Enhancing the Engineering Curriculum:
Defining Discovery Learning at Marquette University

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Abstract— **This paper summarizes the results of our investigation into the feasibility of increasing the level of discovery learning in the College of Engineering (COE) at Marquette University. We review the education literature, document examples of discovery learning currently practiced in the COE and other schools, and propose a Marquette COE-specific definition of discovery learning. Based on our assessment of the benefits, costs, and tradeoffs associated with increasing the level of discovery learning, we present several recommendations and identify resources required for implementation. These recommendations may be helpful in enhancing engineering education at other schools.**

Keywords: Discovery learning, student-centered learning, active learning.

I. INTRODUCTION

The College of Engineering at Marquette University is on a mission to increase the level of discovery learning in our curriculum. Until recently, there was no clear definition of "discovery learning," prompting a survey to determine how faculty defined the term. The results indicated that the pure form of discovery learning (unguided by the instructor, as described in the education literature) was not being practiced. Faculty members were employing a wide range of student-centered and active learning methods, all under the umbrella of discovery learning.

An investigation into the use of the term "discovery learning" in U.S. engineering programs showed that the term is used inconsistently. Some schools have their own, institution-specific definition of the term that includes a variety of learning approaches, such as undergraduate research projects, co-ops and internships, and other forms of experiential learning. Other schools include student-centered learning methods, such as active, problem-based, application-based, and collaborative learning, in their definition. Based on our investigation we concluded that a Marquette-specific definition of discovery learning was warranted.

II. WHAT IS DISCOVERY LEARNING?

A. Definitions from the Education Literature

The education literature reveals different definitions of discovery learning. Presented here are generally accepted definitions of active, collaborative, cooperative, and problem-based learning, terms often associated with discovery learning. (The definitions are drawn from several sources, primarily Prince [1].) Figure 1 summarizes three student-centered learning methods, including inductive learning, which encompasses discovery learning. Although there are no universally accepted definitions of discovery learning in the literature, the accepted view is that discovery learning is a form of student-centered learning in which the focus shifts from the teacher to the learners.

Active learning is an instructional method that engages students in the learning process. In active learning students conduct meaningful learning activities and think about and are connected to what they are doing [2]. While this definition could include traditional activities such as homework, in the education literature active learning most commonly refers to activities that are introduced in the classroom. The core elements of active learning are activities that engage students. Active learning is often contrasted with the traditional lecture format where students passively receive information from an instructor.
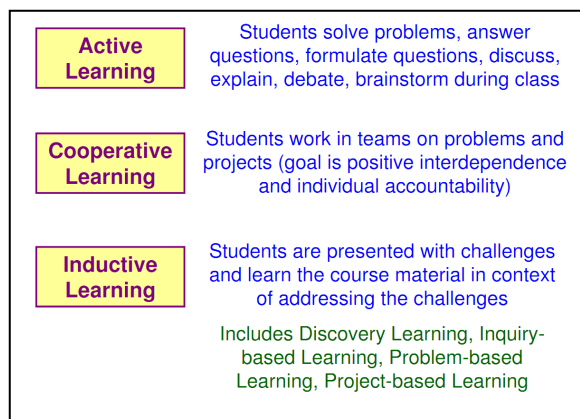

Figure 1.   Summary of three student-centered learning methods. Note that discovery learning is classified as a form of inductive learning.

The more active students are in the classroom, the more engaged they are in the learning process and the more they remember. Edgar Dale's "cone of learning" [3] suggests that student retention, as measured two weeks later, depends on the level of active learning. Classroom activities in which students

simulate a real experience or "do the real thing" involve them the most in the learning process and result in them remembering more of what instructors do and say [4].

Collaborative learning refers to an instructional method in which students work together in small groups toward a common goal [5]. As such, collaborative learning encompasses all group-based instructional methods, including cooperative learning [6-10]. In collaborative learning the emphasis is on student interactions rather than on learning as a solitary activity.

Cooperative learning is a structured form of group work where students pursue common goals while being assessed individually [6,11]. The most common model of cooperative learning includes five specific tenets: individual accountability, mutual interdependence, face-to-face interaction, appropriate practice of interpersonal skills, and regular self-assessment of team functioning [12,13]. The common core element among models is a focus on cooperative incentives rather than competition to promote learning.

Problem-based learning is an instructional method where relevant problems are introduced at the beginning of the instruction cycle and used to provide the context and motivation for the learning that follows. It is always active and usually collaborative or cooperative per the above definitions. Problem-based learning typically involves significant amounts of self-directed learning on the part of the students [1].

