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Works-in-Progress: Introducing Active Learning in Semiconductor Device Course

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Abstract

A study of Semiconductor device concepts is a core area in the electrical and computer engineering curriculum, which introduces the principles and operation of basic semiconductor devices, and device characterization. The primary goal of the course is to develop a solid understanding of the semiconductor concepts and mechanism. This semiconductor device course knowledge is the foundation of many other electrical, electronic circuit courses in the engineering curriculum such as analog and digital electronics and very-large scale integrated (VLSI) devices. To achieve the main goals, instructors should choose various teaching strategies that accomplish a particular course objective. Active engagement of students is a key factor for effective delivery of the subject matters in engineering/technical subjects. As teaching tools in semiconductor devices, incorporation of structure visualization techniques, band engineering and device simulation tools such as Xcrysden, Quantum espresso and nanohub could vastly improve the understanding of the key concepts of semiconductor device. Also, these visualization techniques and simulation tools helps to build up the students' active engagement in the classroom. From this perspective, this article presents how to successfully achieve the course learning outcomes and reinforces the understanding of semiconductor devices by implementing active learning environment using the available models and computer tools in the classroom.

Introduction

Semiconductors can be found everywhere in our modern lifestyle. Any electronic device you can think of made of semiconductors. Evolution of semiconductor industry can be traced back to the invention of the transistor and which could consider as the birth of modern technology era. A decade after the invention of transistor, integrated circuits (ICs) were invented and which initiated the development of faster, smaller, light weighted and cheaper electronic and electric equipment [1]. During the last few decades, ICs integration advanced further to develop high performance, reliable, multi-functional, energy efficient large-scale integrated circuits (LSI), very large-scale integrated circuits (VLSI) and ultra-large scale integration devices (ULSI) [2,3]. Now, almost everything in our everyday life supported by semiconductor-based devices and appliances. As a science/engineering major student, learning the semiconductor device course is essential to understand the fundamentals of semiconductor devices and the semiconductor technology as well as for the future development of the semiconductor field.

Semiconductor device course is one of a professional courses for the electrical and computer engineering curriculum. This course introduces basic concepts and principles, operation of basic semiconductor devices, and device characterization. It provides the foundation required to pursue a career in an electrical / computer engineering profession or higher studies. At the end of the semiconductor device course, the students will get the solid foundation about fundamental theories, concepts, and methods of semiconductor devices, which can apply for real world problems in semiconductor devices and upon successful completion of this course, students are expected to:

- Describe the fundamental semiconductor properties.
- Model and analyze the energy band diagram for semiconductor materials.
- Describe the principle and analyze the operation of pn-junction diode and the Schottky diode.
- Describe the principle and analyze the operation of Metal-Oxide-Semiconductor field Effect Transistor (MOSFET) and the Bipolar Junction Transistor (BJT).

This paper will explain how to achieve the learning outcomes and reinforces the understanding by active learning methods of the semiconductor device course.

Course outline

Following discussion is based on the semiconductor device course offered in the fall 2021 semester as a three-credit hour course. The content of the course mainly divided into two sections: Semiconductor Physics and semiconductor devices. Semiconductor physics section includes Crystal structure, Semiconductor in equilibrium, Carrier Transport and Band structures. Semiconductor device section includes pn junction & Diode, Transistors, Bipolar Junction Transistors (BJT) and Field effect transistor (FET) & metal-oxide semiconductor field-effect transistor MOSFET. [4]

A detailed outline of the sections covered in the course and allocated time for each section are listed here

Material properties, crystal structure, crystal growth

- ✓ Carrier modeling (3 lectures)

Semiconductor models, carrier properties, distribution, and concentration

- ✓ Carrier Action (3 lectures)

Drift, diffusion, recombination-generation

- ✓ pn junction electrostatics (4 lectures)

Fabrication, quantitative electrostatic relationships

- ✓ pn junction diode (4 lectures)

Ideal diode equation, Deviations from ideal behavior, avalanche, Zener and tunnel diodes.

