122nd ASEE Annual Conference & Exposition
June 14 - 17, 2015
Seattle, WA
Making Value for Society
Paper ID #12892

Do you catch my drift? Identification of misconceptions of emergence for the semiconductor phenomenon drift.

Dr. Katherine G Nelson, Arizona State University

Katie just recently finished her PhD at ASU and is currently working as a post doc for Dr. Ann McKenna. Her research interests include complexity learning, cognition, and motivation.

Dr. Sarah Brem, Arizona State University

Faculty at ASU; Cognitive Scientist, and graduate of Northwestern University, conducts research on the public understanding of science.

Dr. Ann F. McKenna, Arizona State University, Polytechnic campus

Ann F. McKenna is a Professor in the Ira A. Fulton Schools of Engineering and Director of The Polytechnic School at Arizona State University. Prior to joining ASU she served as a program director at the National Science Foundation in the Division of Undergraduate Education, and was on the faculty in the Department of Mechanical Engineering and Segal Design Institute at Northwestern University. Dr. McKenna received her B.S. and M.S. degrees in Mechanical Engineering from Drexel University and Ph.D. from the University of California at Berkeley. Dr. McKenna is also a Senior Associate Editor for the Journal of Engineering Education.

Eva Pettinato, Arizona State University

Eva is a Master's student in Aerospace Engineering at Arizona State University. She is interested in using photovoltaics as a power source for space applications. Her research with QESST, Quantum Energy and Sustainable Solar Technologies, is primarily concerned with the photolithography process and how it can be used to optimize solar cells, though her involvement with QESST expands into educational outreach for all grade levels.

Dr. Jenefer Husman, Arizona State University

Jenefer Husman received a doctoral degree in Educational Psychology from the University of Texas at Austin, in 1998. She served as an Assistant Professor at the University of Alabama from 1998 to 2002, when she moved to Arizona State University. In 2008 she was promoted by ASU to Associate Professor. Dr. Husman serves as the Director of Education for the Quantum Energy and Sustainable Solar Technology Center - an NSF funded Engineering Research Center. Dr. Husman is an assistant editor of the Journal of Engineering Education, has been a guest editor of Educational Psychology Review, served on editorial board for top educational research journals, and currently sits on the editorial board of Learning and Instruction. In 2006 she was awarded the U.S. National Science Foundation CAREER grant award and received the Presidential Early Career Award for Scientists and Engineers from the President of the United States. She has conducted and advised on educational research projects and grants in both the public and private sectors, and served as an external reviewer for doctoral dissertations outside the U.S. She publishes regularly in peer-reviewed journals and books. Dr. Husman was a founding member and first President of the Southwest Consortium for Innovative Psychology in Education and has held both elected and appointed offices in the American Psychological Association (APA) and the Motivation Special Interest Group of the European Association for Research on Learning and Instruction.

Do you catch my drift? Identification of misconceptions of emergence for the semiconductor phenomenon drift

Abstract

Recent research in learning science has focused on students' misconceptions about emergence. In emergent phenomena, the interactions of the agents in the phenomenon aggregate and form a self-organizing pattern that can be seen at a higher level. One such emergent system, drift, is a fundamental mechanism for semiconductors. The purpose of this study was to demonstrate the presence and prevalence of misconceptions about emergence students have about drift, and to determine what relationships existed between the identified misconceptions. Forty-one undergraduate engineering students participated in the written protocol study. Participants' responses were coded and analyzed using written protocol analysis. A total of 10 emergent misconceptions were observed for drift. Sixty-three percent of participant responses exhibited an emergent misconception, with participants typically anthropomorphizing the electrons' actions in the phenomenon. Quantitative analyses were completed utilizing non-parametric Kendall's tau_b correlation demonstrated significant relationships between the goal-directed nature of the phenomenon and electron volition (0.45, <0.05), the predictability and causal reasons for the phenomenon's pattern (0.31, <0.05), and the not random predictable aspects of the phenomenon (0.31, $p<0.05$). Results indicated that undergraduate engineering students hold misconceptions related to emergence regarding drift and that these misconceptions are prevalent. Furthermore, the relationships observed indicated that learners may view emergence in particular ways – offering insight into how educators can better prepare and develop learning material.

