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Developing a Student Learning Strategy to Bridge Virtual Learning and Hands-on Activity

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Introduction

Recently, energy security has been a global priority driven by dramatic increases in oil and gas prices. Given a high priority in the U.S. national agenda, solar cell technologies are receiving increased attention to secure energy sources and are undergoing rapid technical advancements. In this sense, strong educational support is vital and current educational curricula should reflect cutting-edge trends and needs in this sector.[1] Particularly, students are challenged more than ever to be creative and think critically in order to confront contemporary issues related to solar technologies. Such a demand requires students to be equipped with solid theoretical and practical knowledge as a singular "body of knowledge".[2] This is of paramount importance in that scientific discoveries have been made when solid background knowledge of principles, concepts, and theory is synergistically combined with scientific processing skills. To foster such capabilities in students' learning, inquiry-based learning [3,4,5,6] is hailed in the literature as the effective pedagogical approach to allow students to perform like scientists. In this approach, students develop a hypothesis based on previously learned concepts, design and conduct activities, and analyze the results, thus subsequently reinforcing the underlying concepts.[7]

Traditionally, either virtual or physical hands-on activities as part of an inquiry-based learning have been adapted to promote student learning experiences.[8,9,10] Consequently, there has been much intensive discussion about the pros and cons between virtual vs. physical learning as a more effective method of promoting student learning. The virtual learning allows students to see and understand the underlying principles with graphical visualization that cannot be observed directly from physical activities.[10] Therefore, a more complete understanding of theoretical concepts can be achieved with personalized experiences.[11] These activities are also often performed at their own pace, thereby increasing students' motivation, interests, and retention of knowledge.[11] Another argument for virtual learning is that with physical hands-on activities alone, students often struggle with an abrupt leap from theory to practice. However, physical activities still present students many more variety of multifaceted complex situations where outcomes do not turn out as expected, a recognized limitation of the virtual world. In these cases, physical hand-on activities provide discovery-based learning[12] which allows students to investigate what could have gone "wrong" and "why". Given their strengths and limitations, the ideal strategy would seem to employ both types of hands-on activities whenever possible. Particularly, the balanced approach of combining virtual and physical hands-on activities can consolidate theoretical understanding and surely make the synergistic transition from theory to real problems.

To explore the effectiveness of combined virtual and physical hands-on activities in students' learning, topics of organic photovoltaics (or solar cells) as a rising new technology[13] were used as the new content that was infused in the new learning materials and strategies. Organic photovoltaics have gained tremendous research interest as a new category of semiconductor materials having the potential for realizing flexible, easily-processible, and low-cost solar energy sources capable of replacing inorganic solar cells.[13] Organic semiconductors are categorized as a disordered system distinct from conventional semiconductors and offer great potential and importance as a new learning material, yet surprisingly there are only a few schools that cover them in undergraduate engineering classes.[14] Furthermore, the rapidly evolving field of organic solar technology offers great opportunities for students to experience multidisciplinary topics involving elements of advanced materials science, optics, solid-state electronics, and physics. This is critical in that researchers and engineers increasingly face complex problems having no clear boundaries between discrete disciplines. Hence, educational environments should cultivate students that are equipped with a set of tools to formulate, solve, and properly tackle multidisciplinary problems.

Particularly, this paper addresses the effectiveness of combined virtual and physical hands-on activities in students' learning which was infused in the capstone senior design project. Senior design projects are open-ended and are similar to the research that scientists perform toward a more comprehensive understanding of nature or new scientific knowledge. As a reinforced learning methodology to greatly assist students' reasoning and problem-solving skills, virtual learning was first integrated at the planning stage of their projects. This approach is in contrast with the typical senior design courses where only limited resources are available for planning experiments. Using virtual learning, students are able to revisit or learn new background theories and principles and identify and test a hypothesis before they actually engage in physical hands-on activities. This reinforced learning strategy efficiently guided students in preparing, confronting, and tackling the open-ended, inquiry-based problem with solid theoretical knowledge and principles. As a result, it provided better planning for the physical hands-on activities. When engaged with physical hands-on activities, virtual laboratories were also used to identify the disparity between theoretical and experimental results and additional activities designed to interpret the differences. This practice truly allowed students to experience the entire scientific process from solid theoretical reasoning obtained from virtual laboratories, to designing their own activities, to initial observations, and to follow-on activities based on the results of earlier activities.

