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On the Use of Analogy to Connect Core Physical and Chemical Concepts to Those at the Nanoscale

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Abstract: Nanoscale science remains at the forefront of modern scientific endeavors. As such, students in chemistry need to be prepared to navigate the physical and chemical concepts that describe the unique phenomena observed at this scale. Current approaches to integrating nanoscale topics into undergraduate chemistry curricula range from the design of new individual nano courses to broad implementation of modules, experiments, and activities into existing courses. We have developed and assessed three modular instructional materials designed to explicitly connect core physical and chemical concepts to those at the nanoscale. These modular instructional materials aim to be readily adapted to existing curricular format and have been designed based on an educational framework for analogy. The findings from a qualitative study involving undergraduate chemistry students indicate that analogical transfer from core physical and chemical concepts to those at the nanoscale can be facilitated through the use of these instructional materials. Conceptual challenges as well as evidence for analogical transfer are provided herein, along with recommendations for instructor implementation and future work.

Introduction

Nanochemistry based instructional materials in the discipline based education research (DBER) literature are plentiful (e.g. Keating *et al.*, 1999; Haynes *et al.*, 2005; Mulfinger *et al.*, 2007; Oliver-Hoyo and Gerber, 2007; Rice and Giffin, 2008; Schnitzer *et al.*, 2010; Soukupova *et al.*, 2010; Muniz and Oliver-Hoyo, 2011; Winkelmann *et al.*, 2011; Campbell *et al.*, 2012; Campbell *et al.*, 2012; Hajkova *et al.*, 2013; Mauer-Jones *et al.*, 2013; Simpson *et al.*, 2013). The target audiences of these instructional materials range from introductory (e.g. Winkelmann *et al.*, 2011; Campbell *et al.*, 2012) to advanced undergraduate levels (e.g. Rice and Giffin, 2008; Schnitzer *et al.*, 2010). Though a variety of topics are covered and the materials are widely reported, they are rarely based upon a theoretical framework for pedagogy to guide the development of concepts. Further, rigorous assessment is generally not provided (Muniz, 2014). Since nanochemistry represents a subtopic of chemistry whose principles are very much related to core physical and chemical concepts, it is arguable that work is needed to explicitly connect these core concepts in a meaningful way to the nanoscale (Hart C. *et al.*, 2000; Russell C. B. *et al.*, 2008).

With respect to curricular design involving nanoscale topics in the DBER, two broad categories emerge: discrete course based (Samet, 2009; Moyses *et al.*, 2010; Tretter *et al.*, 2010; Englander and Kim, 2011; Bentley and Imatani, 2013), which focuses on creating capstone or other individual courses expressly dedicated to nanochemistry, and broad curriculum based (Criswell, 2007; Greenberg *et al.*, 2009; Augustine *et al.*, 2010; Shanov *et al.*, 2010; Kumar *et al.*, 2013;

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Saleh, 2013), which focuses on the diffuse implementation of activities, experiments, and modules within existing courses. Given this range of approaches, instructors would benefit from tools that are modular and can therefore fit within the existing curricular format at a particular institution. Jones *et al.* (Jones *et al.*, 2013) point at the need for curricula and teaching materials and note that existing courses in nanotechnology "…have limited evaluation or educational research that could allow the reader to learn about their impact."

In order to address the gaps outlined above, we have developed and assessed three modular instructional materials that are adoptable into existing chemistry curricula. These instructional materials have been developed based on a theoretical framework for analogy that lends itself readily to the pedagogy of explicitly connecting core physical and chemical concepts to those at the nansocale.

Theoretical Framework

A theoretical framework for analogy was chosen (Gentner, 1983; Gentner and Markman, 1997) to develop and assess these instructional materials designed to explicitly connect core physical and chemical concepts to those at the nanoscale. This framework assisted with sculpting the nature of the language utilized and the probing questions within.

In order to elaborate on how the framework guided the design of the instructional materials, some key terms need to be defined. First, the sources of knowledge are referred to as *knowledge domains*. For our purposes, there are two knowledge domains: the *base* (the original source of knowledge which consists of core chemical and physical concepts) and the *target* (the domain to which knowledge in the base is to be applied – the nanoscale).

Individual components within knowledge domains must be defined in order to critically compare information between the domains. *Object attributes* are said to take a single argument and are related to the intrinsic characteristics of a given item or concept. These can be superficial—such as color. An *object relation* takes two arguments and provides information about the relationship of multiple components in a knowledge domain. Upon defining object attributes and object relations, it is necessary to consider how comparisons of these are made between the base and target knowledge domains. If an object attribute or relation within the base domain can be readily argued to be congruent with one in the target domain, that attribute or relation is said to *map* between the domains.

An analogy is defined when relevant object relations map between base and target, even if object attributes do not map. In our case, the instructional materials have been designed based on maximizing the number of object relations that map between core physical and chemical concepts (base) and those at the nanoscale (target) without regard to how many object attributes map. This allows for the students' focus to be less on superficial aspects (attributes) and more on the interplay between the relevant components in each knowledge domain (relations).

Analogies have been extensively used in the field of science education, as pointed out by Haglund in his review (Haglund, 2013) and also have been explicitly described in the DBER

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literature. For example, analogies have been used to explain such diverse topics as kinetic behavior of transition metal complexes or the operating mechanism of scanning probe microscopy (Cortes-Figueroa *et al*., 2011; Hajkova *et al*., 2013). However, few of these analogies are focused on nanoscale concepts (Burgan and Baker, 2009; Campbell *et al*., 2011; Goss *et al*., 2013; Hajkova *et al*., 2013). Furthermore, few are explicitly targeted at undergraduate students at the advanced level of study (Bridgeman *et al*., 2013; Cortes-Figueroa *et al*., 2011; Horikoshi *et al*., 2013; Iyengar and deSouza, 2014; Wang and Hou, 2012).

Although the use of analogy is generally considered beneficial, a number of shortcomings are pointed out in the literature. For example, Orgill and Bodner (2004) indicate that if students are already familiar with the target concept, the analogy may be viewed as superfluous. Further, the transfer of irrelevant components between knowledge domains can lead to the development of misconceptions in the target domain. Raviolo and Garritz (2009) have echoed these concerns in their review of analogies used to teach chemical equilibrium.

Therefore, we designed the instructional materials with the purpose of being as explicit as possible in guiding students toward connecting the relevant object relations between domains. Guiding questions have been placed within the instructional materials with the aim of minimizing students' transfer of irrelevant object attributes and relations into the target (nano) domain. The nano domain has not been explored in the curriculum of the students involved in the field testing of this work. Therefore, the concepts that are highlighted in the instructional materials are not superfluous for students, but are part of a genuinely novel knowledge domain. Since the nanoscale has not been explored widely in the context of analogies, particularly for advanced undergraduate students, the case can be made that this work addresses a gap in the DBER literature of assessed analogical instructional materials for nanoscale pedagogy in chemistry.

We will now briefly describe each of the instructional materials that were developed for this work, including how this framework has informed their design.

Instructional Materials

Three instructional materials were developed, each with a nanoscale concept as the target domain – localized surface plasmon resonance in the acoustic analogy, quantum confinement and tunneling in the quantum tunneling module, and effects of surface area at the nanoscale. Each nanoscale concept is fundamentally rooted in core physical and chemical concepts which can be explored at first in a more accessible context (base domain) – acoustic behavior, differences between classical and quantum mechanics, and surface area at the macroscale. The instructional materials were designed to be modular in nature so that nanoscale concepts may be explored throughout the undergraduate chemistry curriculum – from general chemistry to capstone courses on special topics – and may be modified to be used in diverse settings such as lecture demonstrations, homework activities, or as a laboratory experiment (our case).