Introduction

The semiconductor industry is broad, encompassing numerous fields related to material science and electrical engineering. Courses in this discipline are well-established and the curriculum has been well-articulated. However, these courses have changed little in recent years – especially considering the great strides that have been made in cognitive psychology related to how students learn. Research on how students learn has shown that students struggle to learn content because they develop misconceptions (e.g. Gentner & Gentner, 1993).[1] The formation of misconceptions can act as a barrier to learning, limiting additional learning within that content area.[2, 3] As such, semiconductor courses must tailor content with student misconceptions in mind.[2, 3] Research is needed to determine what these misconceptions are so that changes can be made to the curriculum. The research addressed in this study specifically looked at misconception formation in the area of semiconductors.

Misconceptions Overview

Research is being conducted in engineering education on how people learn content in engineering(e.g. Streveler, Litzinger, Miller, & Steif, 2008).[4] This work has primarily used the framework of conceptual knowledge acquisition,[4] a framework that builds from the foundations provided from cognitive psychology (e.g. Jetton, Rupley, & Wilson, 1995; Piaget, 1985; Spiro, 1980). [5-7] From these foundations, conceptual knowledge is organized as a memory representation or mental model. A misconception is an alternative conception, or naïve conception, that has resulted due to the formation of an incorrect mental model. [8] For example, students have been taught using an analogy that current is similar to the flow of water. They use their mental model of water to create an analogous mental model for current (a mental model that is ultimately incorrect because it fails when students are asked to describe what happens when a wire is cut – noting that electrons flow out of the wire, instead of accurately describing current in terms of a circuit.)[1]

Research has demonstrated that misconceptions are resistant to change, preventing additional learning related to that concept.[2, 3] Furthermore, learners are not aware that they have formed a misconception - they believe they have understood the material they have been taught. [4] Once formed, misconceptions quickly become integrated into their mental model for that concept and a great deal of time and effort must be exerted to overcome them.[9] Lastly, misconceptions must be overcome for additional learning to occur.[2, 3]

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 some researchers argue that learning about emergence results in misconceptions that are hard to overcome (see Chi, 2005).[10] Within complex systems, the smaller contributions and interactions of individual and identical parts (agents) aggregate to create a self-organizing pattern.[11] These agents act independently – that is, there is no coordination between the agents being orchestrated at a higher level. This pattern occurs when random and unpredictable interactions result in an order that emerges and can be observed at a higher level.[12-13] Examples of emergence include ants foraging, geese flocking,[14] diffusion, [10,15] and evolution.[16] In engineering, an 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.[17] Other examples, like the human 'wave' seen at a stadium, follow the same rules. In this case, the generally identical agents (people) interact independently of each other, without some high level of coordination (there is no one running on the football field leading the wave). The wave emerges from the random interactions of the agents, and no predictable path can be discerned regarding how it will end or continue.

When students improperly conceptualize emergence, as has been shown in engineering[18] and in other domains, students develop misconceptions.[10] In the case of the traffic jam, people incorrectly believe that there is some specific cause (typically a car accident) that has lead to the back-up, and are surprised when no accident can be found. They do not understand how the small interactions between each of the cars, as well as with the environment, can lead to congestion. In engineering, diffusion, a widely cited emergent process,[10, 15] is a topic covered in environmental engineering, chemical engineering, electrical engineering, and other branches. In this process, students typically state that a concentration gradient drives the movement of electrons, chemicals, or people, from areas of high concentration to low concentration. Again, they do not understand the small, but additive, effects that the interacting electrons, chemicals, or people undergo and how these can ultimately lead to the spreading observed in the process of diffusion. Misunderstandings about diffusion in environmental engineering could result in a limited understanding of contaminant fate and transport in the environment. These misconceptions can impact engineering students' understanding of the phenomena.

