by the way it travels." (Level 2)

This student explained that the behaviour of light is based on how the light travels. This idea was added to Level 2 in the construct map to better describe students' understanding at this level.

Summary

A construct map (Table 2) centred around the Wave-Particle Duality progress variable was generated from qualitative interviews about the photoelectric effect and the double slit experiment. Analysis of these interviews resulted in a construct map that models student understanding of duality on a continuum. Following generation of the initial construct map, interviews were coded according to the construct map levels to further refine level descriptions, identify common errors, and to evaluate the construct map's ability to capture the range in student understanding.

This same process illustrated with the Wave-Particle Duality construct map was done for each of the remaining progress variables: (1) Particle Behaviour, (2) Single Wave Behaviour, and (3) Interference.

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2
3 390 Summaries of each progress variable can be found below with their respective construct maps. Further details
4
5 regarding the generation of each of these construct maps can be found in the Supporting Information.
6

7 Particle Behaviour

8 The photoelectric effect is typically introduced in the first semester of introductory chemistry, at the start of the
9
10 unit on the quantum mechanical model of the atom. The photoelectric effect serves as a way to introduce
11
12 395 students to the quantum nature of matter and energy by introducing the dual nature of light. Based on a review of
13
14 the topic treatment by textbooks (Brown et al., 2014; Jespersen, Brady, & Hyslop, 2014; Tro, 2010), students
15
16 need to have an understanding of (1) the properties of a photon, (2) the role of intensity and time in the
17
18 phenomenon, and (3) the sequence of events that result in an electron ejection. Having a working understanding
19
20 of these points is therefore considered the highest level (Level 4) on the Particle Behaviour construct map (Table
21
22 400 4). Interviews revealed that there was variation in how students reasoned about these points when not achieving
23
24 the highest level. These varied ideas were organized into levels shown in the construct map. Details on the
25
26 development of this construct map can be found in the Supporting Information.
27

28 Single Wave Behaviour

29 Waves are first introduced in introductory chemistry to describe electromagnetic radiation. Students then use
30
31 405 wave behaviour to interpret experiments like the double slit experiment and electron diffraction. The introduction
32
33 of these experiments in introductory chemistry assumes students understand (1) the relationship between
34
35 frequency and wavelength, (2) the structure of a light wave, and (3) the way light travels and interacts with matter.
36
37 Having a complete understanding of these concepts is considered the highest level (Level 4) of the Single Wave
38
39 Behaviour construct map, which is shown in Table 5. This construct map captures the kind of variation in
40
41 410 reasoning employed by students to explain the wave nature of light and what happens when light interacts with
42
43 barriers (in this case, a barrier with a single slit). Details on the development of this construct map can be found in
44
45 the Supporting Information.
46

47 Interference

48 The double slit experiment builds upon students' understanding of wave properties to explain constructive and
49
50 415 destructive interference where two light sources can cancel each other out, or their intensities can add together.
51
52 Students are expected to apply their understanding of the relationship between frequency and wavelength to
53
54 explain how interference changes with frequency. For example, students are expected to understand that
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56 changing the frequency would change the number of instances of interference. The Interference construct map
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shown in Table 6 focuses on (1) the mechanism of interference, (2) constructive and destructive interference, and (3) the effect of frequency and wavelength on interference. Having a complete understanding of these concepts outlined above constitutes the highest level (Level 3) of this construct map (Table 6). Using qualitative data from student interviews and review of textbooks (Brown et al., 2014; Jespersen et al., 2014; Tro, 2010), a description of students' understanding about the wave behaviour of light in the context of the double slit experiment was generated. Details on the development of this construct map and its related OMC items can be found in the Supporting Information.