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The following is a description of each of the instructional materials, along with the specific object relations and attributes and how they map (or do not map) between the base (core physical and chemical) and target (nano) knowledge domains.

Acoustic Analogy

This acoustic analogy directly relates the behavior of tuning forks and the localized surface plasmon resonance (LSPR) phenomenon in metallic nanostructures (Muniz and Oliver-Hoyo, 2011; Muniz, 2014). LSPR is a crucial feature to explore at the nanoscale, as it is the basis for the unique optical properties of metallic nanomaterials and their application as chemical sensors as well as their role in the enhancement of Raman spectra in a technique known as SERS or surface enhanced Raman spectroscopy (Willets and Van Duyne, 2007). LSPR occurs due to the collective oscillation of surface electrons, which then resonate with incoming electromagnetic radiation and lead to an absorption event. This scales with the size, as well as the intrinsic properties of the material, just as the size and identity of a tuning fork impact the resonance frequency of its sound.

<u>Base domain</u>: Students experiment with tuning forks of differing lengths but the same composition (aluminum alloy) to observe that an increase in prong length is associated with a decrease in pitch. Students then explore how tuning forks of the same size but differing composition (brass) sound, and observe that the pitch differs as well—this time due to the intrinsic properties of the materials. They quantify (graphically) the frequency and wavelength as a function of the square of the prong length.

More advanced students have the option to explore the Fourier transform module. They strike forks of different sizes and compositions in front of a microphone directly connected to a computer. Waveform vs. time is obtained directly, and students Fourier transform these data to obtain a plot as a function of frequency. There have been a few studies involving undergraduate students in physics that have pointed out that students have a tendency to view sound wave themselves as “material” in nature as opposed ot as a wave in the traditional sense (Houle *et al.*, 2008; Linder and Erickson, 1989; Linder, 1992; Linder, 1993; Wittman *et al.*, 1999; Wittman *et al.*, 2003). Linder and Erickson (1989), in their study about physics graduates’ conceptions of sound, succinctly state that “[students’] wave conceptualization tended to be divorced from conceptualization of sound, and some students went so far as to claim that they felt that it was a mistake to think of sound as a wave.” Therefore, instructors of lower-level undergraduate students may want to use the external microphone to produce a direct visualization of the sound waves due to the mechanical oscillation of the tuning forks.

<u>Target domain</u>: Students are provided with three solutions of Au nanorods: short, medium, and long average lengths with respect to one another. They take electronic absorption (UV-Vis) spectra of these samples, and observe that one peak remains static (the transverse peak) and another red shifts with increasing average length (the longitudinal peak). They are expected to relate this back to what was observed with the tuning forks of constant composition but differing length: the frequency of the longitudinal plasmon mode of the Au nanorods decreased

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(wavelength increased) with increasing average rod length just as the frequency of sound decreased (wavelength increased) with increasing prong length.

Finally, students are provided spherical Au and Ag nanoparticles, each of which is the same average size. They observe that a single plasmon band occurs in each, which is due to the spherical symmetry of the particles. Students are expected to realize that the differing intrinsic properties between the Au and Ag nanoparticles (particularly the dielectric functions) leads to a vast difference in the plasmon modes, just as the differences in intrinsic properties for the aluminum alloy and brass tuning forks led to large differences in the frequencies of sound produced.

Table 1 summarizes the relevant object attributes and relations that were under consideration within this instructional material. Note that we intend to capitalize fully on the mapping of object relations between base and target (core and nano).

Table 1: Summary of relevant object attributes and relations between the tuning forks and metallic nanoparticles.

Object Attributes:	Tuning Fork Base	Mapping	Metallic Nanoparticles Target
Size	Tuning forks are macroscopic	Does not	Nanomaterials are on the nanoscale
Composition	Tuning forks are composed of metallic alloys	Does not	The nanomaterials under study are composed of pure metals
Oscillatory Behavior	Prongs of the tuning forks exhibit oscillatory behavior	Maps	Collectively, the conduction band electrons in the nanostructures oscillate (plasmon)
Object Relations:			
Induction	Striking of a tuning fork on a hard surface induces the oscillation of the fork prongs	Maps	Electromagnetic radiation impinging upon the metallic nanostruture induces the plasmon oscillation
Detection	Oscillation of tuning fork prongs can be detected by hearing or via a microphone	Maps	Plasmon oscillation can be detected by visual inspection of the electronic absorption spectra
Resonance Frequency	Tuning fork’s composition and size determines its resonance frequency	Maps	A metallic nanomaterial’s composition and size determines its LSPR frequency

Quantum Mechanical Tunneling (QMT)

The QMT module involved a slightly different approach to the use of the analogical framework. Since the base and target domains were so disparate, the need to include a “bridge domain” was deemed necessary (Clement *et al.*, 1989; Brown and Clement, 1989; Clement, 1993). In this approach, the bridging concept represents the target domain during the first phase of the activity but then becomes the base domain for the quantum mechanical tunneling in core/shell CdSe/ZnS

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nanostructures (Muniz, 2014; Muniz and Oliver-Hoyo, 2014). The stark contrast between quantum mechanical and classical behavior is something that must be confronted by all students in physical chemistry. It is at the nanoscale where these quantum effects start to predominate over bulk classical behavior; thus, the exploration of quantum effects such as tunneling in the context of the nanoscale is critical in order to gain a fundamental understanding of these systems. This exploration of tunneling in the context of quantum dots sets the stage for further inquiry into the exciting possibilities of quantum mechanics at the nanoscale, e.g. quantum computing (Loss and DiVincenzo, 1998).

Base domain: Students start out in the classical world as they experiment by dropping a steel ball down a ramp with a hill and observe, directly, that the ball will never transcend the barrier (the hill) unless it started with more potential energy than it would have at the top of the barrier.

Bridge domain: Students explore the implications of quantum tunneling in the context of the splitting of the NH_3 symmetric bending mode, a familiar molecule. Students plot the vibrational partition function of the mode, and are expected to conclude that molecules must be inverting through the barrier instead of over (at spectroscopic temperatures). Students contrast the behavior of NH_3 with the isostructural AsH_3 molecule—which exhibits no inversion splitting. Through the plotting of potential energy vs. apical displacement and angle change, they observe that the barrier to inversion is significantly higher in AsH_3 as opposed to NH_3 and that for the probability of tunneling to completely go to zero, the barrier would need to approach infinity.

Target domain: Students theoretically consider bare CdSe quantum dots immersed in an organic solvent matrix, which is assumed to provide an infinite potential barrier. They model this system utilizing a simple particle in a 1-D box approximation and observe the effects of quantum confinement on the energy levels (eigenvalues). Students draw separate eigenfunction and eigenvalue representations for this system. After modeling the bare CdSe dots, students consider CdSe/ZnS core/shell quantum dots, in which the barrier is no longer infinite but is a finite value dictated by the band gap difference between CdSe and ZnS. The 1-D box approximation involves finite "walls" on either side, and students are expected to match the boundary conditions appropriately in their representations. Students are provided the spectroscopic results of Dabbousi *et al.* (Dabbousi *et al.*, 1997) which depict electronic absorption spectra for CdSe/ZnS core/shell quantum dots compared to CdSe bare dots. While the CdSe core size is held the same, a slight spectroscopic red shift is readily observable from the spectra due to electron tunneling into the ZnS layer. Students should relate back to the bridge portion of the activity in which the phenomenon of quantum mechanical tunneling was established.

