Incorporating Inquiry-Based Learning Techniques to Engineering Instruction – A Work in Progress

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ABSTRACT

There has been recent focus, especially at the pre-college level, for introducing and applying inquiry-based learning methods into the classroom. Recently (in 2005), the author attended a NSF sponsored course at the University of Dayton for faculty in science and engineering to learn about Inquiry-Based (IB) techniques. The course was, to my surprise, largely attended by faculty from the traditional sciences, not engineering. Hence, one goal of this paper is to inform my engineering colleagues about IB.

This paper is a work in progress over the past year. I have adapted and implemented some of these IB concepts to mechanical engineering students at Cedarville University in my Engineering Thermodynamics class, a 5-hour semester course. The focus of my approach will be explained in detail. I attempted to make the classroom a more active learning environment using more student participation. I will review my past 4 years of teaching approaches in this same course, discuss successes and limitations, and share the details of my current approaches. It appears that the IB methods have significantly resulted in an improvement in classroom learning. The measures used to assess the IB impact include qualitative and quantitative measures including: student enthusiasm, professional attitude to learning, and students’ weekly quiz scores.

As I continue to refine these IB methods, I will address further opportunities for improvement. One aspect of this paper is a comparison of inquiry-based learning pedagogical methods to other techniques which have graced our educational literature. This will allow the reader to better appreciate what is new to the IB approach.

BACKGROUND ON TEACHING AND LEARNING

As engineering educators, our backgrounds are no doubt quite diverse in terms of our training as teachers. Most engineering educators I have met are without any formal training, in stark contrast to undergraduate and graduate college education majors. The education majors’ research literature and coursework abounds in writings on student learning and models of teaching. In researching and writing this background, it came very apparent to me that a scholarly study and review of education literature is quite profitable. What follows are highlights of literature that most impacted my thinking and teaching improvements.
Lecture, the most common mode of instruction, dominates the landscape of engineering education. In our expository lectures, we tell students about engineering science and theories. In lecture we demonstrate how to use engineering ‘rules’ to solve problems. Lecturing, a time efficient mode of transmitting information, expresses our desire for students to know concepts and techniques. The problem being we are totally unaware of students’ reception of our transmissions (see Alan Van Heuvelen\(^9\), 1991a). Difficulties have been attributed to the following (Knight, R. D.\(^5\), 2004):

- Listeners have an attention span of at best 10-15 minutes
- Most students don’t know how to listen to a lecture or take good notes
- Most lectures reiterate the textbook
- Most lectures focus on formal derivations and deductions, not deeper applications
- Lecture information passes too quickly for adequate critical thought

If I don’t lecture, what else can I do? Several excellent education researchers (for example, Joyce et. al.\(^4\), 2000 and Hewitt, et. al.\(^3\), 1997) have thoroughly documented teaching methods, different styles of learners and teachers, pedagogy development, and view the classroom as a learning community. A central underlying theme in helping students succeed in learning is true concern and interest in each individual student (by the teacher). This theme is similarly expressed in the truth statements found in the Bible – “Love one another as yourself “and “Do to others as you would have them do to you” (NIV\(^2\), 1984). Consider if we place ourselves in our own classroom as a student and answer the following questions:

- Are we pleased in what we see and hear?
- Are we participating and following the logical development – taking good notes?
- Are we engaged in applying principles and problem solving on our own and/or with classmates in the classroom?
- Are we asking questions and encouraged to do so … and getting good answers?
- Are we benefiting from a well designed learning experience/environment, leaving the classroom with valuable learning?

The essence of good teaching is caring to ‘trade places’ with our students, observing ourselves teach, and making changes that positively impact the students while bringing joy to the teacher.

Over the last 40 years, education research literature has documented several teaching methods that help engage and interest students to improve their learning (beginning with Schaefer, R.\(^7\) (1967)). These methods fall under the coined categories of Active, Inquiry-Based (IB), Discovery, and Discussion based Teaching and Learning (see Joyce et. al.\(^4\), 2000, Hewitt, et. al.\(^3\), 1997, Silberman\(^8\), 1996, Bean\(^1\), 2001).

Active learning or (interactive engagement) takes many forms. As mentioned by Knight, (paraphrased/modified from chapter 4, Knight, R. D.\(^5\), 2004) the following is a sampling of some of the more relevant methods:
• **Overview, Case Study (OCS)** method first establishes scientific/engineering concepts while confronting students’ alternative conceptions, culminating in more advanced problem solving. The most advanced problem is termed ‘the case’.

• **Cooperative Group** method allows the instructor to select groups of students who, after lecture presentation of engineering science and problem-solving strategy, work together on more open-ended problems than traditional textbook ones.