- ✓ Bipolar junction transistors (5 lectures)

BJT fundamentals, BJT static characterization, BJT dynamic response modeling

- ✓ Field effect transistors (4 lectures)

General introduction, fundamentals, electrostatics

- ✓ MOSFET devices (4 lectures)

Active learning approaches

Traditional teaching methods typically rely on students learning class material passively, which involves listening to lectures and taking notes. But in general, student attention span during a lecture is limited. To keep the healthy learning environment throughout the lecture period, different active learning methods were introduced as in class activities. These activities help students to refresh their minds and actively engage in the learning process. Many studies show that the active learning approaches increase the students' performance in the classroom than the traditional teaching methods [5,6]. Freeman et.al reported that the STEM degree holders are more favorable for active learning-based lectures than traditional lectures [7]. Brooks DC reported that technological based learning environment improved the students' conceptual understanding about the subjects [8]. There are several active learning methods could be implemented during a classroom environment such as problem/project based learning, small group discussion, case studies, peer teaching [9]. Most students are visual learners and many of them also experience improved learning through the use of technology [10,11]. Therefore, in order to promote active learning environment in the semiconductor device course, graphical presentations, video presentations and hands-on learning activities were implemented. Also, in-class experiments, demonstrations and simulations were conducted to illustrate complex concepts in the class. At the introduction of a novel concept or a complex case related to the subject matter or an advanced mathematics related section, discussions were initiated with real-world situations and real-world examples. Once students understand the concepts qualitatively, mathematical equations were incorporated to quantify the concepts and to strengthen their understanding. Ultimately, one of the primary goals is prepare the students for future opportunities by improving their problem solving and critical thinking skills. Following section discuss the a few active learning tools implemented during the course.

Hands-on learning activities

According the textbook used for the semiconductor device course [4], the first chapter introduces the fundamentals of semiconductors, i.e., atoms and crystal structures of semiconductors. In this chapter it is essential to identify how students visualize and analyze these concepts. Couple of hands-on learning activities could lead the way to visualize the complex concepts.

To visualize the atomic structure of semiconductors, students were guided to conduct small group activities using a molecular structure model. During the class time, following the theory section of crystal structures, students were encouraged to constructed different types of crystal models. The goal of this activity was to picture the 2D and 3D visualization of the crystal structure. Using these models, students were able to understand the lattice points, lattice constant, unit cell, nearest neighbors, coordination number, unit cell, miller indices etc. Figure 01 shows the selected atomic structure models, which were constructed during a classroom activity.

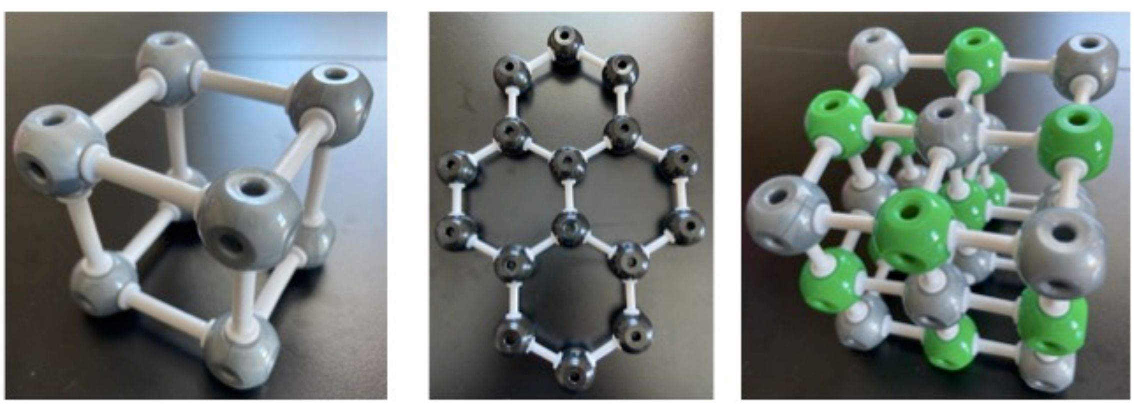

Figure 01: Selected atomic structure models constructed by the students

Problem based activities

In-class worksheet problems were found to be a great addition to improve the active learning environment of the classroom. Following a short theory section or a concept, in-class worksheet problems were given to the students. Students were encouraged to engage and discuss the problems and answer with peers and share their knowledge. Also, they were motivated to express their understanding of the concepts or explain their solutions to the fellow students. The goal of the worksheet problems was to engage all the students in the learning process. As an example, in the chapter 1, the worksheet was designed for understanding the concept of lattice, unit cell and crystal structure. In this activity, students were constructed the crystal structure using a crystal structure model and then completed the in-class worksheet by looking at their crystal models.