Table 2 is a summary of the relevant object attributes and relations that were the focus of this instructional material.

Table 2: Summary of relevant object attributes and relations between the base, bridge, and target knowledge domains of the QMT activity.

Object Attributes:	Classical Domain Base	Maps	Ammonia Inversion Bridge	Maps	Nanoscale Domain Target

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Particle	Steel ball	Does not	Tunneling of a proton across NH_3 plane	Partial	Electrons tunnel; differ from protons in composition
Potential Energy	Gravitational potential relative to lowest point	Does not	Wavefunctions are able to *tunnel through* the potential barrier; motion is quantized	Does	Quantum mechanics allows for tunneling of the electrons through the potential barrier at the CdSe/ZnS interface
Barrier	Hill (macroscopic)	Does not	D_{3h} (planar) intermediate barrier (a function of nuclear potential on either side)	Does not	Rectangular potential barrier between CdSe and ZnS layers
Object Relations: Barrier transcendence mechanism	Condition to cross: Initial PE of the ball must always be = to or > than the PE of the ball at the top of the barrier	Partial	The NH_3 system can only classically transcend the barrier at high temps, as more vibrational states are populated	Maps	Hydrogen atom and electron alike can *tunnel* through a potential barrier as their wavelike properties allow for penetration into the classically forbidden region
Measurable observations	Classical energy expression used to calculate E	Partial	Calculated partition function indicates insufficient energy to classically transcend. Splitting in IR spectrum gives barrier height of the planar (D_{3h}) intermediate	Maps	Tunneling of the electronic wavefunction of the CdSe into the ZnS layer is observed via a slight spectroscopic redshift
Multiplicity of events	Steel ball at each height represents a single event	Does not	Spectroscopy, involving many events and molecules, used to observe tunneling	Maps	<u>Many events</u> involving both core and core/shell quantum dots manifest spectroscopically
Limiting case: potential energy	Transcendence will not occur when PE of the hill is higher than KE of the ball	Does not	PE must be infinite for probability of transcendence to be zero	Maps	PE must be infinite for probability of transcendence to be zero

Dye Sensitized Solar Cells (DSSCs)

This instructional material draws an analogy between the available surface area in a macroscopic paradigm and how surface area plays a crucial role at the nanoscale when it comes to the relative efficiency of two types of dye sensitized solar cells (Muniz, 2014; Muniz and Oliver-Hoyo, 2014). A unique feature of the nanoscale is that very high surface area structures are possible due to the small size of individual nanoparticles. IN addition to being important in the context of catalysis, these structures are also very relevant in the case of dye sensitized solar cells (Bell,

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2003; Park *et al.*, 2000). Though contemporary microscopy techniques (e.g. SEM, TEM) can provide students with images of such nano structures, microscopy images do not constitute a direct experience related to available surface area. In this instructional material, students first experience the effects of surface area with modeling clay and plastic beads. This direct experience of materials with differing available surface area serves to guide them toward extending their findings to the nano paradigm in the context of TiO_2 DSSCs.

<u>Base domain</u>: Students work with two pieces of modeling clay of equal mass. One of the pieces is cut into thirds. They press each portion into a bed of plastic jewelry beads and compare the differences to observe that the portion with more available surface area picks up more beads overall. Additionally, they use electronic calipers to measure the bead diameter and observe that the bead diameter measures larger relative to the piece of clay it immediately occupies than in the case with less available surface area.

<u>Target domain</u>: Students construct two types of dye sensitized solar cells, one based on pure nanoscale anatase TiO_2 and one based on a mixture of nanoscale anatase and rutile TiO_2. The latter involves a polymorph of TiO_2 (rutile) whose individual nanostructures are more elongated, as opposed to the more spherical anatase particles, leading to a smaller available surface area. Students take current and voltage measurements of each cell under the illumination of an overhead projector to calculate the relative efficiency of the cells. They are provided with TEM images (Park *et al.*, 2000), one showing anatase and the other rutile, and are expected to conclude that the cell with the pure anatase is the more efficient one as its higher available surface area would've led to more dye molecules chemisorbing to the surface. Students are also expected to relate the fact that the absorption cross section of a dye molecule is larger relative to the individual piece of nanoscale anatase TiO_2 than to the rutile TiO_2. This is comparable to the notion that the bead diameter also measures larger relative to the smaller pieces of clay (the situation in which more surface area was available overall).

Table 3 summarizes the relevant object attributes and relations pertaining to this instructional material.

Table 3: Object attributes and relations for the clay/bead and dye sensitized solar cell systems.

Object Attributes:	Clay/Bead System **Base**	Maps	Nanoscale System **Target**
Composition	Organic clay and plastic beads	Does Not	Semiconductor TiO_2 and individual dye molecules
Scale	Macro scale objects readily manipulated with the hands	Does Not	Structures of TiO_2 at the nanoscale, dye molecules on the scale of Å's
Object Relations:			
Attachment	Beads attach to the surface of the clay	Maps	Dye molecules chemisorb to the surface of the TiO_2 structures
Surface area relationship	Many more beads per unit can attach to clay that has	Maps	Many more dye molecules can chemisorb to the smaller pure anatase TiO_2 particles.

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	been cut into smaller pieces.		
Impact	Ratio of a single bead diameter, relative to the surface of a unit it occupies is larger for smaller individual units	Maps	The absorption cross section of a dye molecule has a greater impact on the smaller units of TiO_2 (pure anatase).

The acoustic analogy, QMT, and DSSC instructional materials address three important nanoscale concepts (LSPR, quantum confinement and tunneling, and nanoscale surface area effects) in the context of core physical and chemical concepts (oscillatory behavior, the difference between classical mechanics and tunneling in the context of a familiar molecule (NH_3), and macroscale surface area). The purpose of these instructional materials is to explicitly connect the base and target domains. It is worth noting that even in these base domains, conceptual challenges can arise. For example, Wittman and coworkers found that students taking a second-semester undergraduate physics course had difficulties articulating the behavior of mechanical waves and often drew anomalous connections to particle behavior (Wittman *et al*., 1999). As another example, Johnston and coworkers' study of how undergraduate students responded to survey questions on quantum mechanics yielded evidence that students had a fragmented view on the subject altogether (Johnston *et al*., 1998). Thus, it is important for instructors and future researchers to be aware of students' alternative conceptions even within the base domains.

Since analogies also have the possibility to introduce unwanted misconceptions, it is imperative to assess how well students are able to navigate the desired connections between domains as well as provide instructors or researchers with information as to what misconceptions may arise (Orgill and Bodner, 2004; Raviolo and Garritz, 2009). Further, the recent call for assessed teaching materials in the nano domain implies that such materials ought to aim for students to develop a scientifically normative understanding of concepts at the nanoscale (Jones *et al*., 2013). These considerations constitute the basis for the principal research questions in this work:

- Do the newly developed instructional materials promote in students the ability to effectively map core concepts into the realm of nanochemistry? What evidence can be provided to this effect?
- Does analogical transfer enable students to develop a more scientifically normative viewpoint on both core and nano knowledge domains?

To address these questions, a qualitative study was designed in order to probe the nature of students' language during field tests of the instructional materials. Since the nature of analogical transfer is highly linguistic, a qualitative approach was deemed appropriate for the analysis in order to afford deep insights into the impact of these materials.