B. Discovery Learning in Higher Education [14-16]

In discovery learning, students are confronted with a challenge and left to work out the solution on their own [17, 18]. Students are presented with a question to answer, a problem to solve, or a set of observations to explain, and then work in a largely self-directed manner to complete their assigned tasks and draw appropriate inferences from the outcomes, "discovering" the desired factual and conceptual knowledge in the process [17]. The instructor may provide feedback in response to student efforts but offers little or no direction before or during those efforts. The lack of structure and guidance provided by the instructor and the trial-and-error approach consequently required of students are the defining features of discovery learning relative to other inductive methods.

In the purest form of discovery learning, teachers set the problems and provide feedback on the students' efforts but do not direct or guide those efforts. This form of inductive teaching was developed for pre-college education and has not been embraced in undergraduate classes. The method is rarely used in higher education, among other reasons because instructors who hear about it fear – probably with good cause – that they would only be able to cover a small fraction of their prescribed content if students were required to discover everything for themselves. The only way to counter this fear would be to present solid evidence that discovery learning improves learning outcomes without requiring a major sacrifice of content.

There is little empirical evidence for the effectiveness of discovery learning in higher education. What instructors are more likely to adopt is a variant of discovery learning – sometimes called "guided discovery" – in which the instructor pro-

vides some guidance throughout the learning process [19]. In this case, the distinctions between discovery and guided inquiry or problem-based learning tend to disappear [14].

Student-centered methods have been shown to be superior to the traditional teacher-centered approach to instruction, a conclusion that applies whether the assessed outcome is short-term mastery, long-term retention, depth of understanding of course material, acquisition of critical thinking or creative problem-solving skills, formation of positive attitudes toward the subject being taught, or level of confidence in knowledge or skills [16]. Although many studies suggest that discovery learning can enhance students' retention of material, others reach the opposite conclusion. For example, Leonard [20] studied the use of guided inquiry and discovery learning in science laboratory courses, and found no statistically significant differences in student scores on tests and lab reports.

The studies that show a positive effect also suggest that retention is improved only when the learning task is based on previously understood principles. Singer and Pease [21] compared the effectiveness of guided inquiry and discovery learning on the acquisition, transfer and retention of motor skills. They concluded that for learning new tasks, guided inquiry was more efficient, and for transferring learned skills to tasks of similar or greater difficulty there was no difference.

Prince and Felder [14] state:

"*We do not recommend using the pure form of discovery learning – in which students work with little or no guidance from instructors — in undergraduate engineering curricula.*

While the quality of research data supporting the different inductive methods is variable, the collective evidence favoring the inductive approach over traditional deductive pedagogy is conclusive. Induction is supported by widely accepted educational theories such as cognitive and social constructivism, by brain research, and by empirical studies of teaching and learning. Inductive methods promote students' adoption of a deep (meaning-oriented) approach to learning, as opposed to a surface (memorization-intensive) approach. They also promote intellectual development, challenging the dualistic type of thinking that characterizes many entering college students (which holds that all knowledge is certain, professors have it, and the task of students is to absorb and repeat it) and helping the students acquire the critical thinking and self-directed learning skills that characterize expert scientists and engineers."

There is significant evidence for the benefits of involving undergraduate students in independent research [14]. Undergraduate research does not usually qualify as discovery learning because the advisor typically provides significant structure and guidance [22]. The literature supports the use of student-centered learning and teaching methods. However, there is little empirical evidence for the effectiveness of the pure form of discovery learning at the undergraduate level and it is not recommended for use in that setting [15].

C. Definitions from the COE Faculty

In 2010, the Dean of the COE solicited comments from the COE faculty regarding their definitions and impressions of

discovery learning. Specifically, the Dean posed the following question: "What is Discovery Learning and what is your opinion of it at Marquette University?" The responses revealed different definitions of discovery learning among the faculty, underscoring the need for a compelling, unifying definition. Responses included many common themes and attributes, as indicated by the following faculty-suggested definitions of discovery learning:

- Giving students opportunities to solve open-ended problems/challenges that require them to put theory into practice with real-world constraints, and providing them with the tools needed to solve these problems.
- A method of inquiry-based learning in which students utilize their existing knowledge and past experiences to identify new relationships and facts through a process of investigation and self-discovery of the world guided by the instructor. In this framework, students learn to "teach themselves," promoting a philosophy of life-long learning.
- Student-centered learning, more applied and more hands-on. There is less reliance on the traditional lecture as the primary means of communicating. Students are actively engaged in authentic, real-life projects.
- Allowing students to learn through experimentation that reinforces lectures and text-based learning.
- The education practice in which students play an active role in learning. Students are expected to (*i*) apply what they know (from previous courses, from experience, from books and the Internet, etc.), (*ii*) ask questions and formulate their own tentative answers, and (*iii*) deduce general principles from practical examples and laboratory experiences.

