Misconceptions of Emergent Semiconductor Phenomena

by

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ABSTRACT

The semiconductor field of Photovoltaics (PV) has experienced tremendous growth, requiring curricula to consider ways to promote student success. One major barrier to success students may face when learning PV is the development of misconceptions. The purpose of this work was to determine the presence and prevalence of misconceptions students may have for three PV semiconductor phenomena; Diffusion, Drift and Excitation. These phenomena are emergent, a class of phenomena that have certain characteristics. In emergent phenomena, the individual entities in the phenomena interact and aggregate to form a self-organizing pattern that can be observed at a higher level. Learners develop a different type of misconception for these phenomena, an emergent misconception. Participants (N=41) completed a written protocol. The pilot study utilized half of these protocols (n = 20) to determine the presence of both general and emergent misconceptions for the three phenomena. Once the presence of both general and emergent misconceptions was confirmed, all protocols (N=41) were analyzed to determine the presence and prevalence of general and emergent misconceptions, and to note any relationships among these misconceptions (full study). Through written protocol analysis of participants' responses, numerous codes emerged from the data for both general and emergent misconceptions. General and emergent misconceptions were found in 80% and 55% of participants' responses, respectively. General misconceptions indicated limited understandings of chemical bonding, electricity and magnetism, energy, and the nature of science. Participants also described the phenomena using teleological, predictable, and causal traits, indicating participants had misconceptions regarding the emergent aspects of the phenomena. For both general and emergent misconceptions, relationships were observed between similar misconceptions within and across the three phenomena, and differences in misconceptions were observed across the phenomena. Overall, the presence and prevalence of both general and emergent misconceptions indicates that learners have limited understandings of the physical and emergent mechanisms for the phenomena. Even though additional work is required, the identification of specific misconceptions can be utilized to enhance semiconductor and PV course content. Specifically, changes can be made to curriculum in order to limit the formation of misconceptions as well as promote conceptual change.

This work is dedicated to my husband, Erik, for all of his guidance, support, and love and to my son, Oliver, for all of his kisses, smiles, and laughter.

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CHAPTER 1

EXECUTIVE SUMMARY

Recent emphasis on reducing greenhouse gas emissions has led to the development of numerous technologies that utilize clean energy, such as the energy that comes from the sun. Semiconductors are the materials that make up modern day electronics. The electrical conductivity of these materials permits them to conduct electricity under certain circumstances and not others. As such, they can be utilized for many applications like solar energy. Because semiconductor's electric conductivity is sensitive to light, these materials form the basis for photovoltatics (PV). PV represents a class of semiconductors that convert the sun's energy (light energy) into power for human use. PV represents an interdisciplinary field (a field made up of the disciplines of materials science, physics, electrical engineering, etc.) that has grown an average of 20% for the last twenty years. To meet this growth, ample incentives exist to enhance educational practice in the field (Department of Energy, 2011). However, semiconductors have many unique properties that make them difficult to understand and educators may not be aware of the learning barriers that exist for PV (Nelson, Brem, Husman, Bowden, & Honsberg, 2011), barriers that could limit future growth in the field. Although education researchers have defined many barriers to student learning, the study of misconceptions has become particularly relevant for scientific phenomena (Carey. 1986).

Misconceptions are incorrect understandings of scientifically held conceptions (Vosniadou, 1994). Students develop misconceptions because of how they construct knowledge based on their perceptions of the world around them (Clement, 1982) and sometimes through instruction (Nicoll, 2001). Once formed, misconceptions can become cemented into learners notions of the physical world (Sinatra, Brem, Evans, 2008) requiring significant time and effort to be overcome (Dole & Sinatra, 1998). For the field of semiconductors, misconceptions have been identified related to topics of diffusion, current, and doping, for example. Research has not been done to look at misconceptions that are learning barriers to student understanding of PV.

Recent research in learning science has focused on students misconceptions about emergence, a particular type of complex system. Emergence represents a class of phenomena that have certain traits; the interactions of the agents in the phenomena aggregate and form a self-organizing pattern. This pattern emerges from the system and can be seen at a higher level. Examples of emergence include traffic jams and flocking geese (Johnson, 2001). For PV, emergence plays a role in the electron conductivity, current, voltage, and power generation in solar devices. Misconceptions about emergence represent misunderstandings of how emergent systems work and the features that characterize them (Jacobson, 2001; Chi, 2005). Misconceptions about emergence have been observed in emergent phenomena such as diffusion (Chi, 2005) grain growth in materials (Blikstein & Wilensky, 2009), slime molds, flocking geese, foraging ants (Brem, Sinatra, Stump, Reichenberg, & Heddy, 2012), and ants, traffic jams, slime molds, and wolf-sheep predation (Jacobson, 2011). Even though prior studies have identified emergent misconceptions in engineering phenomena (e.g. grain growth of materials (see Blikstein & Wilensky, 2009)) existing research studies have not considered emergent phenomena in semiconductors and PV.

Three emergent phenomena represent fundamental mechanisms that are inherent in the Photovoltaic effect (the process of converting the sun’s light into energy) (Honsberg and Bowden, 2010). They are *diffusion*, *drift* and *excitation*. Diffusion describes the random movement of electrons as they move from areas of high concentration to low concentration. Drift captures the mechanisms of electrons moving in the net direction opposite of an electric field. Drift and diffusion are domain-general semiconductor mechanisms. Excitation, a PV specific phenomenon, describes the process of electrons gaining energy from photons and participating in conduction.

The purpose of this study was to demonstrate the presence and prevalence of misconceptions students have about these three semiconductor phenomena (diffusion, drift, and excitation). Misconceptions were divided into two categories; general and emergent. General misconceptions represented misconceptions about the general mechanisms of the phenomena whereas the emergent misconceptions specifically considered faulty understandings of emergence. This study also looked at the similarities and differences between and among the misconception for the three phenomena. First, the research determined what misconceptions were present across all phenomena, and if they were related and how (i.e. were they related across all three phenomena or just two). Second, the study looked at the differences in the (both general and emergent) misconceptions across the three phenomena. In this case, for example, would certain misconceptions be observed for diffusion that were not observed for drift?

Forty one undergraduate engineering students participated in the written protocol study - providing written responses to questions that probed their understanding of a video simulation of diffusion, drift, and excitation. Participants watched a simulation of each phenomenon and then were asked open-ended and Likert-style questions. Participants' responses were coded and analyzed using written protocol analysis. Protocol analysis, as described by Ericsson & Simon (1985) can be used to gather information about a participant using an introspective approach, integrating both qualitative and quantitative research methods.

An initial set of 20 participant responses were analyzed in a pilot study in order to determine if general and emergent misconceptions were present. Using these responses, a semi-open coding of the data (see Chi, 1997) was conducted to develop the codebook for this work. A total of 35 general misconceptions and eight emergent misconceptions were observed for the three phenomena. Furthermore, for the three phenomena, 80-90% of responses exhibited a general misconception and 30-60% of responses exhibited an emergent misconception.

For the full study, the author conducted another semi-open coding using all of the participants responses (N=41). Additional codes were found for both general and emergent misconceptions. Similar to the pilot study, the general and emergent misconceptions were prevalent in participants' responses, found in 80% and 55% of responses, respectively. The most prevalent general misconceptions had to do with misunderstandings of the attraction of negatively charged electrons to positively charged carriers or areas in the solar cell, the predictable nature of the phenomena, and incorrect notions of the rules of physics and the role these rules play in determining what occurs in the solar cell. The most prevalent emergent misconceptions were related to anthropomorphizing the electrons' actions in the phenomena, that there were specific causes that resulted in the pattern observed with the phenomena, and again, regarding the predictable nature of the phenomena. Qualitative analysis and theoretical similarities between codes informed the development of groups that were used to organize misconceptions that shared similar themes. Quantitative analyses, utilizing non-parametric techniques, demonstrated significant relationships between some of the misconceptions within the groups, but not all (both for general and emergent misconceptions). Additional relationships were explored between specific misconceptions (both general and emergent) that were found in each of the phenomena. Some misconceptions were significantly correlated with the presence of a similar misconception in other phenomena (e.g. the attraction misconception noted above was found in responses for both diffusion and drift, and was significantly correlated between the two phenomena). Differences were analyzed at the group level to note significant differences between the misconceptions formed for each phenomenon. Most differences were observed between either diffusion or drift and excitation for the general misconceptions, and across all three phenomena for emergent misconceptions. Lastly, responses were analyzed to determine if participants were primed for one phenomenon because they observed the phenomena in sequential order. Although priming was detected qualitatively, the quantitative analyses found priming to be negligible.

Results indicate that undergraduate engineering students hold both general and emergent misconceptions regarding semiconductor phenomena. These misconceptions were prevalent, being found in the majority of responses for both the general and emergent aspects of the phenomena. The prevalence of these misconceptions indicates that there are significant barriers that students can face when learning fundamental content in PV. General and emergent misconceptions also differed across the phenomena, indicating that learners have misconceptions that are likely phenomenon specific. In this case, considerations for misconceptions need to be addressed for each specific phenomenon. Even though this study sheds light on student misconceptions for PV content, it is not without limitations. Primarily, the misconception codes developed and the way in which these misconceptions were grouped and compared needs revisiting. Despite these limitations, the identification of these misconceptions could provide insight and guidance for educators regarding the struggles students have when learning about semiconductor science and PV content in their courses.

This dissertation is comprised of five chapters. The second chapter reviews all pertinent literature to lay out the impetus for this work, and then describes the research questions being addressed. The third and fourth chapters describe the methods used and the results observed for the study, respectively. The fifth chapter discusses the results, describes their implications, reviews the limitations of the work, and provides possible future research directions.

CHAPTER TWO

LITERATURE REVIEW

When people watch geese flock, or see ants forage, they typically espouse the idea that one leader is directing the actions of the others participating in flocking or foraging - the lead goose in the flying V, the queen ant in the nest. However, the pattern we observe these ‘agents’ (geese, ants) creating is not the result of one leader, but instead is due to the numerous and simultaneous interactions of all of the agents in an unpredictable chain of events governed by small and simple rules (Jacobson, 2001; Johnson, 2001). The pattern ‘emerges’ from the system (foraging, flocking), and these phenomena are, therefore, called emergent, a characteristic representative of complex systems.

Emergence is becoming highly relevant to teach because we are becoming more aware of how the world is increasingly governed by complexity (Jacobson & Wilensky, 2006). This is especially the case in engineering in which emergent phenomena are frequently encountered in undergraduate engineering curricula. For example, diffusion, a widely cited emergent process (Chi, 2005; Marek, Cowan, & Cavallo, 1994) is covered in environmental engineering, chemical engineering, electrical engineering, and other branches. Of concern is how to best teach the content. If students improperly conceptualize emergence, as has been shown in engineering (Blikstein & Wilensky, 2009) and in other domains (e.g. Jacobson, 2001), they can develop misconceptions (Chi, 2005). As is the case with any content area, misconceptions can be detrimental to learning (see Clement, 1982, Clement, 1993; McDermott & Shaffer, 1993; Picciarelli, di Gennaro, Stella, & Conte, 1991; Steinberg, Brown, & Clement, 1990; Streveler, Olds, Miller, & Nelson, 2003), and a great deal of effort must be exerted in order for these misconceptions to be overcome (Dole and Sinatra, 1998).

Research on misconceptions is not new. Numerous studies have been conducted to determine the types of misconceptions that exist in various topics of science (see Clement, 1982; Clement, 1993; McDermott & Shaffer, 1993; Picciarelli, di Gennaro, Stella, & Conte, 1991; Steinberg, Brown, & Clement, 1990) engineering (see Streveler et al., 2003), and emergence (e.g. Chi, 2005; Jacobson, 2001). Even though this research is being conducted, it is lacking applications within the field of engineering. Researchers in engineering education are aware of misconception formed from limited understandings of emergence (see Yang, Streveler, Miller, Slotta, Matusovich, & Magana, 2012), but few studies have been reported (see Blikstein & Wilensky, 2009 and Yang et al. 2012).

The purpose of this research is to demonstrate the presence and prevalence of misconceptions generally, in addition to those resulting through faulty understandings of emergence. This chapter will provide an introduction to the engineering content area for this work – a type of semiconductor. It will then review pertinent literature on misconceptions; included will be a description of what they are, how they are formed, how they impact learning, and then a review of literature on misconceptions for semiconductors. Lastly, the chapter will provide a discussion on what emergence is, describe misconceptions related to emergence, and how emergence relates to semiconductor engineering. By providing this background, the impetus for this work and the specific research questions being addressed will be discussed.

Semiconductors

The semiconductor manufacturing industry as a whole makes up 10% of the global GDP. Companies like Intel, which hold the largest share of the semiconductor manufacturing market in the world, are located in the US and as such, provide ample economic incentives for the US to enrich current educational traditions in the field (Semiconductor Industry Association, 2013). Semiconductor science has been taught in undergraduate engineering university programs for years, so the content covered and the level of depth has been well-articulated. The content taught has applications in material science, electrical engineering, and physics.

One area of semiconductor science is photovoltaics (PV) engineering. PV is the design, build, and set-up of PV arrays for the direct conversion of solar energy for human needs (Honsberg & Bowden, 2010). It is a rising field, having an average growth of 40% over the last twenty years (US Department of Energy, 2011). The field requires an interdisciplinary understanding of electrical engineering, materials engineering, semiconductor physics, and sustainability. Because great strides are being made to encourage the growth of interdisciplinary fields in engineering and because solar energy needs are increasing, both economically and environmentally (National Academy of Engineering, 2010), PV is poised to be an exemplar for interdisciplinary work for uses of solar energy.

The photovoltaic effect is the fundamental process in the harnessing and use of solar energy in PV devices. Quite simply, the photovoltaic effect is the conversion of the sun’s light energy into electrical energy. In the process, light energy in the form of photons is absorbed by a solar cell, a photovoltaic device. These solar cells are made of semiconductor materials, and thereby conduct electrons under certain conditions. When a photon is incident on the photovoltaic and is absorbed, electrons in the semiconductor lattice become excited, and participate in conduction. Because of the device design, a current and voltage are produced. There are many mechanisms that govern the production of current and voltage in a photovoltaic, and the overall photovoltaic effect (Honsberg & Bowden, 2010). One mechanism is transport, governed by diffusion and drift. Another mechanism essential to current and voltage generation in the solar cell is electron excitation. Overall, the design, research, and development of PV requires an understanding of key fundamental semiconductor mechanisms that govern the photovoltaic effect and the ultimate generation of power by solar cells. Failure to understand these mechanisms could result in poor engineering designs. The next section describes how misunderstandings (misconceptions) about fundamental semiconductor mechanisms could arise.

Misconceptions

Misconceptions can be detrimental to learning (see Clement, 1982; Clement, 1993; McDermott & Shaffer, 1993; Nicoll, 2001; Picciarelli, di Gennaro, Stella, & Conte, 1991; Steinberg, Brown, & Clement, 1990; Streveler et al., 2003), therefore, understanding what they are can add insight into ways in which educators can best facilitate learning, especially in PV (Nelson et al., 2011). Additionally, considerations for how they can be overcome, once they have been identified, can be critical for helping learners understand content (Vosniadou, 1994). The theoretical traditions in misconceptions research reflect the cognitive constructivist perspective which notes that students’ acquisition (or construction) of knowledge is dependent upon their prior knowledge and the role they play in perceiving and interacting with the world around them (Cobb, 1994). Knowledge is a memory representation that can take the form of schemata (Spiro, 1980), multidimensional packets of organized information in the mind (Jetton et al., 1995). As a learner acquires knowledge, these structures are enriched and restructured (Piaget, 1985). Misconceptions, also termed alternative conceptions, or naïve conceptions, occur when an incorrect knowledge structure has formed for a specific concept (Smith, Disessa, & Rochelle, 1993). Misconceptions are a novice’s incorrect or alternative representation for a scientifically held/correctly held conception – the correct knowledge structure (Vosniadou, 1994).

Cognitive psychologists have been looking at misconceptions for many decades and as a result, have identified numerous misconceptions about the workings of the physical world. For example, Clement (1982) showed the existence of a misconception regarding Newtonian motion and forces in novice physics students. These novices held a different view of what forces are acting on members of the system (in this case a coin toss) than experts on Newtonian physics. Novices believed that the upward force of the coin toss and the downward force of gravity were affecting the motion of the coin in the air, whereas the correct Newtonian expert conception would note that, when in motion, only gravity would be affecting the motion of the coin.

Research on misconceptions has been well-studied in science education, but it is lacking in other fields like engineering education. As far back as 1986, researchers in cognitive psychology have seen the need to connect with researchers in science education regarding work on misconceptions (see Carey, 1986). Advances in science education regarding misconceptions have benefited the field of engineering education (e.g. Clement (1982)'s work on misconceptions regarding Newtonian mechanics – required content for all engineering majors). However, specific content in engineering needs analysis for misconception formation, and as a result, calls have been made in the community to conduct this work. For example, after providing a discussion on how it is that people learn content in engineering, with misconceptions formation being identified as a learning barrier, Streveler, Litzinger, Miller, & Steif, (2008) go on to encourage future research in the field of engineering education to focus on misconception formation. Despite this, few studies have emerged.

Studies that have been conducted for undergraduate engineering regarding misconception formation have primarily focused on thermal sciences and circuits. It should be noted that research in engineering education has looked at misunderstandings of engineering content through the use of concept inventories (e.g., Steif & Dantzler, 2005). However, these inventories are not developed to identify misconceptions, and more so, do not include all misconceptions students can have for the specific concepts being assessed. As such, the work done on concept inventories will not be described in this literature review for misconceptions studied in engineering education. For thermal sciences, students have a hard time understanding the differences between steady state and equilibrium situations and the differences between energy and heat (Streveler et al., 2003). In circuits, students incorrectly describe current as being like the flow of water (Picciarelli et al., 1991). Also in circuits, students use the terms for Ohms law interchangeably (McDermott & Shaffer, 1993).

Within PV, minimal research has been done to examine what students do not understand in PV and how the curriculum should be designed to reflect these challenges (Nelson et al., 2011). However, research has been conducted to specifically look at misconceptions students have when learning about semiconductors (e.g., Chen, Pam, Sung, & Chang, 2013; Fayyaz, Iqbal, and Hashmi, 2005; García-Carmona, & Criado, 2009; Wettergren, 2002). Wettergren (2002) looked at students' conceptions of diffusion, holes, and doping in semiconductors, finding that students hold incomplete or incorrect conceptions of these phenomena. Misconceptions for diffusion were observed to be related to the movement of electrons as passing through a barrier, evening out as they move toward areas of larger concentration, or at a process level where electrons are moving in an out of the material. Participants incorrectly described holes as spots that accept or deliver electrons, the absence of ions, or as an electron state. Misconceptions on doping were noted as a layer placed on the semiconductor surface, or some sort of substance added to the semiconductor.

A study by Fayyaz et al. (2005) sought to identify the learning bottlenecks student have when learning about semiconductors. The study found that students struggle with content related to holes, doping, drift and diffusion current, and temperature effects. In the case of drift and diffusion current, the misconception is associated with confusion between conventional current and current resulting from drift and diffusion. Whereas, in the case of holes, doping, and temperature effects, the misconceptions observed were related to the underlying mechanisms of these processes (Fayyaz et al., 2005)

Garcia-Carmona and Criado (2009) took an in-depth look at the interaction of electron-hole pairs and doping. Their research indicated that students perceived the 'hole' as evidence of damage in the crystalline structure of the semiconductor material and that doping was a means to repair the material’s defect (Garcia – Carmona & Criado, 2009).

Chen and colleagues (2013) conducted a study to assess conceptual change of misconceptions for semiconductor concepts. As part of that work, they developed a set of misconceptions. Misconceptions were found in topics related to holes, drift and diffusion, and concepts associated with diodes and basic circuits. The researchers noted that the misconception of diffusion and drift was that there was confusion about these mechanisms, but no additional detail was provided about what that confusion meant (Chen et al. 2013).

Overall, these studies show that students develop misconceptions when learning about semiconductors. Despite the fact that none of these studies looked at the misconceptions student develop when learning about PV, many of the semiconductor misconceptions described included misunderstandings by their participants regarding the phenomena of diffusion and drift, fundamental mechanisms for semiconductors and PV . The identified misconceptions for diffusion and drift ranged from poor understandings of the mechanisms the underlie these phenomena (e.g. Wettergren, 2002), to confusion about how these mechanisms are tied to current (e.g. Fayyaz et al., 2005 and Chen et al., colleagues, 2013). The identification of the types of misunderstandings for these fundamental PV phenomena can serve as a launching point for this study.

Emergence

One class of phenomena that is gaining interest in misconception research is complex systems, especially those that are described as emergent. Interest has piqued because the world in which we live in is growing in complexity (Jacobson & Wilensky, 2006), and because some researchers argue that learning about emergence results in misconceptions that are hard to overcome (see Chi, 2005). Regardless, there is a need to look at misconceptions formed for emergence in PV because numerous mechanisms for semiconductors are emergent. This section will describe what emergence is, what the misconceptions of emergence look like in engineering, and how these misconceptions are formed.

Within complex systems, the smaller contributions and interactions of individual parts (agents) aggregate to create a self-organizing pattern (Wilensky & Resnick, 1999). This pattern occurs when random and unpredictable interactions result in an order that emerges that can be observed at a higher level (Jacobson, 2001; Johnson, 2001). Examples of emergence include ants foraging, geese flocking (Johnson, 2001), diffusion (Marek et al., 1994; Chi, 2005), and evolution (Sinatra et al., 2008). Another example would be a traffic jam. The cars carry out simple rules; drive the speed limit, keep a reasonable distance from the other cars, etc. However, after some time, these rules manifest into traffic jams because the cars interact randomly with one another and with the environment (i.e. the road), leading to a certain chain-of-events that ultimately results in an unpredictable traffic nightmare (Resnick, 1996).

All of the examples provided herein have certain characteristics that define them as emergent. Emergent phenomena have the following key domain-general features: synergism - the simultaneous and autonomous interactions that the agents undergo, irreducible – there is no pre-ordered specific progression or path that results in the observed pattern, non-linear - the current interaction events depend on the previous interaction events, novel - the features of the interactions occurring among agents cannot be seen within the individual agents' interactions, and unpredictable - the interactions that occur within the phenomena would likely not occur again (Brem et al., 2012).

As stated previously, the world is increasingly being governed by complexity (Jacobson & Wilensky, 2006). In order for humans to better understand the world, emergence should be taught and be taught in a way to dispel misconceptions. This is especially the case with engineering. For example, diffusion, a widely cited emergent process (Chi, 2005; Marek, Cowan, & Cavallo, 1994) is a topic covered in environmental engineering, chemical engineering, electrical engineering, and other branches. However, when students improperly conceptualize emergence, as has been shown in engineering (Blikstein & Wilensky, 2009) and in other domains (e.g. Jacobson, 2001), students develop misconceptions (Chi, 2005). Misunderstandings about diffusion in environmental engineering, for example, could result in a limited understanding of contaminant fate and transport in the environment.

Another example of emergence in engineering is grain growth of materials (Blikstein & Wilensky, 2009). Grain growth is an emergent process such that the simple rule of thumb – large grains grow and small grains shrink – does not hold up under all conditions because there is a random and unpredictable element of grain growth. Grain size is crucial in material design because it will ultimately determine when that material will deform. When engineers are developing design solutions using materials, simplifications using the conventional rule of thumb do not always hold up, and as such, could lead to poor design solutions where materials deform faster, or at lower thresholds than expected. Thus, within engineering, emergence must be accounted for in design solutions, such as the civil engineer designing traffic systems with traffic jams in mind, the environmental engineer working to clean up a contaminated site, and the materials engineer making decisions for materials for various parts.

Cognitive psychologists have begun to get a clearer picture of people's conceptualizations of emergence (e.g. Chi, 2005). For example, diffusion has already been characterized as an emergent process and research has shown that the learning of diffusion results in misconceptions (e.g. Chi et al., 2012; Marek et al., 1994). Chi (2005), Chi et al. (2012), Jacobson (2001), Jacobson et al. (2011), Hmelo-Silver & Azevedo (2006), and Hmelo-Silver, Marathe, & Liu (2007), have taken strides in developing theories related to how misconceptions of emergent phenomena are formed (see Table 1). This research is described below.

Table 1

Learning of Emergence Research Summary

Key Player	Misconception Description
Chi (2005) and Jacobson (2011)	Misconceptions arise as learners place emergent phenomena in incorrect ontologies (direct or clockwork)
Brem et al. (2012)	Misconceptions arise when learners incorrectly describe the features of emergent phenomena
(Hmelo-Silver & Azevedo, 2006; Hmelo-Silver, Marathe, & Liu, 2007)	Complex systems are defined using lower-order descriptions (structure) versus higher order descriptions (function and behavior)
Blikstein and Wilensky (2009)	Content is oversimplified and generalized so that non-emergent system mechanisms are applied to descriptions of emergent phenomena.

According to Chi (2005), emergent phenomena can be correctly conceptualized through emergent ontological attributes. Misconceptions result when the learner places the conception in an incorrect ontology. For example, an engineer may incorrectly solve a problem by believing the system is static when the system is in fact dynamic. The different 'kinds' (ontology) of systems would lead to different ontological characteristics that would direct the learner to solve and view the problem in different ways. Chi (2005) has shown that novices describe emergent phenomena within the direct (direct is indicative of a class of phenomena whereby the processes that underlie these phenomena are direct such as the heart pumping blood) ontological category. That is, the misconception arises because people incorrectly describe the emergent process using direct ontological attributes. This was the case with the learner who incorrectly described a dynamic problem within a statics ontology. Chi et al. (2012) reinforced this finding as part of their study related to conceptual change and emergence.

Jacobson (2001), and Jacobson and colleagues (2011) proposed the complex systems ontology framework. In this framework there are two types of ontologies, clockwork and complexity. Clockwork ontologies reflect how learners construct understandings for phenomena that have attributes of process and order (similar to Chi (2005)'s direct ontology), indicative of a misconception. Conversely, complexity ontologies are related to features of emergence. Novices have clockwork-type ontological attributes whereas experts have complexity-type ontological attributes (Jacobson, 2001), and experts use these complexity-type ontological attributes when problem solving with complexity topics (Jacobson et al. 2013). Also, a learner may have some attributes that reflect the clockwork ontology, and others that reflect the complex ontology (Jacobson et al., 2011).

Other learning and emergence experts have focused on the differences between novices and experts understandings of the content. Hmelo-Silver & Azevedo (2006), and Hmelo-Silver et al., (2007) have developed their structure-behavior-function (SBF) framework as a way to describe how learners come to understand complex systems. Their research has shown that novices can describe the structures of complex systems, but lack the higher-order behavior and function descriptions that experts hold for those complex systems. Therefore novices incorrectly describe the phenomena – a misconception.

Blikstein and Wilensky (2009) have similar findings to Hmelo-Silver & Azevedo (2006), and Hmelo-Silver et al., (2007), in that learners embedded in the content hold overly simplistic definitions of the phenomenon being explored. Blikstein and Wilensky (2009) conducted research to assess the effectiveness of their intervention at promoting understanding of emergence within the domain of materials science. Prior to the intervention, the participants held misconceptions on engineering content characterized as emergent. The participants incorrectly described the grain growth process in materials by oversimplifying what occurs (ignoring the presence of randomness) and using the rules-of-thumb prevalent in the field (already described on page 15).

Brem and colleagues (2012) describe misconceptions as resulting from incorrect understandings of the features of emergence. Misconceptions were noted when the participants provided inaccurate descriptions that are tied to the features of emergence for the phenomenon. For example, if a learner incorrectly describes the unpredictable feature of emergence as being predictable (they incorrectly describe the phenomena as something that they could predict happening a certain way), then they have a misconception about the content (Brem et al. 2012).

Conceptions and misconceptions of emergent phenomena have been demonstrated to be domain-specific (Brem et al., 2012; Goldstone & Sakamoto, 2003; Hmelo-Silver et al., 2007). Recall that the features of emergence are domain-general (see page 17) (Brem et al., 2012) such that the features of emergence (and the mathematical properties of emergence) are representative of the phenomenon in all domains (e.g. diffusion). Goldstone and Sakamoto, 2003, found that the emergent feature (randomness) did not transfer across different domains. Therefore, the learning of emergence is not necessarily domain-general unless learners can specifically abstract the information that they know from the emergent phenomena in one domain and transfer it to other domains (Goldstone & Sakamoto, 2003). As such, and similar to work in expertise, the understanding of the phenomena itself is dependent on the specific domain for that situation. Brem et al. (2012) has shown that within-domain knowledge can promote the understanding of complexity within that domain but not outside of that domain. For example, if a simulation program is programmed for diffusion of dye in water the likelihood for learning about diffusion of dye in water is enhanced, however, diffusion used with other agents in other scenarios is not. Therefore, when considering misconception formation for emergence, it should be assessed within a specific domain.

Conceptual Change

Once misconceptions about emergence are identified, steps can be made to correct them in the process of conceptual change. Misconceptions act as both barriers and cognitive bottlenecks for additional learning because they are resistant to change and as a result must be overcome for additional learning to occur (Dole & Sinatra, 1998). Learners believe they understand the material; their naïve theories of the physical world reinforce their perceptions of their accounts of concepts and processes for the phenomena at hand (Sinatra et al., 2008), so there is nothing to warn them that they have misunderstood what they have been taught (Evans, 2008). For example, Picciarelli et al., (1991) noted that even though the undergraduate students in their study had successfully passed (even with high marks), they still held misconceptions related to circuits in their physics courses. Once in place, misconceptions quickly become rooted and cemented into learners naïve theories of the physical world, and a great deal of time and effort must be exerted to overcome them (Sinatra et al., 2008). Furthermore, engaging in conceptual change which is necessary for overcoming misconceptions is extremely difficult and often fails (Dole & Sinatra, 1998).

As with all misconceptions, misconceptions of emergent phenomena are resistant to change (see Chi et al., 2012 and Jacobson et al., 2011). Chi (2005) takes this further by arguing that misconceptions of emergent phenomena are harder to overcome than other non-emergent misconceptions because they require a radical restructuring of knowledge from one ontology to the next (Chi, 2005) (e.g. a restructure from 'static' to 'dynamic') as part of her ontological shift model. According to Chi et al. (1994) and Chi (2005) conceptual change occurs when students make radical shifts from certain ontological categories to correct ontological categories – the ontological shift model. It is postulated that this lateral shift in knowledge is much harder to do because it requires an ontological shift, rather than a move within the ontology (Ferrari & Chi, 1998). Studies that have attempted to promote conceptual change of emergent misconceptions have had some success. Jacobson et al. (2011) observed an intermediate level of understanding of emergence; certain participants still held some novice ontologies, but also had developed expert level emergence ontologies after an intervention. Therefore, these participants went through certain ontological shifts (novice ontological attributes to expert ontological attributes), but not all. Chi et al. (2012) also observed positive conceptual changes for emergent misconceptions through an intervention.

In addition to Chi et al. (1994)'s ontological shift model of conceptual change, other models have been described in the literature, albeit not within the context of emergence. This literature review will only discuss six models, including the ontological shift model already described. Table 2 provides a brief overview of these six models of conceptual change.

Table 2

Conceptual Change Models

Model	Author	Mechanism for Change
Theory Change	(Carey, 1985)	Conceptual change occurs through the refinement and enrichment of naïve theories about the topic
Knowledge in Pieces	(diSessa, 1988)	Change occurs as the learner restructures/reorganizes the pieces of knowledge through greater levels of systematicity so that it more accurately represents the phenomena.
(Re)Subsumption	Ohlsson (2009)	As new theories are entertained to describe a concept, the learner subsumes a different theory without considering the conflict between the new and the old theory for the conception
Ontological Shift	Chi et al., (1994)	Misconceptions are overcome as learners re-categorize their conception from an incorrect ontology to a correct ontology
Argumentation	(Kuhn, 1991)	As learners construct arguments and engage in argumentative discourse for the correct conception, they adopt the correct concept because they see it as the truth
Cognitive Reconstruction of Knowledge	Dole & Sinatra (1998)	By having learners actively engage in their conceptual change process by having them read and reason about content that contrasts incorrectly and correctly held conceptions for a particular topic.

The first major model presented in Table 2 is the theory change model. In this model, conceptual change occurs when a learner adds to their naive models for a phenomenon until it is correct. It is similar to how science has evolved. Earlier theories of scientific phenomena – such as what electricity was – were once naïve. However, more information was collected and as a result, these naïve theories about electricity became more specialized, refined, and enriched into more expert theories of the phenomenon (Carey, 1985). The theory change model, therefore, likens conceptual change to the historical process of enriching naïve scientific models to more scientifically accurate models, similar to Kuhn’s paradigmatic shift model of scientific revolutions (Kuhn, 1962), in that in order for the change to happen.

Different than both the ontological shift and the theory model is the ‘knowledge in pieces’ model described by diSessa (1988). This model juxtaposes naïve theories or misconceptions with correct conceptions regarding how knowledge is organized in one’s schema for the phenomenon. A misconception or naive conception results from an inaccurate organization of the pieces of knowledge for that content, whereas a correct conception results from an accurate organization of the pieces of knowledge. Conceptual change occurs as the learner restructures the poorly organized knowledge into correctly organized knowledge representations (diSessa, 1988). diSessa has primarily applied this conceptual change model to content in physics (e.g. diSessa, 1993).

The resubsumption model describes conceptual change as a process of subsuming a new theory to replace a prior (misconception) theory for a concept. As learners acquire knowledge, they develop new theories to explain the phenomenon. The learner then opts for a new theory to replace the existing one without ever having to refute the previous theory (misconception). Different than all of the aforementioned theories, change is not a result of confronting the conflict that occurs between a correct and incorrect mental representation for the content, but instead is a change that occurs as learners chose between two or more theories that they have for the concept (Ohlsson, 2009).