Methodology

Each of the instructional materials was field tested with advanced students, who engaged in the activities in a small group setting (group sizes ranged from a maximum of seven to a minimum of two). Students enrolled in two undergraduate laboratory courses (advanced measurements

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and advanced synthesis laboratories) fully participated in the study by performing the activities, partaking in group discussions, and being individually interviewed by the researcher. All students involved in the field testing had taken the appropriate prerequisite courses for the advanced level labs they were enrolled in, and thus had been exposed to fundamental content material. In the case of the QMT instructional material, students that partook in the field testing were enrolled in the advanced measurements laboratory, for which at least one semester of physical chemistry is a prerequisite. Table 4 shows the number of students and groups that were involved in the field testing of the instructional materials. Students signed anonymous informed consent forms prior to participating, and pseudonyms were assigned to each student in the following form: SnGm, where n is the student number and m is the group number.

Table 4: Number of students, groups, and group sizes for each instructional material.

Instructional material	Total number of students	Number of groups	Minimum group size	Maximum group size
Acoustic analogy	24	4	4	7
QMT	11	3	3	5
DSSC	11	4	2	3

The pertinent data consisted of hand-transcribed audio recordings of the following:

- <u>Small group discourse</u>: All discussions that took place within students' small groups. This is a rich source of students' conceptual development and analogical transfer.
- <u>Post-activity interviews</u>: One-on-one semi-structured interviews with the investigator to gain insight into how students connect concepts on an individual basis once confronted with the progression of the activities they had engaged with.

The group discourse required 3-4 hours (the time of a typical laboratory period) depending on the group. For the acoustic analogy and QMT activities, groups participated in the field testing one group at a time. For the DSSC activity, the four groups participated simultaneously within the same lab space. Post-activity interviews took approximately 5 to 10 minutes each depending on the individual student being interviewed.

A discourse analytical perspective, described by Duit and coworkers (Quine, 1992; Duit *et al.*, 1998, Duit *et al.*, 2001), was adopted in order to systematically categorize students' language within the relevant excerpts of the data. Duit et al.'s work involved the use of analogies to introduce secondary school physics students to chaotic systems, such as Foucault's pendulum. The discourse component of their analysis of a student group as they progressed through the analogies was rooted in an analytic epistemology developed by W. V. Quine. Two basic epistemic components were brought forth by Duit et al. (2001) that most informed our coding scheme were:

- Observation sentences: "Link language and the world that (the) language is about."
- Observation categoricals: Collections of observation sentences that articulate a particular generality (Quine, 1992).

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This served as a lens through which to view students' conceptual development within the context of the small-group setting via their language. As such, it was deemed appropriate to be adapted and expanded upon to suit our research, since this study focuses on the nature of students' language in the context of their learning environment and how this informs their interactions with the analogies.

In order to apply this perspective in a consistent manner, a coding scheme was developed and commercial software was utilized to tag relevant excerpts from the data with appropriate coding (SocioCultural Research Consultants, 2013). The coding scheme is as follows:

1. Physical observation statements and categoricals: Most general code whose purpose is to focus on students' expression of what they experience and how these experiences are, in turn, expressed verbally.
2. Misconceptions: Erroneous or scientifically invalid statements about any particular component of the activity.
3. Comparison and contrastive statements: Statements that compare one component of the activity to another; can be intra- or inter-domain, or even external in the case of establishing spontaneous analogical transfer. External transfer is a separate sub-code.
4. Reformulations: Corrections to misconceptions; such corrections may be group-induced, investigator-induced or carried out by an individual who has expressed their own misconception.
5. Background statements: Any statement that invokes a group member's prior exposure or knowledge of the topic(s) at hand.
6. Investigator intervention: Statements made by the investigator to cultivate students' group discussion or assist in conceptual development. Simple procedural advice is not included in this category.

The coding scheme incorporates and expands on the observation sentences and categoricals used by Duit and coworkers and developed by Quine (Quine, 1992; Duit *et al*., 2001). These basic components have been placed into the most general and crucial code (physical observation statements and categoricals), upon which the remainder of the codes are inextricably linked. Of particular note is that the code most related to analogical transfer, comparison and contrastive statements, will always coincide with a physical observation statement or categorical. Further, misconceptions and reformulations will often have their root in students' physical observation statements and categoricals. This theoretical perspective is crucial to understanding how the activities either promote (or do not promote) analogical transfer from the base to target knowledge domains. This, in turn, assists with the answering of both principal research questions.

Results and Discussion

For each of the instructional materials, two important findings precipitated from the analysis: conceptual challenges and evidence of analogical transfer. The former are described with the goal of informing future researchers and instructors of the types of difficulties students may

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confront. The latter helps build arguments to address the research questions. Shown below are representative excerpts from the analysis that are illustrative of the main purpose of the work.

Acoustic Analogy-Conceptual Challenges

Key conceptual challenges revealed by the analysis of the data consisted of the following:

a. Difficulty in modifying the dielectric tensor expression to properly reflect the anisotropy of a nanorod as opposed to a sphere.
b. Tendency to assume that the difference in density was a factor in the differences in plasmon absorption in the Ag and Au nanoparticles.

For the first of the conceptual challenges, investigator intervention was, at times, required to facilitate scientifically normative discussion. Consider the following exchange within the group discourse of group 3:

AA Excerpt 1

S4G3: *Modify the equation to describe a nanorod, because that equation is for a spherical nanoparticle.*
S2G3: *Ok.*
S4G3: *And so we're trying to modify it for a nanorod. How do we do this?*
S2G3: *(Laughs). Good question.*
S1G3: *I don't see anything spherical about this.*
(…)
Investigator: *So what do you notice about the dielectric matrix?*
S2G3: *It is a three by three.*
Investigator: *Yeah, what do you notice about the terms in there? Are any of them different?*
S2G3: *No, they're the same.*
S6G3: *Ooh.*
S2G3: *Because a sphere has the same x, y, and z coordinates. So the rod's going to have different x, y, and z coordinates.*
S4G3: *So, instead we would have-.*
S5G3 *(Interjects): The z would be different, right?*

The students in group 3 are initially confused about how to approach the problem. Note that the investigator poses a general question about the nature of the dielectric matrix, to which a very general response is given by S2G3—who simply states that the matrix dimensions are three by three. When the investigator follows up this question with one directly confronting whether the terms are different, the nature of the discourse immediately changes. Student S2G3, in their comparison and contrastive statement, immediately becomes aware of the fact that the coordinates of the sphere will remain equivalent, in a Cartesian sense, but that they will need to modify the coordinates. The follow up from S5G3 specifies, correctly, that the z axis would need to be modified.

The other conceptual challenge that precipitated from the analysis of this acoustic analogy was based on students' problems with anomalously mapping the differences in density of the material

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to the differences between the plasmon absorption in the spherical nanoparticles. Consider the following excerpt from group 1:

AA Excerpt 2

S2G1: *Why, why is the silver before the gold?*
S5G1: *It's a different metal.*
S6G1: *We don't know if it's going to be before or after, we just know it's going to be different.*
S2G1: *Oh, ok.*
S3G1: *We can make a guess as to the density of the material.*

Student S2G1 poses a question asking why the spherical Ag nanoparticles would exhibit a plasmon band at a lower wavelength than the Au. S5G1 is aware that this is due to the fact that the metals are of different identities. Further, student S6G1 properly recognizes that, given the information they have immediately available to them, the only prediction they would be able to make is that the plasmon bands would be at different wavelengths. S3G1, however, makes a misconception statement that the density is related to the differences in the positions of the plasmon bands within the spectra. While Au and Ag certainly have different densities, it is the difference in the dielectric functions for each of the metals that leads to the difference in plasmon absorption energy.

Aside from the conceptual challenges illustrated here, there was significant evidence of analogical transfer in the data. This evidence was found both within the group discourse and post-activity interview data.

