Tool-Based Curricula and Visual Learning

Dragica Vasileska, Gerhard Klimeck, A. Magana, and S. M. Goodnick

***Abstract*—In the last twenty years nanotechnology has revolutionized the world of information theory, computers and other important disciplines, such as medicine, where it has contributed significantly in the creation of more sophisticated diagnostic tools. Therefore, it is important for people working in nanotechnology to better understand basic concepts to be more creative and productive. To further foster the progress on Nanotechnology in the USA, the National Science Foundation has created the Network for Computational Nanotechnology (NCN) and the dissemination of all the information from member and non-member participants of the NCN is enabled by the community website www.nanoHUB.org. nanoHUB's signature services online simulation that enables the operation of sophisticated research and educational simulation engines with a common browser. No software installation or local computing power is needed. The simulation tools as well as nano-concepts are augmented by educational materials, assignments, and tool-based curricula, which are assemblies of tools that help students excel in a particular area.**

As elaborated later in the text, it is the visual mode of learning that we are exploiting in achieving faster and better results with students that go through simulation tool-based curricula. There are several tool based curricula already developed on the nanoHUB and undergoing further development, out of which five are directly related to nanoelectronics. They are: ABACUS – device simulation module; ACUTE – Computational Electronics module; ANTSY – bending toolkit; and AQME – quantum mechanics module. The methodology behind tool-based curricula is discussed in details. Then, the current status of each module is presented, including user statistics and student learning indicatives. Particular simulation tool is explored further to demonstrate the ease by which students can grasp information. Representative of Abacus is PN-Junction Lab; representative of AQME is PCPBT tool; and representative of ACUTE is SCHRED, which has 97 citations in research papers and is the most popular tool on nanoHUB.org.

Surveys were collected from three courses offered at Arizona State University. These courses were: EEE434/591, the Quantum Mechanics class offered in the fall 2007; EEE 101 Engineering Design, offered in the spring 2008; and EEE533 Semiconductor Device and Process Simulation, offered in the fall 2009. The study consisted of students participating in a voluntary Likert-scale survey that focused on: *Learning outcomes, Evidence of the learning, Pedagogical approach and Usability aspects.* In particular, the survey investigated how intuitive the tools are.

The results of the study identified differences in the way students perceived the nanoHUB.org simulation tools. Graduate and undergraduate students reported more positive experiences with nanoHUB.org simulations than freshman students did. Potential explanations for these differences are: a) freshman students have not fully developed graphical literacy skills; b) students may lack the prior knowledge required at the time they interact with the tool; and c) students may lack interests in the topic and have not yet seen the value of how these tools can be applied toward their own learning goals. A potential support to overcome some of these difficulties may be by embedding just-in-time instructional supports together with the simulation tools.

***Index Terms*—ABACUS, AQME, nanoHUB, tool-based curricula.**

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I. INTRODUCTION

Learning theorists [1] have demonstrated that people vary in the manner in which they absorb, process, and recall what they are taught. Verbal learners, a group that constitutes about 30% of the general population, learn by hearing. They benefit from class lectures and from discussion of class materials in study groups or in oral presentations, but chafe at written assignments. Experiential learners - about 5% of the population - learn by doing and touching, and clinical work, role-playing exercises, and moot court are their best instructional modalities. Visual Learners - the remaining 65% of the population - need to see what they are learning, and while they have difficulty following oral lectures, they perform well at written assignments and readily recall material they have read. Empirical research supports the conclusions that when students are matched with teaching methods that complement their learning styles, their absorption and retention is significantly enhanced. Moreover, variations in learning styles have been linked to gender: women tend to be more visually oriented than men, who are generally more kinesthetic, and consequently female students are systematically more prone to suffer the deleterious effects of learning style-teaching method mismatch than men.

In addition to regular student, we often encounter in the classroom students with learning disabilities. The term learning disability (LD) is used to refer to a range of neurological conditions that affect one or more of the ways

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that a person takes in, stores, or uses information [2]. Learning disabilities are specific, not global, impairments. For example, a person may have a LD which impacts on her ability to understand written information; the same information, delivered orally or visually, presents no problem. The term includes such conditions as dysgraphia (writing disorder), dyslexia (reading disorder), dyscalculia (mathematics disorder) and developmental aphasia.

Learning disabilities affect all areas of life to the extent that the affected mode is used in that area. They are most often noticed in school settings, where certain learning modes are employed more than others, causing the weaknesses caused by the LD to stand out. Learning disabilities are usually identified by school psychologists through testing of intelligence, academics and processes of learning. It is now well-known now that desktop-based computer technology plays an important role in the education of students with disabilities.

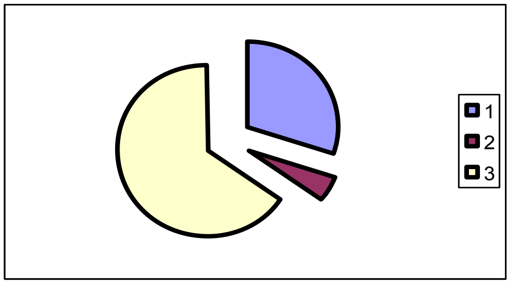


Fig. 1. 1- total % of verbal learners; 2- total % of experiential learners and 3- total % of visual learners.

It is also important to stress that visual memory is a part of memory preserving some characteristics of our senses pertaining to visual experience. We are able to place in memory information that resembles objects, places, animals or people. Some authors refer to this experience as “our mind’s eye” through which we can retrieve from memory a mental image of the original object, place, animal or person. Eidetic imagery is perhaps the only kind that produces actual visual memory that can be looked at similarly as if looking at the actual picture. There are two kinds of memory related to eidetic imagery: photographic memory and iconic memory. The phenomenon of photographic memory is usually displayed by some individuals' exceptional skills in mental organization *and it is this type of memory that we will exploit in student/researcher learning via the use of the visualization and simulation software that has friendly graphical user interface and is deployed to the general public via www.nanoHUB.org*.