• **Peer Think/Pair/Share** method involves small group of students to think about solving a problem individually, then bring their comments for discussion among their small group. Afterwards, the instructor brings closure either by speaking with each individual group and/or with the entire class (all groups).

• **Research-Based Textbooks** attempt to deal directly with student’s conceptual (including preconceived notions) beliefs, balance qualitative reasoning and quantitative calculations. This reduces the amount of material covered in lieu of teaching the learners to learn independently.

Inquiry-Based learning overlaps Active learning in its many forms. IB "requires an interchange of ideas among learners in small groups and encourages sharing with the educator and the larger class"(chapter 11, Joyce et. al. 4, 2000). It appears that IB is historically an older name for Active Learning. However, unique to the IB method is out-of-class exercises where in-class Active Learning is further developed. For example, using well-written homework assignments, out-of-class inquiry learning allows students to:

  o Develop and apply problem-solving strategies
  o Construct a personal foundation for abstract thinking
  o Understand cause and effect relationships
  o Analyze, synthesize and evaluate
  o Take responsibility to learn (ultimate goal)

Many educators use Discovery and Discussion. In the Discovery method (student centered, teacher directed, Hewitt, et. al. 3, 1997), student groups are given a challenging question to be answered- data supplied, printed and/or actual objects studied. Students are to apply their reasoning in groups to generalize patterns. Students often repeat the process with additional objects to broaden their analysis. The teacher brings closure. This is a precursor to invention – drawing out characteristics, grouping positive attributes, highlighting needed improvements, and allowing for creative expression.

The Discussion method (student centered, student directed, Hewitt, et. al. 3, 1997) allows students to work on complex, abstract problems in a way that their own discussions, analyses and conclusions/designs ultimately dictate the shape of the lesson/project. At Cedarville University, this method is at times partly used by our faculty (I have used it) in our capstone, two semester projects of our Senior Design course.

It is important to note that in reading about educational research, I found various coined phrases essentially describing the same teaching/learning methods, and visa versa. For example, some authors define the Discussion method as “classroom Q&A (question and answer time) used in the expository lecture method.”

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The methods noted above (as well as the literature references) are the toolboxes by which I began my work in progress to implement IB methods in required sophomore and junior level engineering courses. This paper will focus mainly on Engineering Thermodynamics for Mechanical Engineering majors. Before I describe these implementations, I will review my previous teaching methods and approaches.

PREVIOUS TEACHING METHODS

My career in teaching spans a period of 20 years, with a block of teaching spanning the late 1980’s to early 1990’s, followed by my current block of teaching 2001-present. In my first block of teaching as a young assistant professor, I used expository lectures with good handwritten examples. Problems were solved on the white/black board in real time and some time was given to class discussion and Q&A. My method of teaching mimicked my ‘best teachers’ at the Universities of Illinois-Urbana and Delaware (my undergrad and graduate schools, respectively). My teaching goals were to provide students sound lectures notes so that anyone not following in lecture had a good set of notes to ‘figure things out’ on their own. I ‘grew up’ (my professors all used expository lectures) in such a learning environment (and survived) and knew no other method.

As a young professor, I set a goal to teach better than my teachers, with their methods fresh in mind. Perhaps the most important improvement I made in my first block of teaching was to provide students with complete solutions to problems. I would walk the students through an inquiry approach of formulating strategies for problem solving. The goal was to build their confidence in learning sound problem solving skills and to encourage them whenever possible thru brief discussions. This focus gave students examples of how to: i) ‘see’ a complex problem and break it down by recognition of problem type, ii) enumerate knowns and unknowns, iii) understand missing data and locate that data, iv) recall engineering science relations needed to bridge the gap toward a solution, v) reflect on the work being sure the solution was sound and logical. Students practiced this inquiry approach in their homework. Over time, I realized a proper workload was equally important - giving students challenging problems but not exasperating them.

In returning to teach in 2001 after 9 years had passed, I continued using my former teaching approach. The student feedback from that experience was in positive, and so no major changes were made. In returning to academia, it is noteworthy to point out several differences I observed in my classroom environment:

1. Student class sizes were at least twice as large (increase from 10-15 to 25-45)
2. Larger class size minimized the intimacy of normal Q&A discussions in lecture
3. Larger class size increased the diversity of students and their learning styles
4. Student study habits were more varied – requiring faculty management of students
5. Cultural changes in students - their acceptance of lectures vs. AV rich class environments
The above differences required me to modify my teaching methods. The large classroom sizes necessitated more careful attention to learning styles of the average student. I still had the opinion that a successful lecture was one where content was presented, sample problems were solved, and in the process students’ questions were taken and answered. Behind this approach was the fact that the dialogue I had was generally with the brightest, most prepared students in the class. The other students were being left behind, with passive learning and no engagement. The value of the lecture could be seen as very high and rewarding for some, while others had obtained less value. With part of the class not actively learning, a spill over effect resulted in some students falling behind, and adopting the ‘survival’ method of ‘cramming’—completing homework and studying for exams the night before. We all know last minute work often leads to poor student grades and poor learning.

