



## **Engineering and Physics Students' Perceptions about Learning Quantum Mechanics via Computer Simulations**

**Ms. Yu Gong, Purdue University**

Yu Gong is a graduate student in the School of Engineering Education and School of Electrical and Computer Engineering at Purdue University. She holds B.S, M.S. degrees in electrical engineering from Jiangsu University in China. Her researches focus on model-based learning in nanotechnology education.

**Tugba Yuksel, Purdue University, Curriculum and Instruction & Dept. of Physics and Astronomy**

Tugba Yuksel is a Ph.D. candidate in curriculum and Instruction department at Purdue University. She has received her B.S and M.S degrees in physics education program from Hacettepe University in Turkey. She registered to a master program in department of physics at Ankara University in Turkey. At the end of the second semester, she leave her program and came to Purdue university. She holds another M.S degree in science education from Purdue University. Her research interest is mainly on examining how undergraduate level students use their model-based reasoning in the process of learning quantum mechanics and identifying new instructional strategies which helps to support visualization and model-based reasoning.

**Dr. Alejandra J. Magana, Purdue University, West Lafayette**

Alejandra Magana is an Assistant Professor in the Department of Computer and Information Technology and an affiliated faculty at the School of Engineering Education at Purdue University. She holds a B.E. in Information Systems, a M.S. in Technology, both from Tec de Monterrey; and a M.S. in Educational Technology and a Ph.D. in Engineering Education from Purdue University. Her research is focused on identifying how model-based cognition in STEM can be better supported by means of expert technological and computing tools such as cyberinfrastructure, cyber-physical systems, and computational modeling and simulation tools.

**Prof. Lynn A. Bryan, Purdue University**

Lynn A. Bryan is a Professor and Director of the Center for Advancing the Teaching and Learning of STEM (CATALYST) at Purdue University. She holds a joint appointment in the Department of Curriculum and Instruction and the Department of Physics. She received her B.S. in Chemistry from the Georgia Institute of Technology and her Ph.D. in Science Education from Purdue University. Her research focuses on teachers' development of knowledge and skills for teaching in instructionally innovative settings involving novel curriculum reform and technology enhanced environments.

# Engineering and Physics Students' Perceptions about Learning Quantum Mechanics via Computer Simulations

## Abstract

Quantum mechanics (QM) is an important topic in engineering and physics, necessary for both the mathematical and physical prediction and explanation of a particle's behavior at atomic and subatomic levels. Computer simulations provide an advantage for helping students make sense of abstract concepts and visualize complex phenomena in the process of developing a conceptual understanding of quantum knowledge. Students' experiences and attitudes about learning via computer simulations can inform educational design and improve content delivery. In this paper, we studied students' perspective about how simulations influenced their QM learning. Results of this study showed that most students agreed that simulations are helpful for their QM learning. The positive feedback from freshman and sophomore students focused mainly on basic interactive functions of simulations. Such functionality included: ease of operation, direct visualization, and animated demonstration. Senior level students were more critical of simulations in their descriptions, pointing out the limitations of the models behind the physical explanations and the authenticity of the computational representations. Based on these research findings, we provided recommendations to improve simulation-based instructional design.

## Background and Motivation

Quantum mechanics (QM) constitutes the theoretical basis to explore unknown physical phenomena in the quantum world, which enables scientists and engineers to use the different features of atomic and molecular structures to develop innovative technologies. The concepts and objects in the quantum world are hard to visualize and difficult to describe because of their abstract nature. In learning QM, students are required to abandon models and intuitive analogies they have learned in classical physics.

Invisibility and counterintuitive transitions are two major challenges for students when studying QM<sup>1-2</sup>. Cognitive studies have demonstrated that students experience difficulty in learning physical concepts when those concepts are not directly observable<sup>3</sup>. In QM study, most of the phenomena cannot be demonstrated using manipulative or concrete models that closely and precisely represent reality. Indeed, educators and researchers have debated about issues regarding teaching and learning of QM for several decades—e.g., when is it developmentally appropriate to introduce QM ideas? What are the most effective pedagogies for teaching QM? Research has shown that quantum concepts generally have been taught via traditional instructional methods, often resulting in disappointment and confusion for students as they make the transition from a deterministic to a probabilistic perspective<sup>4-5</sup>.