Acoustic Analogy-Evidence of analogical transfer

In focusing on students' ability to make normative connections both intra and inter-domain it is found that students in all groups were, quite readily, able to establish the relationship between prong length and frequency and wavelength of sound produced. Within the base domain, students were successful at understanding the idea that banging the tuning forks provided energy to the system to induce oscillations. In terms of transfer to the target domain, students were successful in understanding the induction of oscillatory behavior in each domain. For example:

AA Excerpt 3

S6G1: *Ok, what is exciting these plasmon modes? The input of light?*
S1G1: *Yeah.*
S6G1: *Just like us banging the tuning fork, we're shining light on it.*

The type of comparison and contrastive statement made by student S6G1 indicates that they directly mapped the activity of striking the tuning forks to the light impinging on the metallic nanostructure.

An exemplary excerpt of students' analogical transfer of the length of the tuning fork prongs to the length of the gold nanorods can be seen in this discussion within group 1:

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AA Excerpt 4

S2G1: *What's the question?*
S3G1: *It's saying as the rods get longer, will the frequency or wavelength of light get longer or shorter? Based on our-.*
S6G1 (Interjects): *Based on increasing average rod length.*
S3G1: *So if you remember the longer tuning forks had the lower tone which was higher in energy? Or was it lower in energy?*
S2G1: *Higher. No.*
S6G1: *The lower the tone is lower in energy.*
S3G1: *So the longer it is, it requires less energy. So that's an analogy to this, that means the shorter one should be, right, lower. So blue would be the shortest.*

S3G1 immediately links the length of the tuning forks to the length of the nanorods. They do not, however, immediately remember the relationship between prong length and energy. S6G1 intervenes with a physical observation statement that asserts that lower tone corresponds to lower energy. This is then explicitly mapped to the target domain by student S3G1 at the end of the excerpt.

Apart from the anomalous transfer of density into the target domain, students were successful in characterizing the role of intrinsic properties in both the tuning forks and nanomaterials. Consider the following excerpt:

AA Excerpt 5

Investigator: *This is the silver and this is the gold.*
S6G1: *Ok, so light blue (referring to the color on the spectrum plot) is silver, and.*
Investigator: *They're the same exact size as that.*
S2G1: *Right.*
S6G1: (Reading question initially). *So this is like the brass compared to the aluminum.*
S3G1: *I guess we were supposed to discuss that before.*
S6G1: *Um, so, yeah it's an analogy to the. Yeah. Ok.*

S6G1 refers, in a comparison and contrastive statement, to the target domain in the context of the base domain, stating that the gold and silver are like the brass and aluminum. This is indicative that the students reflected on the intrinsic differences of the metals when formulating their response.

Multiple excerpts showing analogical transfer from the Acoustic Analogy have been uncovered. There was evidence of students' success in relating the prong length and frequency relationship in the tuning forks to the longitudinal plasmon mode in the Au nanorods. This aspect required investigator prompting within the post-activity interviews. Students were highly successful at mapping the concept that different materials exhibited different resonance frequencies in both domains. This occurred despite the anomalous mapping of density into the target domain, which constituted one of the conceptual challenges. Overall, transfer of the intrinsic properties occurred more readily than transfer of the dimensions of the structures. It seemed that students

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more easily connected the differences between the materials in each case (aluminum vs. brass with the tuning forks, and Au and Ag with the nanomaterials) than the effects of size within materials of the same composition (tuning fork prong lengths, and short, medium, and long Au nanorods). Strength and prevalence of analogical transfer is, therefore, highly contextual within a given activity. .

Quantum Mechanical Tunneling (QMT) -Representational Challenges

The most prevalent, and pertinent, form of conceptual challenge in the QMT activity was representational in nature. Representational challenges with respect to the depiction of eigenfunctions and eigenvalues and with respect to tunneling have been well documented in the physics education literature (Morgan *et al.*, 2004; Wittman *et al.*, 2005; McKagan and Wieman, 2006; Singh and Zhu, 2009). Singh and Zhu, for example, reported advanced undergraduate physics students' struggles with cusps, discontinuities, and improper axis labelling of such systems (Singh and Zhu, 2009). Despite the fact that the QMT activity explicitly asks students to separate the eigenfunction/eigenvalue representations, challenges still arise. Consider the following excerpt from group 1 during the third portion of the activity where students are investigating the particle-in-a-box in the context of quantum dots:

QMT Excerpt 1

S1G1: *Does it [the wavefunction] have to touch the ends?*
S4G1: *Yeah.*
S1G1: *Can't it touch the sides of the box here?*
S4G1: *No, because the potential is zero, so there's zero probability that it can be there.*
S2G1 *(simultaneously): No.*
S1G1: *I just remember seeing a graph...*
S2G1: *Because you probably saw it like this. [Draws potential with wavefunctions superimposed on the energy levels].*
S1G1: *Yes.*
S2G1: *This is multiple, overlayed at each other.*
S1G1: *Ahh.*
S2G1: *This, right here, zero.*
S4G1: *Yeah, it's still zero, yeah.*
S1G1: *Well, how does this one work then because it's going up?*
S4G1: *It's like, it's like if you put a new line through it, yeah.*
S1G1: *Ok, I see what you're doing.*

Student S1G1 expresses the misconception that the wavefunction can touch the sides of the box in the case where an infinite potential is present on each side of the box. S2G1 offered a reformulation that included a drawing of the type of overlaid plot, which was the origin of student S1G1's misconception. Later, student S1G1 understands that it is an overlayed plot and that the representation "zeroes out" at each quantum number (n value). This is an example, however, of how such representations can be misleading.

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Figure 1 shows an example of this type of overlaid plot that was sketched by students within the target portion of the activity.

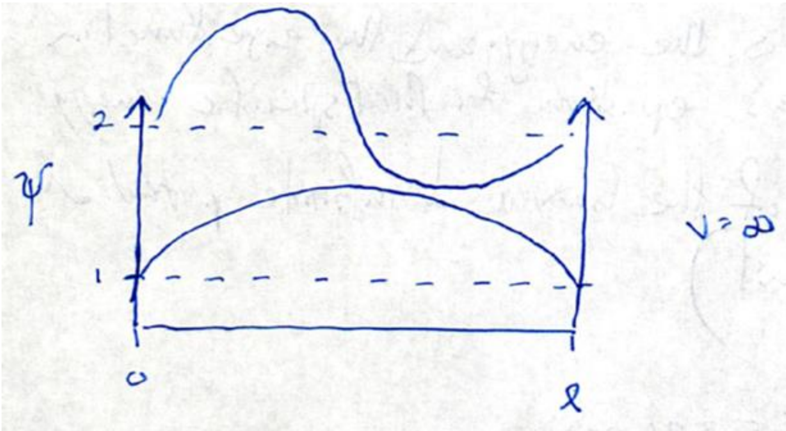

Figure 1: Sketch constructed by students to represent the infinite-potential one-dimensional particle-in-a-box approximation to the CdSe quantum dots. Reprinted with permission from Muniz and Oliver-Hoyo, 2014, *J. Chem. Educ.*, DOI: 10.1021/ed400761q. Copyright (2014) American Chemical Society.

The overlay suggests that the eigenfunctions themselves have a higher ψ(x) value with increasing quantum number, n.