Discussion

This work resulted in the identification of four progress variables that comprise an understanding of the nature of light: (1) Particle Behaviour, (2) Single Wave Behaviour, (3) Interference, and (4) Wave-Particle Duality. Construct maps aligned with these progress variables offer important insights into potential pathways to the quantum mechanical concepts that are key for understanding and applying light-matter interactions. By offering models for how students reason about the wave-particle duality of light, we hope to center light-matter interactions (LMI) in the chemistry curriculum. In response to ongoing efforts to identify the concepts that are key to learning chemistry (Cooper & Stowe, 2018; Sevan & Talanquer, 2014), we argue that the centrality of LMI to the practice of chemistry and to modern technology (Forbes, 2015) make it essential for chemistry learners. Further, increased instructional attention to LMI aligns with existing efforts to introduce quantum theory to chemistry and physics learners in introductory chemistry (Holme & Murphy, 2012) and physics (Cheong & Song, 2014) which can support students in developing a visual-conceptual quantum mechanical model (Dangur et al., 2014). This visual-conceptual quantum mechanical model can be productively built on throughout a learner's undergraduate experience. The findings presented herein offer a detailed picture of what a visual-conceptual model entails.

Some of the ways we observed students reasoning about particulate light behaviour aligns with previous findings. For example, Level 2 on the Particulate Behaviour construct map (Table 4) outlines an understanding of photons additively transferring energy to a surface and corresponds to a classical understanding of light. Students who showed this level of understanding often had difficulty with the relationship between exposure length and energy, or intensity and energy. Students applying classical ideas to quantum mechanical phenomena has been previously observed in the context of quantization (Didiş et al., 2014). Students who displayed a Particulate

Behaviour Level 3 understanding relied less on the classical notion of energy accumulation by recognizing that light energy does not accumulate. However, these students often used the word “constant” to describe light energy which seems to be based upon equations relating energy and frequency. Additionally, Bain and colleagues (2019) demonstrated that “constant” can be a loaded term in chemistry contexts. While Particulate Behaviour Level 3 students were able to generate correct predictions about changes in intensity or exposure length, they struggled with understanding *why* energy did not accumulate.

Our findings about students’ understanding of wave behaviour align with findings from studies in physics (Ambrose, Heron, Vokos, & McDermott, 2002; Ambrose, Shaffer, Steinberg, & McDermott, 1999; Wosilait, Heron, Shaffer, & McDermott, 2002). Namely, problematic reasoning about the wave nature of light emerges from across these findings: treating wave behaviour like a classical particle. Physics students explained single slit diffraction similarly to what we observed with our chemistry students. Students who provided Single Wave Behaviour Level 2 (Table 5) explanations during interviews often described the barrier as an obstacle that disturbs the trajectory of the light and allows only some light through the slit. In physics, students explained that “*part of the amplitude is cut off*” when light waves pass through a single slit with only some particles of light making it through the slit (Steinberg et al., 2005). This reliance on classical particle behaviour showed up later in chemistry interviews when participants used collisions between light and the barrier or light with itself to explain illuminated regions on the screen. Our findings about students’ understanding of wave behaviour align with findings from studies in physics (Ambrose et al., 2002, 1999; Wosilait et al., 2002). Namely, problematic reasoning about the wave nature of light emerges from across these findings: treating wave behaviour like a classical particle. Physics students explained single slit diffraction similarly to what we observed with our chemistry students. Students who provided Single Wave Behaviour Level 2 (Table 5) explanations during interviews often described the barrier as an obstacle that disturbs the trajectory of the light and allows only some light through the slit. In physics, students explained that “*part of the amplitude is cut off*” when light waves pass through a single slit with only some particles of light making it through the slit (Steinberg et al., 2005). This reliance on classical particle behaviour showed up later in chemistry interviews when participants used collisions between light and the barrier or light with itself to explain illuminated regions on the screen.