With this in mind, researchers have started to develop and test innovative teaching strategies and educational tools for the teaching and learning of QM among different age groups. For example, Olsen<sup>6</sup> conducted a study to examine high school students' conceptual understandings after traditional QM lecture. His essential finding was that students could only show a partial understanding on the wave-particle duality. Some students continued to demonstrate non-normative conceptions that were rooted in classical point of view, e.g., electrons' momentum and kinetic energy. In a study examining meaningful learning process,

Hilger et al.<sup>7</sup> used mind and concept maps to facilitate the concept learning on quantization, uncertainty, state, and superposition of states to third-year high school students. Throughout the unit, students articulated their understandings with mind and concept maps, which indicated the some level of sophistication in definitions and connections between terms. As another example, Fanaro et al.<sup>8</sup> adjusted the Conceptual Structure of Reference (CSR) based on the Feynman's Path Integral Method and designed a Proposed Conceptual Structure for Teaching (PCST) to teach high school students some fundamental ideas of quantum mechanics without using mathematical formalism. During the intervention, students used simulation software that designed to visualize the double slit experiment without involving mathematical formalism. The researchers found that students were able to justify the given quantum phenomena, draw graphs based on the data and compare the results, and predict the results of simulation after setting the initial conditions.

At university level, Johnston and colleagues<sup>9</sup> examined how third-year-level students who completed traditional quantum mechanics course conceptualized wave-particle paradox, wave properties and probability. They conducted a survey consisting of open-ended, content-focused questions. After analyzing students' responses, researchers found that even though students' models seemed to be advanced at the individual level, there were no connections between models that constituted the components of a consistent structure. The researchers concluded that learning occurred only on the surface level. Students were not able to internalize and logically construct knowledge. In a similar study, Müller and Wiesner<sup>4</sup> investigated students' learning of basic quantum phenomena such as photon, electron, atom models, and the Heisenberg uncertainty principle using virtual laboratories. They found that almost all students accurately conceptualized the quantum phenomena. Zollman and his colleagues<sup>2</sup> argued that quantum mechanics learning is not as difficult as it is commonly perceived. They suggested that non-science high school and first year college students have the capacity to comprehend quantum mechanics without classical mechanics backgrounds. However, to accomplish this, instruction has to be carefully and internationally designed. Thus, they developed a new instructional design for quantum mechanics that included hands-on activities and a computer-based simulation. 175 teachers in 160 schools implemented the instructional unit in their classrooms. The results indicated that visual QM tools facilitated the learning of students who were considered "novice" in science and math. The materials also increase the understanding of QM concepts for science and engineering students.

In these studies, computer-based simulation tools were extensively used in increasing students' quantum learning, both conceptually and practically<sup>2-3</sup>. On one hand, the visualization capabilities, especially dynamic behavior, provided idealized representations of complex underlying mathematical models of quantum phenomena that could not be described by words or observed by experiments<sup>2</sup>. On the other hand, the interactive capabilities of simulations showed great advantages in helping students test as well as manipulate abstract concepts, and therefore improved their learning by facilitating students' building of dynamic models. Further, an implication of these studies is that new computer simulation designs should consider research-based cognitive and pedagogical studies to effectively integrate them in classroom settings. One of examples is the Quantum Interactive Learning Tutorials (QuILTs) along with the peer instruction tools developed by the research group in University of Pittsburgh<sup>10</sup>. The feature of QuILTs simulation modules is that the developers combine verbal tutorials to guide students to discover the non-normative conceptions and then scaffolds their development of normative conceptions. As supplemental materials, the tutorials play an important role in bridging "the gap between the abstract quantitative

formalism of quantum mechanics and the qualitative understanding necessary to explain and predict diverse physical phenomena”<sup>10</sup> (p.47).

Another commendable simulation tool is the Physics Education Technology (PhET) simulation series from University of Colorado Boulder. The PhET simulations feature multiple scientific visualizations of basic concepts<sup>11</sup>. With dynamic guidance and feedback when exploring scientific puzzles and phenomena, students can create intuitive models along with interactive connections between concepts under study. All of these inquiry features make PhET simulations educationally effective tools for engaging students in physical science learning.