Computer Modeling

Computer simulations and incorporation of computer programs in teaching activities are also an effective way of improving the learning outcomes. After students were familiar with the crystal structure modelling, crystal structure visualizing softwares were introduced. In semiconductor device course, students were trained to use Xcrysden software to visualize the crystal structures. Xcrysden is a molecular modeling and visualization software and it can be run in the UNIX platform [12].

Sample Activity: Understand the unit cell and electronic band structure

STEP-01: Create an input file for the unit cell: (Unix platform)

- ✓ Bravais lattice type
- ✓ The lattice constant
- ✓ Number of atoms and types of atoms in the unit cell
- ✓ Atomic masses
- ✓ Atomic positions of each atom in the unit cell

STEP-02: Visualize the structure (Using Xcrysden)

- ✓ Open the Xcrysden
- ✓ Go to open pwscf file

STEP-03: Band Structure calculation (Quantum espresso package)

- ✓ Generate k points in high symmetric points
- ✓ Optimization of the atomic coordinates to minimize the forces
- ✓ Calculate the electronic bands for high symmetric points in the crystal cell.

The goal of this activity was to introduce the concepts about crystal structure and calculating the electronic band structures. During this classroom activity, students were guided to create an input file for relevant crystal structure using a text editor such as Vi-editor (STEP-01) in the above chart). The following chart shows the sample input file for Silicon crystal structure.

Sample input file for silicon crystal structure

```
&CONTROL
   prefix='silicon'
   Outdir='./'
   pseudo_dir = './'
 /

 &SYSTEM
   ibrav = 2
   celldm(1) = 5.431
   nat = 2
   ntyp = 1
   ecutwfc = 18.0
 /

 &ELECTRONS
 /

ATOMIC_SPECIES
 Si  28.085  Si.pz-vbc.UPF

ATOMIC_POSITIONS crystal
 Si 0.00 0.00 0.00
 Si 0.25 0.25 0.25

K_POINTS automatics
4 4 4 0 0 0
```

Students use this input file to visualize the crystal structure during the lecture (STEP-02). Moreover, they can understand and visualize the lattice constant, number of atoms in the unit cell, bonding length and angles and bravais lattice types for different semiconductor materials such as Graphene, Al, Ge etc. Visualization angles created by Xcrysden software were used to identify the pure and doped crystal structures, which is shown in Figure 02-(a). Further, students were guided to use the created input file to calculate the electronic band structures for given materials as shown in Figure 02-(b), which will discuss in the next section.

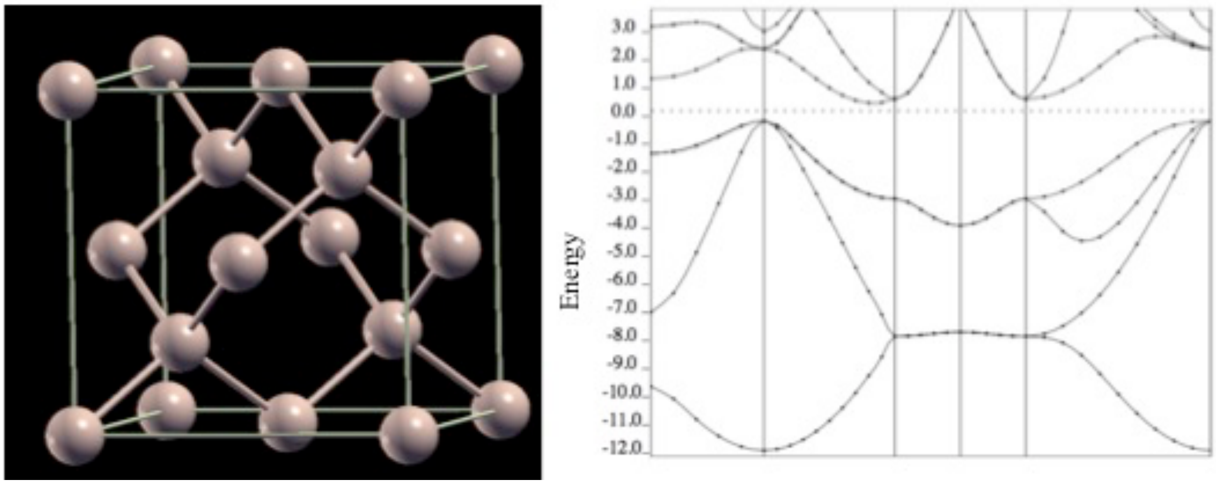

Figure 02: (a) Si Crystal structure modeled from Xcrysden and (b) electronic band structure for Si