As Vosniadou (2007) noted, conceptual change, is not just a cognitive process, it as an affective one as well – a ‘hot’ model of cognition. This goes further than the aforementioned ‘cold’ models of cognition building from previous work conducted by Pintrich et al. (1993) on a conceptual change framework coined intentional conceptual change. One intentional conceptual change model is argumentation. Argumentation describes how the construction of arguments for a specific concept can lead to conceptual understanding (Wiley & Voss, 1999). Key to this theory is the construction of an argument that the learner actually believes is the truth, a truth that reflects a more advanced epistemic belief about the products of knowledge being supported by claims and theories, and not as being concrete (Kuhn, 2001). By taking part in argumentative discourse, learners become more engaged in the content and possibly alter their epistemic beliefs. Therefore, through the process of argumentation, learners' view of knowledge can be altered such that their understanding of a concept evolves and develops from being a fact to a plausible explanation (Kuhn, 2003). Students' participation in argumentative discourse has been shown to enhance thinking skills and promote conceptual understanding (Wiley & Voss, 1999).

The Cognitive Reconstructions of Knowledge Model (CRKM) is another intentional conceptual change model (Dole & Sinatra, 1998). Vital to this model is that the learner has become aware that they have the misconception and are interested in correcting it. Specifically, if a learner has a more malleable belief for that conception, and is exposed to a rhetorically compelling (Dole, 2001) and personally meaningful alternative explanation for that conception, they are more likely to restructure their knowledge and replace their incorrect conception with the correct one. One approach to promote this has been the use of refutational texts, a mechanism for learners to consider the difference explicitly (Dole, 2000; Hynd, 2003). When learners engage in refutational texts, they are provided a description of the misconception, the misconception is then refuted, and then the scientifically held correct conception is provided (Hynd, 2001).

Broughton, Sinatra, and Reynolds (2010) found that refutational texts, if properly attended to by the participant, led to participants overcoming misconceptions using a CRKM approach (Broughton, Sinatra, & Reynolds, 2010). Intentionality has recently been considered in engineering education, where an intentional conceptual change framework was used to assess conceptual change related the learning of Newtonian physics (Ranellucci et al., 2012), albeit not using the CRKM or argumentation.

Only one of the aforementioned six models described here have been specifically analyzed as learners attempt to understand concepts of emergence for (see Chi et al. 2012; Jacobson et al. 2011). Even though other researchers have not explored students' understandings of emergence within certain conceptual change models, some studies exhibit undertones of some of the other models described here. Blikstein and Wilensky (2009) incorporate facets of the knowledge in pieces model into their research regarding how students learn certain materials engineering phenomena. Furthermore, Jacobson et al. (2011)'s research has nuances of both an ontological shift and an epistemic beliefs revision perspective. Therefore, their research reflects aspects of Chi et al (1994) ontological shift model and the Kuhn (2001) argumentation model.

One characteristic that ties nearly all of these models together is that the learners have to become aware that there is a conflict between what they think they know about that concept and what the correct conception is. The ontological shift, knowledge as pieces, and theory change models describe the presence of conflict arising as the learner constructs knew knowledge. Specifically, for the theory change model, this conflict occurs as the learner adds to their existing knowledge and discrepancies exist between the theory they've created for the concept and the new theory (Carey 1985). Like scientific debate, the learner then must go back and forth to rationalize what is correct and what is incorrect between the theories. For the ontological shift and knowledge in pieces models, the conflict arises as the learner attempts to describe the concept using the knowledge representation they have for that concept and dissonance occurs (Chi et al., 1994; diSessa, 1988). Differently, the argumentation and CRKM theories provide a more specific mechanism for conflict to be recognized and furthermore, for that conflict to be addressed. These models don't necessarily describe why the conflict arises, but instead focus on where the conflict occurs and how to correct it. The CRKM uses rhetorically compelling messages, possibly through refutational texts (Hynd, 2001), to bring both the conflict to the attention of the learner and then a platform for the learner to actively engage with the correct conception. Whereas, with argumentation, the conflict arises as the learner engages in argumentative discourse and in the process of constructing an argument based for the concept (Kuhn, 2001). Of these five models only one model, resubsumption, indicates that conceptual change is possible without the learner becoming aware of the conflict between their misconception and the correct conception (Ohlsson, 2009).

Only two models described are considered more 'hot' models of cognition; argumentation and the CRKM. Not all conceptual change experts believe that intentional ('hot') conceptual change is needed for conceptual change to occur. In fact, some have even argued that intentional conceptual change may not be required for the learning of all content and instead, may only be needed to learn content that is complex and difficult (Vosniadou, 2003). The complexity of emergence and the arguments made that emergence can lead to the formation of robust misconceptions (see Chi, 2005), provides justification for considering conceptual change with intentionality in mind. Argumentation does not specifically focus on the motivational aspects required for conceptual change to occur but instead focuses on the role of epistemic beliefs (Kuhn, 2001). The CRKM features the role that engagement plays in the conceptual change process, and includes additional features such as whether or not the material is personally meaningful to the learner or if the learner is dissatisfied with their understanding for the concept (Dole & Sinatra, 1998). Even though cold conceptual change models (resubsumption, ontological shift, knowledge in pieces, and theory change) are useful for capturing the cognitive processes involved for conceptual change to happen, they may not shed light into why conceptual change is so hard to occur (Dole and Sinatra, 1998). Even though Chi et al. (2012) documented positive conceptual change of their participants as they overcame misconceptions of emergence, the ontological shift model is a cold conceptual change model and doesn’t reflect the role that affect can play in conceptual change.

Overall, the theory change, ontological shift, and resubsumption are similar because they describe change as a shift from one naïve theory to another more expert level theory within a cold conceptual change framework. The knowledge in pieces model does not focus on the theories of knowledge but more so on how the knowledge needs to be reorganized. But, like the ontological shift and theory change models, the knowledge in pieces model overall describes conceptual change as a restructuring of knowledge from novice to expert representation. The resubsumption theory is also a cold conceptual change model, however, unlike the other cold conceptual change models, it does not require the learner to acknowledge that there is a conflict between the misconception and correct conception. The CRKM and argumentation model share some unique similarities; both include intentionality and both focus on providing tools that can promote conceptual change, not just model the cognitive processes. All of these models provide insight into possible modes for conceptual change that could be potentially used to describe and possibly encourage learners as they overcome misconceptions for emergent semiconductor phenomena.

Emergent Phenomena for Photovoltaics

Building from the limited research on emergent misconceptions in engineering education, this study examines misconception formation in students' understandings of PV semiconductors. Three different fundamental emergent processes were chosen for exploration of misconceptions (general and emergent) for this study because they are fundamental topics covered for undergraduate engineering students. The three phenomena, diffusion, drift, and excitation, are not just PV specific; they are fundamental processes for understanding semiconductors in general. These phenomena are taught in materials science, electrical engineering, and physics degree programs. Researchers have already described how students have limited understandings of both diffusion and drift (e.g. Chen et al., 2013; Fayyaz et al., 2005; Wettergren, 2002). That work has not been extended to consider excitation, and has not considered drift and excitation in terms of emergence.

Diffusion is an electron transport process whereby electrons move from areas of high concentration to low concentration as a result of the interactions of the electrons. Diffusion in PV systems involves carriers, the electrons and the holes that participate in conduction when sunlight is incident on the device. For the purpose of explanation, the focus will be just on electron carriers. Electron carriers are generated in large quantities near the surface of the solar device, where the majority of sunlight is absorbed, exciting electrons to participate in conduction. The electron carriers *appear* to move in a net direction from this area of high concentration of electron carriers toward areas of lower concentration of electron carriers within the photovoltaic (Honsberg & Bowden, 2010), see figure 1. The movement is *actually* the result of the small but additive effects of the electron carriers interacting with each other, randomly colliding and producing that pattern.

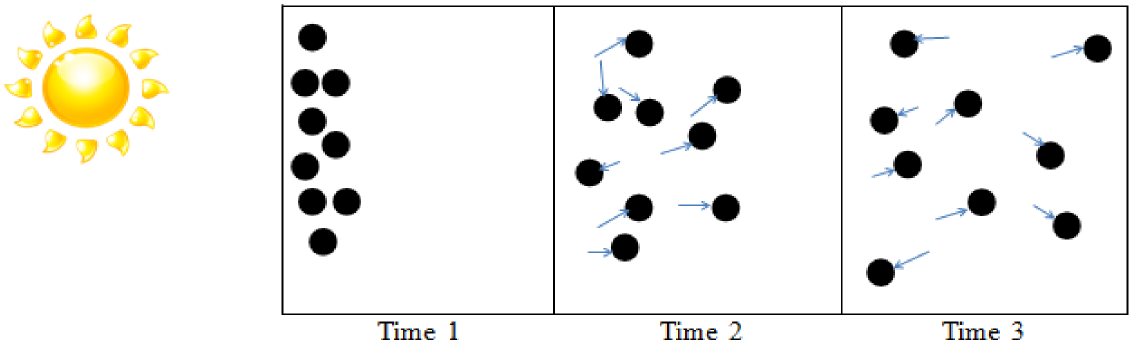

Figure 1: Net Diffusion Movement of Electrons in a PV device. Electrons are represented as black dots inside a solar cell. The arrows indicate the movement of the electrons.

A potential emergent misconception students may have regarding diffusion is that the movement of electrons is due to the concentration gradient between the two areas driving the movement. This has been observed in similar work on diffusion in a different domain (Marek et al., 1994). For emergence, Chi (2005) notes that students incorrectly describe the process of diffusion as being direct, whereas Chi and colleagues (2012) take it a step further, stating that the misconceptions are part of the direct schema. As such, in

Chi (2005) and Chi et al. (2012), the participants' state that the agents are carrying out specific and direct functions that result from some causal action (a misconception).

In the process of drift, electron carriers move in a certain net direction, opposite to the applied energy field placed on the device. Similar to diffusion, electron carriers move in a certain net direction due to random motion. During electron movement however, when electrons collide with other electron carriers, the net movement of that electron carrier is made up of two vectors that impact the net direction. The first vector is the random vector and the second is the energy field vector, see figure 2. The movement of electron carriers is the result of both the random additive effects of electrons interacting, and the energy field.

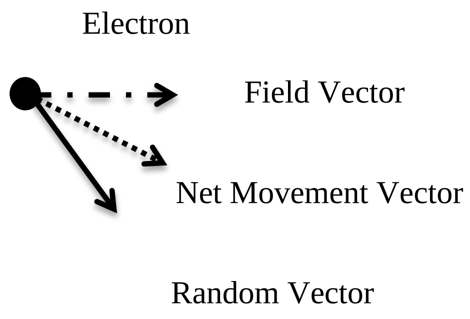

Figure 2: Movement of Electron due to Drift

Therefore, drift is similar to diffusion with one additional rule acting on the system. Recall that previous studies have shown that students develop misconception regarding drift (e.g. Fayyaz et al., 2005; Wettergren, 2002). No research on emergent misconceptions has considered drift. However, building on what has been observed with diffusion, it can be postulated that learners could describe a direct causal factor (the energy field) for electron movement.

Excitation, a PV specific phenomenon, occurs when an electron becomes excited into the conduction band when a photon is incident on the device. The photon (if it has enough energy) excites the electron by freeing it from its bound atomic state. The electron will jump from its bound atomic energy state (valance band) to a higher energy state (conduction band), allowing it to move freely about the semiconductor material lattice. Once the electron is in the conduction band, it can participate in conduction, thereby being a part of solar cell's current. This is a random process, and as such, can be characterized as emergent. No research has considered how students conceptualize excitation, particularly within the context of emergence.

Misconceptions regarding diffusion, drift, and excitation can have major implications on content being taught that builds from these foundational concepts. Recall the 'hole' misconception observed in the study by Garcia-Carmona and Criado (2009). The 'hole' misconception created a learning bottleneck such that it prevented adequate understandings of related and higher-level content (e.g. doping). In the case of the three phenomena being studied here, if the learner develops misconceptions regarding diffusion, then they will have already developed a misconception regarding drift. At a higher level, misconceptions of drift and diffusion could lead to misconceptions regarding the transport mechanisms in a solar cell, and ultimately misconceptions for current and voltage generation. Similarly, if learners have a limited understanding of how and why electrons can gain enough energy to move freely about the material, they could develop faulty representations about the impact that a photon has on the photovoltaic device. This alone could lead to misconceptions regarding current and voltage generation in a solar cell. Overall, misconceptions regarding diffusion, drift, and excitation could manifest into misconceptions at the solar cell power generation level and their ultimate design, build, and manufacturing.

Research Objectives

A review of literature indicates students develop misconceptions through their interactions with the physical world, through instruction, and as they rationalize what they have seen with what they have learned (see Clement, 1982, Clement, 1993; McDermott & Shaffer, 1993; Nicoll, 2001; Picciarelli, di Gennaro, Stella, & Conte, 1991; Steinberg, Brown, & Clement, 1990; Streveler et al., 2003). Also, a review of literature suggests that learning emergence can result in the formation of misconceptions (see Blikstein and Wilensky, 2009; Brem et al., 2012; Chi, 2005; Chi et al. 2012; Jacobson 2001; Jacobson et al. 2011). Even though research on misconceptions (see Streveler et al., 2003) and emergent misconceptions in engineering has been conducted (see Blikstein and Wilensky, 2009; Yang et al., 2012), research in these topics are limited in depth and scope in engineering education. Misconception research has considered the types and prevalence of general misconceptions students have related to semiconductor science (Chen, Pam, Sung, & Chang, 2013; Fayyaz, Iqbal, and Hashmi, 2005; García-Carmona, & Criado, 2009; Wettergren, 2002). This research shows that learners come away with misconceptions related to numerous fundamental concepts - diffusion and drift being among them. Even though misconception research has been conducted with semiconductors, the misconceptions described do not consider the emergent features of the phenomena. Certain semiconductor (PV) phenomena exhibit features of emergence – namely diffusion, drift, and excitation. Research has described emergent misconception formation related to diffusion in other contexts (see Chi, 2005, Chi et al, 2012; Marek et al., 1994), but not related to drift and excitation in the photovoltaic effect.

Therefore, the purpose of this research is to determine the misconceptions formed related to three PV phenomena that exhibit features of emergence – diffusion, drift, and excitation. This research is meant to add to the limited work in engineering education on misconceptions as a whole, and to make recommendations for future curricular enhancements to the field of PV. This study aims to:

1. Determine what the general misconceptions are students have regarding diffusion, drift, and excitation.
2. Determine what the emergent misconceptions are students have regarding diffusion, drift, and excitation.
3. Assess the prevalence of both types of misconceptions in order to grasp the potential scope of the issue in semiconductor/photovoltaics engineering.
4. Determine the relationships between the different misconceptions within the phenomena and across the phenomena.
5. Determine the differences in misconception formation across the three phenomena.

It is predicted that participants will have misconceptions about diffusion and drift (as already observed in existing semiconductor misconception literature, (e.g. Fayyaz et al., 2005), and for excitation. Additionally, it is predicted that participants will hold misconceptions for the emergent features of these three phenomena, building from previous research done on diffusion (e.g. Chi, 2005). Consistent with the literature (e.g. Brem et al., 2012), it is predicted that the different general and emergent misconception themes that emerge from the analysis will occur at different frequencies within and across the different phenomena.

CHAPTER 3

METHODS

Participants

Participants were recruited from three different level-one engineering circuits courses at a large Southwestern University in the United States. A level-one circuits course was chosen because it assumes enrolled students have a basic understanding of physics and have been previously exposed to concepts related to electricity and basic material properties. A total of 41 engineering undergraduates participated in the study, receiving $30 each in compensation. Participants consisted of 33 males and eight females. The participants in this study had taken at least one physics course (One course = 10%, two courses = 76%, three courses = 10%, and four courses = 4%). The majority of participants had just completed their second physics course on electricity and magnetism. A minority of participants had taken a materials science course or courses (29%). Participants included students majoring in numerous engineering disciplines, with mechanical and biomedical engineering being the largest majors (aerospace = 17%, biomedical = 27%, chemical = 2%, computer science = 2%, electrical = 12%, industrial = 8%, and mechanical = 32%). Participants primarily described themselves as being in their second year of undergraduate school (freshman = 5%, sophomore = 80%, junior = 12%, and senior = 2.4%), and, of those that reported it, the overwhelming majority were between the ages of 18 and 24 (18-24 = 90%, 25-34 = 3%, and 35-44 = 6%).

Materials and Procedure

The current study employed a protocol whereby participants were asked to provide written responses to questions that probed their understanding of a simulation task for each of the three emergent phenomena operationalized in previous chapters: Diffusion, Drift, and Excitation. Similar procedures have been recommended and described for cognitive research aimed at gaining insight into participants' knowledge representations (e.g. Chi, 1997). The participants completed an instrument containing open-ended and Likert-style items related to the simulation. The instrument was adapted from the instrument described in Brem and colleagues (2012) study of misconceptions related to emergence. The Brem et al. (2012) instrument was developed to probe students conceptions regarding the emergent phenomena of slime molds, flocking geese, and foraging ants. The adapted instrument used here was tailored such that the questions posed were specifically related to the semiconductor/PV emergent phenomena previously noted. However, the simulation and instrument formats, and types of questions used were modeled from Brem et al. (2012). The specific elements of the instrument used here are described below in more detail.

In the protocol, participants were asked to view a simulation and then answer questions related to what they saw. Two versions of the survey were developed. Version A was different from Version B in the sequence of observed simulations and the associated questions. Version A began with Diffusion, followed by Drift, and then finished with Excitation. Conversely, Version B began with Excitation, followed by Diffusion, and then finished the survey with Drift. The same demographic questions, in the same sequence, were asked at the end of both survey versions. Two versions of the survey were developed in order to account for priming effects, or the possibility that previous simulations may impact observations in subsequent simulations. The ordering had Diffusion always followed by Drift because it was anticipated that the participants may become confused if Diffusion was used after Drift, and therefore, may respond within a Drift framework. Recall that Drift is similar to Diffusion but has one additional rule acting on the system. The survey took approximately 90 minutes to complete.

Each phenomenon was illustrated using Adobe Flash Professional CS6, and each simulation was video-captured using Camtasia 8.0, so that the same run could be shown to all participants. A screenshot of each of the simulations can be found in Appendix A. A key was used to identify all of the important elements in the simulation so that the participants could use it as a reference continuously when viewing the simulations. No explanatory text was included. Also, no unnecessary agents were included (e.g. holes) so as to not distract the participant and allow them to focus on the specific important agents being represented in the simulation. The agents were represented by icons that captured the basic appearance of the real entity (e.g. an electron was depicted as a sphere). The participants were told before the simulation began what icons would be used, and what they would mean. Further, participants were told what it was that they were viewing in each simulation such that they were aware that they were looking at a photovoltaic, and were drawn towards specific actions that would occur (specifically in the Drift simulation). This was done to ensure that the participants would focus on relevant events and start the simulation with the same prior knowledge about the simulations. Instructions can be found in Appendix B.

Each simulation lasted approximately 90 seconds. Participants viewed the entire simulation two times before proceeding to the survey questions. There were a total of five questions for the Diffusion simulation module, seven questions for the Drift module, and six questions for the Excitation module. The number of questions varied because of the nature of each of the simulations. For example, in the Drift section, certain questions were asked twice, once for when the electric field was on and once for when the electric field was off. Broad questions were used first in each of the three protocol sections (e.g., #1 and #2 below), moving to more specific questions that captured key aspects of emergent phenomena (e.g., #3 below). All questions can be found in Appendix B. The questions were designed to be as similar as possible across modules, substituting in the appropriate phrases:

1. Describe the movement of the electron(s) in the solar cell/when the electric field is on and off/during each photon event. Use as much detail as possible.
2. Based on your knowledge of physics and electrons, what determines how and where the electrons move in the solar cell/when the electric field is on/off/ during each photon event? Use as much detail as possible.
3. Imagine an electron, in a similar solar cell, under the same scenario, moving again. How similar do you think the movement of the electron would be to what you observed in the video/when the electric field is on/off/ during each photon event?

Participants were instructed to write as much as possible when responding to the questions, giving as much detail as they could provide. All questions related to the content required a response, and participants were not able to go back to change their responses. Questions were piloted on experts in semiconductor science and experts in cognitive science. Specifically, three PhD candidates studying PV and two PhD students conducting research in cognition and emergence were recruited. The PV experts provided feedback about the simulations (the keys and the phenomena) and about the correct use of language for the questions. The experts on cognition and emergence provided feedback about the emergent features being captured in the simulations and to ensure that the questions were probing for the participants' mental representations of the phenomena. Feedback on the overall survey, and their actual question responses were taken into account and minor changes were made; some of the language was altered in the survey questions and more demographic questions were added (specifically, questions related to prior coursework in materials science). The final survey was made up of 39 questions; one consent to participate in the study question, 28 questions related to the simulations, and 10 demographic style questions. The demographic questions included questions related to gender, major, and age, as well as questions specifically aimed at ascertaining the highest level of physics and materials engineering coursework each individual participant had successfully completed. All demographic-style questions can be found in Appendix B.

Coding and Analysis

Pilot Study

Coding: For the pilot study, data from half of the original population (n = 20) was analyzed to determine if the protocol would provide the data needed to address the intended research goals. Specifically, the author wanted to confirm that the protocol was capturing both general and emergent misconceptions the participants had for the simulations in their responses in the instrument. The characteristics of these participants were consistent with the overall sample population described previously.

The participant responses were analyzed using written protocol analysis (see Ericsson & Simon, 1985). Protocol analysis, as described by Ericsson & Simon (1985) can be used to gather information about a participant using an introspective approach, integrating both qualitative and quantitative research methods. This information-processing approach allows researchers to look at a person's cognitive processes, specifically allowing for key information about the knowledge individuals have for the specific protocol task to come out of their written reports. Ericsson and Simon argue that by asking participants to think aloud (in this study, participants are asked to write down their thoughts), their conceptions can be better observed because it relies on them attending to information in their short term memory. Building from Ericsson and Simons (1985) work, Chi (1997) describes the verbal analysis approach which is a methodology aimed at better focusing on individual representations for the content. Unlike Ericsson and Simon (1985), Chi (1997)'s verbal analysis approach focuses less on the processes (typically demonstrated through problem solving tasks) and more on the knowledge representation for the content for the task. For this study, because the intent was to demonstrate the knowledge representations for the three phenomena, the analysis of the protocols followed Chi (1997)'s approach. The written responses in this study were used to gather information regarding how the participant mentally represents the content at hand – in this case diffusion, drift, and excitation.

The verbal analysis method utilizes both top-down (deductive) and bottom-up (inductive) coding (Chi, 1997). From a deductive perspective, the questions used in the protocol are typically framed using existing theory. As such, some of the codes observed in the participant responses are oftentimes framed within that particular theory. When approaching the protocols inductively, additional codes and hypothesis can emerge from the data outside of existing theory, similar to what is described by grounded theory research methods (see Charmaz, 2006). As such, this method attempts to capture as much information from the protocols, guided by existing theory or not (Chi, 1997).

For the current study, coding was conducted using the verbal analysis framework summarized by Chi (1997). To develop the specific codebook used for this work, the author conducted a semi-open coding of the data (using just data from Version A of the survey) in order to develop and capture the codes that emerged from the data. Coding was done first for the general misconceptions, guided by the studies described in the literature review where misconceptions about the *general mechanisms of a semiconductor* were identified (see Chen et al. 2013; Fayyaz, Iqbal, and Hashmi, 2005; Wettergren, 2002). Coding was then done for the emergent misconceptions, guided by prior research on emergence, specifically by the Brem et al. (2012) study of emergence. Codes were organized as general misconception codes and emergent misconception codes.

For the general misconceptions codebook, the author first looked for the themes described by Chen et al. (2013), Fayyaz, Iqbal, & Hashmi (2005), and Wettergren (2002) that matched or were similar to themes that were emerging from the participant responses. Themes in the Chen et al. (2013), Fayyaz, Iqbal, & Hashmi (2005), and Wettergren (2002) studies that were not similar to or easily mapped on to the themes observed here were not included. Once these comparisons were made, the author went back through the data, allowing for additional themes/codes to emerge that were not already being captured from the initial codes. Through the process, it became clear that unique codes were needed for each phenomenon for the general misconceptions scheme because general misconceptions were observed to be specific to the phenomenon.

For the emergent misconceptions codebook, a similar approach was taken except that emergence misconception themes emerging from the data were compared with the Brem et al. (2012) codebook and the features that define emergence that were described in Chapter Two. The emergent misconception themes that were found were not unique to each phenomenon, and as such, general codes were developed that were used across all three phenomena.

General Misconception Codes: A total of 10 general misconception codes emerged from the Diffusion phenomenon responses, 14 from the Drift phenomenon responses, and 11 from Excitation phenomenon responses. The misconception code themes were validated using an expert in semiconductor science and photovoltaics. The author met with the subject matter expert and discussed each of the themes that emerged from the data. Any themes that the subject matter expert felt were not indicative of a misconception (i.e. the response was indicative of a correct conception) were removed from the codebook.

During coding, the author looked at each participant's response for each question. If the response exhibited one of the general misconceptions codes, it was coded as "GM" or general misconception. Alternative codes included U - "Uncodable," or A – "Absent of Misconception." Uncodable responses included all responses that were either missing or unreadable. Absent of misconception responses included those that could not be coded as a general misconception or uncodable, indicating that a misconception was not present in the response. Absent of misconception was used instead of correct conception because a lack of misconception does not necessarily mean a correct representation (the text could be off topic). For example, one participant response for the question asking why the electrons move for the Diffusion simulation was:

“Based on my knowledge of physics and electros, what determine how and where the electrons move in the solar cell is reproduction”

In this case, the participant is talking off-topic by using the term reproduction.

To assess inter-rater reliability, the codebook and 10 protocols were given to a second researcher, who also has a background in engineering and education. The codebook included a list of guidelines for the researcher to follow when coding, in addition to a description of the three phenomena and what the correct conception should look like for each – Diffusion, Drift, and Excitation. These instructions and the codes can be found in the codebook in Appendix C. Prior to coding, the researcher and the author met to discuss the coding process. This researcher had no contact with the author during their coding. The researchers applied the codes with 0.92 agreement. The author and the second researcher met to discuss and resolve any disagreements. For example, some questions in the protocol specifically asked about the movement of the electrons being random. The second researcher was only applying the ‘random-like’ misconception codes to those specific questions, even if a participant’s response to another question exhibited a ‘random-like’ misconception code. See Table 2 for examples of ‘random-like’ codes. After discussing this, the author and the second researcher agreed that the presence of this theme in any participant response should be coded as a GM, regardless of whether or not the response was specifically for the question about randomness. The final codes were then recoded into dichotomous variables such that general misconceptions were coded as a one, and absent of misconceptions were coded as a zero. Analyses are described later on.

The general misconception codes and descriptions can be found in Appendix C and are summarized in Table 2. Because the purpose of the pilot study was not to determine the type and frequency of each general misconception for the three phenomena, these codes merely were used to indicate the presence of a general misconception so as to justify additional work on the protocol analysis (the full study).

Table 3

General Misconception Codes

Diffusion	Drift	Excitation
Fields	Explicitly Fields	Attractive
Charges	Direction	Incorrect Excitation
Material Properties and Device Configuration	Charges Present	Fields
Predictable	Charges/Electric Field Not Present	Material Properties and Device Configuration
Random Atomic	External	Predictable
Not-Random	Predictable	Movement
Not Rules	Random Atomic	Incorrect Movement
Rules	Not Random Electric Field	Rules
Volition	Not Random	Incorrect Rules
	Random	Concept of Energy
	Rules	Volition
	Not Rules	
	Volition	

As shown in Table 2, some codes were very specific to the phenomenon (for example, the Movement code was only found in the Excitation phenomenon question responses). However, other codes were present across two or all three phenomena, such as fields, predictable, rules, incorrect rules, and volition. Codes used across phenomena, however, were still characterized as having arisen in the context of a specific phenomenon, as described above. The following table, Table 3, represents one code and associated descriptions and exemplars from each of the phenomena. All exemplars used in the codebook can be found in Appendix C. Even though the purpose of the pilot study was not to consider specific misconceptions related to the three phenomena, these codes are provided here to indicate that general misconceptions were present in the participant responses.

Table 4

General Misconception Codes, Descriptions, and Exemplars

Phenomena	Code	Description	Exemplar
Diffusion	Random Atomic	Randomness of the electrons is associated with its movement around an atomic (path, orbit, cloud), not at a material level (when the electron is free)	“I know that electrons were once believed to follow a certain path around the nucleus of atoms or molecules, but now it is believed that they simply "float" around in an electron cloud, going any which way they desire.”
Drift	Charges Present	Refers to electron movement as being the result of either the attractive forces of a positive charge (sometimes referred to as proton), or the repulsive force of a negative charge (sometimes referred to as an electron) because like charges repel and opposite charges attract	“The only determination of the movement of the electrons when the electric field is off is the forces due to the other electrons. An electron that is not close to others at any moment in time will continue to move in the direction it is headed. However, when it gets close to another electron, the forces between the two electrons will reflect them away from each other as they are both carriers of the same charge.”
Excitation	Concept of Energy	Energy is lost, gained, or created (it is not transferred) when the electron moves to a higher energy level and/or back down	“It seems that electrons moves during a photon event randomly, but it will move from a valence band to a conduction band by creating higher amounts of energy that it was not putting out before.”

Emergent Misconceptions Codes: After all responses were coded using the general misconception coding scheme, they were re-coded using the emergent misconception scheme. A total of seven general emergent misconception themes emerged from the data across all three phenomena. Similar to what was done with the general misconception codes, final codes for emergent misconceptions were validated by an expert on emergence. The emergent misconception codes and descriptions can be found in the codebook in Appendix C and are summarized in Table 5.

For analysis purposes, if the response exhibited one of the emergent misconceptions codes, it was coded as “EM” or emergent misconception. As with the case of the general misconception theme, alternative codes included U - “Uncodable,” or A – “Absent of Emergent Misconception.” “Uncodable” and “Absent of Emergent Misconception” were handled in the same way as they were for general misconceptions. The emergent misconception codes were used across all three phenomena because the literature indicated that the features of emergence are domain-general, and as such, emergent misconception codes were not phenomenon specific at a general description level. Because the pilot study was only intended to determine the presence of emergent misconceptions, all codes were included, such that codes that weren’t potentially represented in all three phenomena were still included in the code list.

Again, the coding scheme and a set of instructions were given to a second researcher to apply to half of the participants’ data (n=10) using the same procedure as for the general misconceptions. The researchers applied the codes with 0.97 agreement and any disagreements were resolved through discussion. As with the general misconceptions, final codes were recoded into dichotomous variables such that emergent misconceptions were coded as a one, and absent of misconceptions were coded as a zero. Analyses are described later on.

Because the purpose of the pilot study was not to determine the frequency and type of emergent misconceptions related to the phenomena, these codes merely were used to support the presence of an emergent misconception if present in the participant’s response. The following table, Table 4, represents each of the emergent misconception codes, and associated descriptions, and exemplars. The codes are provided here to indicate that emergent misconceptions were present in the open responses.

Table 5

Emergent Misconception Codes, Descriptions, and Exemplars

Code	Description	Exemplars
Non-cooperative	The electrons work together to create the pattern	“The Electrons moved in such a way that caused them to be uniformly distributed throughout the cell”
Goal-Directed	Describes the behavior or movement of electrons as being performed to meet a certain purpose or goal w/in associated with the emergence movement pattern.	“It’s rules based in the sense that if two electrons get near each other, they are going to want to move apart”
Reducible	The emergent properties are being accounted for at the level of the interacting electrons.	“Once put into motion, the electron moves to the boundary of the material, or until it comes in proximity of another electron that then causes a repulsive force causing the direction of the electron to change”
Centralized Control	Reference to a specific factor directing, leading, guiding, or having ‘bound’, etc. the electrons to carry out certain actions.	“they will go wherever the repulsive forces direct them towards”
Causality	Describe a causal direct factor for the observed macro pattern. Likely no mention of the emergent pattern resulting from the interactions of the individual electrons.	“Electrons will move in the opposite direction of the electic field. Therefore, the electric field was pointing from left to right because the electrons were flowing to the left. Electrons. Electrons flow from low potential to high potential.(- to +)”
Predictability	The specific electron movement will be similar/the same (not noting the overall pattern of electron/(s)) if the scenario were re-run.	“ if the conditions of the scenario are the same, then the electrons will behave similarly if not exactly the same as they did in the first animation”

Predictability Change	One large change in the system at the start will cause a large change in the system as a whole. One small change in the system at the start will cause small change in the system.	“Technically, I think that the electrons will move in exactly the same way as long as they are placed in exactly the same starting positions, if they are not placed in exactly the same starting position, then they will have a completly different movement pattern…”
Not-Random	Electron movement overall is considered not random – or is specifically states as such	“When the electric field is turned on, the electrons will move towards the positive side of the electric field so they will not be random. When the electric field is turned off, the electrons will indeed move in random directions since there is no force being applied to it.”

Analysis: Upon completion of the coding for both general and emergent misconceptions, a set of analyses were conducted to address the following specific questions:

1. Do the participants hold general misconceptions related to any or each of the phenomena, and if so, what is the frequency?
2. Do the participants hold emergent misconceptions related to any or each of the phenomena, and if so, what is the frequency?

Analyses were conducted using IBM SPSS statistical software in order to run basic descriptive statistics of the data to answer the above questions. The results of all of the analyses can be found in the following chapter.

Full Study

Coding: For the full study, data from entire population (N = 41) was used to address the research goals described in Chapter Two. In the full study, the codes for both general and emergent misconceptions were adapted from the codebook previously generated for the pilot study and from both the codebook created by Brem and colleagues (2012) and from the general misconceptions described in the literature about semiconductor phenomena (see Chen et al. 2013; Fayyaz, Iqbal, and Hashmi, 2005; Wettergren, 2002). Additional codes were added and existing codes were refined because the full study codebook was developed using both versions of the survey, using the entire sample population (N = 41). Similar to the pilot study, a general misconception scheme and an emergent misconception scheme was used.