Some of these difficulties source from inadequate and intuitive concepts about the nature of a light wave, which was echoed by Henriksen et al. (2018). Chemistry students posited a variety of ways to explain the nature

of a wave, specifically, the alternating pattern corresponding to nodes and antinodes. Students at Level 1 of the Single Wave Behaviour construct map (Table 5) described the peaks of waves as corresponding to visible light and troughs of waves as corresponding to darkness. Level 3 (Table 5) students applied classical particle behaviours to explain the alternating pattern as varying densities of photons. These intuitive concepts of wave behaviours limit learners from interpreting a diffraction pattern, understanding the significance, and, importantly for chemistry, applying wave behaviour to matter (Henriksen et al., 2018). For this reason, similar to Henriksen et al. (2018), we see value in explicit instruction about the classical nature of waves.

Indeed, students extended problematic and intuitive ideas about wave behaviour to the double slit experiment. For instance, students who provided explanations aligned with Level 0 on the Interference construct map (Table 6) relied on shadows to explain dark regions (areas of deconstructive interference) on the screen. It is likely that these explanations source from intuitive explanations about optics (Galili & Hazan, 2000). Galili et al. (2000) posit that there is insufficient instruction regarding shadows, possibly because instructors may view this topic as too easy, which leaves learners to rely heavily on their experiences. We observed intuitive reasoning persisting through to even more sophisticated levels. For example, Level 2 of this construct map (Table 6) indicates an understanding that waves are capable of both constructive and destructive interference, but interference only explains some regions of light on the screen. Some illuminated regions on the screen result from light that is unobstructed and subsequently passes through the slit while some illuminated regions are the result of interference. While it is tempting to assume that learners will abandon their reliance on intuition as they develop more sophisticated reasoning about a phenomenon, we see evidence of hybrid reasoning. In this context, learners hang on to their intuitive notions and merge them with productive conceptions of interference.

We see further evidence of this when students generate their own models of light to help them combine wave and particle behaviour to explain wave-particle duality. We see this model development as a productive first step in understanding the complex and abstract concept of duality. As highlighted in students' general understanding of light waves, physics and chemistry students have developed models of light where "*each point on the wave is a little particle*" (Steinberg et al., 2005). Students who produced this explanation also generated similar figures as the chemistry students we interviewed (see Figure 4 from our previous work) (Authors, 2020). While these models certainly have limitations and do not indicate a sophisticated understanding of duality, they represent a deliberate effort to reconcile wave and particle behaviour. Importantly, these models serve chemistry learners quite well. In

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3 these contexts, learners were often able to generate accurate predictions about the photoelectric effect and
4 diffraction using these models. For this reason, we posit that general chemistry instruction should support learners
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7 505 in at least beginning the process of reconciling the behaviours.

9
10 **Implications for Research and Practice**

11 Because students' understanding of light is under-explored, instructors lack models of students'
12 understanding to inform their instruction. For instructional purposes, the construct maps generated in this study
13 provide a general model for instructors about the range of ideas students may have about light. Many of our
14 findings from this study align with similar findings from physics (Ambrose et al., 2002, 1999; Wosilait et al., 2002),
15 510 which lends further validity to the maps. Alonzo and Elby (2019) argue that level-based models of cognition offer
16 two criteria of good models that make them useful as instructional models: utility and generativity. Level-based
17 models of cognition can provide an important starting point when considering instructional and curricular practices
18 and support instructors in generating new ideas about student understanding. We encourage instructors to draw
19 on the ideas shown in the construct maps to interpret students' current level of reasoning and determine next
20 steps in instruction for helping students learn and progress. For example, say students generate a variety of
21 predictions about what they expect to see on a screen behind two slits, an instructor can use the Interference
22 construct map (Table 6) to differentiate the predictions and evaluate their students' understanding at that time.
23 One productive next step may be to revisit the structure of a light wave. One way to do this may be to show a
24 common representation of electromagnetic radiation as constituted by orthogonal electric and magnetic
25 520 components and explicitly discuss the structure in terms of nodes and anti-nodes. In this way, the construct maps
26 offer instructors insight to respond to and address student reasoning.