Computer Simulation

Computer simulations could use to visualize physical concepts that are hidden in the abstract mathematical language. In Semiconductor device course, semiconductor band engineering is one of the advanced topics, which involves numerous mathematical equations and mathematical concepts. Quantum Espresso (QE) program was incorporated to introduce the band structure theory to the students [13]. Quantum Espresso is an open-source software which can be used for calculating electronic band structures using first principle calculations. Students were trained to use the QE to calculate the simple band structures such as Si, GaAs, Graphene. These calculations were beneficial to understand the concepts of energy band levels, Fermi energy, carrier concentration, band gap, density of states and effective mass.

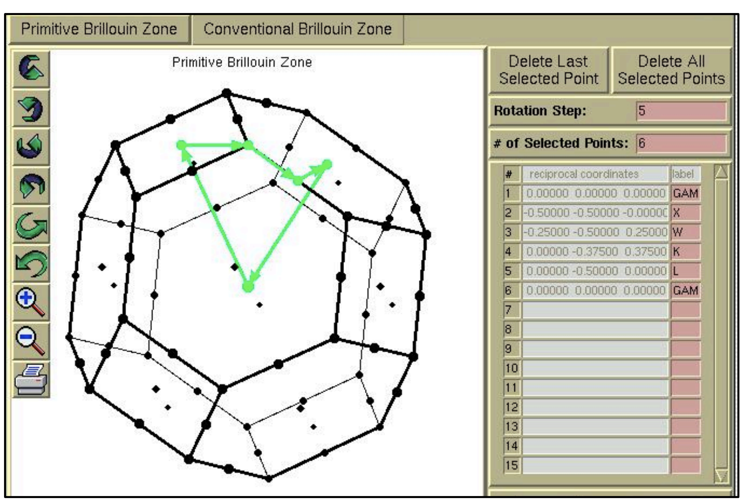

Figure 03: Generated high symmetric points for FCC lattice structure using Xcrysden

According to STEP 03, students were guided to use the created input file as shown in above to identify and generate the high symmetric k points in the crystal structure using the Xcrysden software. The generated k points can be used to calculate the band structure of selected crystal structures. The Figure 03 shows the generated high symmetric k points for silicon crystal using Xcrysden software. Figure 02-(b) shows the calculated band structure for pure Si crystal structure using the QE software as a classroom activity.

After students gained firm knowledge about these concepts, it would be effortless to introduce the working principle of semiconductor devices such as pn junction and fields effect transistors (FET). Construction (modeling, designing, and simulating) of pn junction diode is a great example to demonstrate the knowledge of semiconductor concepts learned so far in the course. During this section of the semiconductor device course, the working principle of pn junction theory and pn junction device properties were introduced to the students. To buildup the understanding of this section, "nanohub" simulations were incorporated as an active learning tool. "nanohub" is a collection of simulation tools which can be used for material related computational simulations [14,15]. In this course, students were directed to use a few nanohub tools such as pn junction lab, 2DFET [16,17].

As a classroom activity, students were instructed to modify the pn junction diode parameters to using nanohub tools to observe the effect of various parameters. This class activity guide students to creatively understand the future developments of the devices.

Sample Activity: Analyze and understand the concepts of semiconductor devices using the depletion approximation

STEP-01:
Create a pn junction for given parameters using nanohub tool.

- ✓ Example: A Si pn junction is at room temperature under equilibrium conditions. It consists with a p-doping density of $N_A = 2 \times 10^{15}$ /cm^3 and an n-doping of N_D = $1\text{x}10^{15}$/cm^3.

STEP-02:
Compute and analyze the several characteristic curves and parameters for the created device.

- ✓ Example: Depletion layer width, boundaries and potentials
- ✓ Plot charge density, electric field, and electrostatic potential as a function of position

STEP-03:
Compare and analyze the results by changing the doping density , temperature and width of the device.