Simulation use has been extensively accepted as an innovative instructional approach for quantum mechanics education<sup>11</sup>. As the foundation of modern engineering and nanotechnology, quantum mechanics has immense influence on multiple engineering disciplines as well as science disciplines. Hence, as part of a design-based process for creating simulations, it is important to consider different perspectives on how students perceive simulations as learning tools. With this in mind, the overarching research question for this study was:

- *What are engineering and physics students’ perceptions of the educational value of using simulation tools for quantum mechanics learning?*

## **Method and Research Design**

This work is part of Quantum Learning in Engineering And Physics (Quantum LEAP) project. The Quantum LEAP project aims to develop an integrated framework for the design and assessment of effective simulation-based learning environments for quantum education based on studies about engineering and physics students’ non-normative conceptions and metacognitive learning strategies.

*Research Design.* The presented study is guided by interpretive research design. Interpretive research design enables the researcher to presume that knowledge and understanding are results of interpretation and based on individual’s subjective experiences<sup>12</sup>. Interpretive researches consider that knowledge and understanding are socially constructed and that the researcher plays an important role in explaining the process of knowledge/understanding construction<sup>13-14</sup>.

Our goal with this research setting is to investigate human-technology interaction in a natural social setting<sup>13</sup>. To achieve this goal, an interpretive researcher focuses on obtaining meaning from data sources such as interviews and observation<sup>15</sup>. Therefore, with this study we focused on analyzing content that was obtained from students’ ideas about their learning with the help of simulations.

*Participants and Context.* The presented study is a part of large-scale study started in Spring 2014. Eleven engineering and physics students from a Midwestern University were interviewed to reveal their perceptions about learning with simulations. Table 1 shows participating students’ gender, disciplines, academic level, as well as their pseudonyms used in the data analysis.

*Data Collection.* Initially, students who volunteered for the study were required to fill out a background survey that included demographic information along with information about their prior courses in QM. The participants were chosen based on the information given on the

survey. Students' self-report of comfort level on QM concepts was one of the important criteria for choosing participants in order to have a possible spectrum for different levels of metacognition. The additional interview questions were asked right after students completed the initial QM content interview. We used semi-structured interview questions to understand students' ideas and experiences<sup>16</sup>. The interviewer avoided asking leading questions but encouraged interviewees to lead the conversation. To elaborate students' answers, some probing questions were used during interview. The guiding questions for interview questions were:

- What is the best way for you to study quantum mechanics and its concepts?
- Have you ever used simulations? For learning purpose?
- Do you think simulations help your study? Why or why not?
- What functions in simulations are helpful for your study? Or what function do you think will be helpful?

Table 1: Participants background information

Student Code	Gender	Major	Academic Level
P_Fr_01	Male	Physics	Freshman
P_So_01	Male	Physics	Sophomore
P_Ju_01	Male	Physics	Junior
P_Ju_02	Male	Physics	Junior
CE_So_01	Female	Chemical Engineering	Sophomore
CE_So_02	Female	Chemical Engineering	Sophomore
CE_Ju_01	Female	Chemical Engineering	Junior
CE_Se_01	Male	Chemical Engineering	Senior
CE_Se_02	Male	Chemical Engineering	Senior
CE_Se_03	Male	Chemical Engineering	Senior
NE_Se_01	Male	Nuclear Engineering	Senior

*Data Analysis.* Our data analysis process was an iterative one involving continual examination and discussion. Interview data were analyzed using constant comparative methods of analysis<sup>17</sup>. In the first phase of analysis, the students' interview responses were transcribed from both audio and video records. The research team looked for patterns in students' responses that reflected their subjective reasoning. Each of the first two authors individually identified and grouped distinct responses. The grouped categories were used to structurally describe participants' reflections on their learning experiences. In the second phase of analysis, the first two authors discussed finding results from independent analysis and generated overview descriptions of participants' common experiences. Then, all authors discussed and achieved a consensus on group categories based on research questions and commonalities in students' reflections with each other. The final explanations and conclusions were developed by all of the authors.

## Results

During the analysis of transcripts, three major categories regarding students' attitudes about using simulation tools for learning purposes were identified. In-depth analysis revealed that students in the same categories had diverse experiences and consequently different ideas.

**Category 1. Simulation tools are useful in helping students understand abstract concepts.**

Specifically, students described the value of simulations in their QM learning from four perspectives—(1) visualizing abstract concepts and processes, (2) building models, (3) calculating complex math, and (4) testing input-output relations interactively.