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41 Finally, generating these construct maps revealed levels of reasoning that were more or less productive for
42 explaining experimental outcomes. In the Wave-Particle Duality map (Table 2), for example, Levels 1 and up
43 include an effort to reconcile wave and particle behaviour. For many students, just the effort to reconcile the
44 525 behaviours enabled a host of predictions, even if they could not fully explain the behaviour of light. As students
45 progress in studies across STEM, an understanding of the photon as a discrete unit of light that is described by
46 wave properties equips them to interpret and make sense of a variety of phenomena (e.g., spectroscopy or
47 photosynthesis). We believe this positions the general chemistry instructor with the job of initiating this process of
48 reconciling the two behaviours. To do this, instructors must surface and interact with students' existing ideas
49 530

about the classical behaviour of particles and waves. As shown in this work, prompting students to make predictions and construct explanations about the double slit experiment and the photoelectric effect can accomplish this. Further, the construct maps can offer resources for interacting with these ideas once surfaced.

These construct maps serve as models of the way student reasoning about the wave-particle duality of light can vary in sophistication. In the two qualitative studies conducted herein, these models represent and capture the variation. However, these models should be subjected to empirical testing to evaluate their capacity to explain two features of students' learning. The first is the degree to which a student consistently employs reasoning from a particular level on a construct map. That is, do students select to the same level of reasoning for all OMC items corresponding to a single progress variable? The second feature is how students may progress through levels. Because these models were generated from cross-sectional interviews at a single time point, while they capture important variation in sophistication, they do not offer information about the temporal progression a student might undergo. One way to test this is to offer OMC items longitudinally—at the end of 1st year chemistry and again at the end of 2nd year chemistry. Longitudinal administrations of OMC items could also offer information about how these progress variables interact; that is, how may a learner's progress in thinking about particle behaviour enable progress with thinking about wave-particle duality?

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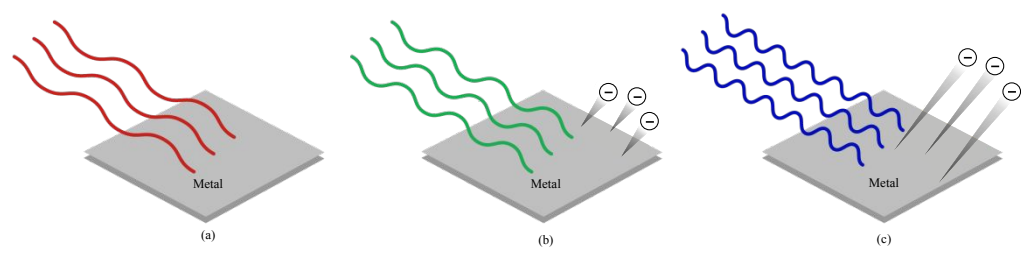


Figure 1. A sequence of figures shown to students during the interview, where (a) shows light below the threshold frequency, (b) shows light above the threshold frequency, and (c) shows light above the threshold frequency with a higher frequency than (b). Interview participants were asked to make predictions about the various lights interacting with the metal and explain ejecting electrons.

Table 1. Number of interviews collected across chemistry courses.

<i>Study population</i>	<i>Particle Interviews</i>		<i>Wave Interviews</i>
	<i>Fall 2018</i>	<i>Spring 2019</i>	<i>Fall 2019</i>
General Chemistry I	14	--	11
General Chemistry I (majors)	--	--	10
Organic Chemistry	3	--	11
Physical Chemistry	1	1	1
Biological Physical Chemistry	--	7	--

For Peer Review Only

Table 2. Construct map describing distinct levels of students’ understanding about Wave-Particle Duality.

<i>Level</i>	<i>Description</i>	<i>Common errors</i>
3	Light has both wave and particle properties that simultaneously exist. Experimental setup dictates which behaviour is observed.	
2	Light is made of particles that travel in waves. The way light travels dictates the way it behaves.	• Individual particles follow sinusoidal wave pattern
1	Light is made of particles that are “organized” in waves. Light behaves as a wave or a particle depending on the phenomenon being explained.	• Entire length of wave is comprised of particles
0	No understanding of duality	• Duality is purely descriptive • Unable to merge continuous and discrete together • Understanding of discrete or continuous independently • Difficulty understanding how light can have both continuous and discrete properties simultaneously

Table 3. Distribution of students across Wave-Particle Duality construct map levels.