As with the pilot study, coding was conducted using the verbal analysis framework summarized by Chi (1997). Using the pilot study codebook as a starting point, the author compared the codes that emerged for both the general and emergent coding schemes with the pilot study codebook. Any codes that were not captured by the pilot study codebook were noted and then compared to the *general semiconductor mechanism misconceptions* reported on in the literature (general misconception scheme) and the themes utilized in the Brem et al. (2012) codebook (emergent misconception scheme). Themes reported on in the literature (both general and emergent) that were not similar to or easily mapped on to the themes observed here were not included. Once a comparison to the themes previously reported on in the literature was made to the new codes, the author went back through the data, allowing for additional themes/codes to emerge that were not already being captured from the initial codes. Because emergence is a domain-general phenomenon, the misconceptions described in the literature provided a strong foundation for coding. Therefore, the majority of codes for the emergent misconception codebook were arrived at deductively. Conversely, the codes for the general misconception codebook were arrived at more inductively because little theoretical foundation was provided from the literature. As with the pilot study, unique codes were developed for each phenomenon for the general misconceptions scheme. The emergent misconception themes were not unique to each phenomenon so general codes were used across all three phenomena.

The first coding of the data considered only the codes related to the general misconceptions coding scheme in the codebook. A total of 16 general misconception codes emerged from the Diffusion phenomenon responses, 18 from the Drift phenomenon responses, and 21 from Excitation phenomenon responses. Some codes were similar across the phenomena, whereas others were not. As with the pilot study, themes were validated using an expert in semiconductor science and photovoltaics. However, only new codes or codes that were altered from those developed for the pilot study were validated by the PV subject matter expert.

During coding, the author looked at each participant's response for each question. If the response exhibited any of the general misconceptions codes, it was coded for that specific misconception. Alternative codes included U - "Uncodable," or A – "Absent of Misconception." Both were coded similarly to how it was explained in the pilot study.

To assess inter-rater reliability, the codebook and 14 protocols were given to a third researcher, who also has a background in engineering and education. Note that the researcher used for the full study was different than the researcher used in the pilot study. The codebook included a list of guidelines for the researcher to follow when coding, in addition to a description of the phenomena and what the correct conception should look like for each – Diffusion, Drift, and Excitation. These instructions and the codes can be found in the codebook in Appendix E. Prior to coding, the researcher and the author met to discuss the coding process. During this time, the author worked through examples with the researcher in order to make sure the researcher was applying the codes correctly. Once these examples were worked through, the researcher worked independently on additional examples, asking for help as needed, until the researcher felt prepared to code the protocols. This researcher had no contact with the author during their coding of the protocols. The researchers applied the codes with 0.85 agreement and any disagreements were resolved through discussion. As with the pilot study, disagreements had to do with codes not being applied to all responses (the third researcher was applying certain codes to certain protocol question participant responses). The final codes were then recoded into dichotomous variables such that each general misconception was coded as a one, and absent of misconceptions were coded as a zero. Uncodable was marked as an NA and treated as missing data, being excluded from the quantitative analysis. Analyses are described later on. The general misconception codes and descriptions can be found in Appendix D and are summarized in Table 5 for Diffusion, Table 6 for Drift, and Table 7 for Excitation.

Table 6

General Misconception Codes for Diffusion

Code	Description
Fields	Electron movement is the result of an electric field or a magnetic field
Other Factors Gravity	Electron movement is the result of other forces not already specified, specifically gravity
Other Factors Energy	Electron movement is the result of other forces not already specified, specifically in terms of energy.
Solar Prime	Use terms of photons, carriers, holes, energy levels, bands, and other solar cell descriptors/phenomena to describe electron movement
Charges	Electron movement is the result the attractive forces of a positive charge or the repulsive force of a negative charge.
MP&C	Electron movement is the result of the device, determined by the material's properties. This is a circuits perspective.
Amounts	Electron movement is the result of a concentration gradient.
Atomic	Confuse electron movement with bonding and overall atomic nuances (i.e. energy levels, orbitals, bands)
Random Atomic	Randomness of electron movement is described in terms atomic movement (path, orbit, cloud).
Random	Even though the electron movement is described as random, the justification for the randomness is incorrect.
Predictable	The electron movement (micro) will be similar/the same if the scenario were re-run.
Incorrect Predictable	When describing the movement of electrons as predictable, an incorrect justification for why is given.
Pattern	Electrons will move patternistically - until they are uniformly laid out, etc.
Not Random	Electron movement is considered not random.
Not Rules	There aren’t rules to explain electron movement.
Rules	Electron movement occurs based on the laws/rules dictated by physics.

* Note that MP&C is abbreviated or Material Properties and Configuration

Table 7

General Misconception Codes for Drift

Code	Description
Fields	Electron movement is the result of an electric field or a magnetic field
Direction	Same as Fields except the direction of the movement of the electron resulting from the field is incorrect.
Charges Present	Electron movement is the result of other forces not already specified, specifically gravity
Random Efields/Charges Not Present	If there is no electric field, Charges are not present, so the electrons will move randomly.
MP&C	Electron movement is the result of the device, determined by the material's properties. This is a circuits perspective.
Pattern	Electrons will move patternistically - until they are uniformly laid out, etc.
External	Electron movement can be influenced by the barriers of the cell or by where they are released
Solar Prime	Use terms of photons, carriers, holes, energy levels, bands, and other solar cell descriptors/phenomena to describe electron movement
Energy	Describe electron movement in terms of energy states, conservation of energy, or stable states
Predictable	The electron movement (micro) will be similar/the same if the scenario were re-run.
Random	Even though the electron movement is described as random, the justification for the randomness is incorrect.
Random Atomic	Randomness of electron movement is described in terms atomic movement (path, orbit, cloud).
Not Random Efield	Electron movement is considered not random, unless in the presence of an efield.
Not Random	Electron movement is considered not random.
Polarity	Confuse potential with polarity in terms of electric fields and electron movement.
Not Rules	There aren't rules to explain electron movement.
Rules	Electron movement occurs based on the laws/rules dictated by physics.
Incorrect Rules	Rules specified are incorrect.

* Note that MP&C is abbreviated or Material Properties and Configuration

Table 8

General Misconception Codes for Excitation

Code	Description
Charges	Photons, bands, field, or holes, will attract or repel the electrons.
Atomic vs. Bound	Do not understand the difference between bonded atoms and singular atoms in space.
Energy Vs. Physical	Overall notion that blends energy movement with a physical movement of electrons.
Incorrect Excitation	Electron moves to a lower energy state in the presence of a photon.
Incorrect Photon	Mechanism of photon is incorrectly described (in terms of wavelength and energy).
More Photons	More (many) photons dictate electron movement to the conduction band.
Fields	The photon creates a magnetic or electric field and movement occurs as a result of the e-field/m-field.
MP&C	Material conductance, properties, device set-up, etc. allow electron movement to conduction band.
Steady/Stable State	Electrons move until they reach a stable or steady state.
Bands	Incorrect understanding of bands in terms energy. Bands are considered distinct levels.
Within Band General	Incorrect description of the movement of the electron within the band.
Within Band Spot	Incorrect description of the movement of the electron within the band related to the electron finding its correct location.
Within Band Energy	Incorrect description of the movement of the electron within the band related to incorrect understandings of energy.
Movement	State that there is not electron movement unless there is an event or 'force' of any kind acting on the electron.
Incorrect Movement	Electrons will always move because of various forces.
Predictable	The specific electron movement will be similar/the same.
Incorrect Unpredictable	When describing the movement of electrons as predictable, an incorrect justification for why is given.
Other Factors	Electron movement occurs because of other factors not already described: gravity, concentration gradient, etc.
Rules	Electron movement occurs based on the laws/rules of physics.
Incorrect Rules	Rules specified are incorrect.
Concept of Energy	Energy is lost, gained, or created when the electron moves to a higher energy level and/or back down.

* Note that MP&C is abbreviated or Material Properties and Configuration

Certain codes were applied to the participant responses more than others (as will be shown in Chapter Four), and some codes were observed across two or more of the phenomena. A description of some of these specific codes is provided here in order to show how the general misconception codes were used to capture certain misconceptions

The Charges/Charges Present general misconception code captured the misconception that a charge was causing (through repulsion or attraction) the electron movement within the device. For Diffusion and Drift, the misconception was that the movement of the electrons was the result of the electrons repelling each other. For Excitation, the misconception was that the movement of the electron to the conduction band was the result of the photons, the bands, etc. attracting the electrons. For example, as one participant stated:

> “Electrons are negative charges, and as a result of this they will repel each other because of the principle of like charges repelling and opposite charges attracting”

For all three phenomena this misconception indicated that learners used what they know about electro-chemistry and atomic bonding to rationalize why electrons move; balance of charges or polarity.

The Predictable misconception was that the participants described the phenomena as being predictable at the level of the individual interactions of the electrons (for Diffusion and Drift), or for the photon’s transfer of energy to the electron (for Excitation). For example, as one participant stated:

> “Technically, I think that the electrons will move in exactly the same way as long as they are placed in exactly the same starting positions…”

The Predictability code was applied to general misconceptions across all three phenomena.

Other general misconception code examples are Fields for Drift, and Energy versus Physical and Movement for Excitation. When participants noted that the electrons moved toward the positive end of the electric field, they exhibited a Fields misconception for Drift because they did not accurately describe the random element of that movement. Like with the Charges/Charges Present misconceptions, the participants appeared to confuse conduction with the atomic nuances of electro-chemistry. For the Energy versus Physical general misconception for Excitation, the participants confuse electron movement between energy levels with an actual physical movement of the electron. Lastly, the Movement general misconception indicated that participants believe that electrons can stop moving, even though electrons (like all matter) are constantly moving unless at 0 Kelvin.

After all responses were coded using the general misconceptions coding scheme, they were recoded using the emergent misconception scheme. A total of 10 emergent misconception themes emerged from the data across all three phenomena. Final codes were validated by an expert on emergence similar to what was done for the new and altered codes (based on the pilot study) for the general misconception coding scheme. The emergent misconception codes and descriptions can be found in the codebook in Appendix D and are summarized in Table 8.

Table 9

Emergent Misconception Codes

Code	Description
Non Cooperative	The electrons work together to create the pattern, or move in order to equilibrate.
Volition	Describes the movement of electrons as being intentional or having anthropomorphic characteristics
Goal Directed	Describes Volition as being performed to meet a certain purpose or goal w/in association with the movement pattern.
Singular	The pattern carried out by all electrons is described at an electron (micro) level.
Centralized Control	Reference to a specific factor directing, leading, guiding, governing, etc. the electrons to carry out certain actions.
Causality	Describe a causal direct factor for the observed macro pattern.
Predictability Change	Don't understand how a small or large change to the system could manifest.
Predictable	Don't understand how a small or large change to the system could lead to small or large change.
Simple Rules	Note that the electrons do not follow rules that can be linked to the macro level pattern observed.
Not Random	Electron movement overall is considered not random

As an example, the Causality emergent misconception code captured the misconception that the emergent phenomenon pattern could be explained by a direct, causal factor. This code is linked to the irreducible, synergism, and nonlinear features of emergence and had been used in previous research (see Chi, 2005). Examples of this code found in participant responses were found for the diffusion simulation;

> "Since electrons contain equal charges, they will tend to repel each other thus causing the movement away from the center of the cell."

The drift simulation;

> “Electrons will move in the opposite direction of the electic field. Therefore, the electric field was pointing from left to right because the electrons were flowing to the left. Electrons flow from low potential to high potential.(- to +)”

And the excitation simulation:

> “The strength of the photon will cause the electron to jump between energy levels”

Note that for Diffusion there was no ‘event’ or ‘factor’ in the simulation that the participants could have used to describe the cause (e.g. the electric field for drift or the photon for excitation).

The Predictable emergent misconception was described for the general misconception coding scheme. Note that the Predicable misconception is linked to the unpredictable feature of emergence. There are subtle differences for this code between the general and emergent coding schemes. The Predictable code for *general* misconceptions *required a justification* for why the participant described the phenomena as predictable, with justifications linked to the other codes that emerged from the data for that particular phenomenon (e.g. Charges for Diffusion). When coding for *emergent* misconceptions, a misconception was noted if the participant stated that the phenomenon was Predictable *with or without* justification. Thus, the Predictable misconceptions were more selective for the general misconception coding scheme. For example, when responding to the question about the predictability of the phenomenon, one respondent stated:

> “I believe that due to the fact that both solar cells are under the same laws of physics, and that electrons are going to move in the direction of the electric field

> that they are put in, that a similar solar cells electrons is going to move the same way…"

Thus, the participant notes that that the phenomenon is predictable because of the presence of the electric field. An emergent misconception related to the unpredictable feature of emergence has been documented in previous research (see Brem at al. 2012) and was used as a guide when developing this code for the codebooks used here. The Not Random codes were utilized similarly as the Predictable codes for the two coding schemes.

For analysis purposes, if the response exhibited one of the emergent misconceptions codes it was coded as that specific emergent misconception code. As with the case of the general misconception theme, alternative codes included U - "Uncodable," or A – "Absent of Emergent Misconception." "Uncodable" and "Absent of Emergent Misconception" were handled in the same way as they were for general misconceptions. The emergent misconception codes were used across all three phenomena because the literature indicated that the features of emergence are domain-general, and as such, emergent misconception codes were not phenomenon specific at a general description level.

Again, the coding scheme and a set of instructions were given to a third researcher to apply to one-third of the participants' data (n=14) using the same procedure as for the general misconceptions. The researchers applied the codes with 0.87 agreement and any disagreements were resolved through discussion. Final codes were then recoded into dichotomous variables such that emergent misconceptions were coded as a one, and absent of misconceptions were coded as a zero. Uncodable responses were marked NA and were treated as missing data, being excluded from the quantitative data analysis. Analyses are described later on.

Groupings: After codes were developed, the author went through the codes in order to try to organize the misconceptions. When looking at the misconception codes for both the general mechanisms and emergent processes of the phenomena, it became clear that certain codes were similar to others either theoretically or because the participant responses indicated a qualitative link. In order to address these commonalities, the researcher first created a list of codes that were either theoretically linked or shared a participant response qualitative similarity to one additional code. This list has been summarized in Table 9.

Table 10

Theoretically Linked General Misconception Pairs

Diffusion		Drift		Excitation	
Fields	Charges	Fields	Direction	Fields	Charges
Fields	MP&C	Fields	Charges Present	Fields	MP&C
Charges	MP&C	Fields	MP&C	Charges	MP&C
Predictable	Not Random	Fields	Polarity	Predictable	Random
Predictable	Rules	Direction	Charges Present	Incorrect Unpredictable	Incorrect Rules
Predictable	Pattern	Direction	MP&C	Concept of Energy	Within Band
Not Random	Rules	Direction	Polarity	Concept of Energy	Within Band Energy
Not Random	Pattern	Charges Present	MP&C	Concept of Energy	Incorrect Excitation
Rules	Pattern	Charges Present	Polarity	Concept of Energy	Incorrect Photon
Incorrect Predictable	Random	MP&C	Polarity	Concept of Energy	Bands
Incorrect Predictable	Not Rules	Predictable	Not Random	Concept of Energy	Stable/Steady State
Random	Not Rules	Predictable	Not Random efield	Within Band	Within Band Energy
Random Atomic	Atomic	Predictable	Rules	Within Band	Incorrect Excitation
Other Factors - Gravity	Other Factors - Energy	Predictable	Incorrect Rules	Within Band	Incorrect Photon
Random	Random Atomic	Predictable	Pattern	Within Band	Bands
		Not Random	Not Random efield	Within Band	Stable/Steady State
		Not Random	Rules	Within Band Energy	Incorrect Excitation
		Not Random	Incorrect Rules	Within Band Energy	Incorrect Photon
		Not Random	Pattern	Within Band Energy	Bands
		Not Random efield	Rules	Within Band Energy	Stable/Steady State

	Not Random efield	Incorrect Rules	Incorrect Excitation	Incorrect Photon
	Not Random efield	Pattern	Incorrect Excitation	Bands
	Rules	Incorrect Rules	Incorrect Excitation	Stable/Steady State
	Rules	Pattern	Incorrect Photon	Bands
	Incorrect Rules	Pattern	Incorrect Photon	Stable/Steady State
	Random	Random Charges/efield	Bands	Stable/Steady State
	Random	Random Atomic	Energy V Physical	Charges
	Random	Not Rules	Energy V Physical	Fields
	Random Charges/efield	Random Atomic	Energy V Physical	MP&C
	Random Charges/efield	Not Rules	Energy V Physical	Within Band Spot
	Random Atomic	Not Rules	Energy V Physical	Concept of Energy
	Fields	Not Random efield	Energy V Physical	Within Band
	Fields	Random Charges/efield	Energy V Physical	Within Band Energy
	Charges Present	Random Charges/efield	Energy V Physical	Incorrect Excitation
			Energy V Physical	Incorrect Photon
			Energy V Physical	Bands
			Energy V Physical	Stable/Steady State

* Note that MP&C is abbreviated or Material Properties and Configuration

Using that list, the author then clustered codes that shared a higher level qualitative relationship. Again, these relationships were based on either theoretical linkages between the misconception codes or because of qualitative similarities observed between the codes in the participant responses. These groups, the codes that make up the groups, and the theoretical link can be observed in Table 10, 11, and 12 for Diffusion, Drift, and Excitation, respectively. Furthermore, examples are provided in Table 13 to demonstrate the theoretical linkage and qualitative similarities of the groups.

As seen in Tables 10, 11, and 12, five groups were created for Diffusion, three for Drift, and five for Excitation. All three phenomena shared three similar groups; Electricity and Magnetism, Predictability, and Not Predictable. The Electricity and Magnetism group included general misconceptions that described the movement of the electrons using terms and mechanisms related to attraction, potential, etc. The Predictability group included general misconceptions that noted that the movement of electrons was predictable, and as such, could not be random because electrons are following rules. The Not Predictable group included general misconceptions that noted that the movement of electrons was not predictable and random (which is correct), because there were rules related to themes of Charges or Fields, etc. (incorrect) or no rules altogether, to explain what was occurring.

Diffusion and Excitation shared one additional group, the Atomic group. The Atomic group was used to capture misconceptions that incorrectly described electron movement at an atomic level (i.e. using terms related to orbitals, etc.). Diffusion had one additional group, the Other Factors group which encompassed general misconceptions that described other forces as causing the movement of the electrons. Excitation had the last unique group, the Energy group, which encompassed general misconceptions related to misunderstandings of energy.

Table 11

Theoretical General Misconception Group Variables for Diffusion

Group Name	Group Variables	Theoretical Link
1. Electricity and Magnetism	Fields, Charges, MP&C	Overall notion of attraction or potential difference at an electron level, field level, or device level
2. Predictability	Predictable, Not Random, Rules, Pattern	If something is predictable, then it cannot be random, and must be following rules
3. Not Predictable	Incorrect Predictable, Random, Not Rules	Conversely, if something isn't predictable, then there are underlying reasons to make it so
4. Atomic	Random Atomic, Atomic	Describe electron movement at an atomic level
5. Other Forces	Other Forces - Energy, Other Forces - Gravity	There are other forces dictating electron movement
excluded variables	Solar Prime, Amounts	

Table 12

Theoretical General Misconception Group Variables For Drift

Group Name	Group Variables	Theoretical Link
1. Electricity and Magnetism	Fields, Direction, Charges Present, MPC, Polarity	Overall notion of attraction or potential difference at an electron level, field level, or device level
2. Predictability	Predictable, Not Random, Not Random - efield, Rules, Incorrect Rules, Pattern	If something is predictable, then it cannot be random, and must be following rules
3. Not Predictable	Random, Random - charges/efield present, Random Atomic, Not Rules	Conversely, if something isn't predictable, then there are underlying reasons to make it so
excluded variables	External, Energy, Solar Prime	

Table 13

Theoretical General Misconception Group Variables For Excitation

Group Name	Group Variables	Theoretical Link
1. Electricity and Magnetism	Fields, Charges, MP&C	Overall notion of attraction or potential difference at an electron level, field level, or device level
2. Predictability	Predictable, Rules	If something is predictable, then it cannot be random, and must be following rules
3. Not Predictable	Incorrect Unpredictable, Incorrect Rules	Conversely, if something isn't predictable, then there are underlying reasons to make it so
4. Energy	Concept of Energy, Energy vs. Physical, Within Band Movement, Within Band Movement - Energy, Incorrect Excitation, Incorrect Photon, Bands, Stable/Steady State	Notions of energy in terms of transfer, movement, or generally
5. Atomic	Atomic Vs. Bound, Within Band Movement-Spot	Bonded atoms and free electrons
excluded variables	Incorrect Movement, Movement, More Photons, Other Factors	

Table 14

Examples of Protocols for General Misconception Groups

Group	Examples
Electricity and Magnetism	“When the electric field is off, the electrons move from negative to positive polarity.” “Electrons will move in the opposite direction of the electric field. Therefore, the electric field was pointing from left to right because the electrons were flowing to the left. Electrons flow from low potential to high potential.” “Electrons move based on electric potential as well as the composition of the material they are in”
Predictability	“I believe that due to the fact that both solar cells are under the same laws of physics…that a similar solar cells electrons is going to move the same way. Yes the movement is chaotic but the general results will be the same.” “Technically, I think that the electrons will move in exactly the same way as long as they are placed in exactly the same starting positions … they will still be governed by the same physical laws.” “No its is not random because there are laws that govern the movement of electrons and these laws cannot be broken…This is not a random movement
Not Predictable	“I know the in the material electrons move randomly because they s no attractions inside” “each time the electron jumps to the conductance band it will not always be exactly the same.” “The movement of electron in the material kind of random so it’s not like a rule-based movement.”
Atomic	".. now it is believed that they (electrons) simply "float" around in an electron cloud, going any which way they desire." “Electorns flow form atom to atom, as one electon is picked up, one is released.” “An electron with a high enough energy will leave the valence band of an atom and orbit further from the positively charged nucleus.”
Other Forces	“I believe that gravity has a huge effect on how and where the electron moves in the solar cell. Also, electric fields and energy play a major role as well.”
Energy	“It moves within the conduction band to reach a stable state after becoming excited.” “If there is energy left after expending the energy used to get to that band, it will move further into the band.” “In order for an electron to move from valence to conduction bands, it requires energy from an outside source. The photons here provide the energy for the electron movement.”

Note: Examples are not grouped for each of the phenomena, but are instead given to show the theoretical linkage and qualitative similarities

The Predictability group, as an example, clustered misconceptions that shared qualitative similarities. A participant had the following response when answering the question about the phenomenon being random (as shown in Table 13):

> “No its is not random because there are laws that govern the movement of electrons and these laws cannot be broken. The elctrons will feel forces in all different directions and will go in the same direction as the largest force. This is not a random movement as random would mean that they just go wherever they feel like going at the time.”

In this example, the participant’s response was indicative of two qualitatively linked misconceptions (Not Random and Rules) that were included within the Predictability group.

As with the general misconceptions, for the emergent misconceptions the author clustered codes that were theoretically linked and/or shared qualitative similarities. Because there fewer variables than with the general misconception coding scheme, the author did not generate a list of related misconception codes first. In Table 14, the group, the codes that make up the groups and the theoretical link are shown. Examples from the protocols are provided in Table 15 to describe the theoretical linkage and qualitative similarities of the groups.

Table 15

Theoretical Emergent Misconception Group Variables

Group Name	Group Variables	Theoretical Link
1. Causal	Causality, Centralized Control	Overall notion there is a factor that leads to the pattern
2. Predictability	Predictable, Predictability Change, Not Random, Simple Rules	If something is predictable, then it cannot be random, and must be following rules
3. Volition	Volition, Goal Directed	Intentionality
excluded variables	Singular, Non-Cooperative	

Three groups were created to capture the theoretical grouping of emergent misconception codes. The Causal group captured emergent misconception codes that described a certain factor either causing or controlling what occurred in the phenomena. The Predictability group, similar to the Predictability group for the general misconception groups, noted that because the phenomena was predictable, the mechanisms could not be random and that the agents in the phenomena must being following rules. In addition, for this group for the emergent misconceptions grouping, this group reflected the theme that a small change to the system could not be predicted. The last group, the Volition group, encompassed emergent misconception codes that noted intentionality when describing the actions of the agents.

Table 16

Examples of Protocols for Emergent Misconception Groups

Group	Examples
Causality	“They will go wherever the repulsive forces direct them towards” “Electrons will move in the opposite direction of the electic field. Therefore, the electric field was pointing from left to right because the electrons were flowing to the left. Electrons. Electrons flow from low potential to high potential.(- to +)” “When the electric field is on, the electric field acts as a pathway of electron movement. These electrons try to attract to the negative side of the electric field. this result in an order movement of electrons when the field is on.”
Predictability	“Technically, I think that the electrons will move in exactly the same way as long as they are placed in exactly the same starting positions, if they are not placed in exactly the same starting position, then they will have a completly different movement pattern as the forces that they feel from the different directions will be slightly different.” “No its is not random because there are laws that govern the movement of electrons and these laws cannot be broken." “The movement of electrons in the material kind of random so it’s not like a rule-based movement” “If the conditions of the scenario are the same, then the electrons will behave similarly if not exactly the same as they did in the first animation”
Volition	“It’s rules based in the sense that if two electrons get near each other, they are going to want to move apart” “Once it is in the band it moves around because it is not sure exactly where it is supposed to go it goes around until it is placed in the right spot.” "This is not a random movement as random would mean that they just go wherever they feel like going at the time.”

Analysis: Upon completion of the coding for both general and emergent misconceptions, a set of analyses were conducted to address the following specific questions, tied to the research questions described in Chapter Two:

1. What are the specific general misconceptions observed with each phenomena and at what frequency do they occur?
2. What are the specific emergent misconceptions observed with each phenomena and at what frequency do they occur?
3. Are there significant phenomena-specific differences related to the general and emergent misconceptions observed in the participants' responses?
4. What are the general trends related to both the general and emergent misconceptions present in the data?
5. Does the sequence of the simulations result in a priming effect, such that the types and number of both general misconceptions and emergent misconceptions in latter simulations is different than those in the earlier simulations

Analyses were conducted using IBM SPSS statistical software in order to make note of any trends in the data and to run basic descriptive statistics of the data. Non-parametric statistical analyses were utilized because the data was non-normal. Relationships between the misconception variables utilized Kendall's tau_b correlation coefficients. Relationships were assessed between the list of variables that were theoretically linked/shared qualitative similarities (Table 9) for the general misconceptions and for the theoretically linked groups (Tables 10, 11, and 12) for the general misconceptions and for the theoretically linked groups (Table 14) for the emergent misconceptions. To create the groups in SPSS, composite scores were generated using the scores from each of the general misconception variables that make up that group. Analyses were conducted using these composite scores. Relationships were also assessed for similar general and emergent misconceptions observed across the phenomena. Lastly, relationships between gender and all of the misconceptions (general and emergent), and between prior knowledge and all of the misconceptions (general and emergent) were assessed. All significant correlations were flagged and are reported on in the following chapter. Differences were analyzed for both the theoretically linked general and emergent misconception groups across each of the phenomena by using both the Kruskal-Wallis and Mann-Whitney U tests. Differences also considered gender and prior knowledge. All significant differences were flagged. The results of all of the analyses can be found in Chapter Four.

CHAPTER 4

RESULTS

Pilot Study

Descriptive Statistics

The number of general misconceptions related to each phenomenon were determined for each participant and for each question for each phenomenon. General misconception scores were computed for each participant by taking the number of misconceptions per phenomenon and dividing that by the total number of questions. For the sample size of n = 20, general misconception scores were obtained for Diffusion (M = 0.93, SD = 0.12), for Drift (M = 0.83, SD = 0.20), and Excitation (M = 0.93, SD = 0.13). Uncodable and absent of misconception scores were obtained for Diffusion (M = 1, SD = 0 and M =1.43, SD = 0.53), Drift (M=1.33, SD = 0.58 and M = 2.82, SD = 1.55), and Excitation (M = 1, SD = 0 and M = 2.89, SD = 1.15), respectively. Similarly, for the emergent misconceptions, scores were obtained for Diffusion (M = 0.51, SD = 0.21), for Drift (M = 0.59, SD = 0.27), and Excitation (M = 0.34, SD = 0.21). Uncodable scores were the same as with those reported with the general misconceptions. Absent of emergent misconception scores were obtained for Diffusion (M = 1.68, SD = 0.70), Drift (M = 2.82, SD = 1.55), and Excitation (M = 2.89, SD = 1.15).

In addition to overall scores for general and emergent misconceptions, misconceptions were computed for each question for each phenomena. Means and standard deviations for each question are listed in Table 16. Participants did not exhibit general misconceptions for each response to each question for each phenomenon, as was also the case for the emergent misconceptions – as indicated by the standard deviations in Table 16.

Table 17

Means and Standard Deviations by Question

Phenomena	Question	General		Emergent	
		M	SD	M	SD
Diffusion	Based on your knowledge of physics and electrons, what determines how and where the electrons move in the solar cell?	1	0	0.05	0.23
	What do you know about electron movement inside a material that made you answer that way? Use as much detail as possible. (question in reference to similar scenario if repeated)	0.8	0.41	0.7	0.47
	What do you know about electron movement inside a material that made you answer that way? (question in reference to electron movement being random?)	0.9	0.31	0.65	0.48
	What do you know about electron movement inside a material that made you answer that way? (question in reference to electron movement being rule based?)	1	0	0.5	0.51
Drift	Based on your knowledge of physics and electrons, what determines how and where the electrons move in the solar cell when the electric field is off?	0.79	0.42	0.37	0.5
	…when the electric field is on?	0.9	0.32	0.53	0.51
	What do you know about electron movement inside a material that made you answer that way? Use as much detail as possible. (question in reference to similar scenario if repeated for electric field being off)	0.79	0.42	0.53	0.51
	What do you know about electron movement inside a material that made you answer that way? Use as much detail as possible. (question in reference to similar scenario if repeated for electric field being on)	0.74	0.47	0.79	0.44

	What do you know about electron movement inside a material that made you answer that way? Use as much detail as possible. (question in reference to electron movement being random?)	0.95	0.23	0.63	0.5
	What do you know about electron movement inside a material that made you answer that way? Use as much detail as possible. (question in reference to electron movement being rule-based?)	0.9	0.31	0.6	0.47
Excitation	Based on your knowledge of physics, what determines how and where the electron moves in the solar cell during each photon event? Please use as much detail as possible.	0.9	0.32	0.05	0.23
	Based on your knowledge of physics, why does the electron move to the conduction band? Why does it move within the conduction band? Use as much detail as possible.	0.95	0.22	0.15	0.37
	What do you know about electron movement inside a material that made you answer that way? Use as much detail as possible. (question in reference to similar scenario if repeated)	0.94	0.24	0.82	0.34
	What do you know about electron movement that made you answer that way? Use as much detail as possible. (question in reference to electron movement if there are no photons?)	0.95	0.23	0.16	0.37
	What do you know about electron movement that made you answer that way? Use as much detail as possible. (question in reference to electron movement being rule-based?)	0.95	0.23	0.26	0.49

* Note that these questions have been truncated and summarized to fit the table. Full questions can be found in Appendix B.

Full Study

General Misconceptions

Descriptive Statistics

The author generated a frequency count of each misconception code for each participant. Because codes were applied to two different protocol versions, the author sought to determine if there were any significant differences between the two versions in the prevalence (frequency) of these codes. In order to assess the difference between these two versions, the author conducted a Mann-Whitney U non-parametric difference test of two independent samples. No significant differences were found for the general misconception codes between the two versions, as shown by the z-approximation test scores reported in Table 17. As a result, the author collapsed the data, including both versions in the analyses conducted for general misconceptions.

Table 18

Mann-Whitney U Test of General Misconceptions for Version A and Version B

Diffusion	z	Drift	z	Excitation	z
Fields	-0.31	Fields	-0.65	Charges	-0.58
Other Factors Gravity	0.00	Direction	-0.44	Atomic vs. Bound	-1.14
Other Factors Energy	-0.76	Charges Present	-1.73	Energy Vs. Physical	-1.21
Solar Prime	-2.30	Random Efields/ Charges Not Present	-0.67	Incorrect Excitation	-0.49
Charges	-1.71	MP&C	-0.52	Incorrect Photon	-0.26
MP&C	-0.63	Pattern	-2.13	More Photons	-1.02
Amounts	-1.45	External	-0.60	Fields	-0.02
Atomic	-2.03	Solar Prime	-1.40	MP&C	-2.45
Random Atomic	-0.55	Energy	-1.74	Steady/Stable State	-0.46
Random	-1.32	Predictable	-0.37	Bands	-0.64
Predictable	-0.44	Random	-0.43	Within Band General	-0.85
Incorrect Predictable	-1.73	Random Atomic	-1.02	Within Band Spot	-0.03
Pattern	-0.96	Not Random Efield	-0.05	Within Band Energy	-0.45
Not Random	-0.44	Not Random	-0.17	Movement	-1.39
Not Rules	-1.36	Polarity	-1.02	Incorrect Movement	-1.25
Rules	-0.19	Not Rules	-1.02	Predictable	-1.22
		Rules	-0.14	Incorrect Unpredictable	-0.03
		Incorrect Rules	-0.30	Other Factors	-0.55
				Rules	-0.23
				Incorrect Rules	-0.53
				Concept of Energy	-0.30

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Using the collapsed data, an overall general misconception score was computed to determine the prevalence of general misconceptions. General misconception scores were computed for each participant by taking the number of misconceptions per domain and dividing that by the total number of questions. For the sample size of 41, general misconception scores were obtained for Diffusion (M = 3.1, SD = 14.5), for Drift (M = 3.25, SD = 17.3), and Excitation (M = 1.48, SD = 13.7). Therefore, on average, each participant held approximately three general misconceptions for Diffusion, three for Drift, and 1.5 general misconceptions for Excitation. Uncodable and absent of misconception scores were obtained for Diffusion (M = 1, SD = 0.58 and M =1.45, SD = 0.72), Drift (M=1.36, SD = 0.77 and M = 2.05, SD = 1.51), and Excitation (M = 1, SD = 0.53 and M = 1.62, SD = 0.96), respectively. Furthermore, the prevalence of general misconceptions was computed for Diffusion (87%), Drift (75%), and Excitation (80%), and as a whole (80%).The prevalence of the uncodable and absent of misconception codes was computed for Diffusion (4.3% and 8.9%), Drift (2.0% and 23%), Excitation (3.9% and 16.1%), and as a whole (3.3% and 16.7%), respectively.