Based on these responses and other comments from the COE faculty, we concluded that the pure form of discovery learning was not actually being practiced in the COE. Instead, a guided form of discovery learning, active learning, cooperative learning, and other forms of guided inquiry-based learning were being employed.

III.   EXAMPLES OF DISCOVERY LEARNING

A.   Examples of Discovery Learning in the COE

There are many examples of student-centered learning methods, including guided discovery learning, being practiced in the COE. These range from student projects to in-class activities in courses in each department. A few examples are presented here.

Extracurricular Student Projects

Faculty-mentored teams of students are currently involved in a wide range of extracurricular projects that give students the opportunity to apply what they have learned in their undergraduate experience (be it from the classroom, laboratory, co-op position, internship, etc.) to the solution of a problem. Many of these projects are part of national and international student design competitions such as the Formula I Race Car, Concrete Canoe, Solar Powered Boat, and Human Powered

Vehicle, sponsored by professional organizations and societies, such as:

- American Society of Civil Engineers (ASCE)
- American Society of Mechanical Engineers (ASME)
- Association of Computing Machinery
- Biomedical Engineering Society
- Engineering World Health
- Engineers Without Borders (EWB)
- Institute of Electrical and Electronics Engineers (IEEE)
- Institute of Transportation Engineers
- National Collegiate Inventors and Innovators Alliance (NCIIA)
- Society of Automotive Engineers (SAE)
- Society of Manufacturing Engineers (SME)
- Solar Energy Society

In the past few years students participated in the SAE Aero Competition, NASA Lunabotics Challenge, Rocket Competition (Wisconsin Space Grant Consortium), MATE International Remote Underwater Vehicle competition, BMEstart design competition, and others.

Courses and Programs

In the COE many courses in the curriculum include attributes of discovery learning methods. The following represent only a small sample of such courses.

- BIEN 1100 and 1110: Introduction to Biomedical Engineering Methods I and II. These courses include open-ended design challenges, lectures, readings, and exams. Students are presented with problems and customer needs and are encouraged to find the information needed to solve the problem. Design challenges reflect the multidisciplinary nature of the biomedical engineering curriculum and require students to solve problems involving physiological monitoring, data acquisition, medical imaging, biomaterials, and rehabilitation engineering. Students are encouraged to apply the tools and information provided to them through class lectures, readings, and laboratory experiences. The course includes a module on business and entrepreneurship and uses an application-based approach to teach students about the design process. The resources needed to successfully teach this required freshman course include TAs, administrative support, and many guest speakers.
- BIEN/ELEN/COEN/EECE/MEEN 4920/4998: Principles of Design/Senior Design. This capstone design course is the culmination of the undergraduate biomedical, electrical, computer, and mechanical engineering curricula and requires students to apply what they have learned from previous coursework and co-op, internship, and research experiences. Students work on multidisciplinary project teams for two semesters to solve real-world problems. Projects are advised by COE faculty members who provide technical guidance and assistance to student teams. Required course deliverables mimic those that are used in industry and required by ISO 9001. This team-based project design experience allows students to learn about the design process, apply knowledge acquired in previous

courses, and develop communication, teamwork, and project management skills.

▪ Construction Engineering Management Program. This program provides students with a hands-on, applications-based learning experience through the use of guest lecturers, field trips to construction projects on campus and throughout Milwaukee and Chicago, Associated General Contractors (AGC) student chapter meetings and trips, American Society of Civil Engineers (ASCE) student design competitions, and many open-ended team project assignments. Significant financial resources required to run the program are provided by an endowment.

▪ ELEN/COEN/EECE Courses. Many courses taught in the electrical and computer engineering program contain elements of student-centered and applications based learning. These courses include projects that require students to design, simulate, and build prototypes, create useful databases, write programs in various languages to perform various functions, and test a CPU. These courses require students to synthesize and apply what they have learned.