<i>Level</i>	<i>Number of Students</i>			
	<i>General Chemistry</i>	<i>General Chemistry Majors</i>	<i>Organic Chemistry</i>	<i>Physical Chemistry</i>
3	1	5	2	2
2	2	3	3	1
1	2	0	3	0
0	6	2	3	1

Table 4. Construct map describing distinct levels of students’ understanding about the Particle Behaviour of light.

Level	Description	Common errors
4	Particles of light are discrete units of energy, explained through threshold frequency.	
3	Particles of light have constant energy based on the frequency of light.	• Light particles are always moving so energy can't build up
2	Particles of light additively transfer energy.	• An increased number of photons results in a higher energy transfer • An increased number of photons results in faster electron ejection • Longer light exposure of lower frequency light will eventually result in electron excitation
1	Particles of light are the same as electrons.	• Once electrons are ejected, they are called photons • Conflation of atomic emission and photoelectric effect • Particles of light have a charge
0	Particles of light have a mass and a force.	• Photons collide with electrons • Photons collide with each other and scatter (double slit context) • Photons disturb molecules resulting in vibrations/excitations

Table 5. Construct map describing distinct levels of students' understanding about the Single Wave Behaviour of light.

<i>Level</i>	<i>Description</i>	<i>Common errors</i>
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 6. Construct map describing distinct levels of students’ understanding about Interference

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 of light collected on a screen. Frequency is related to the amount of time associated with interference.	• Illuminated regions are from constructive interference and 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.

Particle behaviour of light

Construct map

The photoelectric effect is typically introduced in the first semester of general chemistry in the quantum unit. The photoelectric effect serves as a way to introduce students to quantum mechanics and the dual nature of matter by introducing the dual nature of light. Students are expected to think about this phenomenon in terms of a threshold frequency, which is defined as the minimum amount of energy required to eject an electron from a metal surface. This is where students encounter the idea of discrete amounts of energy that are transferred to the surface via particles of light, or photons. Discrete energy can be contrasted with continuous energy when introducing how intensity and time factor into electron ejections. If students have an understanding of discrete energy, they are expected to understand that increasing intensity or time when radiating below the threshold frequency will have no effect because the energy of the light is not high enough to eject the electron. Similarly, they are expected to understand how intensity and time play a role in the ejection of electrons when light is above the threshold frequency.

Based on a review of the content coverage, students need to have an understanding of (1) the properties of a photon, (2) the role of intensity and time in the phenomenon, and (3) the sequence of events that result in an electron ejection. Having a complete understanding of these points is considered the highest level on this construct map. Interviews revealed that there was variation in how students reasoned about these points when not achieving the highest level. These varied ideas were organized into levels shown in the construct map in Table 4.

When a student used Level 4 reasoning, it was typically evidenced by making accurate predictions that included a mechanistic explanation of the outcome. For example, when asked to consider the effect of increasing the intensity of a light that is above the threshold frequency, one student provided the following explanation:

“A more intense light... would have the same frequency or wavelength. And so, if you shine the more intense light on the metal, that just means we're going to eject more electrons. So, all have the same kinetic energy, but there'll be more of them since there's more photons being shined on the metal.” (Level 4)

Here, the student explains that changing the intensity of light does not affect frequency, but the number of incoming photons. Subsequently, increasing the intensity results in more electrons being ejected. This example provides evidence that students have an understanding of the phenomenon that aligns with the expected understanding outlined by the course material and Level 4 in Table 4.

As reasoning deviated from a Level 4 understanding, it was typically evidenced by incorrect or absent predictions and explanations. For example, when asked to predict the outcome of increasing intensity, the student demonstrated an accurate understanding of the relationship between energy and intensity but connected that to an outcome in a problematic way, which placed this explanation at a Level 3.