II. TOOL-BASED CURRICULA

Control of energy has become a common problem facing both the electronics industry in terms of thermal management and energy efficiency, not to mention solid state lighting, as well as in energy conversion of optical to electrical energy (and vice versa). The device scaling crisis has motivated researchers from all over the world to look for replacement of conventional field-effect transistor in digital applications as well as analog applications. Strained-Si devices have been proposed, alternative device technologies have also been explored. What will be the next device that will replace conventional silicon MOSFETs is not clear even to the Intel Corp. Many alternative structures such as nanowire transistors, carbon nanotubes, nanoribons, etc., graphene devices (these are some of the many choices being explored at the moment) have been proposed.

There is one common theme that describes all these alternative devices: they are small, so the atomic arrangement will affect the material properties, they operate more or less on quantum-mechanical principles, therefore requiring the latest developments in material science, great physics insight, and most importantly, they need state of the art modeling tools.

Several factors motivate us to focus on development of future generation software tools and integrate them into 21st Century Educational Courses and seminars. If we take, for example, the conventional silicon transistor, it consists of more then 60 elements which material properties we have to know to be able to predict its operation. Furthermore, as transistors get scaled into nanometer dimensions, quantum effects become more prominent and knowledge of Quantum Mechanics is essential. In addition, there is a continuous trend to scale the transistors to get faster devices and more functions on the chip. The conventional way of doing scaling no longer works and two general avenues are typically pursued by the industry: alternative materials and alternative device structures. Again, knowledge of the properties of the materials along, for example, various crystallographic directions becomes essential.

The above discussion suggests that new paradigms of learning are necessary for training students in the vibrant and constantly changing field of nanoelectronics. Since computers play more and more important role in person’s everyday life, they have to be incorporated into the student learning process. Prof. Vasileska and Prof. Klimeck propose a novel methodology, the so-called tool-based curricula, to be used for training future engineers in the nanoelectronics field. This new methodology consists of assembling a set of tools, together with demos on how to use the tools, the objectives of the tool and what can be learned with them, assembly of solved problems, homework assignments including solve a challenge problem which is related to real world applications. Examples of such assemblies of tools and their capabilities are given in the following three subsections.

A. ABACUS

The purpose of the ABACUS tool-based curricula is that via simulations students get working knowledge for the operation of basic semiconductor devices. In order to understand the operation of bipolar devices, for example, it is crucial to understand the physical principles of the operation of a PN diode under forward and reverse bias conditions and in the presence of different generation/recombination processes including Shockley-Read-Hall generation/recombination and Auger generation/recombination (PN Junction Lab).

On the other hand, MOS capacitors are integral part of every MOSFET device, so understanding the operation of

MOS capacitors is crucial for the understanding of MOSFET devices. Several tools are developed and offered for this purpose with different levels of approximation listed below under a common name MOS Capacitors. One of them is based on the idealized delta-depletion approximation, the second one exploits the exact analytical model for semiclassical charge description, and the third tool is able to do either semiclassical or quantum-mechanical calculation of the charge self-consistently in the MOS Capacitor where appropriate.

MOSFET devices, that are a backbone of 99% of today's integrated circuits, can be analyzed using the MOSFET Lab. Various effects can be predicted such as punch-through (occurs when source and drain depletion regions touch), DIBL=Drain Induced Barrier Lowering (leads to finite output conductance), transistor breakdown caused by the impact ionization process, etc.

In summary, the following tools comprise ABACUS that is designed for the purpose of better understanding the operation of semiconductor devices:

- Crystal Viewer
- Periodic Potential Lab
- Piece-Wise Constant Potential Barrier Tool
- Bandstructure Lab
- Carrier Statistics Lab
- Drift-Diffusion Lab
- PN Junction Lab
- BJT Lab
- MOS Capacitor Lab (classical calculations)
- MOSFET Lab (classical calculations)

As one of the most popular labs from the ABACUS learning module is the PN-Junction lab. This lab not only describes the operation of a PN diode, the interplay of the drift and diffusion processes, and of the generation-recombination mechanisms, but it nicely illustrates the need for simulation for the case when modeling asymmetric junctions. Namely, if one looks at the electric field profile plot for a diode with $N_A=10^{16}$ cm^{-3} and $N_D=10^{18}$ cm^{-3}, then one finds that the depletion charge approximation underestimates the peak electric field by a large margin. The numerical solution, on the other hand, predicts the correct breakdown field. The peak electric field for the diode example considered here is shown in Fig. 2.

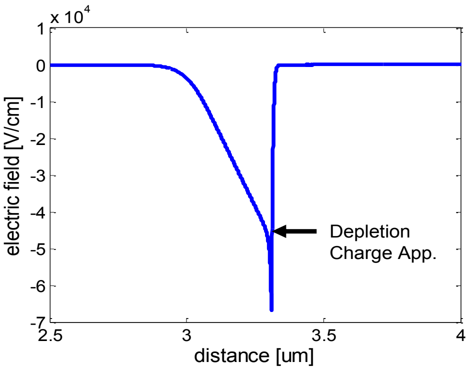


Fig. 2. Electric field profile in a pn-diode with $N_A=10^{16}$ cm^{-3} and $N_D=10^{18}$ cm^{-3} and equilibrium conditions.

The usage statistics of the PN Junction Lab is given in Tables 1-3.