Another example of a representational challenge can be found with students' confusion about the quantum number, n, with the coordinate x:

QMT Excerpt 2

S1G2: *So we want to construct a, construct two diagrams, one representing energy versus coordinate, the coordinate equals n, right?*
S2G2: *That should be... a parabolic, right? Because it's n-squared, it's not n. So when n's two, it's just...*
Investigator: *n is just the quantum number, right?*
S1G2: *Just the quantum number... So when you say coordinate, energy versus the coordinate, with the first energy level clearly marked...*
Investigator: *So what is the physical coordinate here? Like what is...just think about what you're modeling, right?*

Here, the investigator needs to intervene in order to ensure that students do not create an erroneous representation in which they would plot the energy versus the quantum number. This moved toward reformulating the misconception statements made by students S1G2 and S2G2.

In addition to the representational challenges associated with the QMT activity, rich examples of analogical transfer—including spontaneous external transfer—were present.

QMT-Evidence of analogical transfer

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Students were able to clearly separate the behavior of quantum mechanics from that of classical mechanics upon their exploration of the bridging concept. For instance, in group 3:

QMT Excerpt 3

S4G3: *Alright, so both sides of the barrier are interacting, that means that you would be able to make it over the potential without having that much energy.*
S1G3: *Yeah, so you'd have to, um...*
S4G3: *(Interjects) Which doesn't make sense in the classical sense. Since, like, with the ball it sort of stops.*
S1G3: *Yeah, so, yeah that excitement isn't enough, it's not greater than the barrier right? So the only way it can interact is tunneling out of the...*
S4G3: *So I guess since the, uh, the wavefunctions are probability distribution, so I guess there's some very small probability that it would be, like, flipped. So that's how it would occur at room temperature.*
S1G3: *Yeah.*

Student S4G3's physical observation statements refer explicitly to the base knowledge domain: "...with the ball it sort of stops." The language of quantum mechanical tunneling is utilized by S1G3 in a scientifically normative way—they are aware that the interaction can only be occurring across the barrier without having to go over it classically.

During the exploration of the target knowledge domain, an interesting exchange took place between students in group 2:

QMT Excerpt 4

S1G2: *Without, you know, being able to observe or examine something with a spectroscopic technique, you might be only able to see, you know, two events. You know? Uh.*
S2G2: *Ok. Or like events that are big enough for us to see with our eyes.*
S1G2: *Yeah, that are macroscopic as opposed to, you know, this microscopic technique allows you to see there's other things going on.*
S2G2: *Even things that are really small can, can...*
S1G2: *Yeah, see...it's kind of like a microscope. You see something on the outside, use a microscope and you can see...*

Note the spontaneous analogical transfer by student S1G2 in comparing microscopy to spectroscopic techniques. Students S1G2 and S2G2 are articulating the differences in the way measurements are taken at the macroscopic level as opposed to microscopic. This is reflected further in the post-activity interview of student S3G2:

QMT Excerpt 5

Investigator: *Um, describe in the context of all you've experienced with the activity and what we've discussed what the connections are between each segment of the activity.*
S2G2: *So I guess the first part kind of tells you 'hey this is the world that we live in, this is what ninety nine percent of things that we see and experience, this is the way they look' but then we*

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go down the smaller microscopic site and then we see that you can actually treat these with quantum mechanics and then have many more variables to observe and then how they actually change the perspective of potential energy from what you see in real life to small molecules and particles.
Investigator: *Ok.*
S2G2: *So we just like went down by a level each time.*

Student S2G2 focused on the differences in scale exemplified in the activity with their comparison and contrastive statements. This understanding of the progression of the activity is crucial, as the students move from the classical world to the quantum world and ultimately into the domain of tunneling in the context of nanostructures.

One of the most interesting exchanges occurred in group 1, when a particular student (S1G1) has become frustrated with the concept of tunneling during the third portion of the activity:

QMT Excerpt 6

S2G1: *Well in the event of the infinite box, you know, just CdSe in a (sic) organic matrix, you have effectively an infinite box. In the case that you coat it with the ZnS you give it a squishy outer layer. You give the box, um, not so rigid sides. Instead of a steel box, you make it like a paper bag.*
S5G1: *So it loses some energy.*
S2G1: *Yeah so it can relax a little.*
S1G1: *Pshhht. I give up on tunneling; I don't understand tunneling...I just...*
S5G1: *Don't think of it as tunneling, just think of it as like, ok, if you have like he was saying a metal box and you throw a bouncy ball in it, like it's going to hit, like you know.*
S1G1: *I don't see how this relates to any of this energy.*
S5G1: *Yeah, no, like that's what I'm saying. Like it has much more strict, it has a lot higher energy because it's bouncing off the walls like it's very confined. Whereas if you put it in a big plastic bag that's like blown up and you bounce it it's going to smash into the walls and you know it's going to have like, it's going to lose a lot of energy because it's not as confined.*

This illustrates students' use of spontaneous external analogical transfer to help mitigate the difficulties of student S1G1. Note that student S2G1 initially invokes knowledge from a domain external to the current knowledge domain by comparing the ZnS layer to being "squishy" or "like a paper bag." When S1G1 is still frustrated with the concept, S5G1 builds upon the external transfer established by S2G1 and utilizes the classical behavior of a particle (bouncy ball) in the context of a "big plastic bag" to illustrate that the system has less energy upon being less "confined." Note also the incorporation of the language of "confinement" into the argument, as this is a major concept in understanding quantum behavior.

In addition to this, students in group 3 have the following exchange:

QMT Excerpt 7

S1G3: *Yeah, um, like so it wouldn't be in a classical [wouldn't be in the classically forbidden region] because its potential is too high for the energy. Like, uh, the energy level of the particle*

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is lower than the potential energy, so classically it wouldn't be able to get out there, but, get outside the box. But, since it can tunnel then it can, and we can show that it is because the wavelength is shifting when you put the shell around it. So it's acting like it has a larger box.
S2G3: *Hmm.*
Investigator: *Any other comments?*
S2G3: *Seems reasonable.*
S4G3: *Yeah, so like the steel ball would never end up somewhere where it doesn't have enough potential energy.*

S1G3 explicitly states that the tunneling, which is observed in the CdSe/ZnS core/shell structures, would not have occurred in the classical case (linking back to the purpose of the bridge to draw a line of demarcation between the classical and quantum worlds). Further, their physical observation statements that the particle (electron) can tunnel into the classically forbidden region with the ZnS shell and that the wavelength shifts since "...it's acting like it has a larger box" imply an understanding of the effects of quantum confinement (or, in this case, a reduction in the confinement). The most scientifically normative of the diagrams from the third portion of the activity, as seen in Figure 2, resulted from group 3's discourse.

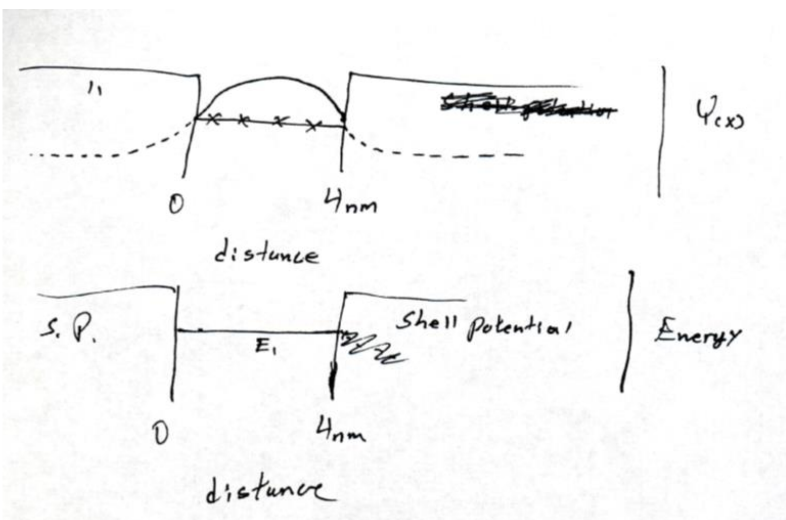

Figure 2: Separated eigenfunction and eigenvalue diagrams from group 3. Reprinted with permission from Muniz and Oliver-Hoyo, 2014, *J. Chem. Educ.*, DOI: 10.1021/ed400761q. Copyright (2014) American Chemical Society.