Frequencies, means, and standard deviations were computed for each of the general misconception codes, as shown in Table 18. Recall that the general misconception codes are phenomenon specific. For Diffusion, the Charges (0.16), Material Properties and Configuration (0.16), Rules (0.13). Predictable (0.08), and Not Random (0.08) codes had the highest frequencies. Misconceptions related to electron movement being governed by the interactive repulsive forces of electrons (Charges) and based on the material properties (MP&C) of the solar cell were the most prevalent for

Diffusion. Additionally, participants held a large amount of misconceptions related to the nature of the laws of physics, noting that these laws ‘control’ movement of electrons (Rules). Participants also thought that the nature of the electron movement could be predicted and that it wasn’t random (Predictable and Not Random). Similarly, for Drift and Excitation, notable codes included Charges Present (0.14), Predictable (0.10), and Rules (0.08), and Charges (0.12) and Predictable (0.09). Therefore, across the three phenomena, the Charges (or similarly named code) and Predictable codes were the most prevalent misconceptions observed.

In addition to the misconceptions related to Charges Present, Predictable, and Rules for Drift, other notable prevalent general misconceptions were the Fields (0.20) and Incorrect Rules (0.07) codes. Fields, being found in nearly 20% of all misconception counts, indicated that participants described the electric field as dictating, controlling, or is otherwise responsible for the electron movement when the electric field is on. This code was only applied if no mention was made to the electrons also having a random component to their movement. The Incorrect Rules code was applied when participants understood that there were simple rules that the electrons were carrying out, but that those rules adhered to themes of the Charges Present and Fields codes, for example. Thus, they still held the misconception that themes of Charges, Fields, etc. were responsible for the electron movement they observed during the protocol.

For Excitation, the codes of Energy Vs Physical (0.19), Movement (0.07), and Incorrect Movement (0.06) were also notable. The Energy Vs. Physical code captured the misconception that participants didn’t understand an energy ‘movement’ versus a physical movement of an electron. These participants would describe the electron ‘moving’ within the energy space being due to physical mechanisms. The Movement code was applied when participants would indicate that electrons are not always moving, even though electrons will always move (vibrate) unless the temperature is 0 K. Conversely, for the Incorrect Movement misconception, participants would note that electrons were always moving, but would improperly justify why by using themes of Charges or Fields for example.

Table 19

General Misconception Descriptive Statistics

Diffusion				Drift				Excitation			
Code	F	M	SD	Code	F	M	SD	Code	F	M	SD
Fields	0.06	0.44	0.92	Fields	0.20	1.83	1.18	Fields	0.04	0.41	0.84
Charges	0.16	1.15	1.24	Charges Present	0.14	1.37	1.53	Charges	0.12	1.05	1.26
MP&C	0.16	1.15	1.11	MP&C	0.04	0.32	0.69	MP&C	0.05	0.37	0.66
Predictable	0.08	0.68	0.47	Predictable	0.10	0.93	0.91	Predictable	0.09	0.80	0.71
Rules	0.13	0.98	0.69	Rules	0.08	0.61	1.07	Rules	0.04	0.32	0.47
Pattern	0.05	0.34	0.62	Pattern	0.03	0.17	0.59	Steady/Stable State	0.02	0.15	0.42
Solar Prime	0.05	0.34	0.85	Solar Prime	0.02	0.15	0.79	Energy Vs. Physical	0.19	1.54	1.32
Random	0.06	0.32	0.52	Random	0.05	0.44	0.74	Incorrect Excitation	0.03	0.15	0.57
Random Atomic	0.01	0.07	0.26	Random Atomic	0.01	0.05	0.31	Incorrect Photon	0.02	0.24	0.70
Not Random	0.08	0.63	0.49	Not Random	0.02	0.29	0.60	More Photons	0.01	0.02	0.16
Not Rules	0.03	0.12	0.33	Not Rules	0.00	0.02	0.16	Other Factors	0.02	0.07	0.26
Atomic	0.03	0.20	0.68	Polarity	0.01	0.07	0.47	Atomic vs. Bound	0.05	0.32	0.82
Other Factors Gravity	0.01	0.07	0.35	Energy	0.05	0.29	0.84	Concept of Energy	0.04	0.34	0.57
Other Factors Energy	0.03	0.20	0.51	Incorrect Rules	0.07	0.63	0.54	Incorrect Rules	0.04	0.34	0.53
Amounts	0.04	0.29	0.56	Random E/C Not Present	0.03	0.22	0.65	Bands	0.03	0.27	0.74
Incorrect Predictable	0.02	0.10	0.37	Not Random Efield	0.05	0.37	0.73	Within Band General	0.02	0.20	0.40
				Direction	0.06	0.24	0.62	Within Band Spot	0.01	0.05	0.22
				External	0.05	0.51	1.23	Within Band Energy	0.03	0.22	0.42
								Incorrect Unpredictable	0.01	0.05	0.22
								Movement	0.07	0.63	0.62
								Incorrect Movement	0.06	0.37	0.58

Note: Similar codes across the phenomena are ordered first

Correlation Analysis

Within Phenomena Correlations: No notable correlations were observed between any of the general misconceptions and gender or prior knowledge. Once variables were paired (see Table 9), and then grouped (see Tables 10, 11, and 12), the author sought to justify these pairings and groups by determining if relationships existed between these specific within-phenomena general misconceptions. The author will first describe the significant relationships observed for the theoretically linked pairs that are shown in Table 9.

All significant correlations for the general misconception theoretical pairs for Diffusion are shown in Table 19. A positive and significant relationship was found between the Predictable and Not Random misconceptions (0.35, $p<0.05$), indicating that when participants described the movement of electrons as being predictable, they also noted that electron movement was not random. Along a similar theme, a positive and significant relationship was found between the Not Random and Rules misconceptions (0.43, $p <0.01$). For this relationship, the participants holding the Not Random misconception also held a misconception related to there being rules that govern electron movement.

Also for Diffusion, a positive and significant relationship was found between the Incorrect Predictable and Not Rules misconceptions (0.47, $p<0.01$). In this case, electron movement was correctly described as unpredictable, but they noted that it was unpredictable because of themes related to electron repulsion, the presence of an electric field, etc. When participants held this misconception, they also held the misconception that there weren’t rules to describe electron movement because there is no way to predict the path of an electron because of themes related to electron repulsion, etc. Although participants understand that the movement of electrons is not predictable, they didn't quite understand that electrons carry out simple rules that don't adhere to themes of electron repulsion, etc. and these factors don't ultimately dictate predictability.

Table 20

Diffusion General Misconceptions

Measure	1	2	3	4	5
1. Predictable	1.00				
2. Incorrect Predictable	-0.20	1.00			
3. Not Random	**.353***	-.367*	1.00		
4. Rules	0.27	-0.12	**.428****	1.00	
5. Not Rules	-0.23	**.471****	.336**	.342**	1.00

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

All significant correlations for the general misconception theoretical pairs for Drift can be found in Table 20. As with Diffusion, there was a strong and significant relationship between the Predictable and Not Random misconceptions for Drift (0.34, $p<0.05$). Different than with Diffusion, a strong and positive relationship was found between the Predictable and Rules misconceptions (0.30, $p<0.05$). When the participants described electron movement for Drift as being predictable, they also noted that electrons were following laws that govern their movement. Lastly, a positive and significant relationship was found between the Fields and Not Random E Field misconceptions (0.37, $p<0.01$). The Fields misconception code was used for responses that described electron movement resulting from the presence of the electric field. Note that the Not

Random E Field code reflects a misconception whereby the participant describes the movement of the electron is not random due to the *presence of an electric field*.

Table 21

Drift General Misconceptions

Measure	1	2	3	4	5
1. Fields	1.00				
2. Predictable	0.25	1.00			
3. Not Random Efield	.372**	0.05	1.00		
4. Not Random	0.14	**.340***	-0.06	1.00	
5. Rules	0.18	**.304***	-0.06	0.23	1.00

Note: Bolded correlations in the table are indicative of a *grouping* pair significant relationship

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

All significant correlations for the general misconception theoretical pairs for Excitation can be found in Table 21. A positive and significant relationship was found between the Bands and Concept of Energy misconceptions (0.30, $p<0.05$). The Bands code reflects the misconception that energy bands are discrete bands that electrons jump between, not energy probability distributions. The Concept of Energy code reflects the misconception that bands are made up of certain amounts of energy. Therefore, when a participant incorrectly described bands not as energy probability distributions, then they would also note that the electrons jump discrete amounts to go between bands.

Also for Excitation, a positive and significant relationship was found between the Charges and Energy Vs. Physical misconceptions (0.43, $p<0.01$). For this phenomenon, the Charges code represents the misconception that electrons move because of repulsion, a physical movement. A positive and significant relationship was found between the Incorrect Unpredictable and Incorrect Rules misconceptions (0.32, p<0.05). Both the Incorrect Unpredictable and Incorrect Rules codes note that the misconception is not related to a misunderstanding of predictability or rules, respectively, but that the participant justifies the electron movement as unpredictable or as being governed by rules.

Table 22

Excitation General Misconceptions

Measure	1	2	3	4	5	6
1. Charges	1.00					
2. Energy Vs. Physical	.432**	1.00				
3. Bands	0.13	0.15	1.00			
4. Incorrect Unpredictable	0.26	0.28	-0.09	1.00		
5. Incorrect Rules	0.01	0.08	-0.27	**.315***	1.00	
6. Concept of Energy	-0.18	-0.03	**.302***	0.16	-0.08	1.00

Note: Bolded correlations in the table are indicative of a *grouping* pair significant relationship

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Based on the data, specific correlations indicated that some of the groupings proposed are justified in that the data revealed that the misconceptions making up the groups are related, see the bolded correlations in Tables 19, 20, and 21. For the misconceptions in the Predictability groups for Diffusion and Drift, a significant and positive correlation was found between the Predictable and Not Random misconceptions (0.35, p<0.05 and 0.34, p<0.05) for both, a significant and positive correlation was found between the Not Random and Rules misconceptions for Diffusion (0.43, $p<0.01$), and a significant and positive correlation was found between the Predictable and Rules misconceptions for Drift (0.30, $p<0.05$). Also of note was the significant and positive relationship between the Incorrect Predictable and Not Rules misconceptions for Diffusion (0.47, $p<0.01$), and the significant and positive relationship between the Incorrect Unpredictable and Incorrect Rules misconceptions for Excitation (0.32, $p<0.05$), misconceptions that are part of the Not Predictable group. Lastly, there was a significant and positive relationship between the Bands and Concept of Energy misconceptions for Excitation (0.30, $p<0.05$), misconceptions that are part of the Energy group for Excitation.

Next, the author sought to see what relationships existed between the groups within each phenomenon. Group correlations can be seen in Table 22. Two correlations were worth noting. The first was a significant and negative relationship between the Predictability group and the Not Predictable group (-0.31, $p<0.05$) for Diffusion, and the second was a significant and negative relationship between the Predictability group and the Not Predictable group (-0.38, $p<0.01$) for Excitation. For both Diffusion and Excitation these two groups are inversely related. The Predictability group is indicative of a group of misconceptions identifying that participants describe the phenomena as predictable, and the Not Predictable group is indicative of a group of misconceptions variables identifying that participants describe the phenomena as not predictable, but justify this assertion incorrectly.

Table 23

General Misconception Group Correlations

Group	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Diffusion Electricity and Magnetism	1.00												
2. Diffusion Atomic	-0.01	1.00											
3. Diffusion Other Factors	0.00	0.18	1.00										
4. Diffusion Predictability	-0.03	0.00	-0.09	1.00									
5. Diffusion Not Predictable	0.18	0.16	-0.04	-.313*	1.00								
6. Drift Electricity and Magnetism	.285*	-0.22	0.06	0.09	-0.20	1.00							
7. Drift Predictability	0.06	-0.20	0.11	.380**	-.270*	.364**	1.00						
8. Drift Not Predictable	0.02	0.07	0.14	-0.07	0.08	0.22	-0.03	1.00					
9. Excitation Electricity and Magnetism	0.16	0.20	-0.07	.296*	-0.09	0.07	.331**	-0.14	1.00				
10. Excitation Energy	.357**	-0.08	0.10	-0.03	-0.14	0.14	.242*	-0.19	.272*	1.00			
11. Excitation Atomic	0.10	.456**	-0.03	0.07	0.10	0.16	0.00	0.06	.294*	-0.16	1.00		
12. Excitation Predictability	-.362**	-0.28	-0.19	0.25	-.355*	-0.15	-0.01	-0.12	-0.03	-0.23	0.04	1.00	
13. Excitation Not Predictable	0.23	0.16	0.24	0.03	0.02	0.22	.301*	0.09	.317*	0.23	-0.08	-.381**	1.00

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Across-Phenomena Correlations: The author next sought to determine if specific relationships existed across the phenomena for the general misconceptions. These relationships were first explored between the similar general misconceptions observed across the phenomena. Then, relationships were explored between the general misconception groups observed across the phenomena. All across-phenomena correlations can be found in Table 23. A positive and significant relationship was found for Charges Diffusion and Charges Present Drift (0.32, $p<0.05$), Random Atomic Diffusion, and Random Atomic Drift (0.56, $p<0.01$), Predictable Diffusion and Predictable Drift (0.39, $p<0.01$), Not Random Diffusion and Not Random Drift (0.43, $p<0.01$), Rules Diffusion and Rules Drift (0.38, $p<0.01$), Rules Diffusion and Rules Excitation (0.34, $p<0.05$), Solar Prime Diffusion and Solar Prime Drift (see in upcoming priming section), Pattern Drift and Stable/Steady State Excitation (0.35, $p<0.05$), Random Atomic Drift and Atomic Vs Bound Excitation (0.31, $p<0.05$), and Incorrect Rules Drift and Incorrect Rules Excitation (0.35, $p<0.05$). Most of these correlations are found between Diffusion and Drift.

Table 24

Across Phenomena General Misconceptions

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1. Solar Prime Diff	1.00																
2. Charges Diff	-0.16	1.00															
3. Random Atomic Diff	-0.13	0.15	1.00														
4. Predictable Diff	-0.06	0.05	-0.01	1.00													
5. Not Random Diff	-0.24	-0.12	0.02	.353*	1.00												
6. Rules Diff	0.07	-0.01	0.04	0.27	.428**	1.00											
7. Pattern DR	-0.15	.331*	-0.09	0.06	0.25	0.05	1.00										
8. Solar Prime DR	.402**	-0.02	-0.06	-0.09	-0.07	0.03	-0.07	1.00									
9. Predictable DR	-.299*	-0.05	-0.08	.391**	.431**	.289*	0.04	-0.10	1.00								
10. Random Atomic DR	-0.08	0.21	.563**	-0.23	-0.21	0.02	-0.05	-0.04	-0.16	1.00							
11. Not Random DR	-0.12	-0.25	0.05	0.15	.425**	.332*	0.05	-0.13	.340*	-0.09	1.00						
12. Rules DR	0.06	-0.14	-0.19	0.12	0.21	.376**	-0.08	-0.15	.304*	-0.11	0.23	1.00					
13. Incorrect Rules DR	0.09	0.08	0.02	-0.05	-0.02	0.00	0.24	.306*	-0.02	0.12	-0.02	-0.26	1.00				
14. Atomic Vs Bound EX	0.13	0.04	.326*	0.03	-0.05	0.26	-0.14	0.23	-0.01	.310*	0.04	0.00	0.04	1.00			
15. Stable/Stead State EX	0.04	-0.10	0.17	-0.08	0.11	-0.07	.352*	-0.08	0.02	-0.06	.318*	0.08	0.27	-0.16	1.00		
16. Rules EX	0.05	-0.19	-0.19	0.24	0.19	.342*	-0.06	-0.15	0.26	-0.11	0.21	0.28	-.420**	0.12	-0.25	1.00	
17. Incorrect Rules EX	0.19	-0.08	0.00	0.02	0.09	0.10	0.18	0.09	0.14	-0.11	0.27	0.19	.353*	-0.15	0.26	-.349*	1.00

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

For correlations between the general misconception groups, see Table 24. Two relationships are of note. The first is a significant and positive relationship between the Electricity and Magnetism groups for Diffusion and Drift (0.26, $p<0.05$). The second is a significant and positive relationship between the Atomic groups for Diffusion and Excitation (0.46, $p<0.01$). These correlations indicate that there are relationships between the three phenomena at the group level.

Non-Parametric Comparisons

To test differences in misconceptions based on gender, the author conducted a Mann-Whitney U test, looking at all of the specific general misconception variables, prior knowledge, and the groups. A significant difference was observed between gender for the Charges Diffusion general misconception ($z = -2.05$, $p<0.05$). All Mann-Whitney U tests by gender can be seen in Appendix E.

To test differences in misconceptions across the phenomena, the author conducted a Kruskal-Wallis test using the general misconception groups. The groups that were used were those that could be observed across all three phenomena. The first group – Electricity and Magnetism – described electron movement using principles of electricity and magnetism and included codes such as fields, charges, and material properties and configuration. The second group - Predictability – defines a group of variables that are linked to the misconception that the phenomena are predictable, including codes such as predictable, not random, and rules. The last group – Not Predictable – defines a group of variables that are linked to the misconception that the phenomena are incorrectly described as being predictable, including codes such as random, unpredictable, and not rules. Three analyses were conducted to capture differences between the three domains using these groups using the Kruskal-Wallis test. Tests compared all three phenomena along the Electricity and Magnetism, Predictability, and Not Predictable groups, respectively. As indicated by Table 24, the Kruskal-Wallis test indicated that there was a significant difference in the medians for the Electricity and Magnetism group χ^2 (2, N = 123) = 7.06, p = 0.029. Note that mean ranks can be found in Appendix E. No significant difference was observed in the medians for the Predictability and Not Predictable groups.

Table 25

Kruskal-Wallis Test Statistics For General Misconception Groups

Group	Electricity and Magnetism	Predictability	Not Predictable
Chi-Square	7.062	3.705	0.021
df	2	2	2
Asymp. Sig.	0.029	0.157	0.99

Once differences between each of the phenomena were observed, which phenomena differed along each of the general misconception groups was identified using the Mann-Whitney U test. Thus additional tests had to be conducted, each test being a pairwise comparison of two phenomena for the group (Electricity and Magnetism). The first test compared Diffusion and Drift, the second test compared Diffusion and Excitation, and the third test compared Drift and Excitation. Recall that the Atomic group was used to group general misconceptions in both Diffusion and Excitation. Therefore, for Diffusion and Excitation, the Atomic group was also used for pairwise comparisons between the two phenomena. Table 14 notes the name of the group and provides examples from the protocols that links these codes together. A significant difference was observed for the Electricity and Magnetism group for the second test comparison (z = -2.46, p<0.05), but not for the Atomic group, as shown in Table 25.

Table 26

Mann Whitney U test of General Misconception Group Pairwise Comparisons

	Diffusion-Drift Pair	Diffusion-Excitation Pair	Drift-Excitation Pair
Electricity and Magnetism	-1.40	-2.46*	-1.67
Atomic	NA	-0.59	NA

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Priming

Priming was assessed in a two-step process. First, the author looked for the presence of themes that were indicative of the different simulations impacting the responses in subsequent simulations. For Version A, this involved looking for themes that were indicative of Diffusion and/or Drift priming for Excitation. Alternatively, for Version B, themes were sought that were indicative of Excitation priming for Diffusion and Drift. One code was developed that possibly reflected a priming theme, the priming of Excitation for Diffusion and Drift (only found in Version B). The general misconception code, Solar Prime, states:

"May describe electron movement or behavior in terms of photons, carriers, holes, energy levels, bands, and other solar cell descriptors/phenomena"

The second step was to apply this code to the data and look at some basic statistics. Collapsing both versions, the Solar Prime code was detected in 5% of all of the general misconceptions observed for Diffusion and 2% of all of the general misconceptions observed for Drift. A Kendall Tau_b correlation coefficient was computed between the Solar Prime misconception for Diffusion and for the solar prime code for Drift, 0.40, and was found to be significant with a p value less than 0.01. This indicates that there is a strong relationship between the presence of the Solar Prime misconception in protocols between Diffusion and Drift. Lastly, the author looked to see if there was a significant difference in the presence of the Solar Prime misconception between Version A and Version B using the Mann-Whitney U test. Differences between Version A and Version B using the solar prime misconception code for both Diffusion and Drift were found to be non-significant, ($z= -0.77$, $p > 0.05$ and $z = -1.34$, $p>0.05$, respectively). See Table 26. This shows that even though the ‘possible’ solar prime code emerged from the data, the existence of this code across the two versions was no significantly different and, as such, indicates that priming was minimal.

Table 27

Frequencies of Priming Misconception

Version	Solar Prime Diffusion	Solar Prime Drift
A	0.01	0
B	0.08	0.04
Both	0.05	0.02

Emergent Misconceptions

Descriptive Statistics

The author generated a frequency count of each of the emergent misconception codes. Like with the general misconception coding scheme, because misconception codes were applied to two different protocol versions, the author sought to determine if there were any significant differences between the two in the prevalence (frequency) of these misconception codes. The author conducted a Mann-Whitney U non-parametric test of the two independent samples (Version A and Version). There was no significant difference in the frequency for each of the individual emergent misconception codes between the two versions, as shown by the z-approximation test scores see Table 27. As a result, the author included both versions in the analyses conducted for the emergence misconceptions.

Table 28

Mann-Whitney U Test of Emergent Misconceptions for Version A and Version B

Diffusion	z	Drift	z	Excitation	z
Non Cooperative	0.25	Non Cooperative	0.62	Non Cooperative	0.33
Volition	0.68	Volition	0.68	Volition	0.11
Goal Directed	0.56	Goal Directed	0.70	Goal Directed	0.96
Singular	0.97	Singular	1.00	Singular	0.31
Centralized Control	0.95	Centralized Control	0.40	Centralized Control	0.42
Causality	0.34	Causality	0.20	Causality	0.42
Predictability Change	0.52	Predictability Change	0.51	Predictability Change	0.58
Predictable	0.48	Predictable	0.72	Predictable	0.46
Simple Rules	0.58	Simple Rules	0.97	Simple Rules	1.00
Not Random	0.66	Not Random	0.67	Not Random	0.97

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Using the combined data, an overall emergence misconception score was computed to determine the prevalence of emergent misconceptions. Emergence misconception scores were computed for each participant by taking the number of misconceptions per phenomenon and dividing that by the total number of questions. For the sample size of 41, emergent misconception scores were obtained for Diffusion (M = 2.1, SD = 10.8), for Drift (M = 3.5, SD = 18.3), and Excitation (M = 2.2, SD = 14.6). Therefore, on average, each participant had two emergent misconceptions for Diffusion and Excitation and three for Drift. Uncodable scores were the same as with those reported with the general misconceptions. Absent of emergent misconception scores were obtained for Diffusion (M = 1.66, SD = 0.81), Drift (M = 2.69, SD = 1.55), and Excitation (M = 2.87, SD = 1.00). Furthermore, the prevalence of emergent misconceptions was computed for Diffusion (62%), Drift (63%), and Excitation (41%), and as a whole (55%). The prevalence of the uncodable and absent of emergent misconception codes was computed for Diffusion (4.3% and 33.7%), Drift (2.0% and 35%), Excitation (3.9% and 55.1%), and as a whole (3.3% and 41.7%), respectively.

Frequencies, means, and standard deviations were computed for each of the emergence misconception codes for each phenomenon, as shown in Table 28. For all three phenomena, the emergent misconceptions that were the most prevalent were Volition and Predictable (0.2 and 0.18 for Diffusion, 0.15 and 0.12 for Drift, and 0.36 and 0.28 for Excitation, respectively). The Volition misconception code was noted when the participant described the electrons (or the other agents in the system) as having intentionality. The Predictable code was used to note if the participant described the phenomenon as predictable. For Diffusion, the participants also noted that there was something controlling what was occurring in the animation, having the Centralized Control misconception (0.14) and they did not think the electrons were moving in a random motion, having the Not Random misconception (0.15). For Drift and Excitation, only one additional misconception frequency was notable, Causality (0.12 and 0.21, respectively). For this misconception, the participants noted the presence of a specific causal factor for what was occurring in the simulation for the two phenomena.

Table 29

Emergent Misconception Descriptive Statistics

Diffusion				Drift				Excitation			
Code	F	Mean	SD	Code	F	Mean	SD	Code	F	Mean	SD
Non Cooperative	0.11	0.34	0.62	Non Cooperative	0.03	0.12	0.51	Non Cooperative	0.01	0.02	0.16
Volition	0.20	0.68	0.96	Volition	0.15	1.20	1.65	Volition	0.36	0.90	0.92
Goal Directed	0.05	0.15	0.65	Goal Directed	0.03	0.20	0.60	Goal Directed	0.04	0.10	0.30
Singular	0.01	0.05	0.22	Singular	0.02	0.07	0.35	Singular	0.01	0.02	0.16
Centralized Control	0.14	0.46	0.74	Centralized Control	0.07	0.66	1.02	Centralized Control	0.05	0.15	0.36
Causality	0.12	0.22	0.52	Causality	0.12	0.88	1.10	Causality	0.21	0.51	0.90
Predictability Change	0.02	0.07	0.26	Predictability Change	0.02	0.10	0.37	Predictability Change	0.03	0.07	0.26
Predictable	0.18	0.68	0.65	Predictable	0.12	0.93	0.88	Predictable	0.28	0.73	0.63
Simple Rules	0.02	0.07	0.26	Simple Rules	0.01	0.05	0.22	Simple Rules	0.00	0.00	0.00
Not Random	0.15	0.56	0.59	Not Random	0.07	0.46	0.60	Not Random	0.02	0.05	0.22

Correlation Analysis

Within Phenomenon Correlations: No notable correlations were observed between any of the emergent misconceptions and gender or prior knowledge. Similar to what was analyzed for the general misconceptions, the author sought to determine if specific relationships existed between specific within-phenomenon emergent misconceptions for the emergent misconception groupings.

Specific correlations indicated that some of the groups proposed were justified in that the data revealed that the misconceptions making up the groups were related, as shown by Tables 29 and 30. For Diffusion, a positive and significant correlation was found between the Volition and Goal Directed misconceptions (0.37, $p<0.05$), misconceptions in the Volition group. See Table 29. These two misconceptions are theoretically linked in that in order for the Goal Directed misconception to be marked, the participant must note that the actions being carried out by the agents in the simulations require some intentionality. The Goal Directed misconception described the agents as intentionally carrying out an action in order to meet some goal or purpose. Lastly, a significant and positive relationship was found between the Predictability Change and the Not Random misconceptions (0.33, $p<0.05$), misconceptions in the Predictability group. Therefore, if participants noted that the actions carried out by the electrons were not random, then they were also likely to underestimate what a small change in the system could do to the phenomenon.

Table 30

Diffusion Emergent Misconceptions

Measure	1	2	3	4	5	6
1. Volition	1.00					
2. Goal Directed	**.373***	1.00				
3. Centralized Control	-0.21	-0.19	1.00			
4. Predictability Change	0.06	-0.08	0.05	1.00		
5. Predictable	0.08	0.01	.368*	-0.05	1.00	
6. Not Random	-0.04	-0.10	0.04	**.328***	0.22	1.00

Note: Bolded correlations in the table are indicative of a *grouping* pair significant relationship

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Like with Diffusion, a significant and positive relationship was found between the Volition and Goal Directed misconceptions for Drift (0.45, <0.01), misconceptions in the Volition group. See Table 30. Also for Drift, a significant and positive relationship was found for the Predictable and Not Random misconceptions (0.31, $p<0.05$), misconceptions in the Predictability group. This relationship notes that if the participants described the actions of the phenomenon as being predictable, they also described the actions as not being random. For Excitation, no significant relationships were found between the misconceptions that make up the various groups.

Table 31

Drift Emergent Misconceptions

Measure	1	2	3	4	5
1. Volition	1.00				
2. Goal Directed	**.446****	1.00			
3. Causality	-0.02	-0.23	1.00		
4. Predictable	0.24	-0.14	.309*	1.00	
5. Not Random	0.04	-0.17	0.25	**.313***	1.00

Note: Bolded correlations in the table are indicative of a *grouping* pair significant relationship

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Across-Phenomena Correlations The author next sought to determine if specific relationships existed across the phenomena for the emergent misconceptions. These relationships were first explored at the specific emergent misconception level and then for the emergent misconception groups. All across-phenomena specific emergent misconception correlations can be found in Table 31. Only theoretically notable relationships are shown here. A positive and significant relationship was found for Volition Diffusion and Volition Drift (0.62, $p<0.01$), Not Random Diffusion and Not Random Drift (0.40, $p<0.05$), Centralized Control Diffusion and Centralized Control Excitation (0.43, $p<0.01$), Predictable Diffusion and Predictable Excitation (0.36, $p<0.05$), and Causality Drift and Causality Excitation (0.47, $p< 0.01$).

Table 32

Across Phenomena Emergent Misconception Correlations

Measure	1	2	3	4	5	6	7	8	9	10
1. Volition Diff	1.00									
2. Centralized Control Diff	-0.21	1.00								
3. Predictable Diff	0.08	.368*	1.00							
4. Not Random Diff	-0.04	0.04	0.22	1.00						
5. Volition DR	.615**	-0.04	0.11	0.12	1.00					
6. Causality DR	-0.07	0.09	0.11	0.15	-0.02	1.00				
7. Not Random DR	0.03	0.11	0.19	.404**	0.04	0.25	1.00			
8. Centralized Control EX	0.10	.427**	0.01	-0.03	0.26	0.17	-0.08	1.00		
9. Causality EX	-0.06	-0.04	-0.03	0.27	-0.14	.474**	0.23	-0.10	1.00	
10. Predictable EX	-0.04	0.27	.356*	0.09	0.00	-0.15	0.00	0.26	-0.08	1.00

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

For the across phenomena comparisons between the emergent misconception groups, three relationships are of note, as shown in Table 32. The first two include a significant and positive relationship between the Predictability groups for Diffusion and Drift (0.53, p<0.01), and a significant and positive relationship between the Volition groups for Diffusion and Drift (0.59, p<0.01). The third is a significant and positive relationship between the Causality groups for Drift and Excitation (0.30, p<0.05). These correlations indicate that there are relationships between the three phenomena at the group level.

Table 33

Across Phenomena Emergent Group Correlations

Group	1	2	3	4	5	6	7	8	9
1. Diffusion Causality	1.000								
2. Drift Causality	.240	1.000							
3. Excitation Causality	.215	.301*	1.000						
4. Diffusion Predictability	.183	.081	.061	1.000					
5. Drift Predictability	.096	.175	.347*	.527**	1.000				
6. Excitation Predictability	.230	-.048	.111	.220	.184	1.000			
7. Diffusion Volition	-.241	-.123	.024	-.004	.049	-.092	1.000		
8. Drift Volition	-.048	-.031	-.024	.135	.167	-.037	.593**	1.000	
9. Excitation Volition	.162	-.033	.296*	.234	.241	.021	.171	.219	1.000

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Non-Parametric Comparisons

To test differences in misconceptions based on gender, the author conducted a Mann-Whitney U test, looking at all of the specific emergent misconception variables, prior knowledge, and the groups. No significant differences were observed between genders.

To test differences in misconceptions based on the phenomena, the author conducted a Kruskal-Wallis test using the emergent misconception groups. Because the emergent misconception groups were domain-general, each group was used to note any misconception differences between the phenomena. The groups are Causality, Predictability, and Volition. Three analyses were conducted to capture the differences between the three phenomena. Tests compared all three phenomena along the Causality, Predictability, and Volition groups, respectively. As indicated by Table 33, the Kruskal-Wallis test indicated that there was a significant difference in the medians for the Causality χ^2 (2, N = 123) = 10.66, p = 0.005, and for the Predictability χ^2 (2, N = 123) = 8.77, p = 0.012 groups. Note that mean ranks can be found in Appendix E. No significant difference was observed in the medians for the Volition group.

Table 34

Kruskal-Wallis Test Statistics For Emergent Misconception Groups

Group	Causality	Predictability	Volition
Chi-Square	10.664	8.773	2.788
df	2	2	2
Asymp. Sig.	0.005	0.012	0.248

Once differences were found to be significant between the phenomena for both the Causality and Predictability groups, which phenomena differed along these was identified using the Mann-Whitney U test. Thus, additional tests had to be conducted, each test being a pairwise comparison of two phenomena for each of the two groups (Causality and Predictability). The first test compared Diffusion and Drift along these three groups. The second test compared Diffusion and Excitation along these two groups. The last test compared Drift and Excitation along these two groups. As shown in Table 34, a significant difference was observed between the Causality group for the comparison of Diffusion and Drift ($z = -2.73$, $p<0.01$), between the Predictability group for the comparison of Diffusion and Excitation ($z = -2.60$, $p<0.01$), and between the Causality group ($z = 2.82$, $p<0.01$), and the Predictability group ($z = -2.56$ $p<0.01$) for the comparison of Drift and Excitation. Three of the observed differences were between Diffusion/Drift and Excitation pairwise comparisons.