**To help visualize abstract concepts and process.** Visualization is the most salient capability of simulation tools. For the atomic- and sub-atomic-scale world, all concepts and structures are invisible to the human naked eye. Even with high-tech microscopes, most phenomena are impossible to be directly observed. Consequently, students find these ideas counterintuitive. Students who are introduced to QM by simulation, therefore, initially experience astonishment, and most of the time discomfort, due to divergence from classical standpoint.

*“Before I do modern physics, I had some exposure to quantum mechanics in chemistry. I learn like... so it’s quantized. But the first time I looked the whole thing, I just couldn’t imagine how could it be specific, you know, they changed everything”* (Student P\_Ju\_02).

**To help build models.** Visualization capabilities of simulation tools help students depict mental pictures and further build their explanatory models. As some students commented,

*“When you run the simulation, you can see actually how it works; when you actually see these visual images, it also tells you these theories behind”* (Student CE\_Se\_03).

*“We use a lot of quantum in doing...like bonding... how the orbital form into bonds... the models of those help me ... in pulling out ... this is how a s orbital looks like, this is how a s orbital looks like...”* (Student CE\_Se\_01).

Integrated with interactive capabilities, students could manipulate and explore a given phenomenon and understand the abstract concept, for example, one student said,

*“you could drag electrons like different levels and achieve like different colors and say wow that’s cool why did that happen. And you kind of, work through that in your head”* (Student P\_Ju\_01).

**To off-load complicated mathematical calculations.** Quantum mechanics cannot be taught without considering mathematical components. Some students acknowledged the mathematical foundation behind the quantum phenomena and their interconnection:

*“I know quantum mechanics is very difficult to visualize just because so much of the concepts comes out from mathematical analysis”* (Student CE\_Se\_02).

As it is widely accepted by current literature, simulation is an effective approach to visualize mathematical conceptualization and representation behind quantum theories. Moreover, there are high-level requirements on mathematical calculation in quantum mechanics problem solving<sup>9</sup>. “Lengthy calculations are needed to analyze the simplest phenomena, with most real-world phenomena falling outside the realm of our ability to calculate”<sup>18</sup> (p.406). In our study, students acknowledged complicated math calculations that directly increased the difficulty for their learning:

*“Some of the functions that would be incredibly difficult to program for Matlab or to ourselves”* (Student CE\_Se\_02).

For engineering and physics education, most simulations used in introductory level courses actually hide complicated mathematical equations, so that students can focus on conceptual understanding by testing input and output relationships, without increasing more cognitive load. For instance, a student mentioned:

*“You could do calculation on paper but it will take a long time. But if you have a simulation, you can just kind of change things about it”* (Student P\_Ju\_01).

Table 2. Summary of responses for category 1

Category 1	Sub explanatory category	Student code	Key response depiction
<b>Simulation tools are useful in helping students understand abstract concepts.</b>	To help visualize abstract concepts and process.	CE_So_01	...it is nice to see on the simulation. It is very small. You can never feel it in your real life.
		CE_Ju_01	...you can actually see what it going on not just on paper look. ...it is great way to visualized the phenomena and what is going on...have a great insider to the physical processes;
		P_Fr_01	...it is so useful because it is often difficult to reproduce this like in the lab. ...having a picture of you know p orbital or f orbital or whatever helps a lot;
		P_So_01	...a picture is worth a thousand words.
		P_Ju_01	...you could drag electrons like different levels and achieve like different colors and say wow that’s cool why did that happen. ...when you run the simulation, you can see actually how it works;
		CE_Se_03	...when you actually see these visual images, it also tells you these theories behind.
		CE_Se_01	...actually seeing them (orbital and wave function) physically (from the model) really helps me.
	To help build mental model.	P_Ju_01	...you could drag electrons like different levels and achieve like different colors and say wow that’s cool why did that happen. And you kind of, work through that in your head.
		P_So_01	...having a picture of you know p orbital or f orbital or whatever helps a lot. Makes you sort of intuitively get what is going on.
		CE_Se_01	...the model of those help me in pulling out, this is how s orbital looks like, this is how a p orbital looks like. ...simulation definitely helped show how these wavenumbers by summing more and more these wavenumbers, and we got closer and closer to the particle behavior;
		CE_Se_02	...it’s definitely helpful to visualize as much as you can visualize, quantum mechanics.
		CE_Se_03	...it will make your memory more solid, rather than just see in the books of these equations.
	To avoid complicated math calculation.	CE_Se_02	...to calculate some of the functions that would be incredibly difficult to program for Matlab or to ourselves.
		P_Ju_01	...you could do calculation on paper but it will take a long time...But if you have a simulation...you can just kind of change things about it.
	To test input-output relation interactively.	CE_Se_01	...to put in a wide range of variables without actually going in and doing something. You can actually see it.
		CE_Se_02	...being able to see we affect of changing a certain parameter on the system being modeled.
CE_So_02		...it is better when you can change the parameters or so. So you will see what happens when you change the wavelength, thing like that.	
P_Ju_01		...I liked most would be getting to just kind of interaction with it. In the way that it is just not possible with pen and paper.	