Drift and Semiconductors

In the field of semiconductor science, drift is the process of electron carriers moving in a certain net direction, opposite to the applied energy field placed on the semiconductor device. This is an emergent phenomenon. During electron movement, 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, as shown in Figure 1. The movement of electron carriers is the result of both the random additive effects of electrons interacting and the energy field. Overall, electron carriers move in a certain net direction due to random motion.

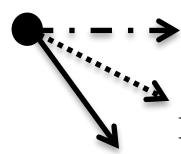

Figure 1: Movement of Electron due to Drift

Previous studies have shown that students develop general misconceptions regarding drift (e.g. Fayyaz et al., 2005; Wettergren, 2002),[19-20] but none have targeted emergent misconceptions. Misconceptions regarding drift can have major implications on learning semiconductor content, especially content that builds from this foundational concept. Misconceptions of drift could result in misconceptions regarding the transport mechanisms in a semiconductor which could lead to misconceptions regarding current and voltage. If, for example, students disregard the random vector of the electron in the process of drift, calculations of current (drift current) could be understated, leading to inflated voltage values. Students would not be able to properly apply equations that build upon the fundamental knowledge for drift to other knowledge (e.g. calculations for voltage). Ultimately, devices such as solar cells could be designed with incorrect voltage specifications, and when plugged into the system, could be underperforming (based on inflated specifications). Overall, these misconceptions could inadvertently lead to faulty understandings of semiconductor content, which could limit students' ability to perform in the field.

Purpose

The purpose of this research was to determine the misconceptions formed related to drift. This research was meant to add to the limited work in engineering education on misconceptions as a whole, and specifically regarding emergent phenomena. This study aimed to:

1. Determine what misconceptions of emergence the participants had for drift.
2. Assess the prevalence of misconceptions of emergence for drift in order to grasp the potential scope of the issue in semiconductor engineering.
3. Determine the relationships between the different misconceptions.

It was predicted that participants held misconceptions about drift. It was predicted that participants held misconceptions for the emergent features of drift, building from previous research done on students' understandings of other emergent engineering phenomena (e.g. Blikstein & Wilensky, 2009).

Methods

Participants

Forty-one participants, engineering undergraduates from a large southwestern university, took part in the study, receiving $30 in compensation. Participants were recruited from an engineering circuits level one course and consisted of 33 males and 8 females. Circuits level one was chosen because the course assumes a basic understanding of physics – the participants should have been previously exposed to concepts related to electricity and basic material properties. Participants typically had taken two physics courses (one course = 10%, two courses = 76%, three courses = 10%, and four courses = 4%), with electricity and magnetism being the more recent and highest level physics course passed. A minority of participants had taken any materials science courses (29%). Participants included students majoring in numerous engineering disciplines: aerospace, biomedical, chemical, computer science, electrical, industrial, and mechanical. Of those that reported, participants primarily described themselves as being in their second year of undergraduate school (freshman = 5%, sophomore = 80%, junior = 12%, and senior = 2.4%), and, 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 participants completed an instrument containing open-ended and Likert-style items that posed questions about drift. The instrument used in this study was adapted from the instrument described in Brem et al. (2012) that was used to identify misconceptions related to emergence.[21] The adapted instrument was tailored for drift in semiconductors.

The study conducted was a written protocol. 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 (1985) 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 the process relies on them attending to information in their short term memory.[22] In this study, participants were asked to view a simulation on drift and answer questions related to what they saw. The drift simulation lasted approximately 90 seconds. Participants viewed the entire simulation two times before proceeding to the survey questions. The survey took approximately 30 minutes to complete. There were a total of seven questions on the topic of drift.

Broad questions were used first (e.g., #1 and #2 below), moving to more specific questions that capture other aspects of the phenomenon (e.g., #3 below).