TABLE I
OVERVIEW

Item	Average	Total
Simulation Users:	-	3,420
Interactive Sessions:	-	11,795
Simulation Sessions:	-	22,938
Simulation Runs:	-	33,015
Wall Time:	11.05 hours	10565.37 days
CPU time:	17.81 seconds	4.38 days
Interaction Time:	2.23 hours	1973.19 days

TABLE II
USERS BY ORGANIZATION TYPE

#	Type	Users	Percent
1	Educational - University	2,634	77.02
2	Unidentified	237	6.93
3	Educational - Unspec. Level	218	6.37
4	Industry	173	5.06
5	National Lab	45	1.32
6	Personal	39	1.14
7	Unemployed	27	0.79
8	Government Agency	25	0.73
9	Educational - Pre-College	24	0.7
10	Military	9	0.26
	Total Users	3,420	100

TABLE III
USERS BY COUNTRY OF RESIDENCE

#	Country	Users	Percent
1	United States	1,755	51.32
2	Czech Republic	242	7.08
3	India	200	5.85
4	Canada	126	3.68
5	Sweden	105	3.07
6	Turkey	86	2.51
7	Korea, Republic of	75	2.19
8	China	63	1.84
9	Italy	58	1.7
10	Germany	55	1.61
	Total Users	3,420	100

B. AQME

Every quantum mechanics book written by physicists, without any exception, is dominated by the discussion of the hydrogen atom and very little of the text is devoted to real world applications. Engineers need something different and that is very nicely captured by Prof. David K. Ferry from Arizona State University in his text "Quantum Mechanics for Engineers".

Namely, things that engineers are mainly concerned with are the differences between closed and open systems. Closed systems can be used to describe quantum mechanical size quantization effects in nanodevices in which there is constrain in the motion of the carriers in one or two or three directions in which case we talk about quasi-two-dimensional electron gas, quasi-one-dimensional electron gas and zero-dimensional electron gas. Bound states calculation lab is developed for this purpose to take into account quantization in one and two spatial directions.

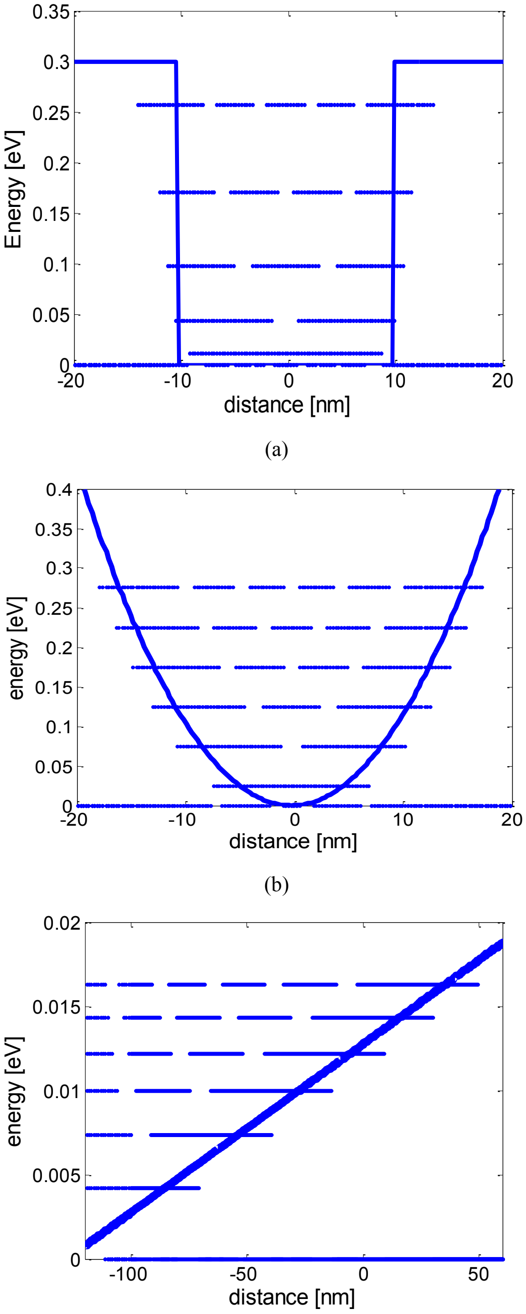
Open systems are, on the other hand, very important to be properly explained because every functioning device is an open system. When describing open systems key thing to know is the energy dependence of the transmission coefficient because once that quantity is calculated one can use the Tsu-Esaki formula [3] and calculate the current.

Another quantity that has to be grasped by students studying semiconductor devices is the real electronic structure of a zinc-blende material of interest. For that purpose we have developed the Periodic Potential Lab that is based on the simple Kronig-Penney model and illustrates nicely how the interaction potential opens gaps in the free-electron dispersion curve. Students also have the opportunity to visualize realistic bandstructure of three-dimensional crystals by running the Bandstructure Lab tool that is based on the validity of the Empirical Pseudopotential method and tight-binding approximation.

In summary, the following tools comprise AQME devoted for understanding basic quantum-mechanical principles needed for understanding the operation of nano-electronic devices:

- Bound-States Calculation Lab
- Piece-Wise-Constant Potential Barrier Lab
- Periodic Potential Lab
- Bandstructure Lab
- SCHRED
- 1D Hetero
- Quantum Dot Lab
- Resonant Tunneling Diode Lab
- Coulomb Blockade Lab

Typical examples for the Bound State Calculation Lab are the investigation of the energy level spacing in rectangular, parabolic and triangular confinement. The lowest eigenenergies for these examples are plotted in Fig. 3.



(a)

(b)

(c)

Fig. 3. Lowest energy eigenstates in a rectangular (a), parabolic (b) and triangular (c) confinement. Notice the differences in the energy level spacing. For rectangular confinement the energy level spacing increases with increasing energy, for parabolic it is constant and for triangular it decreases with increasing energy. These are typical confinement types that occur in nature. The wave functions are sine functions for square confinement, Hermite polynomials for parabolic confinement and Airy functions for triangular confinement.