Moreover, in today’s culture, students’ expectations are highly influenced by their entertainment appetites—which vie for their precious out-of-class time as well as shape their expectations in ‘lecture’. There seems to be a subtle trend toward ‘edutainment’—entertaining education. Engineering educators need to ‘change the pace’ during a lecture to keep students interested and attentive, even if they use traditional methods. Personally, one may conclude that students need to be engaged in the classroom, in any generation, in any course, or curriculum. Students need to be reminded daily that they are building their maturity, growing their analytical skills and engineering toolbox for their future profession. Hence, the stewardship of the instructor/teacher/professor is to shepherd the flock of learners in the best way possible. In the next section, I outline the major changes I implemented to date to improve my teaching methods, which enhanced student learning.

CHANGING MY TEACHING PARADIGM

The most significant changes in teaching methods were first introduced four years ago in both my Engineering Thermodynamics and Computational Methods course for mechanical engineers, the latter a four credit hour sophomore spring semester class which combines an introduction to Matlab and Numerical Methods. The first IB method I employed was Think/Pair/Share; I called this “Team Time”. Students were involved in a 5-minute small group discussion with their peers. Teams of two (or three) spent time in a variety of issues, including: i) problem solving (part or whole), ii) discussing their initial impressions regarding a new phenomena, or iii) defending their expectations of the outcome (or trend) of a complex system. This method allowed for true team building, helped students to learn from their peers, and allowed an instructor to build teacher/learner relationships. When done properly, students were more comfortable voicing their misconceptions, knowing with the confidence that it is ‘ok’ to have preconceived notions that are against scientific principles or experimental results.

One useful way to involve every individual over time was to ask people to share what thoughts or questions their partner(s) had. One or two team time exercises per 50-minute lecture helped liven-up and motivated the students. I verbally rewarded the students for thoughts they presented.

Another important method I used to build confidence among students was to pose problems that were interesting variants of ones they had already seen (about a week prior). I asked everyone to first think through a solution individually. This prepared students for their
actual examination. For the student who answered, I allowed them to explain their logic to the class. This allowed me to gently correct (if necessary), to reinforce other points not made by the student, while providing positive feedback for the effort. This was an excellent time where I opened the floor for any questions. It was important to pause long enough (the 10-16 second pause rule) to wait for more questions, as students needed time to formulate their thoughts and speak up. These two class participation methods built good rapport with my students.

Over the last several years, I also realized I had to assist the students in managing their study time for my courses, especially the weaker half of a given class. The approach I used in the 5 credit hour (M-F) Engineering Thermodynamics course gave one or two 20-minute quizzes/week at the end of a given lecture period. The T-F quizzes were based on material from previous lectures (two or more days ‘old’) as well as last week’s homework (graded and returned). This regular, weekly study habit improved students’ learning and knowledge/problem solving strategy retention. The result was an improvement in hour and final exams scores.

As reported in our ABET 2006 assessment for engineering thermodynamics, student final grades have continually increased over the last three years since the introduction of weekly quizzes (as shown below in Table 1). Weekly quizzes were introduced in Fall 2005, and the median grade steadily increased. Common linkages were identical final exams for 2004 & 2005, and a slight change in 2006. One apparent conclusion was that weekly study (for quizzes) led to improved learning. Classroom participation was observed to be more professional by students while working with their group problem solving teams. The quality of cooperative learning among peers in class improved overall. All students were able to understand topics being covered each day in class and contributed almost equally in team exercises as well as individual question/answer sessions and class discussions. It will be interesting to separate the classroom size factor, as the Fall 2007 class is anticipated to be about the same size as the Fall 2004 class.

Another IB method I introduced was out-of-class inquiry using an open-ended design problem. The specific problem involved designing the most efficient steam power plant based on an outline provided in the literature (Okura, R. et. al., 2003). The students were asked to logically select their own intermediate streams with the goal of maximizing the plant thermal efficiency. They were to compare their results to the claims found in an article supplied to them. The Japanese engineers gave no intermediate conditions, only overall operating conditions. Each student worked independently, and in lecture each student’s result was shared with the class. The best designs were discussed and an award was given to the best design engineer (along with a photo taken).