“Energy I think is somehow constant, so the more you increase the photons, the more with that energy that will hit the metal. So, I think that could make the electrons now move from their stable levels and [are] being emitted.” (Level 3)

The common error often seen with students who provided explanations about energy remaining constant was the idea that the particles were always moving and could not build up energy, or the energy is “dissipating.” Students have many correct ideas about necessary concepts to explain electron ejection but are missing some key components that would enable accurate predictions.

There was also evidence of students not competently reasoning about some of the fundamental concepts needed to explain electron ejection (e.g., the definition of an electron or photon). To explain the electron ejection event, some students conflated photons and electrons. Explanations, then, were typically substituted with intuitive mechanisms in the absence of fundamental concepts. For example, the student below equates the two to explain the ejection event.

“I think photon might just be a name for an electron that's been ejected from an atom, because I can't think of any other thing it'd be. That's what I think it'd be... I think the photons are just the ejected electrons ... I think the photon could be either the name for the ejected electrons, if the metal's ejecting the electrons, and then they could be called photons as they move.” (Level 1)

This excerpt also highlights a common error for Level 1: “once electrons are ejected, they are called photons.” Another common error that arose when students equated electrons and photons was the conflation of atomic emission and the photoelectric effect. This was the case when students explained that the ejecting electrons were the same as photon emission upon electron relaxation. The construct map shown in Table 4 offers a model for explaining how students can vary in their understanding of the photon and use of the photon to explain phenomena.

Single Wave Behaviour

Construct map

Introducing the double slit experiment in general chemistry assumes students have an understanding of (1) the relationship between frequency and wavelength, (2) the structure of a light wave, and (3) the way light travels from a single continuous light source. Having a complete understanding of these concepts is considered the highest level of the construct map, which is shown in Table 5.

The most sophisticated reasoning was characterized by identification of nodes and antinodes in light. This is exemplified by the following explanation:

“I believe the antinode is either on the top or the bottom of the wave, and the node is in the middle, like between them. So, if you had a wave (see Figure S1), so at these two spots (points on the dots at the trough and crest of the wave) you're seeing I think the green band and then at these spots (points towards the dots on axis), you're seeing the black band.” (Level 4)

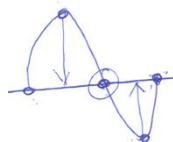


Figure S1. Student's drawing explaining nodes and antinodes.

When students did not identify the node or antinode of light, they offered alternative ways of explaining the alternating pattern observed in the simulation.

For example, to explain the pattern seen in Figure S2, the student described constructive and destructive interference. The constructive interference correlated to the green regions on Figure S2 and the destructive regions correlated to the black regions. This student also provided drawings of what happens when waves constructively or destructively interfere (Figure S4), which revealed productive reasoning about constructive and destructive interference. The error lay in extending this reasoning to a single light source with no barrier.

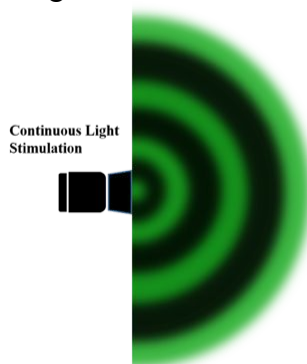


Figure S2. An image similar to the simulation students were shown in the interview. During interviews, students were asked to explain the shape and pattern of the continuous emission.

“When there's green it's constructive interference. But when there's not, I would guess that there's destructive interference. It's like you have two waves, right? [draws Figure S3 below] But since they're like in sync with each other, when you add them together, you'll get double, which is I assume what we're seeing in the green, but if there are two waves but they're out of sync it gets like a flatline, cause they kind of interact with each other to give a zero, which I would assume is the black.” (Level 2)

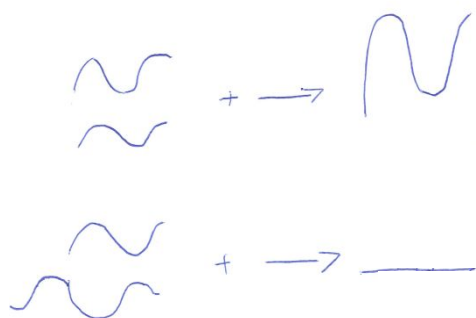


Figure S3. Student's drawing explaining constructive and destructive interference.