The Piece-Wise Constant Potential Barrier Tool not only can be used to investigate transmission and reflection through three segment, 5 segment, 7 segment, 9 segment and 11 segment piece-wise constant barrier construct, but the tool very elegantly demonstrates the formation of energy bands and energy gaps under the option multiple identical barriers. This is illustrated very nicely on the example shown in Fig. 4. Only through such examples students can grasp the concept of formation of energy bands and energy gaps.

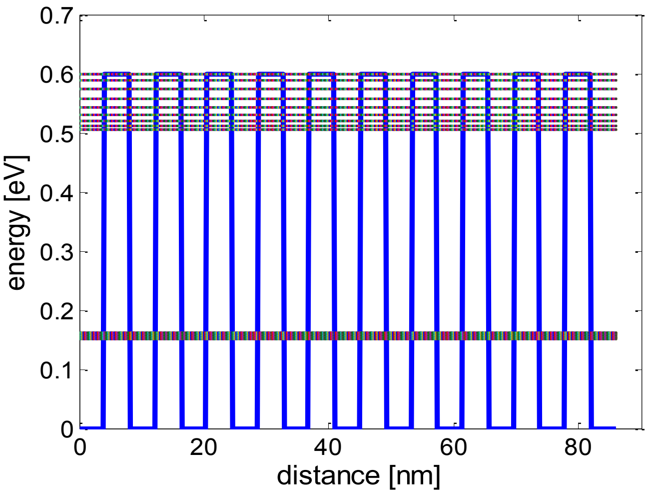


Fig. 4. Multiple-barrier case and formation of energy bands due to the interaction between the wells.

The PCPBT Tool Usage Statistics is given in Tables 4-6.

TABLE IV
OVERVIEW

Item	Average	Total
Simulation Users:	-	254
Interactive Sessions:	-	1,115
Simulation Sessions:	-	2,736
Simulation Runs:	-	3,851
Wall Time:	1 hours	114.35 days
CPU time:	29.26 seconds	22.24 hours
Interaction Time:	26.25 minutes	49.87 days

TABLE V
USERS BY ORGANIZATION TYPE

#	Type	Users	Percent
1	Educational - University	234	92.13
2	Unidentified	6	2.36
3	National Lab	4	1.57
4	Unemployed	3	1.18
5	Industry	3	1.18
6	Educational - Pre-College	2	0.79
7	Military	1	0.39
8	Government Agency	1	0.39
	Total Users	254	100

A critical insight here is the fundamental question of how many atoms are required to obtain a band structure. An analogous example is to start from isolated atom, then bring together two atoms, then three, etc., until n-atoms are used. Further complication can be that the atoms are not aligned on a line, but have their full 3D positions as in real crystals. This second case is examined by the band structure lab whose output is the energy versus wave vector dispersion along high symmetry points in the first Brillouin zone.

TABLE VI
USERS BY COUNTRY OF RESIDENCE

#	Country	Users	Percent
1	United States	142	55.91
2	Italy	17	6.69
3	India	16	6.3
4	Romania	8	3.15
5	Germany	8	3.15
6	Canada	7	2.76
7	China	4	1.57
8	Taiwan	3	1.18
9	Bangladesh	3	1.18
10	Egypt	3	1.18
	Total Users	254	100

C. ACUTE

Continuing technological advances make possible the fabrication of electronic devices with increasing structural and conceptual complexity, and in an expanding variety of material systems. In the field of Computational Electronics, advanced modeling and simulation techniques are created, developed and employed to assist in the invention, design and optimization of micro-, nano- and opto-electronic devices and circuits. Research in Computational Electronics draws upon knowledge from a variety of disciplines, predominantly solid state physics, quantum mechanics, electromagnetics and numerical algorithms, to achieve an accurate description of all aspects of device operation.

Device structure, material composition, and operating principles are all intimately related. For example, the characteristic length scale of devices such as resonant tunneling diodes and quantum dots which rely on coherent quantum effects is constrained to just a few nanometers. Most optoelectronic devices exploit heterojunctions between two or more different materials for confinement of both charge carriers and light; characteristic thicknesses of absorption or gain regions typically vary from around one hundred nanometers to several microns. Power electronic devices, on the other hand, may reach several millimeters in width due to their current-handling requirements, and are increasingly fabricated using materials other than silicon in a quest for superior thermal performance and breakdown voltage. The wide variety of possible applications, material selections, and realizable device structures make Computational Electronics a broad and exciting field.

On the nanoHUB we have created tool-based curriculum that allows users to simulate semiconductor devices that range in behavior and can be explained with purely semiclassical concepts to devices that need fully quantum mechanical modeling to capture their behavior. The tools that comprise ACUTE are:

- Piece Wise Constant Potential Barrier Tool
- Periodic Potential Lab
- Bandstructure Lab
- PADRE Simulator
- Bulk Monte Carlo Lab
- QUAMC 2D – Monte Carlo Device Simulator
- SCHRED – 1D Schrödinger-Poisson solver
- 1D Hetero
- nanoMOS

The most popular tool on the nanoHUB is SCHRED that can be used, for example to qualitatively and quantitatively explain the semiclassical vs. quantum behavior of the carriers in the MOS capacitors which comprise MOSFET devices. The usage statistics of SCHRED is given in Tables 7-9, and SCHRED worldwide usage is illustrated in Fig. 5.