Virtual laboratories

Simulation tools as virtual laboratories were developed for inquiry-based learning that allowed students to create an individualized experience based on a student's skill and knowledge.[11] The interface of simulation tools was designed for students to exclusively focus on probing the underlying principles of systems at multiple learning levels including optical and electrical models. The optical model describes light interactions with materials as a form of electromagnetic (EM) propagation. Electromagnetics is a notoriously difficult subject for engineering students, even though it is a fundamental keystone of solar technologies. To transform the way that the light interaction with materials is taught, structural visualization is applied with virtually stacked planes consisting of dielectric, organic semiconductor, and metallic electrodes through which EM waves propagate. In such frames as shown in Figure 1, the transfer matrix method (TMM)[15] is employed since it enables precise descriptions of EM propagation by taking into account the cumulative effects of reflection and transmission at all interfaces and absorption in each layer of the system. After the matrix equation is numerically solved, the distribution of the EM field, local energy dissipated in the material by use of the Poynting formula, and the rate of exciton generation can be visualized.

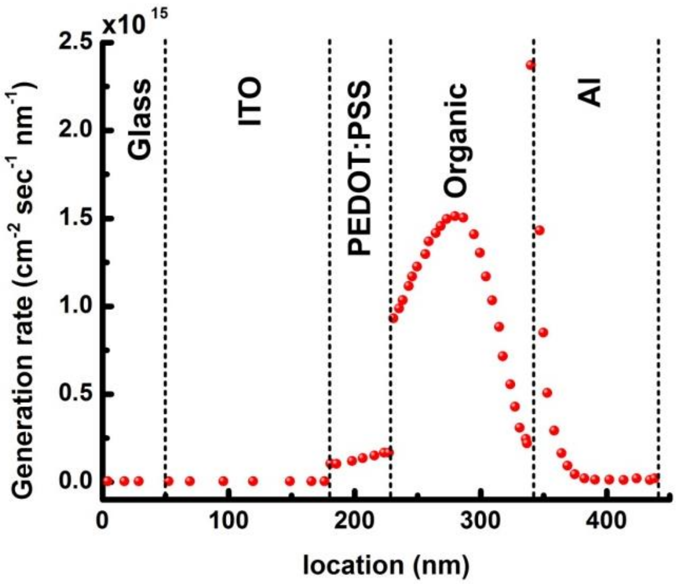

Figure 1. Generation of excitons simulated using TMM model.

For the electrical model, innovative bulk heterojunction (BHJ) blends, where randomly-networked (disordered) donor: acceptor phases have offset energy levels at the interface, is modeled.[16] Figure 2 (a) illustrates the complex dynamic nature of charge transport occurring at the BHJ interface in disordered organic solar cells. The absorbed photons in organic blends generate electron-hole (e-h) pairs or excitons, some of which subsequently dissociate into free charge carriers at the bulk heterojunction interfaces as described by the Onsager-Braun theory. [17] The subsequent transport of dissociated free charge carriers and Langevin bimolecular recombination are incorporated into a drift-diffusion model and used to estimate the current density and efficiency of organic solar cells.[18] These processes are unique features and concepts inherent in disordered organic materials which are solved numerically under illumination. Figure 2 (b) shows examples of free carrier distributions inside organic layers simulated using electrical model.