Overall, the quantum mechanical tunneling activity provided the most detailed source of group discourse data and evidence for analogical transfer, including spontaneous external transfer.

DSSC-Conceptual Challenges

The two main conceptual challenges that resulted from the DSSC activity were:

a. Students' focus on packing efficiency as opposed to available surface area
b. Lack of physical understanding of the absorption cross section

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An excerpt exemplifying the first of these conceptual challenges is as follows:

DSSC Excerpt 1

Investigator: *You took measurements of efficiency of the solar cells that you constructed and matched up the cells with specific TEM images of the semiconductor surface, which is the TiO_2 annealed to the conductive glass; why did you make the assignments you did? I have the sheet here. And, again, these were arbitrary.*
S1G1: *Right, right. I think we generally looked at the picture and looked at the, like, which one like packed the tightest and had more surface area to the picture because I guess that'd be how light would hit it, and so we chose the three smaller blocks to be the one that looked more efficient because like I said the three smaller blocks had a greater surface area.*

Note that S1G1, prior to invoking available surface area, focuses directly on the way in which the TiO_2 nanostructures appeared to pack within the TEM images. This was also present within the group discourse:

DSSC Excerpt 2

S1G1: *[Reads question pertaining to assignment of TEM structure to appropriate solar cell]. Oh, that's the question is determine which one.*
S2G1: *Determine which one's which?*
S1G1: *Which one packs better?*
S2G1: *This one packs better because they, I mean, if you think about it, like, we had smaller pieces of clay, had better efficiency, it's a smaller piece.*

Within this group excerpt, students S1G1 and S2G1 immediately focus on the packing of the structures. Their comparison and contrastive statement to the base domain (with the clay and beads) is done so in the context of how well the structures would pack as opposed to the available surface area. Note that students were never instructed to (nor did they spontaneously) pack the pieces of clay together.

With respect to the second conceptual challenge, students were generally unaware of the physical interpretation of the absorption cross section. This made it particularly difficult for them to relate the parameter and its value relative to the immediate nanostructure it occupied back to how the diameter of a bead measured relative to the piece of clay it immediately occupied. Consider the following excerpt from group 3:

DSSC Excerpt 3

S1G3: *[Reading question] The absorption cross section of a dye molecule is roughly the portion of the molecule that exposes itself to the incident electromagnetic radiation. How would this value relate to the occupied mass and surface area of the TiO_2 nanosctructure and factor into the efficiency of a cell?*
...
S2G3: *Ok, maybe. (Silence). It's the larger the surface area, the better the value. The larger, the larger the occupied mass, the lower the value. Right?*

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S1G3: *What?*
S2G3: *Sounds good to me.*
S1G3: *The lower what value? What value are you talking about?*
S2G3: *[Rereading question] The absorption cross section of a dye molecule... (etc.).*
S1G3: *Occupied mass.*
S2G3: *What value?*
S1G3: *I don't know.*
[Noted frustration with the question at this point]
S2G3: *What value are you talking about?*
Investigator: *The value, I'm referring to the absorption cross section. So how would that, how would that relate to the occupied mass and surface area of the* TiO_2 *nanostructure?*
S2G3: *It would increase when the surface area increased. And it would decrease with the occupied mass?*
Investigator: *So the absorption cross section of the dye is intrinsic to the dye, right? It is its own thing; that's the amount that the dye exposes itself.*
S2G3: *Ok.*
Investigator: *Um, which would depend, um, is, is how much surface area available there is. Right?*
S2G3: *Yeah.*
S1G3: *So.*

The students eventually become frustrated with the question and, despite extensive investigator intervention, are not able to clearly articulate the relevant relationships.

DSSC-Evidence for analogical transfer

Evidence for analogical transfer was found within the data. Consider group 1's exchange:

DSSC Excerpt 4

S1G1: *So its relative efficiency is automatically comparing A to B. So, I imagine so it's a whole, uh, large number it means A is more efficient than B.*
S1G1: *We only did one cell, so I think we can ignore that.*
S2G1: *The answer is A because, um, if it's that much more efficient, think about how much smaller.*
S1G1: *Yeah but I think it, we're trying to base it on the earlier bead stuff.*
S2G1: *Right!*
S1G1: *I thought you were, the whole like, in the earlier thing was like you made two cells and one had like smaller surface area than the other and that's why it would...*
(…)
S3G1: *I don't see how the beads and clay are related to A versus B.*
S1G1: *Neither do I.*
S2G1: *Well, because it's the, think of the clay, er, the beads as the molecu-, er the dye and then think of our slide as the clay, so...*
S1G1 *(interjects): Right.*
S2G1: *...comparing A and B.*
S1G1: *But the difference between A and B was the surface area.*
S1G1: *What's the difference between A and B, like, uh, chemically?*

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[Investigator points at TEM images]
S1G1: *Oh, ok.*

Here, the students are critically comparing the two cells (A and B) and referring back to the base knowledge domain (clay and beads). Ultimately, student S2G1 makes the comparison and contrastive statement linking the beads to the dye and the clay as the ITO slide. Though the latter portion of this comparison and contrastive statement is not the desired result, S1G1 follows up the statement by commenting that the difference between the two is surface area: this is scientifically normative and directly relates back to the base knowledge domain.

Another exchange of interest took place within group 2:

DSSC Excerpt 5

S2G2: *[Reads question]. Which cell is more efficient than the other... (etc.).*
S2G2: *Ok, so A, cell A has allowed more dye molecules to absorb...*
S1G2: *Mhm.*
S2G2: *...um.*
S2G2: *[Reading portion of question] Construct an argument based on evidence from both portions of the activity. Ok, so we have to, like, say why.*
S2G2: *So, essentially the reason cell A is more efficient is because it allows more dye to bond to it. Ok, and so. I. To explain that. Do we need to look at these to explain that?*
Investigator: *These as well, right?*
S1G2: *Which one is which?*
Investigator: *Ahh. Which one would you think would represent which?*
S1G2: *I think this one, because these look like smaller pieces and therefore there's more surface area.*
S2G2: *So. Um. (Long pause). Um, with what, smaller, the titanium surface for A is smaller bits? Or what-not.*
S1G2: *The um. Well, what is this? Like.*
S2G2: *Which one? This one? Ok, this is. Well, this would be, uh, electron, you know, microscope picture of both surfaces of titanium. Because there are two different titanium oxide...*
S1G2: *Right.*
S2G2: *...compounds. This one should be A and that one should be B.*
S1G2: *I see what you're saying. Um, the. The, the cells of the titanium in our sample, in A, are...*
S2G2 *(simultaneously with S1G2): were smaller...*
S1G2: *...than in the other sample, and because they were smaller, there was greater surface area. Because there was greater surface area, more dye was able to, uh, more dye, there was, more dye could fit in and therefore, it, um, could absorb more light and conduct more electricity.*
S3G2: *Yeah, I agree.*

Students in group 2, particularly S1G2 and S2G2, reason that cell A (which is based on the anatase polymorph of TiO_2) should correspond to the TEM image which shows the case with the higher available surface area. Students' exposure to the concept of surface area in this activity allowed for the following type of physical observation statement by S1G2 to be made: "Because

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there was greater surface area, more dye was able to...more dye could fit in and therefore, it...could absorb more light and conduct more electricity." This is congruent with what students experienced directly at the macroscale: the instance where the clay was cut into smaller pieces (higher surface area) allowed more beads overall to stick to the surface relative to the equally sized piece of clay that had not been cut up.