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39 students in 2004, 29 students in 2005, 26 students in 2006

Table 1. Final grades in Engineering Thermodynamics - more IB methods were progressively implementing each successive year.

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Thermodynamics is built on simply stated laws with simple to complex applications. I also helped students construct a personal foundation for their abstract thinking about thermodynamic principles. Thought experiments were given to student to contemplate whether the specific internal energy, $u_{ice}$, of solid ice is less than $u_{steam}$ for steam. Some students were not sure why $u_{ice}$ of solid ice is less than $u_{steam}$. Using the concept of molecular motion and introducing translational, vibrational and rotational molecular energies allowed students to better understand changes in specific internal energy. Similar exercises using molecular logic helped students to understand ranking of specific entropy of pure substances for different phases. These approaches cleared the way to help students retain their fundamental knowledge in thermodynamics.

The next concept requiring development was to help students bridge their incomplete knowledge of the First Law of Thermodynamics, due to the presentation of the Work-Energy Law in Statics and Dynamics. An excellent treatment of the problems associated with teaching the First Law, along with good IB remedies, can be found in chapters 9, 12 and 13 of Knight’s text (Knight, R. D., 2004). Following such an approach, I was able to show how the First Law of Thermodynamics is linked to the Work-Energy Law in all the forms they had previously been taught.

Students were encouraged to develop their ability for gaining deeper insight and unifying concepts. The course textbook, (Fundamentals of Thermodynamics (6th edition), by Sonntag, et. al.) is written in such a way that the same problem analyzed using the First Law is later revisited and analyzed using the Second Law. This approach reinforces student confidence and learning with deeper insight. Along the same lines, I tied simple classroom problem statements to relevant real world situations. For example, the piston cylinder problem of geometry, overused in most texts, may turn-off some students who loose attention with the familiar. However, I have been selective with piston-cylinder problems that are tied to an internal combustion cycle, and students are more interested. Real world problems are much more appealing and reinforcing knowing these are ‘professional grade’ issues. Also, spending a short time telling the background ‘story’ behind an industrial problem enhances students’ interest in lecture. Since students are audio-visual minded, it goes without saying that AV content also stimulates students’ learning.

I strive to complete at least two to four relevant engineering application problems during a lecture ‘hour’. Each class begins with an agenda. The agenda, posted for the day on the white board, lists real world problems and keywords for key concepts of the day. The students can ‘track’ with me during the whole lecture/IB learning experience. The students also know where we will pick up the next day if we do not complete the agenda for the day. This further instills a sense of learning and value of their time. I also emphasize that lecture content and the examples solved in class are highly important for them to fully understand. They pay attention as I explain variants of these problems may appear on their examinations. This approach gives each student a clear understanding of the daily expectations for their learning to supplement semester long goals found in the syllabus.

Another IB method I use is posing open-ended problems in class. I allow each student to work independently, solve part of the problem in a fixed amount of time. The students form
small groups to discuss, and then the class regroups as I review their questions and provide the proper solution strategy/answers. The process is repeated until the entire problem is solved. This allows multiple opportunities for students’ feedback and mimics the work environment they will have when working with a mentor as an engineering intern. During this interaction, students learn ‘rules of thumb’ and learn to select the best methods to solve problems.

In summary, the key IB methods I have implemented are:
1. Think/Pair/Share (and variations) for in-class problem solving
2. Developing cause and effect thinking skills within class exercises
3. Out-of-class inquiry based homework problems
4. Frequent teacher-student feedback – quizzes, individual and group led discussions

FUTURE THOUGHTS FOR IMPLEMENTING IB METHODS

Where does this lead? One area of improvement will be to increase the use of inquiry based homework problems. In designing these problems, I have tried a few approaches. For some, I ask the student to justify their answer in each step of their problem analysis. This requires deeper thinking, and the students are required to explain and justify their work. They will write reasons why they used certain equations and made certain assumptions. These homework problems will help students prepare for the real world of engineering, where problems are typically not of the textbook flavor.

I also plan to use more probing questions to have the students step back and take perspective. For example, questions I have asked include:
- Why do we have only a small set of refrigerant fluids?
- What knowledge base is behind this list of current refrigerants?
- Why did the engineers design the integrated power / refrigeration system as shown?

Interestingly, engineering laboratories often have the same attributes of our expository lectures – preplanned without much inquiry and independent design element. IB methods can be used to redesign engineering laboratory courses as well. In closing, as a final comment on our textbooks, there are only a few textbooks that use the IB methods. The reference I gave earlier to Research-Based Textbooks is a fertile area to explore. The author welcomes those who read this paper to consider writing such texts.
BIBLIOGRAPHY