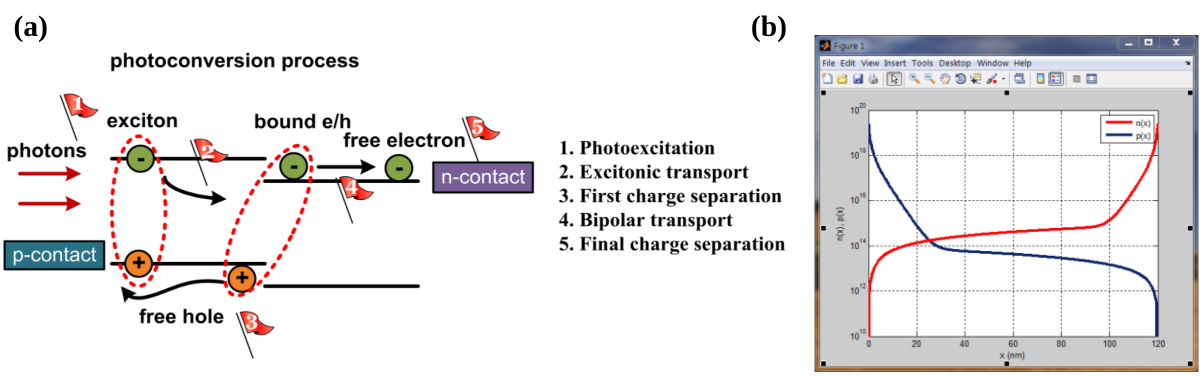

Figure 2. (a)Photoconversion process and (b) distribution of charge carriers inside an organic solar cell.

Organic solar cell simulation has many capabilities for optical and electrical models as follows:

Capabilities of Optical Models	Capabilities of Electrical Models
• TMM optical characteristics in multilayer including reflectance, transmittance, and absorbance spectra • Photon absorption rate profile • Photon energy distribution in multilayer • Layer-specific photocurrent and coupling efficiency with photons	• Exciton generation and charge transfer kinetics in disordered organic system • Distribution of electron and hole, energy bandgap, electrostatic potential, and Langevin recombination • Efficiencies, fill factor, open circuit voltage, and short circuit current density

Currently, simulation tools are developed with MATLAB which were refined to provide more user-friendly graphical user interfaces (GUI). The use of MATLAB has several advantages such as ease of use, platform independence, device-independent plotting, numerous tools, and easy visualization of analytic data into sophisticated graphic outputs.[19] Additionally, since MATLAB is the standard tool for introductory and advanced courses in STEM in academic environments, it allows one to facilitate the adoption of virtual labs into other schools. The GUI of simulation tools were designed to be simple, visual, and consistent with what the user would expect so that students intuitively engage tools without extensive rigor or tutorials. Most importantly, no knowledge of the programming details of the models is required for the users to take advantages of the models' capabilities. Our GUI is mainly divided into three major parts consisting of i) input boxes that allow independent control of various parameters, ii) a visual presentation of the simulation results that displays concepts and principles of science, and iii) the option to output model results in ASCII format so that they can be exported to other platforms for further data analysis and visualization. Figure 3 shows GUI for the optical model consisting of input dialog, menu selection for output, and graphical result.