TABLE VII
OVERVIEW

Item	Average	Total
Simulation Users:	-	1,667
Interactive Sessions:	-	20,431
Simulation Sessions:	-	39,005
Simulation Runs:	-	47,153
Wall Time:	2.11 hours	3423.93 days
CPU time:	41.5 seconds	12.85 days
Interaction Time:	1.11 hours	1234.05 days

TABLE VIII
USERS BY ORGANIZATION TYPE

#	Type	Users	Percent
1	Educational - University	1,223	73.37
2	Unidentified	211	12.66
3	Industry	101	6.06
4	Educational - Unspec. Level	52	3.12
5	National Lab	40	2.4
6	Unemployed	17	1.02
7	Government Agency	11	0.66
8	Educational - Pre-College	10	0.6
9	Personal	10	0.6
10	Military	2	0.12
	Total Users	1,667	100

TABLE IX
USERS BY COUNTRY OF RESIDENCE

#	Country	Users	Percent
1	United States	762	45.71
2	Taiwan	149	8.94
3	India	87	5.22
4	China	49	2.94
5	France	36	2.16
6	Japan	29	1.74
7	Korea, Republic of	29	1.74
8	United Kingdom	27	1.62
9	Italy	27	1.62
10	Germany	24	1.44
	Total Users	1,667	100

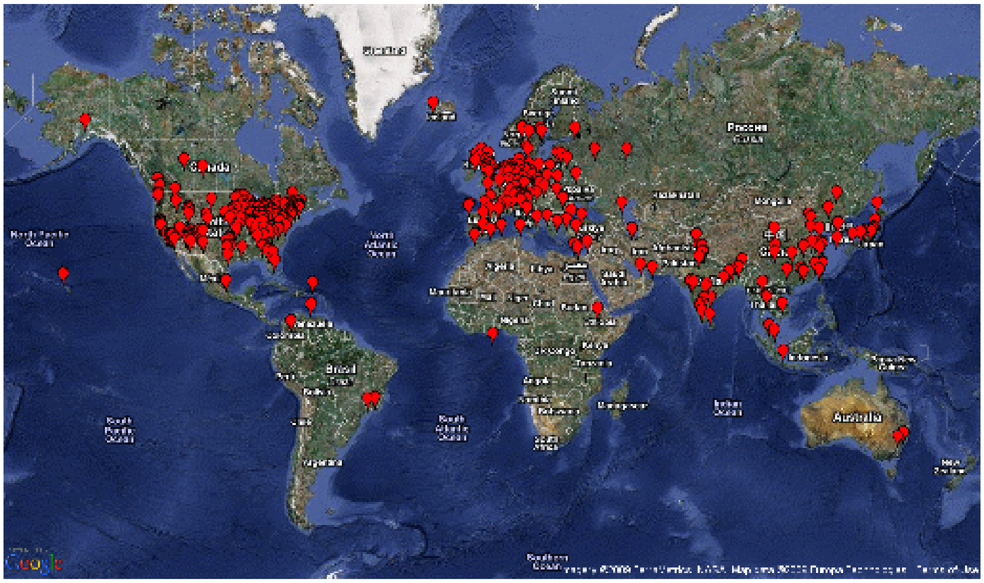
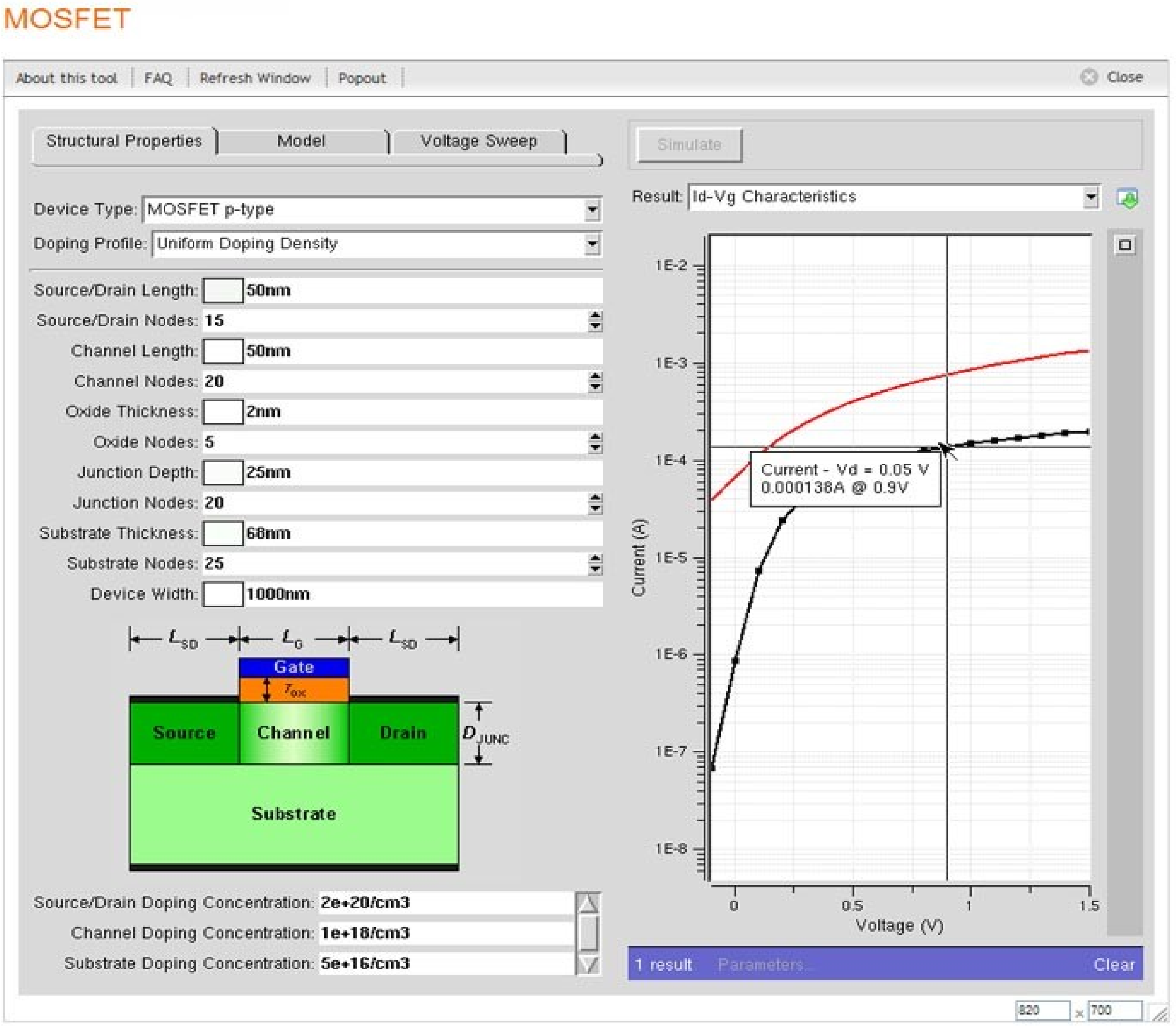


Fig. 5. World-Wide Usage of SCHRED.