**To test input-output relationships interactively.** The interactive features of simulation tools are an important factor to engage students. In addition to learning benefits in conceptual understanding, simulation tools also allow students to test relevant parameters and infer changes in phenomena by simply manipulating input values. For example, one student noted this feature:

*“Being able to see we affect of changing a certain parameter on the system being modeled” (CE\_Se\_02).*

Detailed categories and students’ key responses for category 1 are summarized in Table 2.

**Category 2. Performance and usability considerations of the simulation tools inhibit student learning.**

Students also mentioned some limitations when they used simulation tools for learning. The main problems reported from our participants related to coding and operational difficulties.

**Difficulties in coding the underlying model.** A few students experienced difficulties in programming the underlying model. One student complained:

*“It cost so much time doing the computer code and it should be more time learning it (quantum knowledge)” (Student CE\_So\_01).*

**Difficulties in simulation tools without proper instruction.** Other two students complained about their difficulties in using simulation tools without proper instruction. For example, one student said:

*“I thought that was kind of annoying because I didn’t have enough knowledge to do the simulations sometimes or to understand what the simulation meant” (Student CE\_So\_01).*

A junior student, P\_Ju\_01, recalled his early experience unhappily:

*“We just sat down on a computer and the computer with the program that we’ve never seen...I could do it now, but at that time didn’t know what to do. So it was kind of bummer” (Student P\_Ju\_01).*

Detailed categories and students’ key responses for category 2 are summarized in Table 3.

Table 3. Summary of responses for category 2

Category 2	Sub explanatory category	Student code	Key response depiction
<b>Performance and usability considerations of the simulation tools inhibit student learning.</b>	Difficulties in coding.	CE_So_01	It cost so much time doing the computer code and it should be more time learning it.
	Difficult to use simulation without proper instruction.	P_Ju_01	We just sat down on a computer and the computer with the program that we’ve never seen...I could do it now, but at that time didn’t know what to do. So it was kind of bummer.
		CE_So_01	I thought that was kind of annoying because I didn’t have enough knowledge to do the simulations sometimes or to understand what the simulation meant.

### Category 3. Limitations of simulation tools become apparent for advanced students.

Simulation tools for learning purposes also bring limitations that may impede deep understanding and reasoning. One nuclear engineering student discussed his concerns about the validity of the visual representations of quantum phenomena:

*“I do not think it is realistic to give visual examples for everything in the world of physics or nuclear engineering”* because *“it doesn’t really show what actually happened”* (Student NE\_Se\_01).

He elaborated:

*“We were using that (simulation) just as a tool not as a learning source. I would say that it (simulation) needs to be factually correct. So, you just cannot have an electron shell then an electron could”* (Student NE\_Se\_01).

In his opinion, it was not scientifically appropriate to represent atomic scale concepts or behaviors with which people do not have any direct experience. He also questioned the analogy of that electron that is commonly used in current simulation tools,

*“We don’t even know what the electron looks like. It is not even a sphere”* (Student NE\_Se\_01).

Table 4. Summary of responses for category 3

Category 3	Sub explanatory category	Student code	Key Response Depiction
Limitations of simulation tools become apparent for advanced students.	Incorrect or partial correct simplification and representation.	NE_Se_01	I don’t think it is realistic to give visual examples for everything in the world of physics or nuclear engineering; We were using that (simulation) just as a tool not as a learning source.
			I don’t really care for the simulations because it doesn’t really show what actually happen. We don’t even know what the electron looks like. It is not even a sphere. As soon as I put it on the visual screen...you know I lose integrity of what is going on.