▪ MEEN 2210: Electromechanical Engineering Systems. This required sophomore course is heavily studio based with open-ended design challenges. Students work in teams of two to investigate and solve real-world exercises involving electrical circuits (electronics for sensors, actuators, and controls), electromechanical actuators (solenoid, vibration exciter, DC motor), and control systems. Industrial examples emphasize integration. Students are encouraged to apply analysis, simulation, and hardware tools that they learn through class lectures, outside readings, independent investigations, and laboratory experiences.

B. Examples of Discovery Learning at Other Schools

The following is a small sample of how discovery learning is defined and incorporated in engineering programs at other schools.

▪ University of Delaware. At the University of Delaware (http://www.ugs.udel.edu/DLE/) all students are required to participate in a Discovery Learning Experience, defined as experiential learning that involves instructional experiences (out-of-class and beyond typical curriculum courses). These enrichment experiences exist for students under the supervision of a faculty member. Discovery Learning Experiences include internship, service learning, independent study, undergraduate research, and study abroad.

▪ University of Colorado. The Discovery Learning Program (http://engineering.colorado.edu/dlc/about.html) at the University of Colorado enables students to develop critical thinking, problem solving, and research skills while sharing fresh perspectives as members of integrated research teams. The discovery learning model established by the College of Engineering and Applied Science creates collaborative teams involving undergraduate and graduate students, faculty, and industrial partners. This

advances student learning through an inquiry-based approach that complements the academic curriculum.

▪ Rose-Hulman Institute of Technology. At Rose-Hulman, discovery and student-centered learning appear in extracurricular student projects and in-class, hands-on experiences. Student teams work on competitive project teams for the Eco-Car, Formula SAE, Human Powered Vehicle, and the design/build/fly AIAA national student design competitions. Students do not receive credit for these activities. Faculty mentors and team advisors volunteer their time to work with the students on these projects and do not receive additional salary for their involvement. The school provides a budget of at least $10,000 per project, space to work, and access to test facilities (wind tunnel, composite testing, and other facilities). In addition to extracurricular projects, students are engaged in in-class activities such as fluids laboratory demonstrations and projectile motion modeling, measurement, and validation experiments ending with an in-class competition. A lead equipment technician is employed to design and maintain technical equipment used in classes, laboratories, and student projects.

Of the three schools mentioned above, there is no consensus on the definition of discovery learning or what activities qualify as discovery learning. The University of Delaware considers experiential learning (study abroad, internships, co-op experiences, etc.) to be a form of discovery learning. The University of Colorado regards undergraduate research activities to constitute discovery learning. Rose-Hulman views extracurricular student projects and in-class, hands-on activities to be forms of discovery learning. The disparate use of the term underscores the need for agreement on what constitutes discovery learning within the Marquette COE.

IV. CONCERNS AND TRADEOFFS

Student-centered learning requires a culture in which students take responsibility for their education and shift from passive to active learners. It also requires faculty commitment ("buy-in") to change from traditional "tell-and-test" pedagogies to more active teaching methods. Whether students and faculty embrace these cultural changes is a concern.

Discovery learning will not necessarily replace all lectures, as not everything students must learn is amenable to classroom discovery. Even when students have the capacity to discover complex knowledge, there may not be sufficient time or appropriate resources to complete the task. Formal lecture presentations provide a fairly efficient way of conveying complex knowledge to a large group of diverse learners [23]. A question to be resolved is the appropriate mix of lecture and student-centered methods.

Discovery and other student-centered learning methods involve increased faculty time and resources. A common concern among faculty regarding discovery learning is that they would only be able to cover a small fraction of their prescribed content if students were required to discover everything for themselves. According to Cornell and Clark [24], "Less teacher talk requires more teacher time." Even though motivation and

student learning are enhanced through discovery and student-centered learning methods, it requires more work for teachers when designing projects and preparing for class. From interviews we conducted, faculty indicated a need for additional support personnel to successfully implement student-centered learning methods as well as resources such as additional teaching assistants, technical support staff (e.g., technicians to develop and maintain equipment), and space.

V. IMPLEMENTATION ACTIVITIES

A. Defining Discovery Learning within the COE

The term "discovery learning" (based on its strict definition) does not appropriately capture the current practice in the COE. A more accurate term to reflect what is currently being practiced would be "student-centered learning," which includes active, problem-based, application-based, and collaborative learning.

Our investigation found that other schools use the term "discovery learning" to describe activities and teaching methods that do not fit the traditional definition of discovery learning. These schools have their own, institution-specific definitions of the term. What they are describing would be more correctly described as "student-centered learning."