Figure 04 shows the selected characterizations curves for pn junction obtained from the nanohub tool during a classroom activity.

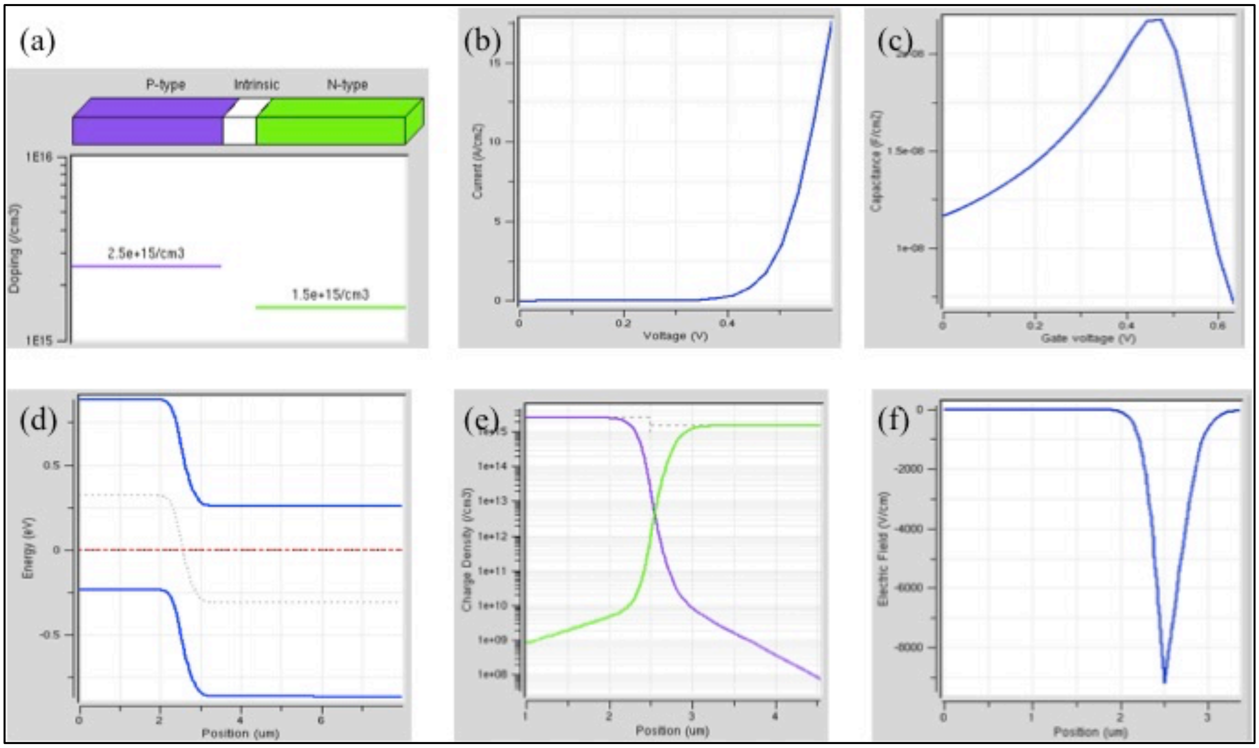

Figure 04: Selected characterizations curves for Si pn junction obtained from the "pn junction lab" nanohub tool; (a). pn junction parameters (b). IV-curve (c) CV-curve (d) Energy band diagram (e). Charge density diagram (f) Electric field diagram

Assessment

Evaluation of students' performance through continuous assessments is important for the students as well as for the future development of the course. Also, the assessment results indicate the evidence for the effectiveness of active learning methods implemented in the course.
To collect the students feedbacks about the active learning methods used in the class, the informal survey was done in the mid of the semester and the following chart shows the evaluation results for informal survey. The following questions were used to get the student's feedbacks.

Q1: Multiple instructional methods were used in the course (e.g. lectures, problem solving, case studies, hands-on-activities, in class activities, computer tools, discussions, etc.).

Q2: The readings, discussions, lectures, in class activities, and/or projects helped me attain the stated learning outcomes of this course.

Q3: The instructional activities and assignments supported the course learning outcomes.

Q4: The activities and assignments challenged me to think more deeply/critically about the course subject matter.

Q5: The in-class activities/simulation/computational tools/small group sessions in this course furthered my understanding of the subject matter.