Table 35

Mann Whitney U Test For Emergent Misconception Group Pairwise Comparisons

	Diffusion-Drift	Diffusion-Excitation	Drift-Excitation
Causality	-2.73**	-0.07	-2.82**
Predictability	-0.30	-2.60**	-2.56**

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

CHAPTER 5

DISCUSSION

It has already been established that learners develop misconceptions when learning about general mechanisms of semiconductors (see Chen, Pam, Sung, & Chang, 2013; Fayyaz, Iqbal, and Hashmi, 2005; García-Carmona, & Criado, 2009; Wettergren, 2002), and further, when they learn about content that is described as emergent (see Blikstein and Wilensky, 2009; Brem et al., 2012; Chi, 2005; Chi et al. 2012; Jacobson 2001; Jacobson et al. 2011). This study was conducted to examine general and emergent misconceptions that learners have for semiconductor content, namely PV. Both general and emergent misconceptions were found to be prevalent in participants' written protocol responses. Certain misconceptions were found to be more prevalent than others and additionally, relationships between misconceptions varied within and across the semiconductor phenomena of diffusion, drift, and excitation. This chapter will discuss the major findings from the study. Specifically for the discussion of findings, the section will include a description of the misconceptions observed in this study and how they relate to misconceptions that have been previously reported on in the literature. Next, the section will provide a discussion on the utility of grouping the misconceptions and what inferences can be made from that data. Then, the section will include a description of the formation of misconceptions and the various themes that emerged from the data. Lastly, the researcher will discuss the implications, explain the limitations of the work, and consider future research applications.

Discussion of Findings

Connections to Prior Research

Numerous codes emerged from the data representing both general and emergent misconceptions. The codes for general misconceptions ranged from misunderstandings about circuits, electricity, bonding, energy, and the nature of science. Similar to general misconceptions that have already been reported in previous research regarding diffusion in semiconductors (see Wettergren et al. 2002), the participants in this study also described the movement of electrons as having a certain pattern; electrons move from areas of high concentrations of electron to low concentrations of electrons (see Amounts code). And, like found by Chen and colleagues (2013), participants were ‘confused’ about the mechanisms for both drift and diffusion as evidenced by their misconceptions in altogether. Further, a study by Fayyaz et al. (2005) observed a misconception that highlighted a confusion between conventional current and drift and diffusion current. Even though the study conducted here did not consider specific misconceptions related to drift and diffusion current, a misconception was observed regarding current in general for diffusion and drift (see the Material, Properties, and Configuration general misconception code in Tables 5 and 6 for Diffusion and Drift, respectively). Thus, the misconceptions observed in this study add support for misconceptions on semiconductor content already reported in the literature.

In addition to supporting some of the findings for the general misconceptions associated with drift and diffusion found in the literature, this study identified other misconceptions for these two phenomena. Additional misconceptions captured in the participant responses that are not semiconductor specific have already been described in some detail in the literature. These include misconceptions related to conservation of energy (e.g., Soloman, 1985), electricity and magnetism (e.g., Maloney, 1985), quantum mechanics (e.g., Styer, 1996), chemical bonding (e.g., Nicoll, 2001), and the nature of science (e.g., Ledermam, 1992). The corresponding similar general misconceptions were Concept of Energy for Excitation, Fields for Drift, Energy versus Physical for Excitation, Charges/Charges Present for all three phenomena, and Rules for all three phenomena, respectively.

The nature of science, as one example from the literature, has been studied extensively (see McComas, 2002) and many misconceptions have been described (see Lederman, 1992; Mackay, 1971; Rubba, Homer, & Smith, 1981). In this field of study misconceptions have been observed related to how science mathematically represents phenomena or the theories regarding why certain phenomena carry out certain rules and how both are perceived as the actual truth (Rubba et al., 1981). Consistent with the literature, participants in this study incorrectly describes the movement of the electrons as being dictated or governed by the rules or laws of physics. For example, one participant noted:

> "Physics is a science of laws and rules, everything that happens in life is due to some rule based theorem and I believe that this photon event is also rule based"

The notion that electron movement follows strict rules of science (in this case physics) demonstrates that the participants possibly did not understand how equations (laws) are theory-based, just approximations that generalize what occurs physically so that scientists can make predictions. The Rules misconception was found in 13%, 8%, and 4% of responses for Diffusion, Drift, and Excitation, respectively. In addition to the Rules misconception, the Predictable misconception may also be indicative of a nature of science misconception. These two misconceptions were grouped into the Predictability group. In addition to the significant relationships observed for these misconceptions both qualitatively and quantitatively, the likelihood that both of these misconceptions are indicative of misunderstandings of the nature of science at a higher level provides further theoretical support for grouping these two misconceptions .

As predicted, the emergent misconceptions for Diffusion observed in this study were similar to those seen in previous research such as that conducted by Jacobson et al. (2011), Chi (2005), Marek et al., 1994, and Chi et al. (2012). As indicated by the Amounts misconception for Diffusion, participants did describe the movement of the electrons to be due to a concentration gradient, much like what was reported by Marek, et al. 1994. Also, as displayed in Table 35, the emergent misconceptions observed were found to be similar to the features of emergence that make up the ‘clockwork’ or ‘direct’ ontologies (misconception ontologies) described by Jacobson et al. (2011) and Chi (2005), and the misconceptions observed in Brem et al. (2012).

Table 36

Misconceptions for Emergent Processes

Chi (2005)	Jacobson et al. (2011)	Brem et al. (2012)	This Study
Distinct Constrained Sequential Dependent Terminating Subgroups Direct Corresponding Differential Status Global goal or Intentional	Linear Centralized Single Predictable Static or Temporal Event	Centralized Control Cooperation Differentiation Goal Oriented	Non Cooperative Volition Goal Directed Singular Centralized Control Causality Predictability Change Predictable Simple Rules Not Random

Note: Underlined misconceptions indicate a similarity to misconceptions observed in this study. Also, Jacobson et al. (2011) clockwork ontological attributes are for complex systems.

The emergent misconception codes used in this coding scheme were guided by the features of emergence described in the literature review, and misconceptions observed (related to those features) found in Brem et al. (2012). For the emergent misconceptions, the Volition, Causality, and Predictable misconceptions were prevalent for all three phenomena. The Volition misconception has been observed in previous research for emergent (e.g. Brem et al., 2012; Chi, 2005) and non-emergent phenomena (see Kallery 2004). In this study, participants were giving anthropomorphic characteristics to the electrons (e.g. they want to move, they behave a certain way, they have needs, etc.). Alarmingly, the Volition emergent misconception was found in 36% of participants' responses specifically for Excitation, albeit less so for Diffusion and Drift. Teleological misconceptions have been studied significantly in relation to evolution and biology (e.g. see Sinatra et al., 2008), and anthropomorphism in the early years of science education (Kallery 2004) and biology (Tamir & Zohar, 1991) from a general misconception perspective. Brem and colleagues (2012) found similar anthropomorphic and teleological descriptions for the emergent phenomena their participants encountered. As did Chi (2005). Further, it is known that, for example, that anthropomorphizing entities such as atoms and electrons (see Taber & Watts, 1996) is done from an early age, and further, that misconceptions are hard to overcome (Dole & Sinatra, 1998; Pintrich, Marx, & Boyle, 1993; Vosniadou, 2007). Therefore, it is not surprising that anthropomorphic misconceptions were observed in the undergraduate students' conceptions observed here, especially those misconceptions formed for emergence.

The Causality emergent misconception was also prevalent for Diffusion, Drift, and Excitation. As Chi (2005) found, the direct causal factor is a common misconception seen in emergent phenomena. Chi (2005) and Chi and colleagues (2012) detected this misconception for diffusion of dye in water, the same phenomenon used in this study although in a different domain.

All of the misconceptions just described are linked to previous research either for the general mechanisms of the semiconductor phenomena or regarding the emergent characteristics of the phenomena in general provide additional validity regarding the types and depth of codes that were generated through the qualitative coding process for this research.

Misconception Groups

The groups that were formed for the general and emergent misconception allowed the researcher to make comparisons within the phenomena and across the phenomena. Even though specific misconceptions were used to capture the misunderstandings for the three phenomena and to observe certain relationships within and across the phenomena, bigger picture comparisons could not be made because not all of the misconceptions reflected the same level of granularity or characteristic. The groups allowed for certain themes to be examined because the codes that made up those groups were commensurable theoretically and qualitatively. For example, the Electricity and Magnetism group represented a higher level content group for the misconceptions indicative of topics related to electricity and magnetism.

From a quantitative perspective, correlations did justify some of the misconceptions grouped. For Diffusion and Drift, the Predictability Group had misconceptions that were correlated with each other (Predictability and Not Random for both, Not Random and Rules for Diffusion, and Predictability and Rules for Drift). For Excitation, the Concept of Energy and Bands misconceptions were correlated for the Energy group and the Incorrect Rules and Incorrect Unpredictable misconceptions for the Not Predictable group. Unfortunately, not all of the general misconceptions within each group were significantly correlated, and furthermore, that at least one set of significantly correlated misconceptions for each group did not exist. Prior research has shown that misconceptions are guided by a learner’s own perception of the working world (e.g., Clement, 1982). Therefore, a learner may hold the Charges/Charges Present general misconception, but that doesn’t mean that they would also hold a Fields general misconception because of how they constructed their knowledge. If the learner’s background is more grounded in chemistry and bonding, the charges misconception would be more probable given the nature of the content covered in chemistry. Whereas, if their background is in physics, this content knowledge could influence the development of the Fields general misconception.

For the emergent misconception groups, the Predictability group was supported by significant correlations between the Predictable and Not Random emergence misconceptions for Drift and by the slightly different Predictability Change and Not Random emergent misconceptions for Diffusion. The Volition group was supported by a significant correlation between the Volition and Goal Directed emergence misconceptions for both Diffusion and Drift. However, as stated in the results, the Volition code was embedded in the Goal Directed code, and therefore, a significant correlation between the two would be expected. No significant relationships were observed for all three phenomena among the misconceptions that made up the Causality group. In this case, the participants may have already provided one possible explanation for why the pattern emerged at the level of the agents (Centralized Control), but not at a higher level (Causality). Similar to the grouping for general misconceptions, emergent misconception groups were not overly supported due to the lack of relationships observed between the misconceptions within each of the groups. Despite the lack of quantitative statistical support to describe the relationships between the misconceptions that form the groups for both the general and emergent misconceptions, the similarities observed qualitatively and based on the literature (e.g. the nature of science misconception relating the Predictable and Rules codes, codes that make up the Predictability group) provide some evidence to support the groupings.

Misconception Formation and Themes

As reported in Chapter Four, the general misconceptions and emergent misconceptions were found to be prevalent (in 80% and 55% of participant responses, respectively). The prevalence of these misconceptions is likely due, in part, to the types of questions asked in the protocol. It is not surprising that the Predictable misconception, for example, was present across all three phenomena as one protocol question for each of the phenomena specifically asked about predictability. The author isn't arguing that the question led to the formation of the misconception, but instead, as evidenced by previous studies that have utilized protocols for emergent misconception research (e.g. Brem et al. 2012), that the question honed in on that particular misconception in participant responses. Similarly, the prevalence of the Rules, Movement, and Random/Not Random general misconceptions likely resulted from protocol questions that directly probed for misconceptions along those themes. Interesting, however, is the prevalence of the Charges/Charges Present code across all three phenomena, the Fields code for Drift, and the Energy versus Physical code for Excitation.

So, why are these specific misconceptions so prevalent across all participant responses? Students develop misconceptions because of the way in which they utilize their perceptions of the world around them or from the ways in which instructors explain the natural world in order to construct knowledge (McDermott & Shaffer, 1993; Picciarelli et al., 1991; Streveler et al., 2003). This prior knowledge, as Smith and colleagues (1993) describe it, is the culprit in misconception formation. Some misconceptions are almost inevitable; as small children we form naïve theories about the world even before we begin formal education. As already described, most undergraduates hold an Aristotelian impetus model of force, a model that they likely developed as small children because of the prior knowledge they had from the perceptual illusions they encountered while watching things move about the world (Clement, 1982; Clement, 1993; Steinberg et al., 1990). Clement (1982) argues that the ‘coin toss’ misconception is grounded in peoples’ perceptions of pushing and pulling that they have experienced in physical world. They then apply these perceptions to notions of forces acting on objects in motion, fusing ideas of force and motion. Thus, learners describe phenomena based on how they rationalize what they observe in the physical world.

Misconceptions also can arise as learners apply prior knowledge that they have acquired in the classroom to new, similar content (see Resnick et. al., 1989 and Nicoll, 2001). In a study by Resnick et al. (1989), students attempted to apply rules that they had already learned to new content, which resulted in errors. For example, student utilized the already learned ‘whole number’ rule when attempting to order new-types of numbers that they encountered. Thus, when comparing the decimal numbers 0.25 to 0.5 (new type of number), students would state that 0.25 was greater because 25 is larger than 5 (whole number rule). Nicoll (2001) describes the misconceptions that form when we simplify learning about the atom by likening it to the solar system, content covered in primary school. Primarily, students come away believing that electrons are solid bodies that move around a nucleus as planets orbit the sun, and, among other issues, have no model for understanding of how electrons interact with other electrons from other atoms (Nicoll, 2001).

Lastly, as students attempt to rationalize what they have observed with what they have been taught, they can form misconceptions. For example, Kaiser, McCloskey, and

Profitt (1986) found that students develop misconceptions about force and motion. In this study a U-shape developmental pattern was observed in which younger and older students have correct conceptions of motion and force, and those in the middle do not. Therefore, intermediate students formed misconceptions, misconceptions that are likely the result of their rationalizations between what they are being taught and what they observe in the real world.

It is possible that, similar to what was reported by Resnick et al., (1989) and Nicoll (2001), the misconceptions observed here are the result of the participants attempting to rationalize what they have already been taught with what they observed in the simulations. For the Charges/Charges present misconception, they are applying what they know about electrochemistry and bonding to the simulations they encountered in the protocol. The participants would have already been exposed to this content in their secondary school chemistry education. This would explain why the participants used similar, yet different content regarding electrons (content typically covered in Chemistry) to explain what they saw in the simulations.

For emergence, the prevalence of the Causality misconception may be due to the presence of a ‘factor’ embedded in the phenomenon (the electric field for drift and the photon for excitation) that could easily be isolated as a cause. It is possible that these ‘factors’ became an easy way for the participants to describe what they were observing in the simulations. For example, in the case of drift, numerous participant responses described the electric field as causing the movement of the electrons in a particular direction. Similar to what has been described by Blikstein and Wilensky (2009), the participants appeared to oversimplify the content, in this case, the cause for how the emergent pattern was manifesting.

Even though the prevalence of the Causality code was the same for Diffusion and Drift, there was no potential primed factor or cause with Diffusion. For diffusion, the participants would create a cause, blending misconceptions for emergence with the general mechanism misconceptions of the photovoltaic (e.g. the cause was due to electron repulsion). This just further indicates that learners attempt to rationalize previously learned content with new content (see Nicoll, 2001). In this case, then, what impact do the general misconceptions for the mechanisms of a system have regarding the formation of misconceptions related to emergence?

This study did shed some light on the relationships between the general misconceptions and between the emergent misconceptions. Numerous similar general misconceptions were observed qualitatively across all three phenomena. Overall, misconceptions for Diffusion and Drift were more related than misconceptions for Diffusion or Drift and Excitation. This is not surprising seeing as Diffusion and Drift share many similarities mechanistically. Interesting, however, were the misconceptions that were related across the unrelated phenomena (e.g. Diffusion and Excitation or Drift and Excitation). These relationships may support previous research that has shown that misconceptions can become entrenched in learners conceptions of the workings of the physical world (Sinatra et al. 2008). Thus, if a learner has a misconception, it is possible that that misconception would be observed in the different phenomena.

Lastly, differences between phenomena were captured both qualitatively and quantitatively (using the groups that were formed). The majority of differences regarding the general mechanisms were observed between both Diffusion and Drift and Excitation. Qualitatively, more similar/semi-similar general misconceptions for Diffusion and Drift were observed. For Excitation, even it similar code names were used to describe the misconception (e.g. Charges), the nuances of the misconceptions were different. In the case of both Diffusion and Drift, recall that the Charges/Charges Present general misconception code represents the misconception that electrons move due to the attraction or repulsion for atomic particles (either electrons or protons). Conversely, for Excitation, the Charges general misconception code describes the movement of the electron to the conduction band because the band itself attracts the electron. The different misconceptions that represent excitation are likely indicative of the obvious difference between excitation and both diffusion and drift. For the emergent misconceptions, even though differences could not be captured qualitatively because the emergent misconception codes were domain-general, differences were captured through comparisons of the emergent misconception groups. As was the case with the general misconception groups, the majority of differences between the phenomena were seen between the Diffusion or Drift pairwise comparisons with Excitation. Only one cluster difference was observed for the pairwise comparison of Diffusion and Drift. Consistent with the literature (see Brem et al. 2012; Hmelo-Silver et al. 2007), it was expected that differences would be observed for the different phenomena because prior research studies have found that misconceptions for emergent vary by domain. Also, even though it was predicted that the misconceptions for Diffusion and Drift would be similar because phenomena are similar, noticeable differences were observed between Diffusion and Drift both from a general and emergent misconception perspective. Even though these phenomena share similarities, their subtle differences were apparent enough to be captured in the qualitative codes. For example, from a general misconception perspective, one misconception was observed for Diffusion regarding the electric field being responsible for electron movement. Whereas, for Drift, three misconceptions were observed, each capturing a specific misunderstanding of electron movement in relation to the electric field; Fields, Incorrect Direction and Polarity. Again, misconceptions research has shown that misconceptions vary by domain (Brem et al. 2012).

Implications

The prevalence of both general and emergent misconceptions in participants' responses is troublesome. Some of the general misconceptions identified indicate a lack of fundamental knowledge that participants should have covered in chemistry, physics, and materials science. For example, the Atomic versus Bound general misconception code for Excitation describes the misconception as:

> Do not understand the difference between bonded atoms and singular atoms in space. As such, describe electron movement in terms of atomic theory (orbitals and localized attraction to the nucleus, interchange valence band with valence electron/valence orbital, describe movement of electron in terms of electron movement within the atomic orbital). Do not understand that the electron has been 'freed' from a bond. May also refer to electron structure (in terms of the atom). May use the term electronegativity.

The misconception indicates a lack of fundamental content knowledge about atoms. The participants in this study should have encountered content related to atoms in high school chemistry. Even though the participants should have encountered this content, they still exhibited misconceptions, misconceptions that are impeding their learning of PV.

Certain general misconceptions that were observed across all phenomena are not particularly indicative of a misconception that is semiconductor or PV specific. For example, Charges (Diffusion and Excitation) or Charges Present (Drift) misconception is indicative of misunderstandings related to bonding that are being applied to concepts for electrical circuits (note that this is also fundamental content covered in chemistry and physics). Learners could easily have this same misconception for other phenomena in physics. With that in mind, the misconceptions observed here (those that are on fundamental content and those observed across the phenomena in this study) can be used to shed light on misunderstandings for other similar content areas, informing educators in other related fields.

Building from this, the data also showed that some misconceptions for diffusion were also observed for drift. Recall that drift is diffusion with one additional rule acting on the system due to the presence of an electric field. Therefore, the participants that had misunderstandings of lower level content (diffusion) exhibited similar misconceptions for higher level content (drift). This reinforces what has already been observed in the literature; misconceptions become entrenched in learners theories of the physical world (Sinatra et al. 2008), and overcoming them requires effort (Dole & Sinatra, 1998; Pintrich, Marx, & Boyle, 1993). These misconceptions are barriers to the learning of subsequent and higher level content. For PV specifically, the lack of understanding of diffusion and drift both are indicative of a lack of understanding of aspects of current, voltage, and ultimately, power generation.

The presence of misconceptions on fundamental content, misconceptions across the phenomena, and misconceptions that may be indicative of limiting learning of higher level content can all have implications for learning PV. For example, the formation of general misconceptions related to the semiconductor and PV phenomena studied here have ramifications such that they could lead to limited engineering designs for PV. For example, the Material Properties and Configuration misconception captures misunderstandings between the properties of materials and a device. The misconception code notes:

> This is a circuits/electricity/or material design or property perspective whereby electron movement is dictated by solar cell's terminals (positive terminal and negative terminal) and or current (flow of electrons), sometimes using language associated with a device, or describes movement based on the shape of the material. Movement occurs such that electrons move toward the positive ends of the cells, which is influenced by the potential difference between the + and – end, as well as the conductivity of the material (some materials allow electrons to move more freely about).

For this misconception, which was especially prevalent in protocol responses for Diffusion, learners believe that electron movement is induced by an applied voltage. This is completely counter-intuitive to the photovoltaic effect where an internal voltage (and current) is generated because of the electron movement at a material level (predicated on photons exciting electrons). For this example, the implications are severe; the learner does not understand one of the most fundamental pieces of the solar power industry, the photovoltaic effect.

In terms of emergent misconceptions this study adds to the existing body of knowledge of research on emergent misconception formation, providing further evidence that students have misconceptions about emergent phenomena. These misconceptions are just as troublesome as the general misconceptions. The Causality code, for example, describes the misconception that participants note that there is one thing that is causing the emergent pattern. The code is:

> Describe a causal direct factor for the observed macro pattern. Likely no mention of the emergent pattern resulting from the interactions of the electrons.

For Excitation, for example, the participants exhibited this misconception as they explained that the photon was causing the electron to move to the conduction band, an oversimplification of the process. They fail to understand that the photon is not directly responsible for the movement of the electron; there are many pieces that interact for the electron movement to occur (the photon has to hit a specific electron, have a certain amount of energy, the electron has to have a certain amount of energy, etc.). This oversimplification could result in higher than normal calculations for power generation of the solar cell. Oversimplification of emergent phenomena has already been described as a major problem for engineering (see Blikstein & Wilensky, 2009), so the implications go beyond what was observed in this study

Taken together, general and emergent misconceptions can impact learners' success in PV. Generally, misconceptions are indicative of a lack of understanding of the content, which could result in learning challenges for students as they pursue a degree and ultimately a career in this field. Further, misunderstandings could lead to poor work quality and limited technological advancements in PV design. As such, the general and emergent misconceptions described here can provide insight for educators teaching semiconductor and PV content. First, one suggestion is for educators to tailor content based on the general and emergent misconceptions that were the most prevalent across participants' protocols. Engineering educators are pressed for time; they rarely cover all of the content that is in their syllabus (Sheppard et al. 2009). Thus, by having engineering instructors focus on the misconceptions that appear to be the most prevalent when learning about semiconductors and PV, they may get the most bang-for-their-buck; saving time and encouraging correct conception formation. However, this does not consider additional non-prevalent individual misconceptions that learners could have, so certain students could have misconceptions for this content that are not being attended to by their instructors.

Second, emphasis could be placed on limiting the oversimplification of content. For example, the common notion of the wave-particle duality taught to physics students reinforces an overly simplistic and narrow approach to describe a photon (Jones, 1991), a variation-on-a-theme of the Energy versus Physical misconception. By educators not oversimplifying the content, this misconception could potentially be avoided when students learn about this content. In terms of emergence, emergent content should be presented in greater detail instead of being oversimplified, as has been described by Blikstein and Wilenskey (2009). In the example provided above about the emergent misconception and causality, the oversimplification could result in poor performance specifications for solar devices. Unfortunately, as mentioned above, faculty are pressed for time (Sheppard et al. 2009), so oversimplification may not be easily avoided. Further, accurately teaching semiconductor and PV content such that it captures the features of emergence is hard to do because this content is not easily observed; the small interactions of the electrons are hard to see.

Third, educators should be aware of the ramification that misconceptions can have toward learning content that builds from previously covered material, both between and within courses. They need to reinforce the correct conceptions when covering new, yet similar content. They also need to be cognizant of what misconceptions exist for what is being covered and content that students should already have learned related to what is being covered. For example, if educators can teach semiconductor and PV courses with the misconceptions for covalent bonding in mind, when students go on to apply this content to specific applications in material structures and properties for semiconductors, that misconception barrier could be lessened.

Fourth, educators can also develop course content and exercises or find additional educational resources that reinforce correct conceptions of this fundamental content. However, the educational resources (e.g. textbooks, online content, etc.) educators provide students may also contribute or reinforce misconceptions because they could be embedded in those materials (as was found to be the case for misconceptions regarding the Nature of Science) (Abd-El-Khalick, Waters & Le, 2008). Therefore, when educators develop course content, they need to be aware of the advantage and disadvantages additional educational resources can provide.

Lastly, educators should consider strategies that can promote conceptual change. Although research has documented conceptual change in individuals’ understandings of emergence (e.g., Blikstein & Wilensky, 2009; Chi et al., 2012; Jacobson et al., 2011), misconceptions as a whole must be overcome for additional learning to occur (Posner, Strike, Hewson, & Gertzog, 1982). Of the six models for conceptual change described in the literature review, three could have applications for conceptual change and emergence; ontological shift, argumentation, and the CRKM. However, as already stated, even though the ontological shift model has been used to capture conceptual change for misconceptions of emergence (see Chi et al., 2012), it does not consider intentionality. Therefore, the two remaining models (argumentation and the CRKM) seem plausible when considering conceptual change for misconceptions of emergence. First, these models consider the role that intentionality plays in promoting conceptual change, providing additional insight into the conceptual change process for content that is difficult and may possibly require intentionality for conceptual change to occur. Second, argumentation and the CRKM do not specifically focus on what the reconstruction of knowledge looks like, but instead focus on how to encourage the reconstruction through recognition of the specific conflict between the correct and incorrect conception.

In order to promote conceptual change in the classroom, first and foremost, the learner must be aware that they have the misconception. One example to help learners see that they have developed the misconception as well as promote conceptual change is the use of refutational texts as described by Hynd (2001) and Hynd (2003) and more recently with an application for the CRKM model of conceptual change (see Broughton et al., 2010). When students are learning diffusion, for example, the educator could ask them to complete an exercise that compares and refutes the commonly held Charges misconception with the correct conception for why electrons move from areas of high to low concentration of electrons. From an emergence standpoint, when educators are covering content that exhibits features of emergence, they could add an additional layer to the refutational text by also including the commonly held misunderstandings of emergence associated with diffusion. Not only could this encourage conceptual change, it could also provide an additional opportunity for educators to add more specificity to the content.

Taking it a step further, the educator could also have the students develop an argument for why the misconception is incorrect and the correct conception is correct. As evidenced by previous research (see Wiley & Voss, 1999) the construction of an argument as a product has led to enhanced conceptual understanding. Educators could structure homework problems that utilize both conceptual change strategies (refutational texts and arguments). Students could be expected to complete a refutational text for a common misconception for the content covered in class and then to develop an argument, possibly using that refutational text as a means to construct their argument. During class, time could be allotted for the students to engage in argumentative discourse about the content, using the argument they developed as a launching point for the discussion. As noted above, engagement in refutational texts has led to enhanced conceptual understanding (see Broughton et al., 2010). In the case of argumentation, the outcome would be two-fold. First, the learner would be engaging with the content so as to possibly overcome misconceptions, and enhance their conceptual understanding of the content (see Wiley & Voss, 1999). Second, the learner would be developing their argumentation skills which has been shown to change epistemic beliefs about knowing (Kuhn, 2003). However, in order for both of these strategies to be effective, the educator has to be aware of the misconceptions students have when learning the content covered in their curriculum.

Limitations

The written protocol developed for this study was guided by a similar previous study that was also looking to identify emergent misconceptions. Although the author of this study also sought to identify general misconceptions, the protocol was written with emergent misconception identification in mind. The questions utilized in this study were therefore written in order to extract information from participants about their knowledge of emergence. For example, for the phenomena of Diffusion and Drift, questions specifically asked about predictability, randomness, and rules, all characteristics that make up the features of emergence. In addition to the questions being framed within an emergence perspective, the questions differed across the phenomena. For example, there were no specific questions probing at the non-random characteristics of the Excitation phenomenon, whereas a specific not-random question was utilized for both Diffusion and Drift. Thus, comparisons of misconceptions observed across the phenomena are subjective. For instance, the presence of the Not Random general misconception for Diffusion was correlated with the presence of the misconception for Drift. Neither were correlated with Excitation. As such, making claims about the similarities between Diffusion and Drift should be done lightly. So, why were different questions used? Different questions were used because there were differences between the phenomena that could only be captured by asking specific questions. Even though steps could have been taken to include every question for each phenomena, the length of the protocol would have been a hindrance.

The process of coding was done differently for the general misconceptions than for the emergent misconceptions. The general misconceptions were mostly arrived at through deductive reasoning, whereas the emergent misconceptions were mostly developed inductively (note that misconceptions for both coding schemes were arrived at through both inductive and deductive reasoning, however the general misconception codes favored deductive reasoning and the emergent misconception codes favored inductive reasoning). Even though some previous research existed about the types of misconceptions students may have when learning about semiconductors, the research was so sparse that the author felt that the best way to capture all of the general mechanism misconceptions was to allow them to emerge from the data instead of looking at the data with misconceptions in mind. For the emergent misconception coding the author followed a generally inductive approach that was guided by the definitions of emergence and by the misconceptions already observed and described in the literature. Emergence is domain-general, therefore applying what has been reported in the literature offered an opportunity to better hone in on the emergent misconceptions observed in the protocols. However, approaches that use inductive reasoning can be limiting; narrows the code landscape for the coder, making it so that misconceptions were possibly missed, or that nuanced differences weren’t captured within certain misconceptions.

The general misconception codes did not capture misconceptions at the same level of granularity within each of the phenomena. Some general misconception codes represented detailed misconceptions, whereas others represented a grouping of misconceptions within a similar theme. For instance, certain general misconceptions encompassed numerous pieces that were grouped together. As shown by the Fields code for Drift:

> Specifies that the electron movement or behavior is the result of an electric field or a magnetic field, but doesn't note the presence of 'randomness.' Electrons will move in other directions than the electric field direction because of the polarity of the electric field, potential difference, or due to charges (repulsion or attraction). Flow from positive to negative, or will move to the positively charged side of the e-field. The stronger the field, the stronger the pull from low to high potential.

This code included aspects of polarity, potential, charges based on the electric field, and the presence of a magnetic field. Once coded, there was no way to distinguish between participants who exhibited a fields misconception; some may have exhibited a misconception regarding potential, whereas others a misconception in terms of polarity. Subtle differences were not captured during the coding process because some codes encompassed too many misconceptions. Additionally, some codes captured higher level mechanisms. For example, the Energy versus Physical code describes a higher level misunderstanding of electron movement whereas the Charges code describes a specific misunderstanding of the physical movement of the electron. Even though these misconceptions were predicted to be theoretically linked, comparisons between these misconceptions could not be made because of their different level of granularity. Therefore, claims about the relationships between the codes are limited. It should be noted, however, that the author attempted to make the codes commensurable by grouping them.

Differences between the Predictable and Not Random codes between the general and emergent misconception coding scheme were not well captured in the data. The Predictable and Not Random codes were utilized for both the general and emergent misconceptions. However, the codes for the general misconceptions were slightly different than the codes for the emergent misconceptions in order to account for the *justifications* behind why the participants' described the process as predictable or not random. Even though the author attempted to capture more information about both the Predictable and Not Random misconceptions when coding for general misconceptions, the quantitative analyses indicated that there were minimal differences between codes for general and emergent misconceptions. Therefore, the trends observed for both the Predictable and Not Random general misconceptions may be more indicative of misconceptions for emergence than for the general scientific mechanisms and characteristics of these phenomena that the author was attempting to capture.

Not all of the hypothesized relationships within the groups were statistically significant for both the general and emergent misconceptions. Grouping was theoretically driven, such that codes were grouped when they exhibited similar qualitative descriptions, or because the misconceptions in the group were similar based on content. For instance, the Charges code was linked to the Fields code for Diffusion because both are indicative of content covered in lower level physics courses. However, because few quantitative relationships were observed between the variables, the way the misconceptions were grouped may not be indicative of how they are organized in participants' knowledge representations for the content. The groups were primarily arrived at inductively, as such a more deductive approach could have resulted in groups that were more representative of the data.

Lastly, because the data was ordinal and non-parametric, the author had to utilize statistical analyses that have limitations. Non-parametric statistics lack the power that parametric statistics have (e.g. comparing two groups is much more effectively done when comparing two groups that have normal or similar distributions, such as the case with parametric statistics). More so, non-parametric statistics are useful at explaining the data that they represent, but do not provide the generalizability or extrapolation that parametric statistics allow. Also, like all quantitative analyses, larger samples sizes result in better precision and power. For this study, the sample size of 41 is a value that some recommend to be lower than ideal, especially for the Mann-Whitney U test (See Green & Salkind, 2010). As such, the pairwise comparisons conducted in the analyses are probably less accurate than if the study had yielded a larger sample size. Lastly, fewer statistical tests have been developed for non-parametric statistics, limiting the types of questions that can be asked and the types of analyses that can be performed.

Future Research

The research conducted in this study is merely a first step toward the identification of general and emergent misconceptions students have as they learn about semiconductor and photovoltaic content. Building from the limitations of the work discussed above and using the considerations described in the implications section, a variety of other research studies and analyses should be conducted.

First and foremost, it is recommended that the misconceptions codes that were developed for the study be revisited. As noted in the limitations section, the codes for Predictable and Not Random should have been distinguishable between the general and emergent coding schemes. Therefore, the author needs to decide if the Predictable and Not Random general mechanism misconception codes should exist or if they can be rewritten to capture the more general form of the phenomena. Also, as noted in the limitations section, the author did not maintain the same level of granularity for each of the codes; some codes were more specific and others were more general (encompassing multiple misconceptions). The author needs to determine at what level of granularity the misconceptions should be coded at and then use this throughout. It is possible that the entire codebook will need to be over-hauled; however, it is more likely that certain codes will just need to be teased apart. Once changes can be made to the codes, the author will need to revisit the groups. In addition to the analyses conducted in this study that looked at the correlations between the misconceptions within the groups, the author may want to conduct an actual statistical multivariate cluster analysis.

Regardless of the new coding and grouping, additional analyses need to be done with the data. As already mentioned, a multivariate cluster analysis needs to be conducted in order to see if and how the data clusters. Comparisons between misconceptions should also be done at the level of the specific questions. For instance, for the predictability protocol question, are Predictable misconceptions related to Rules or Not Random misconceptions? These comparisons should be done both within specific questions and by comparing the same question across the phenomena. If determinations can be made regarding the relationships between the various misconceptions then researchers will have a better idea of how it is that learners organize knowledge representations for this content.