III. VISUAL ENVIRONMENT STIMULATING STUDENT LEARNING

nanoHUB.org provides research-quality simulations that experts in nanoscience commonly use to build knowledge in their field. nanoHUB.org leverages an advanced cyber-infrastructure and middleware tools to provide seamless access to these simulations. As described on the nanoHUB.org website, key characteristics of nanoHUB.org simulation tools that make them good resources for incorporation into classroom environments are: a) they were produced by researchers in the NCN focus areas; b) they are easily accessed from a web browser powered by a highly sophisticated architecture that taps into national grid resources; and c) they provide a consistent interactive graphical user interface known as Rappture, which makes esoteric computational models approachable to non-experts. Rappture is a toolkit that allows the incorporation of a friendly graphical user interface with the simulation tools in nanoHUB.org [4]. An example of this interface is shown in Figure 6. In Figure 7 the results from a survey are summarized regarding the GUI and usability, in general, of nanoHUB tools. Three categories of students were being assessed: FS=freshman, US=undergradduate and GS=graduate students.


MOSFET

Device Type: MOSFET p-type
Doping Profile: Uniform Doping Density
Source/Drain Length: 50nm
Source/Drain Nodes: 15
Channel Length: 50nm
Channel Nodes: 20
Oxide Thickness: 2nm
Oxide Nodes: 5
Junction Depth: 25nm
Junction Nodes: 20
Substrate Thickness: 68nm
Substrate Nodes: 25
Device Width: 1000nm
Source/Drain Doping Concentration: 2e+20/cm3
Channel Doping Concentration: 1e+18/cm3
Substrate Doping Concentration: 5e+16/cm3

Result: Id-Vg Characteristics

Current - Vd = 0.05 V
0.000138A @ 0.9V

Fig. 6. MOSFET simulation tool interface.

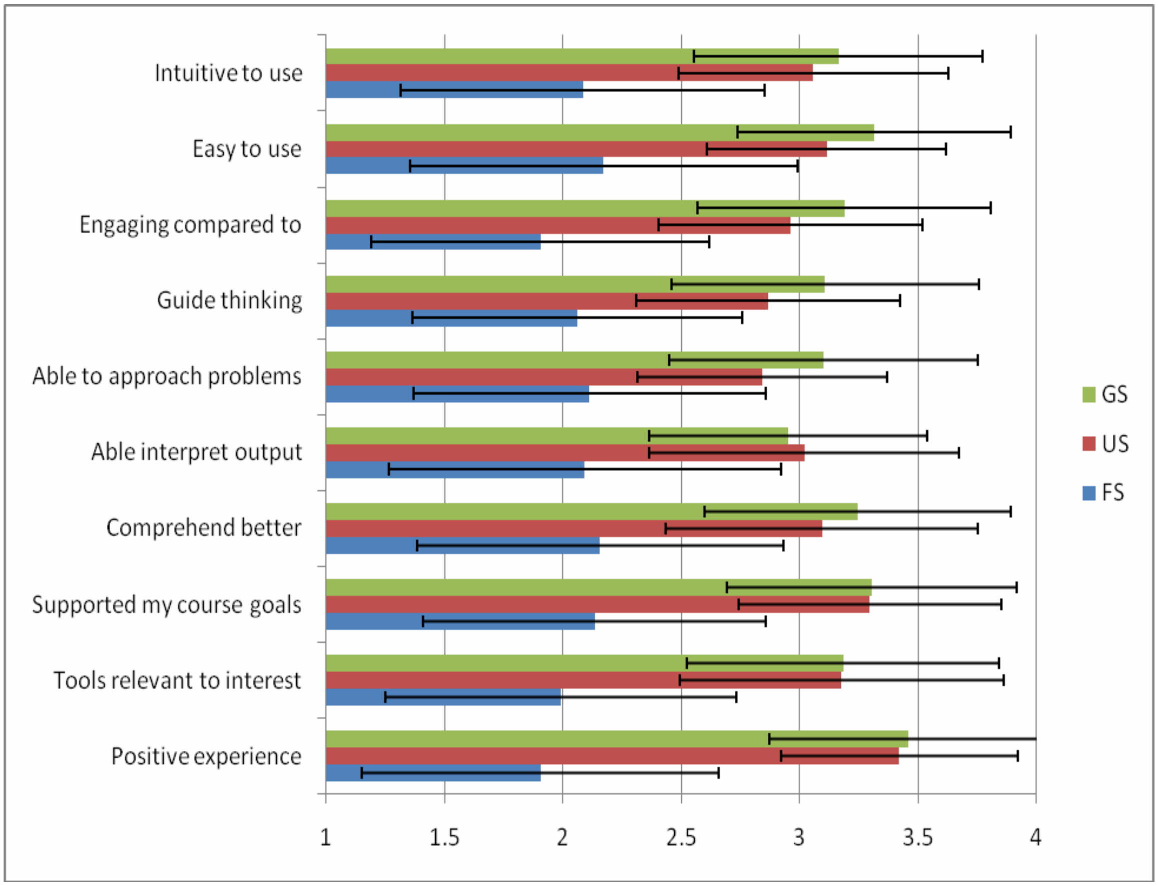


Fig. 7. Summary of responses from the student survey.