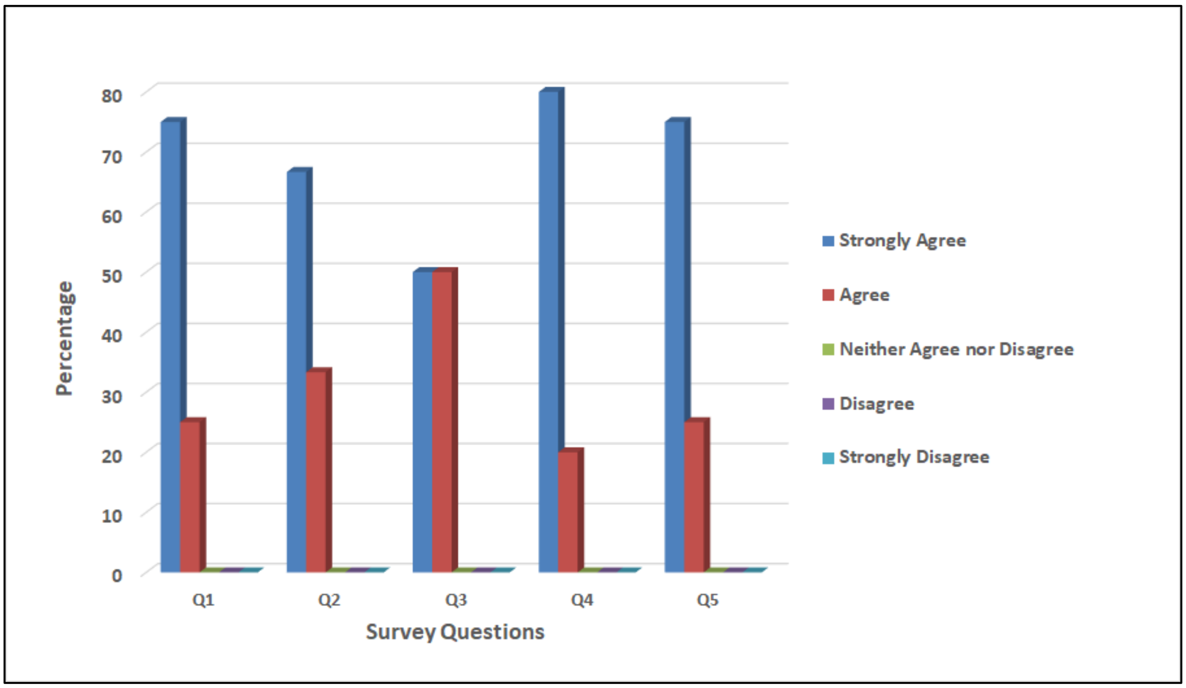

Figure 05: The student's feedback for informal survey.

The student's feedback shows that the activities and assignments done during the semiconductor course were helpful to understand and think more critically about the semiconductor device concepts.

In the current semiconductor devices course, the assessments were based on weekly homework (40%), Two Midterm Exams (15% each), Quizzes (at the end of each sections-10%) and a Final Exam (20%). The simulations activities are included in the homework assessment. Following table shows the direct assessment averages of each category for fall 2021 semiconductor devices course at the Marion University. [Note: this course offered by the author for the first time]

Table 1: Course direct assessment averages for each assessment category

Assessments	Class average
Homework	89.5
Quiz	85.4
Mid Term	79.4
Final	82.25

According to these results, the class average for each assessment is above 75%. It indicates that the active learning methods used in the semiconductor device course have been successful and the students meet their learning goals. Based on the survey responses collected from Marian University at the end of the fall 2021 semester and informal survey done by the instructor (author), students acknowledged the instructors' attempts to create active learning approaches during the Semiconductor device course.

Conclusion

Most of the industries are looking for engineering graduates with solid knowledge as well as excellent technical skills. In order to fulfill the current demand, instructor must train students for defining, understanding, and solving problems with an organized critical way of thinking. Active learning approaches are one of the predominant pathways to train students towards these goals. This article provided the detailed explanations of active learning approaches, which can be used in the semiconductor device course. According to the preliminary results, the students valued the active learning activities implemented during the teaching/leaning process. I believe that active leaning environment is essential for successfully achieve the teaching goals as well as it is beneficial for students' development and society at large

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