Now that a set of misconceptions has been identified, future research should include the development of instruments that can be used to assess the prevalence of these misconceptions in students currently studying semiconductors and PV. Also, because some of the misconceptions were more indicative of fundamental knowledge misunderstandings, assessments could be developed for physics and materials science courses to determine the prevalence of these fundamental misconceptions. Assessments on the prevalence of all of the misconceptions, general, emergent, or fundamental could be used to not only grasp the current misconceptions learners have in courses but also to determine if these misconceptions are lessened by the end of the course.

Lastly, future research could focus on the conceptual change process that learners undergo when overcoming the misconceptions identified in this study. For emergence especially, existing conceptual change models have focused more on the ‘cold’ conceptual change process (e.g., Chi et al. (2012)), or have only included minor affective considerations (see Jacobson et al. (2011) complex system ontology which captures aspects of learners epistemic beliefs). Therefore, studies could be developed to assess intentional conceptual change that utilizes the emergent misconceptions for semiconductors and PV identified here. For example, refutational texts could be developed and assessed to see if they can effectively promote positive conceptual change for emergent misconceptions. In that line, so too could be the use of arguments and argumentative discourse. And additionally, studies could be constructed regarding the integration of both refutational texts and the development of both arguments and argumentation skills for the promotion of conceptual understanding of emergent phenomena similar to what was described in the implications section. Constructing interventions to promote conceptual change for emergence has much larger implications than just promoting conceptual understandings for phenomena in engineering that present features of emergence. These studies could add to the limited body of research in engineering education regarding intentional conceptual change specifically and could also aid in the development of promising interventions that could promote conceptual change for other content as well.

Conclusions

This research study demonstrated that undergraduate engineering students have misconceptions about the general mechanisms and emergent characteristics of the three fundamental emergent PV phenomena of diffusion, drift, and excitation. Through a written protocol and subsequent analysis specific general and emergent misconceptions were identified and were found to be prevalent. Even though some misconceptions observed here reflected misconceptions that have been reported in the literature about learning of semiconductors, physics, chemistry, or emergence, numerous additional misconceptions were observed and characterized for all three phenomena. General mechanism misconceptions typically reflected limited understandings of physics and chemistry, content that the participants learned prior to their undergraduate coursework. Misconceptions for the emergent characteristics of the phenomena were related to oversimplification of the phenomena. Overall, the present findings can be used as a launching point for additional research that helps assess current students learning as they study semiconductors and PV, as well as provide insight to educators teaching these courses.

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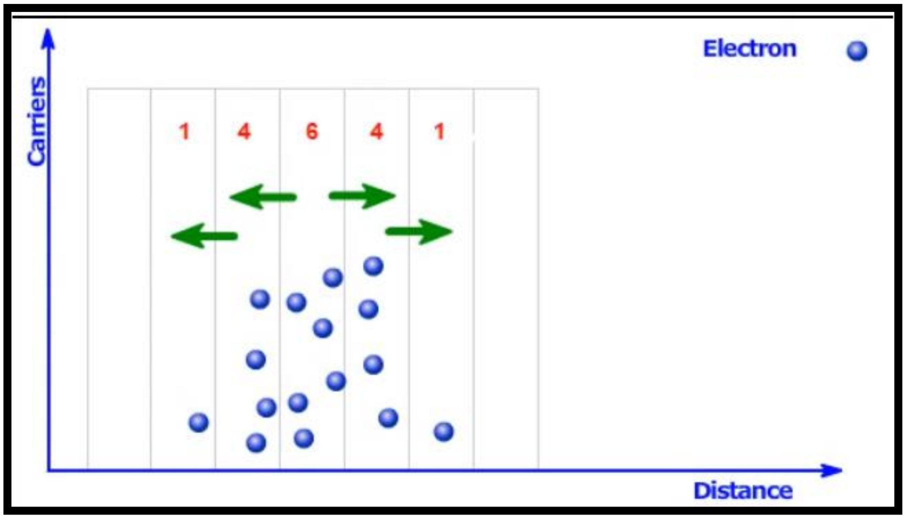
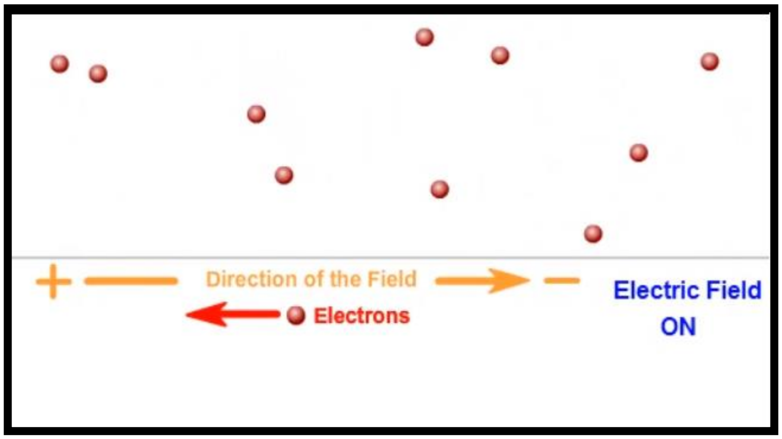
APPENDIX A

SIMULATION SCREEN SHOTS

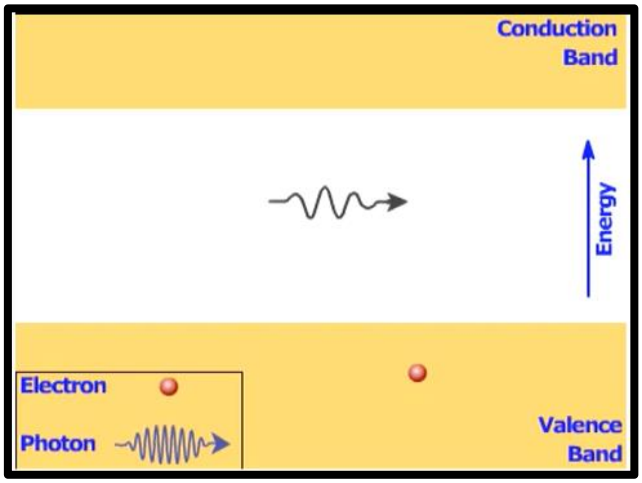
Diffusion



Drift



Excitation



APPENDIX B

SURVEY INSTRUCTIONS AND QUESTIONS

INSTRUCTIONS

In this study, you will be shown 3 video simulations of electrons and asked to answer some questions about them.

The questions require responses of a paragraph or two.

You will be asked similar and/or the same questions about three different phenomena. There are no right or wrong answers to these questions. The videos are complicated and people see different things in them. You may also know very little about what occurs in the animations. Just make your best estimate and do your best to answer each question with as much detail as you can.

You may notice that some of your answers are repetitive. This is ok. Just answer each question completely, even if this means repeating some of a previous response.

The entire task will take approximately 90 minutes. You may take a break between videos if you wish, but please complete a video before taking a break. When you are finished with the survey, raise your hand.

Animation 1

In this video, you will see a group of electrons in a solid material (a solar cell). These electrons move in interesting ways. Each electron is represented by a blue ball.

Please watch the video carefully, and prepare to describe the movement of the electrons.

(watch simulation 1st time)

Let's watch it again.

In this video, you will see a group of electrons in a solid material (a solar cell). These electrons move in interesting ways. Each electron is represented by a blue ball.

Please watch the video carefully, and prepare to describe the movement of the electrons.

(watch simulation 2nd time)

1. Describe the movement of the electrons in the solar cell. Use as much detail as possible.

2. Based on your knowledge of physics and electrons, what determines how and where the electrons move in the solar cell? Use as much detail as possible.

3. Imagine electrons, in a similar solar cell, under the same scenario, moving again. How similar do you think the movement of the electrons would be to what you observed in the video? Please choose one answer, your best estimate.

[==|============|============|==========|==========]

very similar	somewhat similar	somewhat dissimilar	very dissimilar

4. What do you know about electron movement inside a material that made you answer that way? Use as much detail as possible.

5. Is the movement of the electrons in the material random?

[==|===========|============|=========|========]

definitely yes	probably yes	probably not	definitely not

6. What do you know about electron movement inside a material that made you answer that way? Use as much detail as possible.

7. Is the movement of the electrons in the material rule based?

```
[==|===========|============|=========|=========]
definitely        probably           probably     definitely
yes                 yes                not          not
```

8. What do you know about electron movement inside a material that made you answer that way? Use as much detail as possible.

Animation 2

In this video, you will see a group of electrons in a solid material (a solar cell). Initially, there is not electric field applied to the solar cell. Approximately 8 seconds into the animation, the electric field gets turned on. The electrons move in interesting ways under both conditions. Each electron is represented by a red ball.

Please watch the video carefully, and prepare to describe the movement of the electrons when the electric field is off and when the electric field is on.

(watch simulation 1st time)

In this video, you will see a group of electrons in a solid material (a solar cell). Initially, there is not electric field applied to the solar cell. Approximately 8 seconds into the animation, the electric field gets turned on. The electrons move in interesting ways under both conditions. Each electron is represented by a red ball.

Please watch the video carefully, and prepare to describe the movement of the electrons when the electric field is off and when the electric field is on.

(watch simulation 2nd time)

9. Describe the movement of the electrons in the solar cell. Use as much detail as possible.

10. Based on your knowledge of physics and electrons, what determines how and where the electrons move in the solar cell when the electric field is off? Use as much detail as possible

11. Based on your knowledge of physics and electrons, what determines how and

where the electrons move in the solar cell when the electric field is on? Use as much detail as possible.

12. Imagine electrons, in a similar solar cell, under the same scenario, moving again. How similar do you think the movement of the electrons would be to what you observed in the video when the electric field is off? Please choose one answer, your best estimate.

[==|============|============|==========|=========]
very somewhat somewhat very
similar similar dissimilar dissimilar

13. What do you know about electron movement inside a material that made you answer that way? Use as much detail as possible.

14. Imagine electrons, in a similar solar cell, under the same scenario, moving again. How similar do you think the movement of the electrons would be to what you observed in the video when the electric field is on? Please choose one answer,

your best estimate.

[==|============|============|==========|==========]
very somewhat somewhat very
similar similar dissimilar dissimilar

15. What do you know about electron movement inside a material that made you answer that way? Use as much detail as possible.?

16. Is the movement of the electrons in the material random?

[==|===========|============|=========|==]
definitely probably probably definitely
yes yes not not

17. What do you know about electron movement inside a material that made you answer that way? Use as much detail as possible.

18. the electrons in the material rule-based?

[==|===========|============|=========|========]
definitely probably probably definitely

yes yes not not

19. What do you know about electron movement inside a material that made you answer that way? Use as much detail as possible.

Animation 3

In this video, you will see an electron in a solid material (a solar cell). The electron moves in interesting ways. This solar cell is being hit with sunlight (in the form of photons). The electron is represented by a red ball. The photon is represented as a red or blue 'wiggly' arrow.

Please watch the video carefully, and prepare to describe the movement of the electron.

(watch simulation 1st time)

Let's watch it again.

In this video, you will see an electron in a solid material (a solar cell). The electron moves in interesting ways. This solar cell is being hit with sunlight (in the form of photons). The electron is represented by a red ball. The photon is represented as a red or blue 'wiggly' arrow.

Please watch the video carefully, and prepare to describe the movement of the electron.

(watch simulation 2nd time)

20. Describe the movement of the electrons in the solar cell. Use as much detail as possible.

21. Based on your knowledge of physics, what determines how and where the electron moves in the solar cell during each photon event? Please use as much detail as possible.

22. Based on your knowledge of physics, why does the electron move to the conduction band? Why does it move within the conduction band? Use as much detail as possible.

23. Imagine an electron, in a similar solar cell, under the same scenario, moving again. How similar do you think the movement of the electron would be to what you observed in the video during each photon event? Please choose one answer, your best estimate.

[==|============|============|==========|==========]
very somewhat somewhat very
similar similar dissimilar dissimilar

24. What do you know about electron movement inside a material that made you answer that way? Use as much detail as possible.

25. Based on your knowledge of physics, does an electron move in a solar cell if there are no photons?

[==|===========|============|=========|=========]
definitely probably probably definitely
yes yes not not

26. What do you know about electron movement that made you answer that way? Use as much detail as possible.

27. Is the movement of the electron in the material during the photon event rule-based?

[==|===========|============|=========|========]
definitely yes | probably yes | probably not | definitely not

28. What do you know about electron movement that made you answer that way? Use as much detail as possible.

Demographic Questions

29. What is your gender?
Male Female

30. What is your age?
18-24
25-34
35-44
45-54
55-64
65-74
75 or older

31. What is your engineering major?

32. What year are you in school?
Freshman
Sophomore
Junior
Senior

33. How many physics courses have you taken and passed?
1
2
3
4 or more

34. Are you currently enrolled in a physics course?
YesNo

35. What is the name of the highest level physics course you have taken or are currently enrolled in? If you haven't taken any physics courses, type NA in the response box.

36. How many material science courses have you taken and passed?
1
2
3
4 or more

37. Are you currently enrolled in a material science course?
YesNo

38. What is the name of the highest level material science course you have taken or are currently enrolled in? If you haven't taken any physics courses, type NA in the response box.

You have completed the survey. Thank you for your willingness to participate in our study.

APPENDIX C

PILOT STUDY CODEBOOK

Coding Instructions

The following codes represent misconceptions that can be applied to the written responses. Codes have been grouped according to phenomena: specifically different codes exist for each of the different phenomena. However, there is some coding overlap.

1. Code responses using the themed codes described below. Codes represent misconceptions – therefore, for a first pass, just code as misconception. Therefore, if the response has any of the codes below – code as misconception. If there are no codes to represent a response, it will be coded as 'absent of misconception.' These codes will be recorded in the excel sheet → spreadsheet : General Misconceptions Theme
2. Codes will be dichotomously coded in the excel sheet → spreadsheet: General misconceptions. Coded, such that if any coded misconceptions are represented in the written responses they will be coded as 1. If no codes exist then it will be coded as 'absent of a misconception' = 0. The uncodable code will be coded as an NA.
3. Take both the Likert response (where there is one) and narrative into account when coding. If the Likert response and narrative response conflict, code based on what you feel to be the participants' general idea
4. Code all responses from one participant in the order they were written. That is, go through all of the responses for participant 1, then move on to the responses for participant 2, and so on.
5. When finished with all of the participants in the condition(diffusion, drift, or excitation), go back to the first protocols and compare to later participants. Be sure that you were applying the codes the same way from the beginning to end, as people have a tendency to adjust their coding strategies as they go, if they're not careful.
6. Also, to maintain consistency, refer to code book frequently to make sure you don't stray from the code definition/description
7. If you find an item that is difficult to code, assign the dichotomous code as best you can, and star it for further discussion.
8. Try to code all responses in a condition within a few days; this improves consistency. However, don't try to do it all in a marathon session, as your accuracy will tend to suffer.

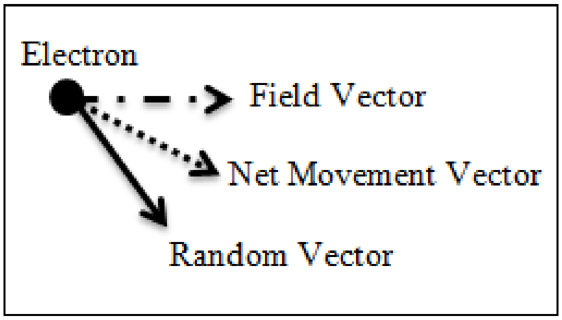
Once you have completed the coding for general misconceptions, go back through the responses and code for emergence misconceptions (which are represented by the letter (E) next to the coded general misconception theme name, and are listed under their own section at the end).

1. Codes responses using the themed codes described below for emergence. Codes represent emergence misconceptions. Therefore, if the response has any of the codes below – code as emergence misconceptions. More than one code can be applied to each response. If there are no codes to represent a response, it will be coded as ‘absent of emergence misconception.’ Alternatively, if the response is not codable – because it cannot be read or blank, code as uncodable. If no emergent misconception is present, and it is not uncodable, mark as “A” absent of emergent misconception. These codes will be recorded in the excel sheet → spreadsheet : E. Misconceptions Theme
2. Codes will be dichotomously coded in the excel sheet → spreadsheet: E. misconceptions D. Coded, such that if any coded misconceptions are represented in the written responses they will be coded as 1. If no codes exist then it will be coded as ‘absent of an emergent misconception’ = 0. The uncodable code will be coded as an NA.
3. Follow steps 3-8 mentioned above

Absent of misconceptions:

Diffusion: Diffusion is a random process, whereby the general pattern of dispersion is predictable, but the exact pattern, and the exact movement of the electrons is not. Electrons move because of quantum mechanics and ‘physical’ interactions with the electrons when they bump into them. They will move randomly. The pattern only appears to be from areas of high concentration to low concentration because of the small and constant interactions of the electrons. These interactions have nothing to do with repulsion → that is, the interaction of the electrons is purely ‘physical’ such that only. The electrons still carry out simple rules: they are constantly in motion, and by nature of this, will interact with other electrons physically.

Drift: This is the same exact thing as diffusion, however, there is one more additional rule placed on the system: the electric field vector. When an electron gets ‘physically’ hit by another electron, the resultant net movement vector is made of up the random vector from the physical hit, and the electric field vector. The field vector is not stronger than the random vector – as shown below:



Again, the process is random, whereby the general pattern of dispersion towards the + direction (opposite the electric field) is predictable, but the exact pattern, and the exact movement of the electrons is not. The electrons still carry out simple rules: they are constantly in motion, the electric field ‘pulls’ them in a certain direction, and by nature of these two things, will interact with other electrons physically.

Excitation:

When a photon penetrates a solar cell, it can excite an electron to a higher energy state if the photon has enough energy. The specific electron it hits is random and further, electron movement isn’t just confined to exciting to a higher energy level (electrons are always in constant random motion within the different bands). It is best if the response doesn’t describe a ‘specific’ electron move, but rather refers to it in a more general way: the electron can move, electrons can move to higher energy levels if, etc. Further, the overall pattern would be similar, in that electrons do get excited to the higher energy levels if a photon with enough energy penetrates the cell and comes in contact with the solar cell. However, the specifics of the pattern (what electrons play a role) and where it jumps to within the conduction band would vary. Therefore, the pattern isn’t predictable.

Diffusion General Misconception Themes

Code: Fields
Description: Specifies that the electron movement or behavior is the result of an electric field or a magnetic field
Exemplar: “The Movement of an electron is dependent upon the electric field forces and magnetic field forces acting upon it”

Code: Charges
Description: Refers to electron movement as being the result of either the attractive forces of a positive charge (sometimes referred to as proton), or the repulsive force of a negative charge (sometimes referred to as an electron) because like charges repel and opposite charges attract. This is at an atomic level (where charges are associated with atomic principles)
Exemplar: “Electrons are negative charges, and as a result of this they will repel each other because of the principle of like charges repelling and opposite charges attracting”

Code: Material Properties and Configuration
Description: This is a circuits perspective whereby electron movement is dictated by solar cell’s terminals (positive terminal and negative terminal) and or current. Movement occurs such that electrons move toward the positive ends of the cells, which is influenced by the potential difference between the + and – end, as well as the conductivity of the material
Exemplar: “Electrons move based on electric potential as well as the composition of the material they are in”

Code: Predictable (E)
Description: The electron movement (micro) will be similar/the same if the scenario were re-run. Justification of similarity at a micro could be linked to the “fields,” “charges,” and “Material Properties and Configuration” themes.
Exemplar: “ if the conditions of the scenario are the same, then the electrons will behave similarly if not exactly the same as they did in the first animation”

Code: Random Atomic
Description: Randomness of the electrons is associated with its movement around an atomic (path, orbit, cloud), not at a material level (when the electron is free)
Exemplar: “I know that electrons were once believed to follow a certain path around the

nucleus of atoms or molecules, but now it is believed that they simply "float" around in an electron cloud, going any which way they desire. Given this information, it does not seem likely that the electrons would work "together" in such a way that was shown in the animation. I answered somewhat similar because the electrons will definitely disperse from being so close together, but the fact that they moved so uniformly seems too idealistic and does not seem like it is a real-world scenario.”

Code: Not-Random (E)
Description: Electron movement as a whole pattern considered not random because of the laws/rules of physics, “fields,” “charges,” and “material properties and configuration” **Note that even though they may say that electrons are moving at random (which is correct), if they say then can be controlled by other things (charges, e-fields, etc.) it is still incorrect and would qualify as saying that the whole pattern is not random.
Exemplar: “No it is not completely random in that you know they will move from higher potential to lower potential, but the specific path of each electron probably is”

Code: Random
Description: Even though the electron movement is described as random, the justification for the randomness is incorrect related to ‘charges-like’ themes, ‘electric-fields-like’ themes, uniform distribution, steady state, ‘material properties and configuration,’ etc.
Exemplar: “I know the in the material electrons move randomly because they s no attractions inside”

Code: Not Rules
Description: There aren’t rules to explain electron movement
Exemplar: “Not exactly sure what rule based is, but I would guess no. I wouldnt think that theres a formula to predict electrons paths...

Code: Rules
Description: Electron movement occurs based on the laws/rules of physics which are dictated by “fields,” “charges,” and “material properties and configuration” **Note that if they state that an e-field will cause the electrons to move a certain direction, it is a misconception if they are absolute about it (i.e. the electron will move randomly unless there is a force), whereas it is correct if they say they refer to e-field

movement using words like ‘overall’ or “generally”, etc.
Exemplar: “Most electron movement follow physical rules. Electrons can't move when there are no charges, thus there is no force of attraction. Since, electrons have a property of negative charge, anything must follow this universal rule. Otherwise, the law would be violated.”
Code: Volition
Description: Describes the behavior or movement of electrons as being intentional. Statements should contain language that reveal electrons intentionality (wants to, tries to, needs to, chooses, intended to, tends to, behaves, etc.)
Exemplar: “When it is off the electrons are always random looking for something to attract to. With no charge no attraction and randomization occurs.”

Drift General Misconception Themes

Code: Explicitly Fields
Description: Specifies that the electron movement or behavior is the result of an electric field or a magnetic field, but doesn’t note the presence of ‘randomness.’ Electrons will move opposite to the electric field direction because of the polarity of the electric field, potential difference, or due to charges. **Note, if they describe the e-field as overcoming the other forces, interactions, etc. then it will qualify here.
Exemplar: “Electrons will move in the opposite direction of the electric field. Therefore, the electric field was pointing from left to right because the electrons were flowing to the left. Electrons flow from low potential to high potential. (- to +).”

Code: Direction
Description: Specifies that the electron movement or behavior is the result of an electric field or a magnetic field, but doesn’t note the presence of ‘randomness.’ Electrons will move in the direction of the electric field direction because of the polarity of the electric field, potential difference, or due to charges. (incorrect direction → towards – or says that electrons are moving in the direction of the electric field)
Exemplar: “When the electric field is on, the electric field acts as a pathway of electron movement. These electrons try to attract to the negative side of the electric field. this result in an order movement of electrons when the field is on.”

Code: Charges Present
Description: Refers to electron movement as being the result of either the attractive

forces of a positive charge (sometimes referred to as proton), or the repulsive force of a negative charge (sometimes referred to as an electron) because like charges repel and opposite charges attract. This is at an atomic level (where charges are associated with atomic principles)
Exemplar: “The only determination of the movement of the electrons when the electric field is off is the forces due to the other electrons. An electron that is not close to others at any moment in time will continue to move in the direction it is headed. However, when it gets close to another electron, the forces between the two electrons will reflect them away from each other as they are both carriers of the same charge.”

Code: Charges/ E-field Not Present
Description: Refers to electron movement as being the result of either the attractive forces of a positive charge (sometimes referred to as proton), or the repulsive force of a negative charge (sometimes referred to as an electron) because like charges repel and opposite charges attract. This is at an atomic level (where charges are associated with atomic principles). However, without the presence of the charges or electric field, they will move randomly
Exemplar: “Based on my knowledge when electric field is off. The electrons moves randomly because there is no attractions among. There is no positive or negative charges around.”

Code: Material Properties and Configuration
Description: This is a circuits perspective whereby electron movement is dictated by solar cell’s terminals (positive terminal and negative terminal). Movement occurs such that electrons move toward the positive ends of the cells, which is influenced by the potential difference between the + and – end, as well as the conductivity of the material
Exemplar: “When the electric field is off, the electrons move from negative to positive polarity.”

Code: External
Description: Movement can be influenced by the barriers of the cell or by where they are released (and at what force they are released).
Exemplar: “Therefore, for the most part, the electrons moved in the direction from where they were released, so they moved to the left.”

Code: Predictable (E)
Description: The electron movement at an electron level (micro level) will be similar/the same if the scenario were re-run. If justified (doesn’t have to be) justification of

similarity at a group level is linked to the “fields,” “charges,” and “Material Properties and Configuration” themes. ** Randomness can be similar if justified along the lines of the repeat scenario (i.e. both scenarios would be random, and therefore similar along the lines of similarity) → otherwise, if noted similar but ‘randomness manner’ not described, then code as predictable ** Noting a general pattern from – to + would be considered correct (do not code as a misconception).
Exemplar: “Technically, I think that the electrons will move in exactly the same way as long as they are placed in exactly the same starting positions, if they are not placed in exactly the same starting position, then they will have a completly different movement pattern as the forces that they feel from the different directions will be slightly different. However, no matter where the electrons are placed in the cell they will still be governed by the same physical laws.”

Code: Random Atomic
Description: Randomness of the electrons is associated with its movement around an atomic (path, orbit, cloud), not at a material level (when the electron is free)
Exemplar: “The electron movement is random, but once the electric field is turned on you can get a general idea of where they are headed. With no outside influence, the electrons simply hover about in their cloud, bouncing freely left, right, up, and down.”

Code: Not Random Electric Field (E)
Description: Electron movement as a whole pattern is considered not random because of the electric field. Likely to make an assumption that an e-field creates a path, directionality, etc. However, note that without the e-field, things would be random. Also, do not explicitly state that the electrons move randomly. Look for key words such as “all electrons,” or “control direction,” etc.
Exemplar: “When the electric field is turned on, the electrons will move towards the positive side of the electric field so they will not be random. When the electric field is turned off, the electrons will indeed move in random directions since there is no force being applied to it.”

Code: Not-Random (E)
Description: Electron movement as a whole pattern is considered not random because of the strength of randomness, laws/rules of physics, “charges,” and “material properties and configuration”, or that randomness is not a rule (thus, they describe randomness not being a rule that the electrons ‘follow’) **Note that randomness = a rule

Exemplar: “No its is not random because there are laws that govern the movement of electrons and these laws cannot be broken. The elctrons will feel forces in all different directions and will go in the same direction as the largest force. This is not a random movement as random would mean that they just go wherever they feel like going at the time.”

Code: Random
Description: Even though the electron movement is described as random, the justification for the randomness is incorrect related to ‘charges-like’ themes, ‘electric-fields-like’ themes, uniform distribution, steady state, ‘material properties and configuration,’ ‘external,’ etc.
Exemplar: “No its is not random because there are laws that govern the movement of electrons and these laws cannot be broken. The elctrons will feel forces in all different directions and will go in the same direction as the largest force. This is not a random movement as random would mean that they just go wherever they feel like going at the time.”

Code: Rules
Description: Electron movement occurs based on the laws/rules of physics .
Exemplar: “ As far as rules, none that I know of. But I'm sure that there are rules that can tell you how much and electron will move in an electric field. There has to be some rule or law that states they they will always move to a positive charge.”

Code: Incorrect Rules
Description: Rules specified are incorrect in that they adhere to the themes of justification for the randomness is incorrect related to ‘charges-like’ themes, ‘electric-fields-like’ themes, uniform distribution, steady state, ‘material properties and configuration,’ ‘external,’ etc.
Exemplar: “There are rules for how electrons act when they come in contact with each other as well as when they come in contact with electric fields. When they come in contact with each other, they will want to get away from each other, and when they are in an electric field where the positive end is to the left, they will want to try to get to the left because opposite charges attract.”

Code: Volition
Description: Describes the behavior or movement of electrons as being intentional. Statements should contain language that reveal electrons intentionality (wants to, tries to, needs to, chooses, intended to, behaves, etc.)

Exemplar: “If the field is on they move in a certain direction but it is off then again they act to fix unbalanced charges in the material.”

Excitation General Misconception Themes

Code: Attractive
Description: Photons or the bands (conduction or valence) will attract the electrons (such that they are ‘charged’ positive or negative, or have a polarity). Strength of attraction plays a role. There is likely a specification of ‘the’ electron versus electrons in general.
Exemplar: “I do not know anything about photons, however, I do know than an electron would only move towards something if it was attracted to it or if it was already moving in the direction of the object. Since the electron was initially stationary, that means that it must have been attracted to the blue and red photon and neither attracted nor repulsed by the black photon. The blue photon must have had a higher attractive force than the red photon though because it caused the electron to move higher.”

Code: Incorrect Excitation
Description: Electron moves to a lower energy state
Exemplar: “I would go with the excitement of the electron and it jumping to a lower state of energy”

Code: Fields
Description: The photon creates a magnetic or electric field. Movement occurs as a result of the e-field/m-field. There is likely a specification of ‘the’ electron versus electrons in general.
Exemplar: “The electric field that is created by the photon.”

Code: Material Properties and Configuration
Description: Material conductance allows electron movement, polarity, solar cell configuration, etc. There is likely a specification of ‘the’ electron versus electrons in general.
Exemplar: “The photon creates an electric field that makes it move from one to another, and electrons always move freely in a conducor.”

Code: Predictable (E)

Description: The specific electron movement will be similar/the same (not noting the overall pattern of electron/(s)) if the scenario were re-run. May or may not justify why. If they do, justification of similarity at a group level is linked to the “attractive,” “photon fields,” and “Material Properties and Configuration” themes as well as its obeying laws of physics. There is likely a specification of ‘the’ electron versus electrons in general.
Exemplar: “I think that the movement would be very similar because the electron is just going to sit there until the photon passes it and depending on the color of the photon that passes it it will do different things. Although the electron will always do the same thing when the same color photon passes over it.”

Code: Movement
Description: No movement unless there is an event or ‘force’ of any kind acting on the electron. (Force could be another electron, charge, e-field, etc.). If movement is linked directly to the photon – the photon could be the only reason for why there is movement. Further, may state that only high energy photons will cause the electron to move. **Note that electrons are always moving, unless temperature is absolute zero. Electrons can move to the conduction band at higher temperatures (that’s the whole point of a semiconductor)
Exemplar: “So I would guess that there has to be some sort of event to make the movment occur, like a photon.”

Code: Incorrect Movement
Description: Electrons will always move because of various forces, repulsion, attraction, electric /magnetic fields, polarity, photons, or refer to movement within atomic or molecular means (shells).
Exemplar: “Althought the electrons may not move from valence to conduction band, they still move wherever they are located because of repelling forces. Even at equilibrium, the electrons are moving back and forth although their net movement is zero.”

Code: Rules
Description: Electron movement occurs based on the laws/rules of physics .
Exemplar: “ Physics is a science of laws and rules, everything that happens in life is due to some rule based theorem and I believe that this photon event is also rule based.”

Code: Incorrect Rules

Description: Rules specified are incorrect in that they adhere to the themes of “attractive,” “photon fields,” and “Material Properties and Configuration,” because of similarity, or because electrons only respond to high energy photons.
Exemplar: “Electrons moves towards the positive charge or away from other negative charges. During a photon event, the electron is blasted by the photons randomly so the movements of the electrons will be random.”

Code: Concept of Energy
Description: Energy is lost, gained, or created (it is not transferred) when the electron moves to a higher energy level and/or back down. May refer to bands as having a certain amount of energy. Confuse wavelength and frequency, time for energy to be lost is described as short, bands have certain amounts of energy, or that photons have ‘positive’ energy.
Exemplar: “In order for an electron to move from valence to conduction bands, it requires energy from an outside source. The photons here provide the energy for the electron movement. The valence band contains the least amount of energy, so in the absence of photon input, the electron will stay in the valence band because of its lack of energy.”

Code: Volition
Description: Describes the behavior or movement of electrons as being intentional. Statements should contain language that reveal electrons intentionality (wants to, tries to, needs to, chooses, intended to, behaves, etc.)
Exemplar: “The most stable state is the preferred location of the electron”

Emergence Misconceptions (use these in addition to those marked with an (E) above).

Code: Non-cooperative
Description: The electrons work together to create the pattern
Exemplar: “The Electrons moved in such a way that caused them to be uniformly distributed throughout the cell”

Code: Goal Directed
Description: Describes intentional behavior or movement of electrons as being performed to meet a certain purpose or goal w/in associated with the emergence movement pattern.
Exemplar: “It’s rules based in the sense that if two electrons get near each other, they are going to want to move apart”

Code: Irreducibility
Description: The emergent properties are being accounted for at the level of the interacting electrons. **The properties should be explained at a higher level.
Exemplar: “Once put into motion, the electron moves to the boundary of the material, or until it comes in proximity of another electron that then causes a repulsive force causing the direction of the electron to change”

Code: Centralized Control
Description: Reference to a specific factor directing, leading, guiding, or having ‘bound’, etc. the electrons to carry out certain actions.
Exemplar: “they will go wherever the repulsive forces direct them towards”

Code: Causality
Description: Describe a causal direct factor for the observed macro pattern. Likely no mention of the emergent pattern resulting from the interactions of the individual electrons. **Think of this as electrons move in a certain pattern because of a certain factor. **Pattern can be deduced when they describe numerous entities (electrons)
Exemplar: “Electrons will move in the opposite direction of the electic field. Therefore, the electric field was pointing from left to right because the electrons were flowing to the left. Electrons. Electrons flow from low potential to high potential.(- to +)”

Code: Predictability Change
Description: One large change in the system at the start will cause a large change in the system as a whole. One small change in the system at the start will cause small change in in the system.
Exemplar: “Technically, I think that the electrons will move in exactly the same way as long as they are placed in exactly the same starting positions, if they are not placed in exactly the same starting position, then they will have a completly different movement pattern as the forces that they feel from the different directions will be slightly different.”