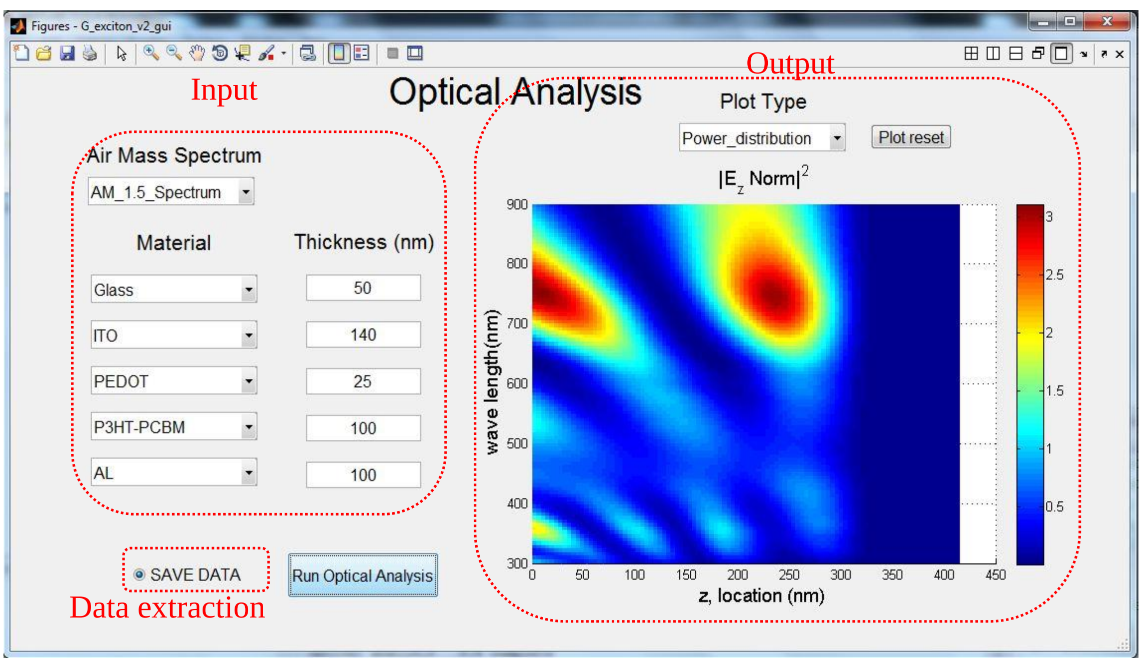

Figure 3. Example of interactive graphical user interface (GUI) developed for the optical model.

Incorporating virtual and physical hands-on projects

A typical two-semester capstone senior design course has a learning sequence as follows: During the first semester students are to select a work team with an appropriate project topic, do a literature search, prepare a work plan, and write a preliminary report. During the second semester, a team creates a design prototype in either virtual or physical hands-on activities, validates, interprets scientific results obtained from hands-on activities, and reports their findings. Senior design projects are open-ended and are similar to the research that scientists perform toward a more comprehensive understanding of nature or new scientific knowledge. At the planning stage in the first semester, students typically approach these projects with theories, principles, and concepts learned from previous classes. Available resources that allow them to set up hypotheses for a project are limited to the literature, journals, media, and books.

As a reinforced learning methodology to greatly assist students' reasoning and problem-solving skills, virtual learning was integrated, as shown in Figure 4. This approach is in contrast with the typical senior design courses where only limited resources are available for planning experiments. Using virtual learning, students revisit or learn new background theories and principles and identify and test a hypothesis before they actually engaged in physical hands-on activities. This reinforced learning strategy efficiently guides students in preparing, confronting, and tackling the open-ended, inquiry-based problem with solid theoretical knowledge and principles. As a result, it provides better planning for the physical hands-on activities. When engaged with physical hands-on activities, simulation tools are also used to identify the disparity between theoretical and experimental results and additional activities designed to interpret the differences. This practice truly allows students to experience the entire scientific process from solid theoretical reasoning obtained from virtual laboratories, to designing their own activities, to initial observations, and to follow-on activities based on the results of earlier activities.

Revised senior design

First semester

T1. Identify problems
T2. Do literature search
T3. Strengthen theories and concepts with virtual laboratories
T4. Prepare a work plan
T5. Test hypothesis with virtual learning
T6. Interpret virtual results and plan physical hands-on experiments based on simulation results
T7. Write preparation report

Second semester

T8. Design prototypes based on findings from virtual experiments
T9. Engage experiments
T10. Perform inquiry-based experiments and correlate experimental results with simulated results
T11. Interpret results and findings
T12. Investigate what is "wrong" and "why" based on theoretical aspects.
T13. Report findings

Figure 4. Reinforced learning strategies for inquiry-based learning.

Evaluations

Implementation of virtual and physical hands-on activities provided students balanced theoretical and practical aspects of device physics of organic solar cells. Such implementation resulted in a high rate of students' positive responses. The effectiveness of this pilot program was assessed qualitatively and quantitatively by an external reviewer. It is found that overall, students responded to the virtual hands-on experiences positively. Among others, students found the virtual hands-on experience effective or very effective in:

- Linking theory to real-world applications (100%).
- Managing a complex and open-ended project (100%)
- Helping them work effectively in a team (100%)

Student also reported that the virtual hands-on experiences require them to always or almost always use the following knowledge, skills and dispositions such as:

- Logic and reasoning (82.7%)
- Problem solving (72.8%)
- Team work skills (81.8%)
- Communication skills (100%)
- Common sense (90.9%)

Students also perceived that combined virtual and physical hands-on activities helped them improve knowledge of theoretical formulas very effectively. Lastly, students also strongly agreed that:

- They found the use of hands-on experiences in the course interesting (81.8%)
- They recommend the course to others (90.9%).

Findings from the final survey, however, suggest that four areas need the instructors' attention. In comparison to other areas, students reported that in the following four areas, the virtual hands-on experience were somewhat, moderately effective, or not effective.