### Discussion

When we compared students’ views regarding simulation-based learning tools rather than traditional teaching, it was quite predictable that almost all students had positive attitudes toward using simulations. However, they also expressed difficulties that inhibited student learning. We note that that difficulties identified in Category 2 were all from novice learners. Thus, we infer that difficulties coming from students’ programming skills and teachers’ insufficient instructions would influence new learners’ simulation experiences in their initial quantum mechanics study. In Category 3, students’ concerns about the limitations of the simulations originated from the possibility of acquiring scientifically incorrect models due to ill-represented models.

Findings from this study are consistent with previous research that describes the perceived educational value of simulation tools for undergraduate and graduate students<sup>19</sup>. It is also consistent with students’ need for additional support when using simulations for learning<sup>19</sup>. One particular struggle that students’ encounter relate to the difficulty of dealing with the graphical user interface, or the difficulty in completing assignments that have a programming component<sup>20</sup>. Thus, additional guidance and scaffolding is needed for students to be able to

not only execute computer models, but also have access to the underlying model in such a way that they are able to manipulate it. A particular strategy that has been identified as helpful is to provide students with a template or blueprint of the code<sup>21</sup>, so students can devote cognitive resources to implementing the underlying mathematical model, rather than focus on aspects of code syntax and configuration.

Another interesting finding relates to advanced students' recognition of the limitations of simulation tools. Models may be defined in several ways<sup>22-23</sup>: (1) models are ways of representation of the reality, not the reality itself; (2) models are from idealization, simplification and abstraction; and (3) models can be used to describe, explain and even predict some behaviors of a system. And therefore, visualized models in simulations are actually instructional analogies, which can promote conceptual understanding. Current research has shown that it is important to use models to reinforce students' reasoning and conceptual understanding<sup>24-25</sup>; meanwhile, it is also difficult to change or replace students' non-normative models with scientifically appropriate ones in their later learning<sup>26</sup>. Visualizations and representative models need to be scientifically accurate and carefully implemented in order to prevent further misconceptions.

We should also remark that all analogical models have limitations in representation, especially for invisible physical concepts in quantum mechanics. For introductory level quantum education, which "comprised of roughly ten years after the formulation of the Schrodinger equation in 1926"<sup>27</sup> (p.38), introductory visualized models and pictures might be helpful to introduce quantum concepts development background and to set up basic intuitions to students. However, when the QM education moves to deeper and higher knowledge level, strict theoretical and mathematical analysis will take over. Senior or graduate level students will have more opportunities to learn quantum theories and equations with practical data from real experiments. With the repeated and hands-on exposure to learning experiences, they will develop more sophisticated understanding and reasoning about what might actually happen in quantum world. A senior interviewee mentioned that he was taking a few graduate level courses and would start graduate life in the following semester. He had many chances to do quantum related experiments so that he preferred to learn from real lab, and to use observable experiment results to confirm or explain the knowledge in textbooks.

### **Implications for Teaching**

The major implications of this study relate to identify how to effectively integrate simulations into QM education for both engineering and physics majors. For introductory level education, we suggest using simulation tools to interactively engage students with the fundamental aspects of quantum phenomena. This includes developing foundational knowledge of quantum concepts and how physical parameters would affect quantum phenomena with proper instructional guidance. For example, the steps that indicate how to run the system, and instructions that explain how to control the influence factors for different results will be helpful.

Once students have generated coherent foundational knowledge, a possible second phase would be to begin understanding the underlying model of a simulation tool. That is, students should be provided with opportunities to modify the underlying model or implement a simple version of the model using software for scientific computing (e.g., MATLAB) that may allow learners to identify the mathematical models governing the scientific principles.

We also recommend that teachers discuss both the advantages and limitations of analogical models used in simulations or other visual materials at the beginning of implementation. Students should be encouraged to scaffold, construct and extend their quantum knowledge based on the simulations, but their conceptual understanding should not be limited to the analogies applied in simulation. The distinction between real phenomena and their model representations needs to be emphasized by instructors to avoid misunderstanding.

A conceptual framework that can be used as an instructional tool to introduce modeling and simulation practices in science and engineering could be the “hierarchy of instructors’ intended learning goals for using modeling and simulation”<sup>28</sup>. This conceptual framework suggest eight qualitatively different categories that detailed ways in which instructors can conceptualized the incorporation of simulation tools as learning activities into courses. These eight categories are depicted in Figure 1 below and can be summarized into two major learning goals: (a) executing (using) simulations to identify and describe the governing fundamental physical principles or behaviors of devices, materials and other artifacts, and (b) building (programming) simulations to apply modeling and computational techniques to approach engineering tasks.