Code: Not-Random
Description: Electron movement overall is considered not random – or is specifically states as such **Note that this code doesn’t apply unless it is specifically brought up.
Exemplar: “No its is not random because there are laws that govern the movement of

electrons and these laws cannot be broken. The elctrons will feel forces in all different directions and will go in the same direction as the largest force. This is not a random movement as random would mean that they just go wherever they feel like going at the time.”

Code: Predictable
Description: The specific electron movement will be similar/the same (not noting the overall pattern of electron/(s)) if the scenario were re-run.
Exemplar: “I think that the movement would be very similar because the electron is just going to sit there until the photon passes it and depending on the color of the photon that passes it it will do different things. Although the electron will always do the same thing when the same color photon passes over it.”

APPENDIX D

FULL STUDY CODEBOOK

Coding Instructions

The following codes represent misconceptions that can be applied to the written responses. Codes have been grouped according to phenomena: specifically different codes exist for each of the different phenomena. However, there is some coding overlap.

1. Code responses using the themed codes described below. The first group of codes represent misconceptions. Therefore, if the response has any of the codes below – check the box for that misconception for each of the questions for each of the phenomena. More than one code can be applied to each response. This will be done for each participant's responses. If the response is not codable – because it cannot be read or blank, code as uncodable. If the response is correct then leave as blank. These codes will be recorded in the excel sheet → spreadsheets : General Misconceptions Version A and General Misconceptions Version B.
2. Take both the Likert response (where there is one) and narrative into account when coding. If the Likert response and narrative response conflict, code based on what you feel to be the participants' general idea
3. If the response to the question doesn't make sense, refer back to the question being asked to see if that adds clarity to their response
4. When you code something that mentions other possible related codes, mark that code as well.
5. Code all responses from one participant in the order they were written for each condition (for both versions, code all diffusion, followed by drift, followed by excitation). That is, go through all of the responses for participant 1, then move on to the responses for participant 2, and so on.
6. When finished with all of the participants in the condition (diffusion, drift, or excitation), go back to the first protocols and compare to later participants. Be sure that you were applying the codes the same way from the beginning to end, as people have a tendency to adjust their coding strategies as they go, if they're not careful.
7. Also, to maintain consistency, refer to code book frequently to make sure you don't stray from the code definition/description
8. If you find an item that is difficult to code, assign it as best you can, and star it for further discussion.
9. Try to code all responses in a condition within a few days; this improves consistency. However, don't try to do it all in a marathon session, as your accuracy will tend to suffer.

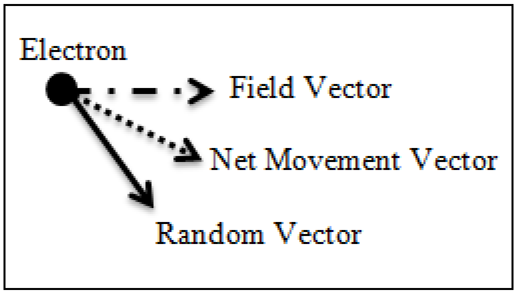
Once you have completed the coding for general misconceptions, go back through the responses and code for emergence misconceptions (which are listed under their own section at the end). Note that some of the codes have specific examples given for each of the conditions, where others do not. This is just meant to aid the coder – it does not imply that these codes are more specific to certain conditions.

1. Codes responses using the themed codes described below for emergence. Codes represent emergence misconceptions. More than one code can be applied to each response. This will be done for each participant's responses. If the response is not codable – because it cannot be read or blank, code as uncodable. If no emergent misconception is present, mark as "A" absent of emergent misconception. These codes will be recorded in the excel sheet → spreadsheets : Emergence Misconceptions Version A and Emergence Misconceptions Version B
2. Follow steps 3-8 mentioned above
3. Note: Excitation is a phenomenon that has certain features of emergence. Therefore, unless they talk about the phenomena paternistically, the coder should not try to apply these codes unless they are specifically asked (predictable and rules questions). Other codes may apply that do not speak of electron movement paternistically – volition, goal direction, and not-random.

Correct Conception:

Diffusion: Diffusion is a random process, whereby the general pattern of dispersion is predictable, but the exact pattern, and the exact movement of the electrons is not. Electrons move because of quantum mechanics and 'physical' interactions with the electrons when they bump into them. They will move randomly. The pattern only appears to be from areas of high concentration to low concentration because of the small and constant interactions of the electrons. These interactions have nothing to do with repulsion → that is, the interaction of the electrons is purely 'physical' such that only. The electrons still carry out simple rules: they are constantly in motion, and by nature of this, will interact with other electrons physically.

Drift: This is the same exact thing as diffusion, however, there is one more additional rule placed on the system: the electric field vector. When an electron gets 'physically' hit by another electron, the resultant net movement vector is made of up the random vector from the physical hit, and the electric field vector. The field vector is not stronger than the random vector – as shown below:



Again, the process is random, whereby the general pattern of dispersion towards the + direction (opposite the electric field) is predictable, but the exact pattern, and the exact movement of the electrons is not. The electrons still carry out simple rules: they are constantly in motion, the electric field 'pulls' them in a certain direction, and by nature of these two things, will interact with other electrons physically.

Excitation:

When a photon penetrates a solar cell, it can excite an electron to a higher energy state if the photon has enough energy. The specific electron it hits is random and further, electron movement isn't just confined to exciting to a higher energy level (electrons are always in constant random motion within the different bands). It is best if the response doesn't describe a 'specific' electron move, but rather refers to it in a more general way: the electron can move, electrons can move to higher energy levels if, etc. Further, the overall pattern would be similar, in that electrons do get excited to the higher energy levels if a photon with enough energy penetrates the cell and comes in contact with the solar cell. However, the specifics of the pattern (what electrons play a role) and where it jumps to within the conduction band would vary. Therefore, the pattern isn't predictable. Stronger, or higher energy photons have more energy and are more likely to excite an electron to the conduction band.

Diffusion Misconception Themes

Code: Fields
Description: Specifies that the electron movement or behavior is the result of an electric field or a magnetic field
Exemplar: "The Movement of an electron is dependent upon the electric field forces and magnetic field forces acting upon it"

Code: Amounts

Description: Specifies that the electron movement or behavior is the result of a concentration gradient, based on the number of electrons, and/or possibly how confined the electrons are (how closely packed).

*note: may refer to electrons or protons as carriers.

Exemplar: “At the start, the density of electrons is highest within the center of the cell and lowest at the edges. Therefore, the electrons move from the area of highest concentration to the area of lowest concentration.”

Code: Other Forces - gravity

Description: Specifies that the electron movement or behavior is the result of other forces not already specified, specifically gravity

Exemplar: “I believe that gravity has a huge effect on how and where the electron moves in the solar cell. Also, electric fields and energy play a major role as well.”

Code: Other Forces - energy

Description: Specifies that the electron movement or behavior is the result of other forces not already specified, specifically in terms of energy being a force (e.g. electron could be moving to different energy states, or looking for a stable state, etc.)

Exemplar: “I believe that gravity has a huge effect on how and where the electron moves in the solar cell. Also, electric fields and energy play a major role as well.”

Code: Solar Prime

Description: May describe electron movement or behavior in terms of photons, carriers, holes, energy levels, bands, and other solar cell descriptors/phenomena

Exemplar: “The interactions of the electrons with photons of light, other electrons, positively charged holes, and other electromagnetic forces will push or pull an electron in different directions.”

Code: Charges

Description: Refers to electron movement as being the result of either the attractive forces of a positive charge (sometimes referred to as proton or carrier), or the repulsive force of a negative charge (sometimes referred to as an electron or carrier) because like charges repel and opposite charges attract. This is at an atomic level (where charges are associated with atomic principles). May note that charges are additive (more like charges together equals greater force)

Exemplar: “Electrons are negative charges, and as a result of this they will repel each other because of the principle of like charges repelling and opposite charges attracting”

Code: Material Properties and Configuration
Description: This is a circuits/electricity/or material design or property perspective whereby electron movement is dictated by solar cell’s terminals (positive terminal and negative terminal) and or current (flow of electrons), sometimes using language associated with a device, or describes movement based on the shape of the material. Movement occurs such that electrons move toward the positive ends of the cells, which is influenced by the potential difference between the + and – end, as well as the conductivity of the material (some materials allow electrons to move more freely about).
Exemplar: “Electrons move based on electric potential as well as the composition of the material they are in”

Code: Atomic
Description: Confuse electron movement with bonding and overall atomic nuances (i.e. energy levels, orbitals, bands)
Exemplar: “Electorns flow form atom to atom, as one electon is picked up, one is released.”

Code: Predictable (E) - diffusion
Description: The electron movement (micro) will be similar/the same if the scenario were re-run. Justification of similarity required; justification at a macro could be linked to the “fields,” “charges,” and “Material Properties and Configuration” themes. **Note: Net, general pattern, overall movement (and other terms like this) indicate no misconception.
Exemplar: “ if the conditions of the scenario are the same, then the electrons will behave similarly if not exactly the same as they did in the first animation”

Code: Incorrect Predictable
Description: Correctly note that the movement of electrons is not predictable, but give incorrect justification for why – linked to other codes (e.g. charges, fields, etc.)
Exemplar: “Although the solar cells are similar yet not the same, the electrons in the solar cell will move in a different way because of the conductivity of the similar solar cell. Not all solar cells will have the same conductivity. Electrons always behave differently when under different conductivities.”

Code: Random Atomic
Description: Randomness of the electrons is associated with its movement around an atomic (path, orbit, cloud), not at a material level (when the electron is free), or due to the presence of many ‘forces’ acting on the electron(s).
Exemplar: “I know that electrons were once believed to follow a certain path around the nucleus of atoms or molecules, but now it is believed that they simply "float" around in an electron cloud, going any which way they desire. Given this information, it does not seem likely that the electrons would work "together" in such a way that was shown in the animation. I answered somewhat similar because the electrons will definitely disperse from being so close together, but the fact that they moved so uniformly seems too idealistic and does not seem like it is a real-world scenario.”

Code: Not-Random (E)
Description: Electron movement is considered not random. Justification may be linked to the laws/rules of physics, “fields,” “charges,” due to normal distribution observed, “pattern,” and “material properties and configuration.” Could also state that it is not random due to the fact that solar cells allow electrons to behave differently. **Note that even though they may say that electrons are moving at random (which is correct), if they say then can be controlled by other things (charges, e-fields, etc.) it is still incorrect and would qualify as saying that the whole pattern is not random.
Exemplar: “No it is not completely random in that you know they will move from higher potential to lower potential, but the specific path of each electron probably is”

Code: Pattern
Description: Electrons will move, possibly in a certain pattern, until they are uniformly laid out, come to steady state, or are equally spaced. **Note: If this is marked, it possibly indicates a link to not-random.
Exemplar: “Electron behavior is predictable in so much that they will keep moving randomly until they are at a steady state pattern.”

Code: Random
Description: Even though the electron movement is described as random, the justification for the randomness is incorrect related to ‘charges-like’ themes, ‘electric-fields-like’ themes, uniform distribution, steady state, ‘material properties and

configuration,’ etc.
Exemplar: “I know the in the material electrons move randomly because they s no attractions inside”

Code: Not Rules
Description: There aren’t rules to explain electron movement. May or may not justify using other codes (e.g. charges, material properties and configuration, etc.).
Exemplar: “Not exactly sure what rule based is, but I would guess no. I wouldnt think that theres a formula to predict electrons paths...

Code: Rules
Description: Electron movement occurs based on the laws/rules (sometimes described as physical laws that movement adheres to) which may be dictated by “fields,” “charges,” and “material properties and configuration.” May also use this to justify how the electron movement is not random. Further, may state that because electron movement isn’t random, there must be rules. **Note that if they state that an e-field will cause the electrons to move a certain direction, it is a misconception if they are absolute about it (i.e. the electron will move randomly unless there is a force), whereas it is correct if they say they refer to e-field movement using words like ‘overall’ or “generally”, etc.
Exemplar: “Most electron movement follow physical rules. Electrons can't move when there are no charges, thus there is no force of attraction. Since, electrons have a property of negative charge, anything must follow this universal rule. Otherwise, the law would be violated.”

Code: Uncodable
Description: No other codes apply. Blanks or unreadable responses should also receive this code. If response is correct, do not use this code.
Exemplar: “Based on my knowledge of physics and electros, what determine how and where the electrons move in the solar cell is reproduction.”

Drift Misconception Themes

Code: Fields
Description: Specifies that the electron movement or behavior is the result of an electric field or a magnetic field, but doesn’t note the presence of ‘randomness.’ Electrons will move in other directions than the electric field direction because of the polarity of the

electric field, potential difference, or due to charges (repulsion or attraction). Flow from positive to negative, or will move to the positively charged side of the e-field. The stronger the field, the stronger the pull from low to high potential.

**may note that electric field force overcomes other forces, rather than noting that the resultant of the two forces leads to the movement vector of the electron

Exemplar: “Electrons will move in the opposite direction of the electric field. Therefore, the electric field was pointing from left to right because the electrons were flowing to the left. Electrons flow from low potential to high potential. (- to +).”

Code: Incorrect Direction

Description: This is the same code as Fields except the direction of the movement resulting from the electric field is incorrect. Therefore, specifies that the electron movement or behavior is the result of an electric field or a magnetic field, but doesn’t note the presence of ‘randomness.’ May say Electrons will move in the direction of the electric field direction because of the polarity of the electric field, potential difference, or due to charges, or for no given reason. May also say that the electrons are moving from positive to negative). May also note the direction of the e-field is wrong (from high to low potential).

(incorrect direction → towards – or says that electrons are moving in the direction of the electric field)

Exemplar: “When the electric field is on, the electric field acts as a pathway of electron movement. These electrons try to attract to the negative side of the electric field. this result in an order movement of electrons when the field is on.”

Code: Charges Present

Description: Refers to electron movement as being the result of either the attractive forces of a positive charge (sometimes referred to as proton), or the repulsive force of a negative charge (sometimes referred to as an electron) because like charges repel and opposite charges attract. This is at an atomic/charge level (where charges are associated with atomic principles – electrons, carriers, protons, etc.). May also refer to unbalanced charges. Attraction or repulsion can only described as occurring between the charges/at the level of the charges.

**note, electromagnetic forces around a proton or electron are their charges.

Exemplar: “The only determination of the movement of the electrons when the electric field is off is the forces due to the other electrons. An electron that is not close to others at any moment in time will continue to move in the direction it is headed. However, when it gets close to another electron, the forces between the two electrons will reflect them away from each other as they are both carriers of the same charge.”

Code: Pattern
Description: Electrons will move, possibly in a certain pattern, until they are uniformly laid out, come to steady state, or are equally spaced. **Note: If this is marked, it possibly indicates a link to not-random.
Exemplar: “It appears that the movement of the electrons from top to bottom is randomized but when the electron field is turned on the movement from left to right is somewhat uniform”

Code: Random – Charges/E-field not present
Description: Refers to electron movement as being the result of either the attractive forces of a positive charge (sometimes referred to as proton), or the repulsive force of a negative charge (sometimes referred to as an electron) because like charges repel and opposite charges attract. This is at an atomic level (where charges are associated with atomic principles). However, without the presence of the electric field, charges are not present, and as a result, the electrons move randomly.
Exemplar: “Based on my knowledge when electric field is off. The electrons moves randomly because there is no attractions among. There is no positive or negative charges around.”

Code: Material Properties and Configuration
Description: This is a circuits/electricity perspective whereby electron movement is dictated by solar cell’s terminals (positive terminal and negative terminal), current (flow of electrons), and materials properties, sometimes using language associated with a device. Movement occurs such that electrons move toward the positive ends/ toward the positive charged area of the cell, which is influenced by the potential difference between the + and – end, as well as the conductivity of the material, thermal factors, density, etc.
Exemplar: “When the electric field is off, the electrons move from negative to positive polarity.”

Code: Energy
Description: Describe movement in terms of energy states, conservation of energy, or stable states (whereby electrons are seeking to find the most stable form or to become grounded)
Exemplar: “concervation of energy causes the electrons to change velocity when they run

into each other or the wall. something about free electrons.”

Code: Polarity
Description: Confuse potential with polarity in terms of electric fields and electron movement.
Exemplar: “Electrons will flow from low polarity to high polarity and thus flow against the gradient of the electric field”

Code: Solar Prime
Description: May describe electron movement and/or behavior in terms of photons, carriers, holes, atomic structures, energy bands, energy states, energy gradients, energy levels, etc.
Exemplar: “The flow of atoms in on the outside of the a couducing materal were electorns are free to flow, and not blocked by the atomic/crystal stuctor of the materail.”

Code: External
Description: Movement can be influenced by the barriers of the cell or by where they are released (and at what force they are released).
Exemplar: “Therefore, for the most part, the electrons moved in the direction from where they were released, so they moved to the left.”

Code: Random Atomic
Description: Randomness of the electrons is associated with its movement around an atomic (path, orbit, cloud), not at a material level (when the electron is free)
Exemplar: “The electron movement is random, but once the electric field is turned on you can get a general idea of where they are headed. With no outside influence, the electrons simply hover about in their cloud, bouncing freely left, right, up, and down.”

Code: Predictable (E)
Description: The electron movement at an electron level (micro level) will be similar/the same if the scenario were re-run. Some justification required; justification of similarity at a group level could be linked to the “fields,” “charges,” and “Material Properties and Configuration” themes. ** Randomness can be similar if justified along the lines of the repeat scenario (i.e. both scenarios would be random, and therefore similar along the lines of similarity) → otherwise, if noted similar but ‘randomness manner’ not described, then code as predictable

** Noting a general pattern from – to + would be considered correct (do not code as a misconception).
Exemplar: “Technically, I think that the electrons will move in exactly the same way as long as they are placed in exactly the same starting positions, if they are not placed in exactly the same starting position, then they will have a completly different movement pattern as the forces that they feel from the different directions will be slightly different. However, no matter where the electrons are placed in the cell they will still be governed by the same physical laws.”

Code: Not Random Electric Field (E)
Description: Electron movement is considered not random because of the electric field. Likely to make an assumption that an e-field creates a path, directionality, etc. However, note that without the e-field, things would be random. Also, do not explicitly state that the electrons move randomly. Look for key words such as “all electrons,” or “control direction,” etc.
Exemplar: “When the electric field is turned on, the electrons will move towards the positive side of the electric field so they will not be random. When the electric field is turned off, the electrons will indeed move in random directions since there is no force being applied to it.”

Code: Not-Random (E)
Description: Electron movement is considered not random because of the strength of randomness, laws/rules of physics, “charges,” and “material properties and configuration”, that randomness is not a rule (thus, they describe randomness not being a rule that the electrons ‘follow’), or that there are things that factor in to controlling the movement. **Note that randomness = a rule
Exemplar: “No its is not random because there are laws that govern the movement of electrons and these laws cannot be broken. The elctrons will feel forces in all different directions and will go in the same direction as the largest force. This is not a random movement as random would mean that they just go wherever they feel like going at the time.”

Code: Random
Description: Even though the electron movement is described as random, the justification for the randomness is incorrect related to ‘charges-like’ themes, ‘electric-fields-like’ themes, uniform distribution, steady state, ‘material properties and configuration,’ ‘external,’ etc.
Exemplar: “No its is not random because there are laws that govern the movement of

electrons and these laws cannot be broken. The elctrons will feel forces in all different directions and will go in the same direction as the largest force. This is not a random movement as random would mean that they just go wherever they feel like going at the time.”

Code: Not Rules
Description: There aren’t rules to explain electron movement. May or may not justify using other codes (e.g. charges, material properties and configuration, etc.).
Exemplar: “The movement of electron in the material kind of random so it’s not like a rule-based movement.”

Code: Rules
Description: Electron movement occurs based on the laws/rules of physics (and/or specified by physics) .
Exemplar: “ As far as rules, none that I know of. But I'm sure that there are rules that can tell you how much and electron will move in an electric field. There has to be some rule or law that states they they will always move to a positive charge.”

Code: Incorrect Rules
Description: Rules specified are incorrect in that they adhere to the themes of justification for the randomness is incorrect related to ‘charges-like’ themes, ‘electric-fields-like’ themes, uniform distribution, steady state, ‘material properties and configuration,’ ‘external,’ etc.
Exemplar: “There are rules for how electrons act when they come in contact with each other as well as when they come in contact with electric fields. When they come in contact with each other, they will want to get away from each other, and when they are in an electric field where the positive end is to the left, they will want to try to get to the left because opposite charges attract.”

Code: Uncodable
Description: No other codes apply. Blanks or unreadable responses should also receive this code. If response is correct, do not use this code.
Exemplar: “The movement of electrons would not be affected very much since there is the electric field is off”

Excitation Misconception Themes

Code: Charges

Description: Photons, bands (conduction or valence), electrons, holes, magnetic (fields), or material property (holes –localized negatively charged materials) will attract or repel the electrons (such that they are ‘charged’ positive or negative, or have a polarity). Strength of attraction plays a role. May also say that the electron move towards the photon. There is likely a specification of ‘the’ electron versus electrons in general. At both an atomic and material level.

Exemplar: “I do not know anything about photons, however, I do know than an electron would only move towards something if it was attracted to it or if it was already moving in the direction of the object. Since the electron was initially stationary, that means that it must have been attracted to the blue and red photon and neither attracted nor repulsed by the black photon. The blue photon must have had a higher attractive force than the red photon though because it caused the electron to move higher.”

Code: Atomic versus Bound

Description: Do not understand the difference between bonded atoms and singular atoms in space. As such, describe electron movement in terms of atomic theory (orbitals and localized attraction to the nucleus, interchange valence band with valence electron/valence orbital, describe movement of electron in terms of electron movement within the atomic orbital). Do not understand that the electron has been ‘freed’ from a bond. May also refer to electron structure (in terms of the atom). May use the term electronegativity.

Exemplar: “An electron with a high enough energy will leave the valence band of an atom and orbit further from the positively charged nucleus.”

Code: Energy vs. Physical

Description: Overall notion that blends energy movement with a physical movement of electrons. Is linked with ‘physical’ movement (attraction etc.) and could use terms like force, or use terms of ‘where’ in terms of where the electron moves to, or use terms like direction.

*Electrons do not move within energy ‘space’

Exemplar: “Electrons are always moving randomly, so there could be a chance that the electron jumps to another band without the photon energy”

Code: Incorrect Excitation

Description: Electron moves to a lower energy state

Exemplar: “I would go with the excitement of the electron and it jumping to a lower state of energy”

Code: Incorrect Photon

Description: Mechanism of photon is incorrectly described (ie inversely described such that high energy photons lead to energy loss of the electron). Photons are improperly described in that the energy of the photons in relation to others is incorrect, creates a current, or that higher energy leads to limited movement, or that they have a specific charge which increases or decreases energy (sometimes confused with proton), or they can change the charge of a band.

*note: Photons excite the electrons. Electrons will jump to a higher energy level (conduction band), if the photon has enough energy to excite the electron to that level.

Exemplar: “Violet light has the shortest wavelength of visible light and therefore also has the highest corresponding energy level when depicted as an arrow. When this high energy photon passed through the soalr cell, the electron remained stationary in the valence band. Blue light has a longer wavelength than violet light and therefore the corresponding photon has less energy than that of its violet counterpart. When this lower energy photon traveled through the solar cell, the electron was pulled across the gap rom the valence band to the conduction band, perhaps because the lower wavelength and energy of the blue light in comparison to the violet light. ”

Code: More Photons

Description: More (many) photons dictate electron movement to the conduction band

Exemplar: “electrons moved in the solar cell during each photon event determine by how often the photons hit the solar cell. The more more often the photon, stronger sunlight, more electrons jumping from the valence band to the conduction band and thus result in more energy.”

Code: Fields

Description: The photon creates a magnetic or electric field, or use the term potential. Movement occurs as a result of the e-field/m-field. May also There is likely a specification of ‘the’ electron versus electrons in general.

Exemplar: “The electric field that is created by the photon.”

Code: Material Properties and Configuration

Description: Material conductance and properties allow electron movement to conduction band, current, solar cell configuration (negative and positive sides(holes and electrons)), etc. There is likely a specification of ‘the’ electron versus electrons in general. Confuse conductor with conduction band.

Exemplar: “The photon creates an electric field that makes it move from one to another, and electrons always move freely in a conducor.”

Code: Stable/Steady State

Description: Electrons move until they reach a stable or steady state. This typically is in reference to within band movement. Also may say that they move to get to their natural state.

**note that movement to these ‘states’ may not be the correct movement or the most stable/steady/natural state may not be correctly described. Regardless, it still applies. Also, if they say that the stable state is in the valance band – that is correct.

Exemplar: “It moves within the conduction band to reach a stable state after becoming excited.”

Code: Bands

Description: Incorrect understanding of bands in terms energy. Bands are considered distinct zones. May also describe movement of the electron assuming that the bands are distinct zone: as such will say that same color photons will impact the electron the same way, as well the same amount of energy. May also say that the bands have some amount of energy (high or low), or that the number of electrons determines the amount of energy required for movement of electrons to either of the bands.

*Note that the bands are localized probabilities of electron presence for a range of energy. Therefore, the top of the band is at a higher energy than the bottom of the band.

Exemplar: “Because the conduction band has loosely packed electrons so the electron can jump over to that band and be re-distributed among the electrons making up the conduction band.”

Code: Within Band Movement - General

Description: Incorrect description of the movement of the electron within the band – linked to other codes (e.g. charges, fields, etc.)

Exemplar: “the electron moves with in the conduction band because there are other electrons repelling it making it move.”

Code: Within Band Movement - Spot
Description: Incorrect description of the movement of the electron within the band related to the electron finding its correct location or spot, or to accommodate other electrons.
Exemplar: "Once it is in the band it moves around because it is not sure exactly where it is supposed to go it goes around until it is placed in the right spot."

Code: Within Band Movement - Energy
Description: Incorrect description of the movement of the electron within the band related to incorrect understandings of energy (e.g. energy transfer, photon using energy/ making the electron lose energy, energy loss as a result of the photon leaving, use energy to move within the band)
Exemplar: "If there is energy left after expending the energy used to get to that band, it will move further into the band."

Code: Movement
Description: No movement unless there is an event or 'force' of any kind acting on the electron. (Force could be another electron, charge, e-field, room (i.e. space for the electron to move to), etc.). If movement is linked directly to the photon – the photon could be the only reason for why there is movement. Further, may state that only high energy photons will cause the electron to move. **Note that electrons are always moving, unless temperature is absolute zero. Electrons can move to the conduction band at higher temperatures (that's the whole point of a semiconductor)
Exemplar: "So I would guess that there has to be some sort of event to make the movment occur, like a photon."

Code: Predictable (E)
Description: The specific electron movement will be similar/the same (not noting the overall pattern of electron/(s)) if the scenario were re-run. Justification required. Justification at group level could be linked to the "attractive," "fields," and "Material Properties and Configuration" themes as well as its obeying laws of physics. There is likely a specification of 'the' electron versus electrons in general.
Exemplar: "I think that the movement would be very similar because the electron is just going to sit there until the photon passes it and depending on the color of the photon that

passes it it will do different things. Although the electron will always do the same thing when the same color photon passes over it.”

Code: Incorrect Movement
Description: Electrons will always move because of various forces, repulsion, attraction, electric /magnetic fields, polarity, photons, or refer to movement within atomic or molecular means (shells). *note: electrons are always moving (vibrating) due to energy from ‘heat’ – therefore, they will move unless the temperature is absolute zero. No other reasons for their constant movement.
Exemplar: “Althought the electrons may not move from valence to conduction band, they still move wherever they are located because of repelling forces. Even at equilibrium, the electrons are moving back and forth although their net movement is zero.”

Code: Incorrect Unpredictable
Description: Correclty describe electron movement as not being predictable, but use an incorrect justification linked to the other codes (e.g. charges, fields, concept of energy, etc.)
Exemplar: “The first electron went all the way across the conductance band and the second electron only made it part way across the conductance band. This leads me to believe that each time the electron jumps to the conductance band it will not always be exactly the same.”

Code: Other Factors
Description: Electron movement occurs because of other factors: gravity, concentration gradient
Exemplar: “Electrons move from a higher concentration to a lower concentration. So as the photon hits the solar cells, it increases the concentration, making the electron move from a lower state to the higher state.”

Code: Rules
Description: Electron movement occurs based on the laws/rules of physics .
Exemplar: “ Physics is a science of laws and rules, everything that happens in life is due to some rule based theorem and I believe that this photon event is also rule based.”

Code: Incorrect Rules
Description: Rules specified are incorrect in that they adhere to the themes of “attractive,” “photon fields,” and “Material Properties and Configuration,” because of similarity, or because electrons only respond to high energy photons.
Exemplar: “Electrons moves towards the positive charge or away from other negative charges. During a photon event, the electron is blasted by the photons randomly so the movements of the electrons will be random.”

Code: Concept of Energy
Description: Energy is lost, gained, or created (it is not transferred) when the electron moves to a higher energy level and/or back down. May refer to bands as having a certain amount of energy. Confuse wavelength and frequency and energy, time for energy to be lost is described as short, bands have certain amounts of energy, that photons have ‘positive’ energy, or that loss of energy in an electron is given off as visual light.
Exemplar: “In order for an electron to move from valence to conduction bands, it requires energy from an outside source. The photons here provide the energy for the electron movement. The valence band contains the least amount of energy, so in the absence of photon input, the electron will stay in the valence band because of its lack of energy.”

Code: Uncodable
Description: No other codes apply. Blanks or unreadable responses should also receive this code. If response is correct, do not mark this code.
Exemplar: “What determines how and where the electron moves in the solar cell during each photon event is when an electron get's on the way of the photon event.”

Emergence Misconceptions

Code: Non-cooperative
Description: The electrons work together to create the pattern, or move in order to equilibrate.
Exemplar: “The Electrons moved in such a way that caused them to be uniformly distributed throughout the cell”

Code: Volition
Description: Describes the movement of electrons as being intentional or having anthropomorphic characteristics, or the electron being affected by other things that are

being intentional or having anthropomorphic characteristics. Statements should contain language that reveal electrons intentionality (wants to, tries to, needs to, chooses, intended to, behaves, etc.), or other thing's intentionality (allows, permits, etc.)
Exemplar: "When it is off the electrons are always random looking for something to attract to. With no charge no attraction and randomization occurs."

Code: Goal Directed
Description: Describes intentional behavior or movement of electrons (volition) as being performed to meet a certain purpose or goal w/in associated with the emergence movement pattern.
Exemplar: "It's rules based in the sense that if two electrons get near each other, they are going to want to move apart"

Code: Singular
Description: The pattern carried out by all electrons is described at an electron (micro) level. May describe the movement pattern of a specific electron. **The pattern should be described at a macro level Note* if they describe the movement pattern at a micro level and then discuss it at a macro level, do not mark this code.
Exemplar: "Once put into motion, the electron moves to the boundary of the material, or until it comes in proximity of another electron that then causes a repulsive force causing the direction of the electron to change"

Code: Centralized Control
Description: Reference to a specific factor directing, leading, guiding, governing, or having 'bound', etc. the electrons to carry out certain actions. May also say the electrons are following laws. *Think of this as something is in control.
Exemplar: "they will go wherever the repulsive forces direct them towards"

Code: Causality
Description: Describe a causal direct factor for the observed macro pattern. Likely no mention of the emergent pattern resulting from the interactions of the electrons. **Think of this as electrons move in a certain pattern because of a certain factor. **Pattern can be deduced when they describe numerous entities (electrons) carrying out a pattern (e.g. moving in an overall direction, having a path, etc.) – general movement doesn't count.

Exemplar: “Electrons will move in the opposite direction of the electic field. Therefore, the electric field was pointing from left to right because the electrons were flowing to the left. Electrons. Electrons flow from low potential to high potential.(- to +)”

Code: Predictable
Description: The electron movement (micro) will be similar/the same if the scenario were re-run. **Note: Net, general pattern, overall movement (and other terms like this) indicate no misconception.
Exemplar: “ if the conditions of the scenario are the same, then the electrons will behave similarly if not exactly the same as they did in the first animation”

Code: Predictability Change
Description: Don’t understand how a small change to the system could manifest. Typically will state that a small change will lead to an overall small change to the system. **note: Correct: any change in the system could cause any small or large overall change in the pattern. The participant doesn’t understand that small perturbations to the system can have a major impact on the pattern.
Exemplar: “Technically, I think that the electrons will move in exactly the same way as long as they are placed in exactly the same starting positions, if they are not placed in exactly the same starting position, then they will have a completly different movement pattern as the forces that they feel from the different directions will be slightly different.”

Code: Simple Rules
Description: Note that the electrons do not follow rules that can be linked to the macro level pattern observed.
Exemplar: “The movement of electrons in the material kind of random so it’s not like a rule-based movement”

Code: Not-Random
Description: Electron movement overall is considered not random – or is specifically states as such. **Note that this code doesn’t apply unless it is specifically brought up.
Exemplar: “No its is not random because there are laws that govern the movement of electrons and these laws cannot be broken. The elctrons will feel forces in all different directions and will go in the same direction as the largest force. This is not a random

movement as random would mean that they just go wherever they feel like going at the time.”

Code: Uncodable
Description: No codes apply. Blanks, unreadable responses, and non-related jargon should receive this code
Exemplar: ““What determines how and where the electron moves in the solar cell during each photon event is when an electron get's on the way of the photon event.””