1. Describe the movement of the electron(s) in the semiconductor when the electric field is on and off. 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 semiconductor when the electric field is on/off? Use as much detail as possible.

3. Imagine an electron, in a similar semiconductor, 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?

Participants were instructed to write as much as possible when responding to the questions, giving as much detail as they could provide. Questions were piloted on experts on semiconductor science and experts on cognitive science. Feedback on the overall survey and their actual question responses was taken into account and minor changes were made. The final survey for drift was made up of eight questions: one asking for consent to participate in the study, seven related to drift, and 10 gathering demographic information.

Coding

Following the protocol analysis description provided by Chi (1997)[23], the codes for misconceptions of emergence were adapted from the codebook generated as part of a pilot study already reported on (see Nelson, 2014)[24] and from the codebook created by Brem and colleagues (2012). Additional codes were added and existing codes were refined because the full study codebook was developed using the entire sample population (N = 41), whereas the Nelson (2014) pilot study codebook only included half of that population. Coding was conducted using the verbal analysis framework summarized by Chi (1997). Chi (1997) describes the verbal analysis approach which is a methodology aimed at better focusing on individual representations for the content. The 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 drift, the analysis of the protocols followed Chi (1997)'s approach.

The Nelson (2014) pilot study codebook was used as a starting point for comparison with the codes that emerged for misconceptions of emergence. Any codes that were not captured by the Nelson (2014) pilot study codebook were noted and then compared to the themes utilized in the Brem et al. (2012) emergent misconception codebook. Another pass through the data allowed 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. The codebook and five protocols were given to an inter-rater (a second researcher) so that they could provide feedback to the primary author on code-interpretation and examples in order to better refine the codebook and codes. Final codes were validated by an expert on emergence and electrical engineering.

During coding, each participant's response for each question was analyzed. If the response exhibited one of the misconceptions for emergence codes, it was coded as EM or misconception of emergence. Alternative codes included U - "uncodable," or A – "absent of misconception." To assess inter-rater reliability, the codebook and 14 protocols were given to a second researcher who also has a background in engineering and education. This researcher had no contact with the author during their coding. The researchers applied the codes with 0.85 agreement and any disagreements were resolved through discussion. Once the data was coded, it was recoded into dichotomous variables such that misconceptions of emergence were 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. Non-parametric statistical analysis was used to make note of any trends in the data.

Results

Misconceptions: A total of 10 emergent misconception themes emerged from the data. The misconceptions of emergence themes are summarized in Table 1.

Table 1. Misconceptions of Emergence Themes, Descriptions, and Exemplars

Emergent Misconception Codes

Code	Description	Exemplar
Non Cooperative	Notes that the electrons work together to create the pattern, or move in order to equilibrate.	"The Electrons moved in such a way that caused them to be uniformly distributed throughout the cell"
Volition	Describes the movement of electrons as being intentional or having anthropomorphic characteristics.	"When it is off the electrons are always random looking for something to attract to. With no charge no attraction and randomization occurs."
Goal Directed	Describes Volition as being performed to meet a certain purpose or goal in association with the 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"
Singular	Describes the pattern carried out by all electrons at an electron (micro) level.	"Once put into motion, the electron moves to the boundary of the material, or until it comes in proximity of another electron…"
Centralized Control	References a specific factor directing, leading, guiding, governing, etc. the electrons to carry out certain actions.	"…they will go wherever the repulsive forces direct them towards"
Causality	Describes a causal direct factor for the observed macro pattern.	"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."
Predictability Change	Does not understand how a small or large change to the system could manifest.	"… if they are not placed in exactly the same starting position, then they will have a completely different

		movement pattern as the forces that they feel from the different directions will be slightly different.”
Predictable	Does not understand how a small or large change to the system could lead to small or large change.	“ …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”
Simple Rules	Notes that the electrons do not follow rules that can be linked to the macro-level pattern observed.	“The movement of electrons in the material kind of random so it’s not like a rule-based movement”
Not Random	Notes that electron movement overall is considered not random.	“This is not a random movement as random would mean that they just go wherever they feel like going at the time.”