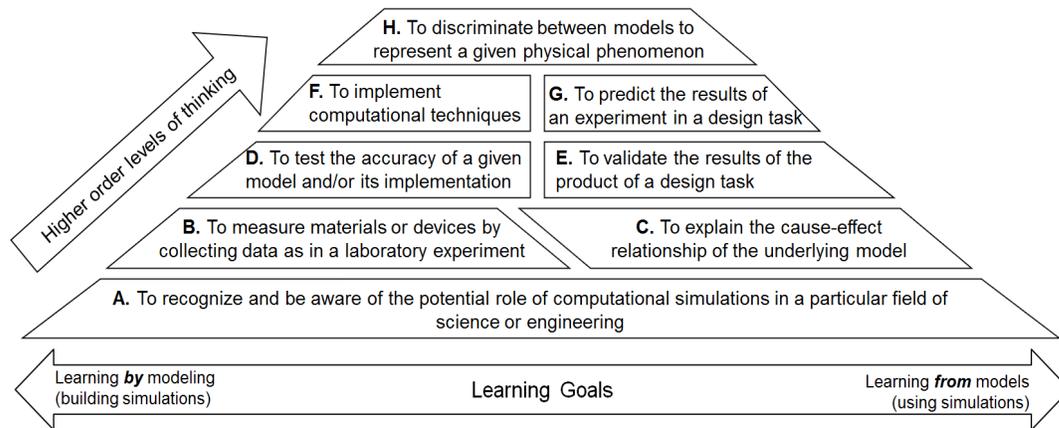


Figure 1. Hierarchy of instructors’ intended learning goals for using modeling and simulation<sup>28</sup>.

Because of the hierarchical nature of this framework that suggest a progression from lower to higher levels of thinking, students could be introduced to different uses of simulation tools, starting with allowing them to identify cause-effect relationships, progressing into implementing the models, and finally to identify when a model has limitations for representing a specific phenomenon and a different one must be used.

### Limitations

We acknowledge that this is a small part of an ongoing project, and thus has limitations. Our study is firstly limited by the sample size. We interviewed 11 students when we started writing this paper. More data will be included for interpretive conclusions in detail. Another limitation is related to the participant population. Because of the time constrain and project coordination, we have only interviewed students from nuclear engineering, chemical engineering and physics as part of initial data collection process. Other relevant majors, such as, chemistry, mechanical engineering, electrical engineering and so on, will be included in future studies. We will report results from more diverse participants.

## Conclusion

Students' experiences and attitudes about the use of simulation tools to support their learning may influence their learning and engagement. Understanding students' experiences and attitudes is important for simulation tool design and pedagogical delivery. In this work, we have studied the role of simulation tools in engineering and physics learning from students' perspectives, especially students' perceptions on their quantum learning experiences with simulations. The preliminary research results show that simulations are an effective analogical and visualization tool to interactively and effectively engage students into introductory quantum mechanics courses. However, simulations also have limitations in concept representations—which is inevitable in atomic/sub-atomic scale quantum physics. Particularly, higher-level students were not satisfied to engage with simplified simulations that represent some of the quantum phenomena. Implications for teaching were also provided to facilitate educators developing more efficient instructional design supported with simulations or any visual representations.

## Reference:

1. Cataloglu, E., & Robinett, R. W. (2002). Testing the development of student conceptual and visualization understanding in quantum mechanics through the undergraduate career. *American Journal of Physics*, 70(3), 238-251.
2. Zollman, D. A., Rebello, N. S., & Hogg, K. (2002). Quantum mechanics for everyone: Hands-on activities integrated with technology. *American Journal of Physics*, 70(3), 252-259.
3. Chi, M. T. H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *The Journal of the Learning Sciences*, 14(2), 161-199.
4. Müller, R., & Wiesner, H. (2002). Teaching quantum mechanics on an introductory level. *American Journal of Physics*, 70(3), 200-209.
5. Mashhadi, A., & Woolnough, B. (1999). Insights into students' understanding of quantum physics: Visualizing quantum entities. *European Journal of Physics*, 20(6), 511-516.
6. Olsen, R. V. (2002). Introducing quantum mechanics in the upper secondary school: A study in Norway. *International Journal of Science Education*, 24(6), 565-574.
7. Hilger, T. R., Moreira, M. A., & Griebeler, A. (2012). The use of mind map and concept maps in quantum mechanics at high school level. *Concept Maps: Theory, Methodology, Technology*. Proceedings of the Fifth International Conference on Concept Mapping, Valletta, Malta, 2012.
8. Fanaro, M., Otero, M. R., & Arlego, M. (2009). Teaching the foundations of quantum mechanics in secondary school: A proposed conceptual structure. *Investigações em Ensino de Ciências*, 14(1), 37-64.
9. Johnston, I. D., Crawford, K., & Fletcher, P. R. (1998). Student difficulties in learning quantum mechanics. *International Journal of Science Education*, 20(4), 427-446.
10. Singh, C., Belloni, M., & Christian, W. (2006). Improving students' understanding of quantum mechanics. *Physics Today*, 59(8), 43-49.
11. Wieman, C. E., Adams, W. K., & Perkins, K. K. (2008). PhET: Simulations that enhance learning. *Science*, 322(5902), 682-683.