APPENDIX E

STATISTICAL TESTS AND DATA

Full Study

General Misconceptions

Diffusion General Misconceptions

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1. Gender	1.00																			
2. Physics Prior Knowledge	-0.14	1.00																		
3. Material Science Prior Knowledge	-0.23	$.301^{*}$	1.00																	
4. Total Prior Knowledge	-0.24	$.595^{**}$	$.847^{**}$	1.00																
5. Fields	-0.27	0.00	$.342^{*}$	0.27	1.00															
6. Other Factors Gravity	-0.15	-0.05	0.11	0.09	0.10	1.00														
7. Other Factors Energy	-0.17	0.21	0.23	0.24	0.05	$.503^{**}$	1.00													
8. Solar Prime	-0.09	-0.07	$.388^{**}$	0.27	0.01	-0.11	0.29	1.00												
9. Charges	-0.26	0.06	-0.06	-0.07	-0.11	-0.09	-0.01	-0.16	1.00											
10. MP&C	0.08	0.10	0.01	0.01	0.17	-0.13	0.12	0.14	-0.21	1.00										
11. Amounts	-0.05	-0.02	-0.19	-0.17	$-.299^{*}$	0.11	0.12	-0.11	0.08	-0.22	1.00									
12. Atomic	-0.22	0.11	0.20	0.16	-0.18	-0.07	$.308^{*}$	$.444^{**}$	0.11	-0.20	0.21	1.00								
13. Random Atomic	-0.19	-0.06	-0.22	-0.19	0.03	-0.06	-0.11	-0.13	0.15	-0.06	0.25	0.24	1.00							
14. Random	0.01	0.08	0.07	0.06	-0.17	-0.14	0.01	$.368^{*}$	0.01	0.19	0.23	0.14	0.02	1.00						
15. Predictable	-0.06	0.02	-0.05	-0.02	0.14	0.15	-0.16	-0.06	0.05	-0.26	-0.10	0.06	-0.01	-0.23	1.00					
16. Incorrect Predictable	-0.04	0.13	-0.06	-0.01	-0.15	-0.06	0.13	0.12	0.11	0.05	0.09	-0.09	-0.08	0.21	-0.20	1.00				
17. Pattern	0.15	-0.09	-0.07	-0.14	-0.13	-0.13	-0.09	-0.04	0.02	0.02	0.16	-0.03	-0.16	-0.16	0.26	-0.16	1.00			
18. Not Random	0.09	0.04	-0.08	-0.04	0.16	0.17	0.04	-0.24	-0.12	-0.05	0.06	0.09	0.02	-0.30	$.353^{*}$	$-.367^{*}$	$.342^{*}$	1.00		
19. Not Rules	-0.25	0.06	-0.05	-0.03	-0.06	-0.08	-0.15	-0.18	0.10	0.04	0.16	-0.12	0.18	0.08	-0.23	$.471^{**}$	-0.22	$-.336^{*}$	1.00	
20. Rules	-0.01	0.20	0.07	0.08	0.04	-0.17	-0.05	0.07	-0.01	0.09	-0.13	0.05	0.04	0.00	0.27	-0.12	$.420^{**}$	$.428^{**}$	$-.342^{*}$	1.00

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Drift General Misconceptions

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1. Gender	1.00																					
2. Physics Prior Knowledge	-0.14	1.00																				
3. Material Science Prior Knowledge	-0.23	.31*	1.00																			
4. Total Prior Knowledge	-0.24	.60**	.85**	1.00																		
5. Fields	0.10	-0.01	-0.14	-0.11	1.00																	
6. Direction	-0.02	0.02	.300*	0.27	0.04	1.00																
7. Charges Present	-0.12	0.12	0.15	0.11	-0.02	0.11	1.00															
8. Random Efields/Charges Not Present	0.20	-0.08	-0.06	-0.07	0.16	0.02	-0.07	1.00														
9. Material Properties and Device Configuration	0.04	-0.20	-0.01	-0.10	-0.08	-0.23	0.03	0.15	1.00													
10. Pattern	-0.04	0.24	0.00	0.07	0.20	0.05	.388**	0.12	0.07	1.00												
11. External	-0.01	0.13	0.15	0.14	.321*	-0.21	-0.04	0.15	-0.07	0.08	1.00											
12. Solar Prime	-0.15	0.22	0.29	0.26	-0.14	-0.10	0.02	-0.08	-0.12	-0.07	0.15	1.00										
13. Energy	-0.18	0.28	0.08	0.15	0.00	-0.01	0.22	-0.15	-0.07	0.07	-0.19	0.26	1.00									
14. Predictable	0.05	0.00	-0.10	-0.06	0.25	0.19	-0.12	0.06	0.17	0.04	-0.05	-0.10	0.20	1.00								
15. Random	-0.09	.294*	0.12	0.16	0.05	0.07	0.25	0.23	0.07	0.16	0.04	0.13	0.17	-0.02	1.00							
16. Random Atomic	-0.11	-0.03	-0.12	-0.11	-0.12	-0.07	0.01	-0.06	0.26	-0.05	-0.07	-0.04	-0.06	-0.16	-0.10	1.00						
17. Not Random Efield	0.13	0.07	-0.12	-0.06	.372**	0.06	-0.10	-0.03	-0.28	-0.02	-0.11	-0.12	0.04	0.05	0.03	-0.09	1.00					
18. Not Random	0.09	0.02	-0.06	-0.07	0.14	-0.11	0.05	-0.05	0.12	0.05	0.20	-0.13	-0.09	.340*	-0.16	-0.09	-0.06	1.00				
19. Polarity	-0.11	0.27	0.13	0.18	0.16	-0.07	0.23	-0.06	-0.08	.447**	-0.07	-0.04	.340*	-0.16	0.19	-0.03	0.23	-0.09	1.00			
20. Not Rules	0.15	-0.03	-0.12	-0.11	-0.12	-0.07	-0.16	-0.06	-0.08	-0.05	-0.07	-0.04	-0.06	0.03	0.19	-0.03	0.23	0.27	-0.03	1.00		
21. Rules	0.10	-0.05	0.01	-0.05	0.18	-0.03	0.01	-0.01	-0.05	-0.08	0.06	-0.15	-0.03	.304*	-0.18	-0.11	-0.06	0.23	-0.11	-0.11	1.00	
22. Incorrect Rules	0.02	0.11	0.05	0.02	0.17	0.19	0.26	0.12	0.07	0.24	0.02	.306*	0.12	-0.02	0.17	0.12	0.09	-0.02	0.12	-0.19	-0.26	1.00

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Excitation General Misconceptions

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1. Gender	1.00																								
2. Physics Prior Knowledge	-0.14	1.00																							
3. Material Science Prior Knowledge	-0.23	.301*	1.00																						
4. Total Prior Knowledge	-0.24	.595**	.847**	1.00																					
5. Charges	-0.17	-0.20	-0.16	-0.24	1.00																				
6. Atomic vs. Bound	-.300*	0.07	0.20	0.14	0.20	1.00																			
7. Energy Vs. Physical	-0.03	-0.25	-0.04	-0.14	.432**	0.03	1.00																		
8. Incorrect Excitation	-0.05	0.16	0.16	0.15	-0.02	0.14	-0.24	1.00																	
9. Incorrect Photon	-0.01	0.17	-0.03	-0.01	-0.04	-0.20	-0.10	0.10	1.00																
10. More Photons	0.25	-0.03	0.13	0.09	0.05	-0.07	-0.04	-0.04	-0.07	1.00															
11. Fields	0.05	0.00	0.09	0.06	-0.03	-0.14	.284*	-0.16	0.04	-0.09	1.00														
12. Material Properties and Device Configuration	-0.03	0.14	0.18	0.14	-0.18	.361*	0.00	0.25	0.10	-0.09	0.12	1.00													
13. Steady/Stable State	0.00	0.20	-0.06	0.01	-0.19	-0.16	-0.03	0.19	.439**	-0.06	0.14	-0.05	1.00												
14. Bands	-0.16	-0.19	0.04	-0.05	0.13	-0.03	0.15	-0.11	0.19	-0.06	0.02	-0.23	0.07	1.00											
15. Within Band General	0.00	-0.22	-.381*	-.391**	0.22	-0.07	0.08	-0.14	-0.22	-0.08	-0.17	-0.17	0.00	-0.01	1.00										
16. Within Band Spot	-0.15	-0.05	0.28	0.23	0.07	0.22	-0.02	-0.06	-0.10	-0.04	-0.13	0.16	-0.08	-0.09	-0.11	1.00									
17. Within Band Energy	0.06	-0.11	-0.13	-0.16	-0.03	0.05	-0.04	0.07	.366*	-0.08	0.04	0.07	0.00	-0.05	-0.26	-0.12	1.00								
18 Movement	-0.03	0.09	0.12	0.17	-0.12	-0.08	-0.07	-0.12	0.09	0.11	0.22	0.11	0.11	0.04	-0.03	-0.04	-0.19	1.00							
19. Incorrect Movement	0.15	0.01	-0.06	-0.08	-0.05	-0.04	0.26	0.17	0.12	-0.10	0.06	0.12	0.11	0.05	-0.08	-0.15	0.27	-.500**	1.00						
20. Predictable	0.19	-0.13	-0.24	-0.21	0.06	0.07	-0.18	-0.03	-0.12	-0.18	-0.27	-0.14	-.313*	0.02	0.20	-0.09	-0.10	-0.14	-0.04	1.00					
21. Incorrect Unpredictable	-0.15	-0.05	-0.18	-0.15	0.26	-0.10	0.28	-0.06	0.19	-0.04	0.15	-0.13	0.25	-0.09	-0.11	-0.05	0.15	-0.04	0.07	-0.26	1.00				
22. Other Factors	0.02	-0.06	0.01	0.01	-0.03	-0.12	-0.17	-0.08	-0.13	-0.04	0.02	-0.16	-0.10	-0.11	0.10	-0.06	0.08	0.13	0.06	.311*	-0.06	1.00			
23. Rules	0.15	-0.11	0.10	0.05	0.04	0.12	0.07	-0.19	-0.04	0.23	0.08	0.15	-0.25	0.01	0.06	0.09	-0.23	0.01	-0.14	0.05	-0.15	-0.19	1.00		
24. Incorrect Rules	-0.18	0.10	0.10	0.11	0.01	-0.15	0.08	0.19	0.16	-0.11	.331*	0.16	0.26	-0.27	-0.20	0.08	0.13	0.04	0.19	-0.23	.315*	0.20	-.349*	1.00	
25. Concept of Energy	0.03	-0.03	0.24	0.16	-0.18	-0.28	-0.03	0.20	0.14	0.22	-0.27	-0.14	0.08	.302*	-0.18	0.09	0.10	-0.23	0.27	-0.21	0.16	-0.18	-0.11	-0.08	1.00

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Across Phenomena General Misconceptions

Measure	1.00	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
1. Other Factors Gravity Diff	1.00																										
2. Other Factors Energy Diff	.503**	1.00																									
3. Solar Prime Diff	-0.11	0.29	1.00																								
4. Charges Diff	-0.09	-0.01	-0.16	1.00																							
5. Amounts Diff	0.11	0.12	-0.11	0.08	1.00																						
6. Random Atomic Diff	-0.06	-0.11	-0.13	0.15	0.25	1.00																					
7. Random Diff	-0.14	0.01	.368*	0.01	0.23	0.02	1.00																				
8. Predictable Diff	0.15	-0.16	-0.06	0.05	-0.10	-0.01	-0.23	1.00																			
9. Pattern Diff	-0.13	-0.09	-0.04	0.02	0.16	-0.16	-0.16	0.26	1.00																		
10. Not Random Diff	0.17	0.04	-0.24	-0.12	0.06	0.02	-0.30	.353*	.342*	1.00																	
11. Rules Diff	-0.17	-0.05	0.07	-0.01	-0.13	0.04	0.00	0.27	.420**	.428**	1.00																
12. Charges Present DR	-0.23	-0.09	-0.11	.323*	-0.22	-0.18	-0.12	-0.17	-0.03	-0.24	0.05	1.00															
13. Material Properties and Device Configuration DR	-0.12	-0.21	-0.01	0.17	-0.17	.304*	-0.10	-0.01	0.12	-0.05	0.06	0.03	1.00														
14. Pattern DR	-0.07	0.10	-0.15	.331*	-0.18	-0.09	-0.20	0.06	0.19	0.25	0.05	.388**	0.07	1.00													
15. External DR	-0.11	-0.02	0.07	0.06	.425**	-0.13	0.17	0.04	0.04	0.22	-0.06	-0.04	-0.07	0.08	1.00												
16. Solar Prime DR	-0.05	.541**	.402**	-0.02	0.17	-0.06	0.10	-0.09	0.09	-0.07	0.03	0.02	-0.12	-0.07	0.15	1.00											
17. Predictable DR	0.26	-0.05	-.299*	-0.05	-0.13	-0.08	-.409**	.391**	0.23	.431**	.289*	-0.12	0.17	0.04	-0.05	-0.10	1.00										
18. Random Atomic DR	-0.04	-0.06	-0.08	0.21	0.25	.563**	0.23	-0.23	-0.09	-0.21	0.02	0.01	0.26	-0.05	-0.07	-0.04	-0.16	1.00									
19. Not Random DR	-0.13	-0.23	-0.12	-0.25	-0.19	0.05	-.355*	0.15	0.04	.425**	.332*	0.05	0.12	0.05	0.20	-0.13	.340*	-0.09	1.00								
20. Rules DR	0.03	0.00	0.06	-0.14	-0.02	-0.19	0.14	0.12	0.11	0.21	.376**	0.01	-0.05	-0.08	0.06	-0.15	.304*	-0.11	0.23	1.00							
21. Incorrect Rules DR	0.16	.372*	0.09	0.08	-0.13	0.02	-0.21	-0.05	0.02	-0.02	0.00	0.26	0.07	0.24	0.02	.306*	-0.02	0.12	-0.02	-0.26	1.00						
22. Charges EX	-0.07	-0.08	-0.21	0.14	-0.01	0.15	-0.28	0.25	0.23	0.14	0.24	-0.02	.287*	-0.14	-0.19	0.15	.446**	-0.15	0.10	0.19	-0.07	1.00					
23. Atomic Vs Bound EX	-0.10	0.00	0.13	0.04	0.01	.326*	-0.01	0.03	0.00	-0.05	0.26	0.25	-0.10	-0.14	-0.21	0.23	-0.01	.310*	0.04	0.00	0.04	0.20	1.00				
24. Stable/Stead State EX	-0.08	0.28	0.04	-0.10	-0.05	0.17	-0.06	-0.08	-0.22	0.11	-0.07	-0.01	0.00	.352*	0.20	-0.08	0.02	-0.06	.318*	0.08	0.27	-0.19	-0.16	1.00			
25. Other Factors EX	.801**	.381*	-0.13	-0.17	0.25	-0.08	-0.18	-0.01	0.08	0.21	-0.12	-0.28	-0.14	-0.09	-0.13	-0.06	.320*	-0.04	-0.16	-0.03	0.20	-0.03	-0.12	-0.10	1.00		
26. Rules EX	-0.15	-0.28	0.05	-0.19	-0.26	-0.19	-0.21	0.24	.373*	0.19	.342*	-0.02	0.10	-0.06	-0.21	-0.15	0.26	-0.11	0.21	0.28	-.420**	0.04	0.12	-0.25	-0.19	1.00	
27. Incorrect Rules EX	.313*	0.26	0.19	-0.08	-0.26	0.00	0.03	0.02	-0.26	0.09	0.10	0.02	0.17	0.18	0.12	0.09	0.14	-0.11	0.27	0.19	.353*	0.01	-0.15	0.26	0.20	-.349*	1.00

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Kruskal-Wallis Mean Ranks for General Misconception Groups

	Phenomenon	N	Mean Rank
Volition	Diffusion	41	72.04
	Drift	41	62.67
	Excitation	41	51.29
	Total	123	
Causality	Diffusion	41	64.91
	Drift	41	51.18
	Excitation	41	56.09
	Total	123	
Predictability	Diffusion	41	61.88
	Drift	41	62.54
	Excitation	41	61.59
	Total	123	

Emergent Misconceptions

Diffusion Emergent Misconceptions

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Gender	1.00													
2. Physics Prior Knowledge	-0.14	1.00												
3. Material Science Prior Knowledge	-0.23	.301*	1.00											
4.Total Prior Knowledge	-0.24	.595**	.847**	1.00										
5. Non Cooperative	0.01	0.03	0.05	0.03	1.00									
6. Volition	-0.22	0.05	0.02	-0.04	0.00	1.00								
7. Goal Directed	-0.19	-0.06	-0.06	-0.07	0.20	.373*	1.00							
8. Singular	0.03	-0.05	-0.18	-0.15	0.10	0.16	.357*	1.00						
9. Centralized Control	0.12	-0.03	-0.06	-0.08	-0.11	-0.21	-0.19	-0.15	1.00					
10. Causality	0.03	-0.21	-0.25	-.283*	0.13	-0.25	-0.12	-0.10	0.19	1.00				
11. Predictability Change	0.17	-0.06	-0.07	-0.07	0.02	0.06	-0.08	-0.06	0.05	-0.12	1.00			
12. Predictable	-0.04	-0.02	-0.21	-0.17	-0.01	0.08	0.01	-0.06	.368*	0.17	-0.05	1.00		
13. Simple Rules	-0.19	0.12	0.08	0.09	0.08	0.06	-0.08	-0.06	-0.19	-0.12	-0.08	-0.15	1.00	
14. Not Random	0.15	-0.01	-0.08	-0.04	0.11	-0.04	-0.10	-0.22	0.04	-0.04	.328*	0.22	-0.11	1.00

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Drift Emergent Misconceptions

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Gender	1.00													
2. Physics Prior Knowledge	-0.14	1.00												
3. Material Science Prior Knowledge	-0.23	.301*	1.00											
4.Total Prior Knowledge	-0.24	.595**	.847**	1.00										
5. Non Cooperative	-0.04	0.12	-0.07	-0.02	1.00									
6. Volition	-0.12	0.16	0.12	0.09	0.27	1.00								
7. Goal Directed	-0.09	0.25	0.10	0.11	-0.10	.446**	1.00							
8. Singular	0.10	0.22	0.00	0.19	-0.06	-0.22	-0.08	1.00						
9. Centralized Control	.304*	0.02	-0.09	-0.10	.357*	0.01	0.01	0.07	1.00					
10. Causality	0.06	-0.20	0.19	0.08	0.07	-0.02	-0.23	-0.20	0.09	1.00				
11. Predictability Change	-0.19	0.13	-0.06	-0.01	-0.08	0.16	-0.10	-0.06	-0.20	-0.13	1.00			
12. Predictable	0.14	-0.11	-0.03	-0.02	-0.06	0.24	-0.14	0.16	-0.05	.309*	0.04	1.00		
13. Simple Rules	0.21	-0.05	-0.18	-0.15	.357*	-0.08	-0.08	-0.05	0.11	-0.20	-0.06	-0.24	1.00	
14. Not Random	0.05	-0.25	-0.08	-0.16	0.12	0.04	-0.17	-0.18	0.05	0.25	0.12	.313*	-0.18	1.00

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Excitation Emergent Misconceptions

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. Gender	1.00													
2. Physics Prior Knowledge	-0.14	1.00												
3. Material Science Prior Knowledge	-0.23	.301*	1.00											
4.Total Prior Knowledge	-0.24	.595**	.847**	1.00										
5. Non Cooperative	-0.11	-0.03	0.13	0.09	1.00									
6. Volition	-0.18	.284*	0.19	0.21	0.19	1.00								
7. Goal Directed	0.04	0.28	0.21	0.22	-0.05	0.07	1.00							
8. Singular	-0.11	-0.03	-0.12	-0.11	-0.03	0.04	-0.05	1.00						
9. Centralized Control	-0.01	0.05	0.22	0.17	-0.07	0.21	-0.14	.382*	1.00					
10. Causality	-0.04	-0.23	-0.05	-0.14	.311*	0.20	0.01	-0.10	-0.10	1.00				
11. Predictability Change	-0.19	-0.06	0.22	0.18	-0.04	0.04	-0.09	-0.04	-0.12	0.04	1.00			
12. Predictable	.293*	-0.09	-0.15	-0.13	-0.19	0.09	-0.25	0.27	0.26	-0.08	-0.02	1.00		
13. Simple Rules														
14. Not Random	-0.15	-0.05	0.01	-0.01	.698**	0.02	-0.07	-0.04	-0.09	.348*	-0.06	-0.27		1.00

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Across Phenomena Emergent Misconception Correlations

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Volition Diff	1.00															
2. Centralized Control Diff	-0.21	1.00														
3. Causality Diff	-0.25	0.19	1.00													
4. Predictable Diff	0.08	.368*	0.17	1.00												
5. Not Random Diff	-0.04	0.04	-0.04	0.22	1.00											
6. Non Cooperative DR	0.06	-0.19	.389*	0.16	0.06	1.00										
7. Volition DR	.615**	-0.04	-0.20	0.11	0.12	0.27	1.00									
8. Goal Direction DR	.457**	0.12	-0.16	0.05	-0.23	-0.10	.446**	1.00								
9. Causality DR	-0.07	0.09	0.01	0.11	0.15	0.07	-0.02	-0.23	1.00							
10. Predictable DR	0.09	0.16	-0.24	0.28	.518**	-0.06	0.24	-0.14	.309*	1.00						
11. Not Random DR	0.03	0.11	0.16	0.19	.404**	0.12	0.04	-0.17	0.25	.313*	1.00					
12. Goal Directed EX	.293*	-0.22	-0.15	-0.22	-0.02	-0.09	0.16	0.14	-0.08	0.04	0.04	1.00				
13. Centralized Control EX	0.10	.427**	-0.18	0.01	-0.03	-0.12	0.26	0.08	0.17	0.26	-0.08	-0.14	1.00			
14. Causality EX	-0.06	-0.04	0.26	-0.03	0.27	0.00	-0.14	-0.22	.474**	.307*	0.23	0.01	-0.10	1.00		
15. Predictable EX	-0.04	0.27	0.07	.356*	0.09	-0.18	0.00	0.05	-0.15	0.19	0.00	-0.25	0.26	-0.08	1.00	
16. Not Random EX	-0.01	-0.15	.510**	-0.06	0.10	.389*	0.05	-0.08	0.22	-0.10	0.24	-0.07	-0.09	.348*	-0.27	1.00

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Kruskal-Wallis Mean Ranks for Emergent Misconception Groups

	Phenomenon	N	Mean Rank
Causality	Diffusion	41	55.4
	Drift	41	75.74
	Excitation	41	54.85
	Total	123	
Predictability	Diffusion	41	67.7
	Drift	41	69.15
	Excitation	41	49.16
	Total	123	
Volition	Diffusion	41	54.9
	Drift	41	65.16
	Excitation	41	65.94
	Total	123	

Diffusion General Misconceptions Mann-Whitney U Test By Gender

	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)	Exact Sig. [2*(1-tailed Sig.)]
Physics Prior Knowledge	70	91	-0.63	0.53	.633[b]
Materials Science Prior Knowledge	63	84	-0.93	0.35	.424[b]
Total Prior Knowledge	57.5	78.5	-1.16	0.25	.281[b]
Fields	69	90	-0.69	0.49	.600[b]
Other Factors Gravity	75	96	-0.68	0.50	.803[b]
Other Factors Energy	78.5	99.5	-0.17	0.86	.910[b]
Solar Prime	78.5	99.5	-0.16	0.87	.910[b]
Charges	40	61	-2.00	0.05	.057[b]
Material Properties and Device Configuration	69.5	90.5	-0.56	0.57	.600[b]
Amounts	72.5	93.5	-0.53	0.60	.699[b]
Atomic	69	90	-0.99	0.32	.600[b]
Random Atomic	72	93	-0.84	0.40	.699[b]
Random	70	91	-0.66	0.51	.633[b]
Predictable	78	99	-0.18	0.86	.910[b]
Incorrect Predictable	74	452	-0.66	0.51	.768[b]
Pattern	70	448	-0.69	0.49	.633[b]
Not Random	61.5	439.5	-1.09	0.27	.372[b]
Not Rules	66	87	-1.13	0.26	.508[b]
Rules	77	455	-0.22	0.83	.874[b]

Drift General Misconceptions Mann-Whitney U Test By Gender

	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)	Exact Sig. [2*(1-tailed Sig.)]
Fields	62.000	440.000	-.909	.364	.398[b]
Direction	66.000	87.000	-1.123	.261	.508[b]
Charges Present	44.000	65.000	-1.809	.070	.089[b]
Random Efields/Charges Not Present	74.000	452.000	-.655	.512	.768[b]
Material Properties and Device Configuration	56.500	434.500	-1.525	.127	.260[b]
Pattern	72.000	93.000	-.842	.400	.699[b]
External	68.500	446.500	-.817	.414	.569[b]
Solar Prime	75.000	96.000	-.677	.498	.803[b]
Energy	78.000	99.000	-.208	.835	.910[b]
Predictable	65.000	443.000	-.795	.427	.479[b]
Random	77.000	98.000	-.224	.823	.874[b]
Random Atomic	78.000	99.000	-.471	.637	.910[b]
Not Random Efield	52.500	430.500	-1.773	.076	.189[b]
Not Random	44.000	422.000	-2.227	.026	.089[b]
Polarity	78.000	99.000	-.471	.637	.910[b]
Not Rules	67.500	445.500	-2.121	.034	.538[b]
Rules	61.000	439.000	-1.117	.264	.372[b]
Incorrect Rules	77.000	455.000	-.216	.829	.874[b]

Excitation General Misconceptions Mann-Whitney U Test By Gender

	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)	Exact Sig. [2*(1-tailed Sig.)]
Charges	78.500	456.500	-.122	.903	.910[b]
Atomic Vs. Bound	60.000	81.000	-1.374	.169	.348[b]
Energy Vs. Physical	71.500	92.500	-.456	.648	.665[b]
Incorrect Excitation	74.500	452.500	-.608	.543	.768[b]
Incorrect Photon	54.000	432.000	-1.773	.076	.222[b]
More Photons	81.000	102.000	0.000	1.000	1.000[b]
Fields	77.000	455.000	-.240	.810	.874[b]
Material Properties and Device Configuration	79.000	457.000	-.119	.905	.946[b]
Steady/Stable State	61.500	439.500	-1.462	.144	.372[b]
Bands	80.000	101.000	-.069	.945	.982[b]
Within Band General	69.000	447.000	-.791	.429	.600[b]
Within Band Spot	75.000	96.000	-.677	.498	.803[b]
Within Band Energy	55.500	433.500	-1.603	.109	.241[b]
Movement	72.000	93.000	-.466	.641	.699[b]
Incorrect Movement	77.000	455.000	-.240	.810	.874[b]
Predictable	76.000	97.000	-.261	.794	.838[b]
Incorrect Unpredictable	75.000	96.000	-.677	.498	.803[b]
Other Factors	75.000	96.000	-.677	.498	.803[b]
Rules	61.500	439.500	-1.143	.253	.372[b]
Incorrect Rules	77.000	98.000	-.222	.824	.874[b]
Concept of Energy	70.000	91.000	-.662	.508	.633[b]

General Misconception Groups Mann-Whitney U Test By Gender

	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)	Exact Sig. [2*(1-tailed Sig.)]
Electricity and Magnetism Diffusion	45.000	66.000	-1.704	.088	.098[b]
Atomic Diffusion	63.000	84.000	-1.251	.211	.424[b]
Other Factors Diffusion	77.500	98.500	-.243	.808	.874[b]
Predictability Diffusion	71.500	449.500	-.452	.651	.665[b]
Not Predictable Diffusion	64.000	85.000	-.927	.354	.451[b]
Electricity and Magnetism Drift	67.500	88.500	-.638	.524	.538[b]
Predictability Drift	37.500	415.500	-2.051	.040	.040[b]
Not Predictable Drift	79.000	100.000	-.106	.915	.946[b]
Electricity and Magnetism Excitation	78.000	99.000	-.143	.886	.910[b]
Energy Excitation	68.000	446.000	-.615	.539	.569[b]
Atomic Excitation	57.000	78.000	-1.494	.135	.281[b]
Predictability Excitation	76.000	454.000	-.247	.805	.838[b]
Not Predictable Excitation	75.000	96.000	-.330	.742	.803[b]

Drift Emergent Misconceptions Mann-Whitney U Test By Gender

	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)	Exact Sig. [2*(1-tailed Sig.)]
NonCooperative_DR	20	56	-1.155	0.248	.662[b]
Volition_DR	19.5	40.5	-0.65	0.516	.573[b]
GoalDirected_DR	21	42	-0.866	0.386	.755[b]
Singular_DR	21	42	-0.866	0.386	.755[b]
CentralizedControl_DR	23.5	44.5	-0.069	0.945	.950[b]
Causality_DR	22.5	58.5	-0.207	0.836	.852[b]
Predictability_DR	24	60	0	1	1.000[b]
Predictable_DR	22	43	-0.281	0.779	.852[b]
SimpleRules_DR	16	52	-1.7	0.089	.345[b]
NotRandom_DR	19	40	-0.735	0.462	.573[b]
NonEmergence_DR	14	50	-1.62	0.105	.228[b]

Excitation Emergent Misconceptions Mann-Whitney U Test By Gender

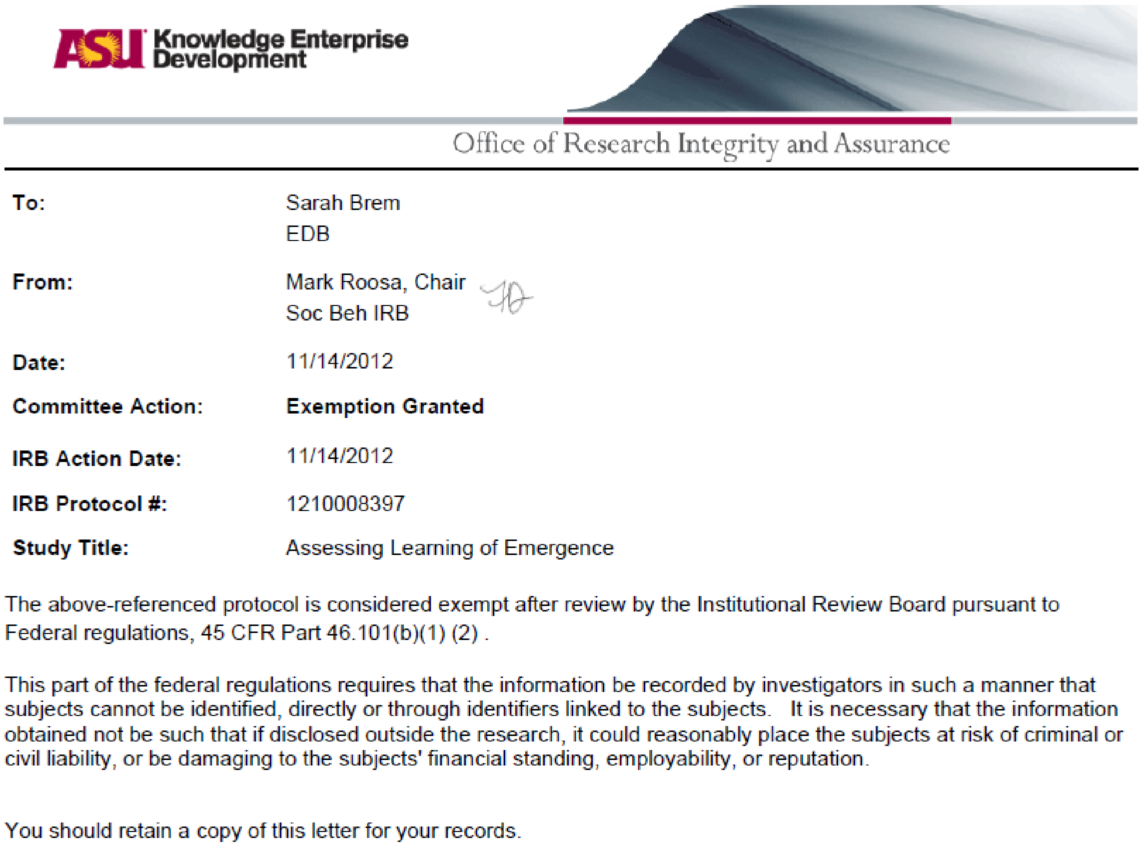
	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)	Exact Sig. [2*(1-tailed Sig.)]
NonCooperative_EX	24	60	0	1	1.000[b]
Volition_EX	23	44	-0.145	0.885	.950[b]
GoalDirected_EX	16	52	-1.7	0.089	.345[b]
Singular_EX	24	60	0	1	1.000[b]
CentralizedControl_EX	23	59	-0.212	0.832	.950[b]
Causality_EX	13.5	49.5	-1.701	0.089	.181[b]
PredictabilityChange_EX	24	60	0	1	1.000[b]
Predictable_EX	18.5	39.5	-0.795	0.427	.491[b]
SimpleRules_EX	24	60	0	1	1.000[b]
NotRandom_EX	24	60	0	1	1.000[b]
NonEmergence_EX	17	53	-1.016	0.31	.414[b]

Emergent Misconception Groups Mann-Whitney U Test By Gender

	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)	Exact Sig. [2*(1-tailed Sig.)]
Causality Diffusion	24	60	0	1	1.000[b]
Causality Drift	21	57	-0.393	0.694	.755[b]
Causality Excitation	15	51	-1.358	0.174	.282[b]
Predictability Diffusion	19.5	55.5	-0.648	0.517	.573[b]
Predictability Drift	22	43	-0.281	0.779	.852[b]
Predictability Excitation	18.5	39.5	-0.795	0.427	.491[b]
Volition Diffusion	23	59	-0.163	0.871	.950[b]
Volition Drift	18	39	-0.843	0.399	.491[b]
Volition Excitation	18	54	-0.83	0.406	.491[b]

APPENDIX F:

IRB APPROVAL DOCUMENTATION



ASU Knowledge Enterprise Development

Office of Research Integrity and Assurance

To:	Sarah Brem EDB
From:	Mark Roosa, Chair Soc Beh IRB
Date:	11/14/2012
Committee Action:	**Exemption Granted**
IRB Action Date:	11/14/2012
IRB Protocol #:	1210008397
Study Title:	Assessing Learning of Emergence

The above-referenced protocol is considered exempt after review by the Institutional Review Board pursuant to Federal regulations, 45 CFR Part 46.101(b)(1) (2) .

This part of the federal regulations requires that the information be recorded by investigators in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects. It is necessary that the information obtained not be such that if disclosed outside the research, it could reasonably place the subjects at risk of criminal or civil liability, or be damaging to the subjects' financial standing, employability, or reputation.

You should retain a copy of this letter for your records.