Overall, the DSSC activity afforded the least instances of evidence for analogical transfer out of the three instructional materials, though it was still certainly present. It is interesting to note that this was, by far, the most "hands-on" or procedurally involved activity of the three. A potential explanation might relate to the work of Young and Talanquer (Young and Talanquer, 2013) in which they explore how different types of small-group activities generated different types of student talk. They found that students' language was most procedural during the manipulation-based activities and least procedural in the exploratory types. Coincidentally, the meaning-making talk was higher in the exploratory activity types as well. Their findings are highly interesting and relevant as they point at evidence to suggest that more scripted and hands-on types of activities tend to focus students attention on "completion of the task rather than an exploration of the content". In our study, this is a potential reason for the lower levels of meaningful student discourse and analogical transfer in the DSSC activity.

Conclusions and Implications

We have successfully utilized a framework for analogy to design modular instructional materials to explicitly connect core chemical and physical concepts to those at the nanoscale. Through the results of our study, we have shown that the instructional materials may successfully promote analogical transfer from the base (core) to the target (nano) domains. Further, we have argued that students were able to express scientific concepts in an increasingly normative fashion between these knowledge domains. By tethering the object relations between the two knowledge domains, students moved towards deeper understanding.

This work has addressed a gap in discipline-based education research by:

a) Creating modular instructional materials which can be integrated into existing curricular designs. These materials were designed to incorporate core physical and chemical concepts and expand upon these concepts in the context of the nanoscale, making them suitable for discrete courses and broad curricular integration alike. Further, the components used in the materials are readily adaptable to multiple physical and pedagogical settings e.g. laboratory, lecture demonstration, or as a homework activity.

b) Explicitly connecting core chemical and physical concepts (oscillatory behavior, the difference between classical mechanics and tunneling in the context of a familiar molecule (NH_3), and effects of surface area at the macroscale) to those at the nanoscale (LSPR, quantum confinement and tunneling, and effects of surface area at the nanoscale) via analogy to address the lack of instructional materials that allow students to apply their core knowledge to the novel domain of nanochemistry.

c) Assessing the efficacy of these instructional materials on promoting analogical transfer.

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As Jones and coworkers have pointed out in the conclusions of their recent review (Jones et al, 2013), the unique and "abstract" nature of the nanoscale means that educators must purposely work towards and develop "meaningful and relevant" nano-related curricula Many of the existing instructional materials for nanochemistry concepts do not directly couple core scientific concepts, with which students are already familiar, to the nano domain. In addition to the pedagogical approach of explicitly connecting core and nanoscale concepts via analogy, our work involved the rigorous assessment of the instructional materials—something that is currently not widely present in nanoscale education. By addressing the gaps outlined above, we have taken a step towards shifting the paradigm of nanoscale education at the postsecondary level more towards an evidence-based state. This provides both researchers and practitioners a springboard upon which to carry out work to further refine innovation of nano education.

The qualitative analysis yielded evidence of scientifically normative analogical transfer for all three of the instructional materials. This is not to claim that there are not challenges, or limitations, as these have been discussed alongside students' successes. Instead, it is to claim that there are enough instances across multiple student cohorts and within each of the developed instructional materials that explicitly show that analogical transfer from core chemical and physical concepts to those at the nanoscale occurs and can be facilitated either within the group or by instructor's intervention. Representative excerpts have been provided to illustrate our findings. The instances of transfer were the highest in the QMT instructional material and the lowest in the DSSC. It is postulated that this is due to the fact that the latter is highly procedural; therefore, the distribution of students' language shifts away from meaningful content-related discussion. This presents an opportunity for future work to explore whether or not there is an optimal level of procedural demand within instructional materials of this kind.

A number of conceptual and representational challenges were found for each of the instructional materials within this study. This leads to a number of implications for the implementation of these instructional materials, and ways in which to mitigate the prevalent challenges:

Within the acoustic analogy activity, the conceptual challenge involving students' difficulty modifying the dielectric tensor to reflect anisotropy might by mitigated with a simple exercise or demonstration involving a scaling matrix before students reach the target portion of the activity. Such a scaling matrix can be used in two dimensions initially, then three dimensions, in order to directly show students the effect of changing the magnitudes of the x, y, and z components (assuming a Cartesian coordinate system is utilized).

The conceptual challenge involving the anomalous transfer of density into the target domain could be addressed with careful investigator intervention if students start discussing density during the latter part of the activity. Instructors should facilitate the discussion towards a more fundamental consideration of intrinsic properties and ask students to critically question what the relevant intrinsic properties are in each portion of the activity. This could help guide students towards making a scientifically normative connection between the base and target domains.

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In the quantum mechanical tunneling activity, the relevant representational challenges have a literature precedent in physics education (Morgan *et al.*, 2004; Wittman *et al.*, 2005; McKagan and Wieman, 2006; Singh and Zhu, 2009). Since the nature of students' exposure to quantum mechanical concepts may have contributed to these challenges, instructors should actively question the nature of students' diagrams as they facilitate the activity. Prudent intervention when students are misrepresenting the physical system(s) is likely necessary; instructors should carefully focus students' attention on the portion of the activity that explicitly guides students how to represent these systems. Results from both this work and previous literature imply that representational competence in undergraduate quantum chemistry is worth further investigation.

The dye sensitized solar cell activity analysis uncovered two conceptual challenges, the first being that students focused on the packing efficiency of the clay and the TiO_2 structures in the TEM images. Since this language was not utilized directly in the context of the activity, it must be brought with students from an external source. It is important to note that the institution at which this study took place incorporates rudimentary solid-state chemistry into its first-year course sequence. Here, the language of packing efficiency is present (e.g. cubic close packing, hexagonal close packing etc.). Instructors should be aware of the possible use of this language and carefully guide students' discussions towards the relevance of the available surface area. Further, students should be guided to utilize the term "efficiency" only insofar as it relates to the efficiencies of the solar cells themselves.

The final of the conceptual challenges discussed is one that is centered on students' lack of physical interpretation of the absorption cross section. Since this is an issue of background knowledge, the instructor could use "down time" within the course of the activity (i.e. between the two parts of the activity) to derive the Beer-Lambert law within the context of the absorption cross section and how it relates to the extinction coefficient. Within this derivation, critical questions should be asked about the probabilistic interpretation of this parameter and what its meaning is beyond simple dimensional analysis. If students are equipped with the physical understanding of this term, it is plausible that analogical transfer will occur more readily and in a scientifically normative fashion.

There are a number of limitations to our study, including the fact that the number of students involved in the study was relatively small, the setting was small-group, and there was no longitudinal component to the study. Future efforts to add to this body of work would benefit from inter-rater reliability to strengthen the qualitative analysis. Further, assessment of the modular instructional materials in different settings (e.g. classroom demonstration, large scale lecture etc.) would be beneficial in supporting the modular nature of these materials.

Our approach, through analogy, is but one way to directly anchor students' prior knowledge in a relevant manner. So long as the relevant connections are made explicit between knowledge domains, it is arguable that novel and cutting edge content in the physical sciences need not be approached as niche topics outside of existing curricula. Rather, the tenants of fundamental principles can be utilized as motivation for the connection of concepts such that students create and maintain a rich, holistic viewpoint of science overall.

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