12. Reeves, T.C., & Hedberg, J.C. (2003). *Interactive learning systems evaluation*. Englewood Cliffs, NJ: Educational Technology Publications.
13. Díaz Andrade, A. (2009). Interpretive research aiming at theory building: Adopting and adapting the case study design. *The Qualitative Report*, 14(1), 42-60.
14. Cavana, R. Y., Delahaye, B. L., & Sekaran, U. (2001). *Applied business research: Qualitative and quantitative methods* (Australian ed.). Milton, Queensland, Australia: J. Wiley.
15. Thomas, P. Y. (2010). Towards developing a web-based blended learning environment at the University of Botswana. (Doctoral dissertation, University of South Africa, 2010).
16. Barriball, K.L., & While, A. (1994). Collecting data using a semi-structured interview: A discussion paper. *Journal of Advanced Nursing*, 19(2), 328-335.
17. Lincoln, Y., & Cuba, E. (1985). *Naturalistic inquiry*. New York: Sage.
18. McKagan, S. B., Perkins, K. K., Dubson, M., Malley, C., Reid, S., LeMaster, R., & Wieman, C. E. (2008). Developing and researching PhET simulations for teaching quantum mechanics. *American Journal of Physics*, 76(4), 406-417.
19. Magana, A.J., Brophy, S.P. & Bodner, G.M. (2012). An exploratory study of engineering and science students' perceptions of nanoHUB.org simulation tools. *International Journal of Engineering Education*, 28(5), 1019-1032.
20. Magana, A. J., & Garcia, R. E. (2010). FiPy and OOF: Computational simulations for modeling and simulation of computational materials. Proceedings of the 117th Annual Conference of the American Society of Engineering Education (ASEE), Louisville, Kentucky, June 20 - 23.
21. Magana, A.J., Brophy, S.P., & Bodner, G.M. (2012). Student Views of Engineering Professors Technological Pedagogical Content Knowledge for Integrating Computational Simulation Tools in Nanoscale Science and Engineering. *International Journal of Engineering Education*. 28(5). 1033-1045.
22. Ingham, A. M., & Gilbert, J. K. (1991). The use of analogue models by students of chemistry at higher education level. *International Journal of Science Education*, 13(2), 193-202.
23. Schwarz, C. V., Reiser, B., Acher, A. Kenyon, L., & Fortus, D. (2012). MoDeLS; Challenges in defining a learning progression for scientific modeling. In A. C. Alonzo, & A. W. Gotwals (Eds), *Learning Progressions in Science: Current Challenges and Future Directions* (101-137). Rotterdam, the Netherlands: Sense Publications.
24. Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, 92(5), 941-967.
25. Schwarz, C.V., Reiser, B.J., Davis, E.A., Kenyon, L., Acher, A., Fortus, D., Shwartz, Y., Hug, B., & Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching*, 46(6), 632-654.
26. Libarkin, J.C., Beilfuss, M., & Kurdziel, J.P. (2003). Research methodologies in science education: mental models and cognition in education. *Journal of Geoscience Education*, 51(1), 121-126.
27. Carr, L. D., & McKagan, S. B. (2009). Graduate quantum mechanics reform. *American Journal of Physics*, 77(4), 308-319.
28. Magana, A.J., Brophy, S.P., & Bodner, G.M. (2012). Instructors Intended Learning Outcomes for Using Computational Simulations as Learning Tools. *Journal of Engineering Education*, 101(2), 220-243.