At the lowest level of the construct map, we observed students who were unable to generate an explanation of the simulation relying on macroscopic ideas. For example, this student reasoned about shadows to explain the alternating pattern.

“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.” (Level 0)

The construct map shown in Table 5 captures the kind of variation in reasoning employed by students to explain the wave nature of light and what happens when light interacts with barriers (in this case, a single slit).

Interference

Construct map

The double slit experiment builds upon students’ understanding of wave properties to explain constructive and destructive interference where two light sources can cancel each other out, or their intensities can add together. Students are expected to apply their understanding of the relationship between frequency and wavelength to explain how interference changes with frequency. For example, students are expected to understand that changing the frequency would change the number of instances of interference. The construct map shown in Table 6 focuses on (1) the mechanism of interference, (2) construct and destructive interference, and (3) the effect of frequency and wavelength on interference. Having a complete understanding of these concepts outlined above constitutes the highest level of the double slit experiment construct map.

Explanations at the highest level were characterized by effective use of interference to explain the alternating pattern that would appear on a screen.

“[You] have points of constructive interference... Like [with] each point there's that overlap... the maxima of the amplitude of the wave, then you know... there would be constructive interference.” (Level 3)

Explanations deviated from the highest level when interference was selectively used to explain illuminated regions on a screen. For example, a student asked to explain the illuminated regions on the screen found in Figure S4, explained that some regions (Region #3) are a result of interference. While the student did not use the terminology of interference, they explained that the waves were combining together which resulted in an illuminated region behind the barrier. They further reasoned that the regions that align with the slit openings (Region #2 and #4) were a result of unobstructed light reaching the screen.

“It makes sense that of course we get two light sources on that screen from each of the openings. But then... in the middle [the light is] kind of combining... So the light that's coming out from the openings and it's going straight forward, it's unobstructed and it's not really interacting with anything else because it's just on its own straight forward path.” (Level 2)

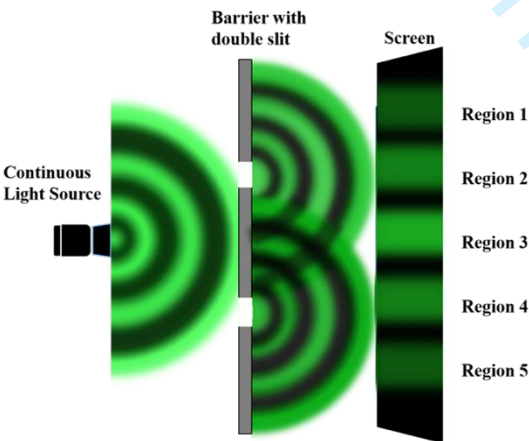


Figure S4. An image similar to the simulation students were shown in the interview. During interviews, students were asked to explain why Regions 1-5 were illuminated. They were also asked to explain the black areas between each of the illuminated regions.

Many students understood the idea of interference but failed to recognize or apply interference to all regions illuminated on the screen. This level of understanding was used to generate Level 2 in Table 6. Similar to the single wave behavior map, the lowest level reasoning captures intuitive reasoning in the absence of key concepts to explain the alternating pattern on the screen. For example, one student invokes shadows from the middle part of the barrier to explain the pattern.

“That's because, since the waves still move out like that but meet in the middle, that's kind of like the remainder of the shadow from that middle part. If the waves didn't move like the way they would, that whole part [Region #3] would be shadow. But since they still like move out and hit each other and are still like pretty strong right there, it's just going to kind of show like the edges of what the shadow would be.” (Level 0)

This explanation provides a basis for Level 0, where the student does not exhibit an understanding of interference or how light waves interact with one another.