An overall misconception of emergence score was computed to determine misconception prevalence. Misconception of emergence scores were computed by taking the median number of misconceptions observed for drift across all participants. For the sample size of 41, misconception of emergence scores were obtained (median = 6). Furthermore, the prevalence of emergent misconceptions was computed for drift (0.63). Frequencies were computed for each of the misconceptions, however other descriptive statistics were not included because the data is non-parametric. The most prevalent misconceptions of emergence were Volition, Predictable, and Causality (0.15, 0.12, and 0.12, 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 the Causality misconception, the participants noted the presence of a specific causal factor for what was occurring in the drift simulation.

Groupings: After themes were observed, the misconceptions of emergence were organized. Certain codes appeared similar to others either theoretically or because the participant responses indicated a qualitative link. In order to address these commonalities, the codes were clustered. Groups are described in Table 2.

Table 2. Theoretical Misconceptions of Emergence Group Variables

Group Name	Group Variables	Theoretical Link
1. Causal	Causality, Centralized Control	Overall notion that 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 misconceptions of emergence	Singular, Non-Cooperative	

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

Once groups were established qualitatively, correlations were run in order to show a quantitative link to the misconceptions of emergence codes within each group. Non-parametric statistical analyses were utilized because the data were non-normal. Relationships between the misconception variables utilized Kendall's tau_b correlation coefficients. A significant and positive relationship was found between the Volition and Goal Directed misconceptions (0.45, <0.05) in the Volition group (see Table 3). Also, a significant and positive relationship was found for the Predictable and Not Random misconceptions (0.31, $p<0.05$) in the Predictability group.

Table 3. Drift Misconceptions of Emergence Correlations

Misconception	1	2	3	4	5	6	7	8
1. Volition	1.00							
2. Goal Directed	**0.45***	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	**0.31***	1.00			
6. Predictability Change	0.16	-0.10	-0.13	0.04	0.12	1.00		
7. Centralized Control	0.01	0.01	0.09	-0.05	0.05	-0.20	1.00	
8. Simple Rules	-0.08	-0.08	-0.20	-0.24	-0.18	-0.06	0.11	1.00

Note: Bolded correlations in the table are indicative of a *grouping* pair significant relationship, misconceptions of emergence not included in the groupings are not included.

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

Discussion

It has already been established that learners can develop misconceptions when they learn about content that is described as emergent.[11, 19, 22] This study was conducted to examine emergent misconceptions that learners have for semiconductors, specifically the concept of drift. Misconceptions of emergence for drift were prevalent, being found in approximately 60% of participant responses. Certain misconceptions were found to be more prevalent than others and, additionally, relationships between misconceptions were observed. Overall, this data presented preliminary evidence regarding the presence of misconceptions of emergence in students' understanding of semiconductor science.

The Volition, Causality, and Predictable misconceptions were the most prevalent misconceptions of emergence observed for drift. The Volition misconception has been observed in previous research for emergent phenomena (e.g. Brem et al., 2012; Chi, 2005). In this study, participants described drift using anthropomorphic characteristics (e.g. electrons want to move, electrons behave a certain way, electrons have needs, etc.). In other related work, it has been demonstrated that anthropomorphizing entities such as atoms and electrons (see Taber & Watts, 1996)[25] is done from an early age, and further, that misconceptions are hard to overcome.[26] 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. As Chi (2005) found, the direct causal factor is a common misconception seen when learners encounter emergent phenomena. The prevalence of the Causality misconception may be due to the presence of a 'factor' embedded in the phenomenon (the electric field for drift) 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. 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.

The Predictability group was supported by significant correlations between the Predictable and Not Random misconceptions of emergence. The Volition group was supported by a significant correlation between the Volition and Goal Directed misconceptions of emergence. Overall, the relationships observed based on qualitative similarities and based on the quantitative analyses indicate that certain misconceptions of emergence are closely related, and further, may help establish a hierarchy of classification of type of misconception for subsequent work in the classroom.