- Apply a broad range of previously learned technical skills and knowledge (27.3%)
- Guessing (54.5%)
- Trial-and-error testing (27.3%)
- Synthesizing large amounts of information (36.4%)

Focus Group Interview

The following two evaluation activities were implemented, aiming to answer two questions: To what extent do the virtual hands-on experiences help students develop their reasoning and problem-solving skills on inquiry-based projects? To what extent do the virtual and physical hands-on experiences enhance students' engagement about learning disordered organic system and their collaboration skills?

A. To what extent do the virtual hands-on experiences help students develop their reasoning and problem-solving skills on inquiry-based projects?

Data from focus group interview were analyzed through inductive analysis. Three themes and patterns were identified:

First, the virtual hands-on experiences "reinforce what students are learning in class" and "see how the solar cells are actually made and fabricated." It served as a tool to "connect dots" for students (Student #1).

“Condensed, as far as amount of words and it was more, like in a textbook, they follow a certain standard. The simulations replaced a lot of what students did in the textbooks. It kind of replaced what would be long drawn out explanations in the book and made them easier to visualize with the simulations” (Student #6).

Second, virtual hands-on experiences offered a ground work for students. “senior project students are putting a solar cell on a rocket so some of the stuff we were using in class related to what we were researching for our senior project. So we were able to take that and interpret that for our senior design project” (Student #3).

Third, simulation tools offered one easy way for students to figure out the underlying principle by simply adjusting variables from simulation tools. “I think just this thing sort of virtual hands-on experiences with all the courses would help because we could change those variables, almost immediately... we can see the whole picture a lot faster.” (Student #2)

B. To what extent do the virtual and physical hands-on experiences enhance students’ engagement about learning disordered organic system and their collaboration skills?

The dominant theme that was identified throughout the focus interview was that the virtual and physical hands-on experiences helped students better engage with their learning by making learning “easier” for two reasons: 1) Virtual and physical hands-on experiences help students understand concepts easier by visualizing them; and 2) allowing students to search topics on the site.

“If we go into a lab and try to fix something for organic solar cells, and we don't have a simulation, doing a trial and error, I think to make an organic solar cell is something about 15 dollars, if you don't have an estimate into how thick the active layer is, and you keep on doing it and keep on messing up, that is a lot of money being lost, so I guess that kind of really makes sense to me how important it is to have a simulation so that way you can know what you're doing when you're making an organic solar cell.” (Student #1)

“It was easier to visualize a few things, like the same thing goes for the last quiz we had, where we had to talk about the different layers. I was actually able to remember how the simulation had shown it, so it was easier for me to remember what the answer was than if I had just saw it in a paper, I would be kind of guessing which one was which. So it helped me kind of visualize things more” (Student #5).

“I guess that we can say after we did some simulations we actually went to his lab and did processing, fabrication, and how to measure stuff was explained. So it was kind of nice to compare the two results, simulation and reality. This kind of simulation or virtual tool, gives you an expectation to whatever you are going to achieve in the lab.” (Student #7)

Conclusion

We implemented virtual and physical hands-on activities for inquiry-based projects using organic solar cells. Based on assessment from an external evaluator, we found that virtual simulation tools of optical, electrical and combined optical and electrical models allowed students to master underlying principles of device physics of organic solar cells with graphical visualization that cannot be observed directly from physical activities. This is because a more complete understanding of theoretical concepts of organic devices was achieved with personalized experience at their own pace, thereby increasing students' motivation, interests, and retention of knowledge. Our finding is consistent with the observation by Dori and Belcher[20] suggesting that the active learning such as visualizations should be integrated in the teaching and experimental work, especially when dealing with abstract concepts. In addition, additional inquiry-based hands-on activities provided discovery-based learning[21] which allowed students to investigate what could have gone "wrong" and "why". This practice truly allowed students to experience the entire scientific process from solid theoretical reasoning obtained from virtual laboratories, to designing their own activities, to initial observations, and to follow-on activities based on the results of earlier activities. As a consequence, combined virtual and physical hands-on activities greatly helped students to explore inquiry-based organic solar cell projects with enhanced reasoning, problem solving, and communication skills. Overall, students not only enjoyed this course but also appreciated the importance of collaborative learning.

Acknowledgement

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