IV. LIKERT-SCALE RESPONSES ON THE USAGE OF NANOHUB TOOLS AT ASU

The results presented in this section include surveys collected from three courses offered at Arizona State University. These three courses were EEE434/591 Quantum Mechanics class offered in the fall 2007, EEE 101 Engineering Design class offered in the spring 2008, and EEE533 Semiconductor Device and Process Simulation class offered in the fall 2009. Twenty students responded the survey for the course EEE434/591, ten students responded the survey for the course EEE 101 and seven students responded the survey for the course EEE533. In addition, three students from the course EEE533 were interviewed to gain an in-depth understanding of their experiences with the simulation tools.

The survey study consisted of students participating in a voluntary Likert-scale survey [5] focused on:

- *Learning outcomes:* identifying how relevant and positive is the use of simulation tools as part of the course (e.g. how simulation tools supported the goals of the course, how relevant is the topic as well as the course in general).
- *Evidence of the learning:* identifying how students learned with and from the simulation tools (e.g. better comprehension of concepts, ability to interpret the output, ability to transfer the learning to new situations).
- *Pedagogical approach:* identifying how useful simulation tools were to students for their learning (e.g. in helping them guide their thinking, in being more engaged with the task and in helping them study a certain phenomena).
- *Usability aspects:* in particular how intuitive the tools are.

For the survey utilized students responded in a scale from one to four: strongly agree, agree, disagree, and strongly disagree to each question. The assigned scores and our interpretation of the responses are as follows:

TABLE X
AVERAGE SCORES FOR THE STUDENT SURVEY DATA

Response	Score	Interpretation
Strongly agree	4	Strongly positive
Agree	3	Positive
Disagree	2	Negative
Strongly disagree	1	Strongly negative

Descriptive statistics was used to analyze the survey responses. In Figure 8 we report responses grouped by content, assessment, pedagogy and usability. In Figure 9 we report detailed scores of students' responses to individual questions.

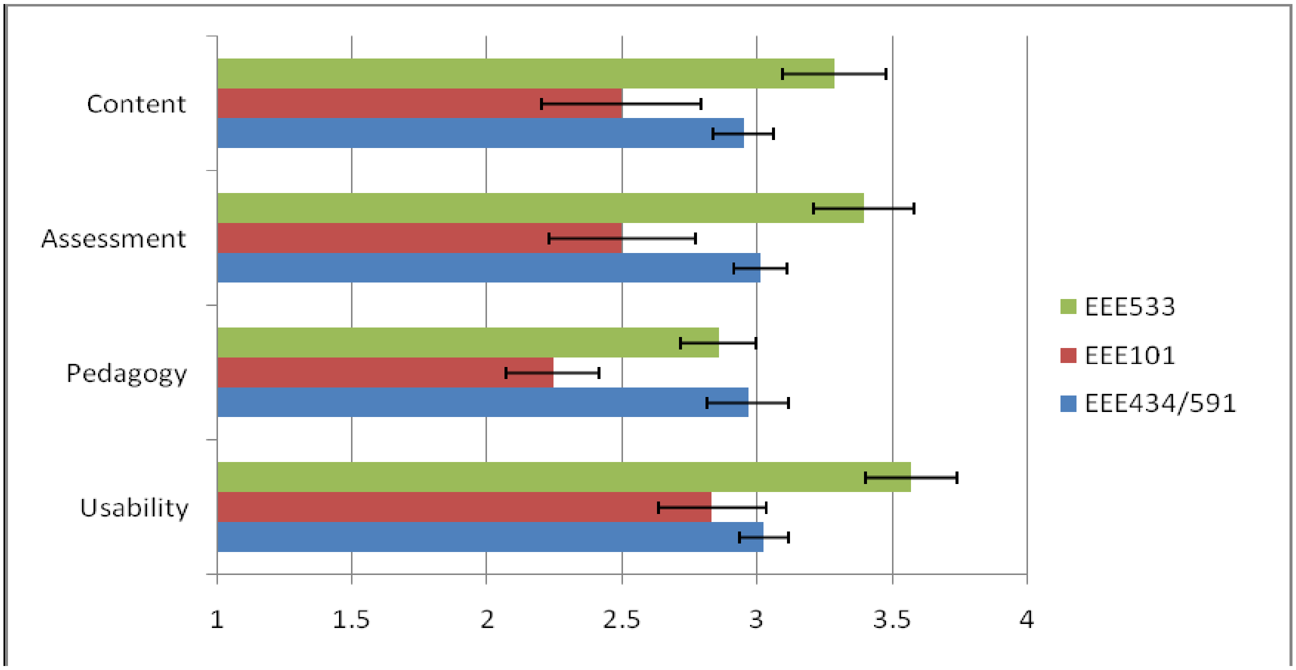


Fig. 8. Responses to survey grouped by content, assessment, pedagogy and usability.

Learning Outcomes (content) - This section focuses on the general experience students had, relevance of the content to whether students thought the simulation tools were relevant to their areas of interest as well as their level of satisfaction. Students from the courses EEE434/591 and EEE101 were positive in their responses of considering nanoHUB as a positive experience while students from the course EEE533 reported using nanoHUB as a very positive experience. Students from courses EEE434/591 and EEE101 reported inconclusive responses of perceiving nanoHUB.org simulation tools as highly relevant to their areas of interest and students from the course EEE533 reported positive responses to this same item. Students attending the EEE434/591 course found nanoHUB.org simulations supporting their goals and expectations of the course. Students attending the EEE101 course found the course as highly relevant to their areas of interest but did not find nanoHUB.org simulations supporting their expectations for the course. Students from the EEE533 course found the course as highly relevant to their areas of interest and found nanoHUB.org simulations as highly supporting their expectations for the course.