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 any field. For example, oversimplification could result in students developing incorrect design specifications for various semiconductor devices. The misconceptions for emergence described here can provide insight for educators teaching semiconductor content. First, educators could tailor content based on misconceptions of emergence that were the most prevalent across participants' protocols. Second, emphasis could be placed on limiting the oversimplification of content. For example, emergent content should be presented in greater detail instead of being oversimplified, as has been described by Blikstein and Wilenskey (2009). Third, educators could become aware of the ramifications that misconceptions can have toward learning content that builds from previously covered material, both between and within courses. Fourth, educators could also develop course content and exercises or find additional educational resources that reinforce correct conceptions of this fundamental content. Lastly, educators could consider strategies that can promote conceptual change.

This research is not without its limitations. For example, the data presented here indicates, in conjunction with research on misconceptions for emergent phenomena, that the participants do seem to have limited understandings related to the emergent characteristics of drift. The language they use indicates that they have misconceptions, however, additional research is needed to really probe at what the participants mean by their statements (possibly interviews) to correctly ascertain what their mental models may be. Even though the construction of the protocol and subsequent protocol analysis is a well-established approached for probing at participants mental models, and ultimately, determination of misconceptions (see Chi, 1997), additional work is needed to delve deeper into these misconceptions.

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 with students currently studying semiconductors. Assessments on the prevalence of these misconceptions could be used not only to grasp the current misconceptions learners have in courses but also to determine if these misconceptions are lessened by the end of the course. Additionally, future research could focus on the conceptual change process that learners undergo when overcoming the misconceptions identified in this study. Constructing interventions to promote conceptual change for emergence has much larger implications than just promoting conceptual understandings for emergent phenomena in engineering. These studies could add to the limited body of research in engineering education regarding intentional conceptual change as well as interventions to promote conceptual change for other content.

Conclusions

This research study demonstrated that undergraduate engineering students have misconceptions about the emergent characteristics of drift. Through a written protocol and subsequent analysis, specific misconceptions of emergence for drift were identified and were found to be prevalent. Even though some misconceptions observed here reflected those that have been reported in the literature about emergence, relationships between the different misconceptions were observed. 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 as well as provide insight to educators teaching these courses.

References

[1] D. Gentner and D. Gentner, "Flowing waters or teeming crowds: Mental models of electricity," in *Mental Models*, D. Gentner and A. L. & Stevens, Eds. Mawhaw, NJ: Erlbaum, 1983.

[2] J. Clement, "Using Bridging Analogies and Anchoring Intuitions to Deal with Students Preconceptions in Physics," *Journal of Research in Science Teaching,* vol. 30, pp. 1241-1257, 1993.

[3] M. S. Steinberg, D. E. Brown and J. Clement, "Genius is Not Immune to Persistent Misconceptions - Conceptual Difficulties Impeding Isaac Newton and Contemporary Physics Students," *International Journal of Science Education,* vol. 12, pp. 265-273, 1990.

[4] R. A. Streveler, T. A. Litzinger, R. L. Miller and P. S. Steif, "Learning Conceptual Knowledge in the Engineering Sciences: Overview and Future Research Directions," *J Eng Educ,* vol. 97, pp. 279-294, 2008.

[5] T. L. Jetton, W. H. Rupley and V. L. Wilson, "Comprehension of narrative and expository texts: The role of content, topic, discourse, and strategy knowledge," in *Perspectives on Literacy Research: Forty-Fourth Yearbook of the National Reading Conference*, K. A. Hinchman, D. J. Leu and C. K. Kinzer, Eds. Chicago: National Reading Conference, 1995, pp. 197-204.

[6] J. Piaget, *The Equilibrium of Cognitive Structures.* Chicago, IL: University of Chicago Press, 1985.