We proposed that a COE-specific definition of the term "discovery learning" be developed. This definition needed to incorporate the following activities and teaching methods that include student-centered learning components:

- Class activities such as hands-on demonstrations, case studies, student projects and presentations, design competitions, laboratory experiments, field trips, and other activities that require students to apply what they have learned in the class.
- Extracurricular activities such as student design projects for national student design competitions, co-op and internship experiences, and other activities that provide opportunities for students to "learn by doing" and apply what they have learned throughout the engineering curriculum.

We adopted the following COE-specific definition of discovery learning, which reflects our strong focus on student-centered learning:

Discovery learning within the Marquette University College of Engineering consists of student-centered learning methods that employ in-class and extracurricular activities that allow students to learn by doing and to apply what they have learned.

We retained the term "discovery learning" for multiple reasons, including its broad meaning and consistency with prior mission statements.

B. Implementating a Plan

The goal of increasing student-centered learning in our curriculum is similar to that of many European Union (EU) countries as part of the Bologna Process intended to improve higher education in the EU [25]. We are accomplishing this goal by meeting four main objectives:

- Increase the use of student-centered learning in the classroom. We are providing faculty with resources for course redesign including educational support in the form of seminars to make faculty aware of the best practices in student-centered learning, and a course development consultant to work with faculty.
- Increase the number and variety of mentored extracurricular projects. Additional opportunities for students to work on project teams outside of class are being provided. To optimize the learning experience, these projects include some level of guided instruction provided by project mentors (faculty members, alumni, or industry sponsors). Various types of extracurricular student projects are encouraged and supported by the COE such as:
  - Projects that allow students to explore areas of interest to them
  - Projects in which students compete in national design competitions
  - Projects sponsored by and of benefit to local industry
  - Assistive technology projects to benefit a single client with a specific disability
  - Service learning projects to solve problems of the developing world or local community
  - Projects based on ideas generated by students with entrepreneurial interests
- Support the current cooperative education and undergraduate research programs. The COE has a successful cooperative education program and provides opportunities for internships and undergraduate research. The COE is continuing to support these activities that provide valuable student-centered learning experiences.
- Overcome institutional barriers to implementation. It is essential to obtain institutional, faculty, and student "buy-in," develop incentives, and reform promotion-and-tenure criteria to reflect the value and importance of a higher level of discovery learning in the COE. To help promote dialogue, solicit ideas for implementation, and foster a change in culture we are initiating a seminar series, conducting focus groups, and considering other activities.

C. Adding Resources

To reach our goal of increasing the level of discovery learning in the COE, we identified the following needed resources:

Educational Support for Faculty
- Course development consultant(s) to assist faculty with course redesign.
- Technicians responsible for design, construction, storage, and maintenance of demonstration equipment, laboratory experiment hardware, course "props," etc., used for in-class demonstrations, laboratory exercises, etc.
- COE seminar series on discovery learning to include guest speakers from within and outside of MU to present best practices in student centered learning.
- Graduate and undergraduate student TA(s), if needed.

Space and Equipment for Student Projects
- Space for student team collaboration and design work, including videoconferencing capabilities.
- Space for storage of prototypes, hardware, etc.
- Facilities for prototyping and testing (machine shop, rapid prototyping equipment, wind tunnel, materials testing, hand tools, etc.).

VI. SUMMARY

The term "discovery learning" as used in the education literature refers to unguided discovery learning and is not what is currently practiced in the COE. Instead, a guided form of discovery learning, active learning, cooperative learning, and other forms of guided inquiry-based learning are being employed. A more appropriate term would be "student-centered learning," which includes methods of active, problem-based, application-based, and collaborative learning.

Our investigation found that other schools use the term "discovery learning" to describe activities and teaching methods that also do not fit with the formal definition of discovery learning. Schools have created their own, institution-specific definitions of the term. What they are describing would more aptly be described as "student-centered learning." We adopted a COE-specific definition for "discovery learning."

The goal of increasing the level of discovery and student-centered learning in the COE is being accomplished by (1) increasing the use of student-centered learning in the classroom, (2) increasing the number and variety of mentored extracurricular projects, (3) supporting our cooperative education and undergraduate research programs, and (4) overcoming institutional barriers to the proposed plan. Implementing this plan requires (1) educational support and resources for COE faculty, (2) faculty as well as student "buy-in" to a culture which shifts responsibility to students for their education, and (3) space and equipment for use by student project teams. The process presented here may be helpful in enhancing engineering education at other schools and is recommended for faculty working to increase the level of active and student-centered learning in their engineering curriculum.

ACKNOWLEDGMENT

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