Evidence of Learning (assessment) - In this section we focused on how students perceived simulation tools as useful for their learning and their ability to transfer it to practical situations. While the students who attended the courses EEE434/591 and EEE533 could comprehend the concepts better by using the nanoHUB.org simulation tools as compared to lectures and readings only, students who attended the course EEE101 reported inconclusive responses on comprehending the concepts better by using the nanoHUB.org simulation tools as compared to lectures and readings only. Similarly, while students from the courses EEE434/591 and EEE533 did not have trouble interpreting the output of the simulation tools, students from the course EEE101 responded inconclusively to the same question. In the questions related to the transfer of knowledge such as confidence on students' ability to use concepts embedded in the simulation tools to approach new problems and students' increased awareness of practical application of the concepts, students from the courses EEE434/591 and EEE533 reported positive experiences while students from the course EEE101 reported inconclusive responses.

Instructional Approach (pedagogy) - In this section our focus is on identifying whether the simulation tools were a useful and engaging cognitive device for students' learning. Students from the courses EEE434/591 and EEE533 reported positive responses of using nanoHUB simulation tools to generate questions that guided their thinking, and also positively reported that using the nanoHUB made the course a lot more engaging for them compared to courses that only use lectures, homework, and readings. Students who attended the course EEE101 reported inconclusive responses that using nanoHUB simulation tools helped them generate questions that guided their thinking, and that using nanoHUB made the course much more engaging for them compared to courses that only use lectures, homework, and readings.

Usability – Students from groups EEE434/591 and EEE101 reported that nanoHUB simulations are intuitive as well as easy to use and students from the group EEE533 reported that nanoHUB simulations are very intuitive as well as easy to use.

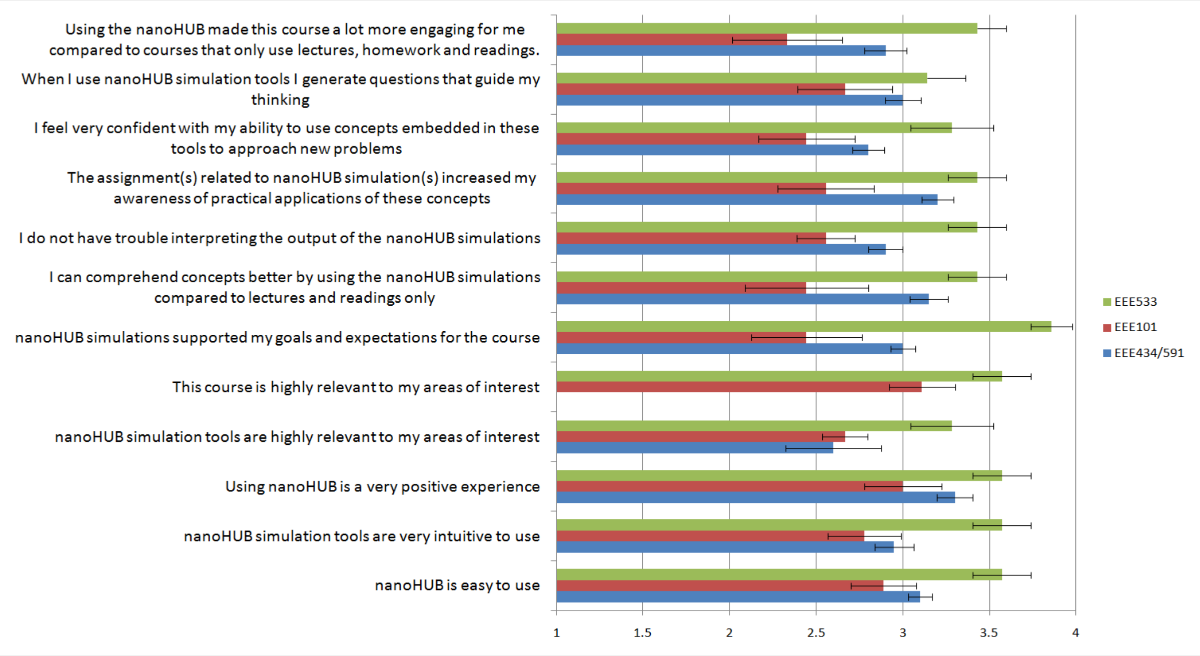


Fig. 9. Detailed Scores of Responses from the Student Survey.

V. CONCLUSION

Some conjectures about the factors that could explain the variance in the results of undergraduate and graduates can be derived from the open ended responses and the correlation analysis. From the correlation analysis of the survey items it was observed that an important factor of students' experiences with nanoHUB.org simulation tools is their perceived value of how the simulation tools can support their course goals, how are these related to their areas of interest, and how the tools can assist them in their learning process. Motivation was also observed as another equally important factor. For example, how students found using the simulation as a positive experience and how that experience was engaging for them.

From the analysis of the freshman students open ended responses, possible explanations of these students' differences of their perceptions of the simulation tools may be that they have not fully developed graphical literacy skills necessary to reason with the data outputted by the computational simulations. Another potential reason for this difference may be that students, at the moment they interact with the simulation tools, lack the prior knowledge required. Finally, it could also be related to a motivational factor since freshman students are still formulating their interests in various professional activities and have not yet seen the value of these tools toward their own goals, like the graduate students do.

These results can be supported with literature related to expert - novice differences. Some of the ways experts differ from novices is that experts are more capable of: a) noticing meaningful patterns of information, b) deeply understand the subject matter by organizing their content knowledge, c) place knowledge in a context of applicability, and d) flexibly and automatically retrieve relevant knowledge [6].

These novice learners may need additional supports to develop their learning process for skills that graduate students have already developed. These additional supports could take the form of introductory materials and guidance in the concepts, anticipated simulation results, and meaning of the results.

Additional research is needed to better understand what exact needs freshmen students have and how additional supports for learning can be provided. These supports could be provided by or embedded in nanoHUB.org.

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