[7] R. J. Spiro, "Constructive processes in prose recall," in *Theoretical Issues in Reading Comprehension: Perspectives in Cognitive Psychology, Linguistics, Artificial Intelligence, and Education*, R. J. Spiro, B. C. Bruce and W. F. Brewer, Eds. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc., 1980, pp. 245-278.

[8] V. Picciarelli, M. di Gennaro, R. Stella and E. Conte, "A Study of University Students' Understanding of Simple Electric Circuits Part 2: Batteries, Ohm's Law, Power Dissipated, Resistors in Parallel," *European Journal of Engineering Education,* vol. 16, pp. 57-71, 1991.

[9] E. M. Evans, "Conceptual change and evolutionary biology: A developmental analysis," in *International Handbook of Research on Conceptual Change*, S. Vosniadou, Ed. New York, NY: Taylor and Francis, 2008, pp. 263-294.

[10] M. T. H Chi. "Commonsense conceptions of emergent processes: Why some misconceptions are robust," *Journal of the Learning Sciences, 14*(2), 161-199. 2005.

[11] U. Wilensky & M. Resnick. "Thinking in levels: A dynamic systems approach to making sense of the world," *Journal of Science Education and Technology, 8*(1), 3-19. 1999.

[12] M. J. Jacobson. "Problem solving, cognition, and complex systems: Differences between experts and novices," *Complexity, 6*(3), 41-49. 2001.

[13] S. Johnson. *Emergence*. New York, NY: Scribner. 2001.

[14] Semiconductor Industry Association. Industry statistics. 2013, http://www.semiconductors.org/

[15] E. Marek, C. Cowan, & A. Cavallo. "Students misconceptions about diffusion - how can they be eliminated," *American Biology Teacher*, *56*(2), 74-77. 1994.

[16] G. M. Sinatra, S. K. Brem and E. M. Evans, "Changing Minds? Implications of Conceptual Change for Teaching and Learning about Biological Evolution," *Evolution: Education and Outreach,* vol. 1, pp. 189-195, 2008.

[17] M. Resnick. Beyond the centralized mindset. *Journal of the Learning Sciences*, *5*(1), 1-22. 1996

[18] P. Blikstein and U. Wilensky, "An Atom is Known by the Company it Keeps: A Constructionist Learning Environment for Materials Science Using Agent-Based Modeling," *International Journal of Computers for Mathematical Learning,* vol. 14, pp. 81, -07-01, 2009.

[19] J. Wettergren, "Understanding concepts needed for semiconductor physics," *European Journal of Engineering Education,* vol. 27, pp. 105-111, 2002.

[20] F. Fayyaz, M. A. Iqbal and Y. Hashimi, "Problems of Learning Fundamentals of Semiconductor Electronics," *International Journal of Pedagogies and Learning,* vol. 1, pp. 3-17, 2003.

[21] S. K. Brem, G. M. Sinatra, G. Stump, R. Reichenberg and B. Heddy, "Misconceptions regarding emergent phenomenon vary by domain and agent," in *Annual Meeting of the Cognitive Science Society,* Sapporo, Japan, 2012.

[22] K.A. Ericsson and H. A. Simon. *Protocol analysis*. Boston, MA: MIT press.1985.

[23] M. T. Chi, "Quantifying qualitative analyses of verbal data: A practical guide," *The Journal of the Learning Sciences*, vol. 6, pp. 271-315, 1997.

[24] K. G. Nelson, "Misconceptions of Emergent Semiconductor Phenomena." (Doctoral dissertation, Arizona

State University), 2014.

[25] K. S. Taber & M. Watts. “The secret life of the chemical bond: Students’ anthropomorphic and animistic references to bonding,” *International Journal of Science Education, 18*(5), 557-568. 1996.

[26] J.A. Dole, & G.M. Sinatra. “Reconceptualizing change in the cognitive construction of knowledge,” *Educational Psychologist, 33*(2-3), 109-128. 1998.