AC 2012-5124: REAL-WORLD APPLICATIONS OF MATHEMATICAL AND SCIENTIFIC PRINCIPLES IN THE CURRICULUM FOR COLLEGE AND CAREER SUCCESS

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Real-World Applications of Mathematical and Scientific Principles in the Curriculum for College and Career Success

Abstract

With a large expected need for scientists, engineers, and technologists it is increasingly critical to the world economy to interest and train students in the technical disciplines. Student interest in mathematics and science is often positively influenced by an understanding of the practical applications of the principles they are expected to learn. Furthermore, specific applications often lend themselves to demonstration and alignment with certain principles and teaching techniques. Students who show an interest in mathematical and science principles, gained through an understanding of the applications of these principles, are more likely to persevere in their degree programs and experience career success.

The difficulty in presenting applications to students often lies with the constraints on classroom time and with limited instructor training. This pilot effort involves incorporating applications into the curriculum by identifying relevant applications, subsequently identifying foundational skills associated with such applications, and then linking the application to one or more basic principles. Additional considerations to be discussed include instructor training and preparation, alignment to expected academic outcomes and assessments, and subsequent continuous improvement processes.

Introduction

Many funding agencies, such as the National Science Foundation, have made predictions in recent years regarding the need for scientists, engineers, and technicians[1]. The Bureau of Labor Statistics, in the Occupational Outlook Handbook, specifies that employment for engineers is expected to grow from the time period between 2008-2018 by 7-13%. while that for engineering technicians will grow between 3-6%[2.] While relatively modest, overall job opportunities are expected to be good. However, job prospects for new graduates and displaced workers may seem less favorable than in these official reports, depending on regional and industry needs.

In addition to job availability, a large focus has been placed recently on the persistence of students in their college programs, with close attention paid to the amount of federal funds used to support students who do not persist in their academic programs until graduation. The apparent loss of federal financial aid dollars, as well as lost income and employment taxes, are being used to make an argument against funding certain programs and majors. Furthermore, the rate at

which student debt has risen, especially for many who cannot readily find employment, is a great concern as well.

Additional pressure on the technical job market comes from the retirement of current practitioners. The National Science Foundation's statistical indicators predict that a larger proportion of doctorate holders are near retirement than are those with bachelors and masters degrees[1]. Gender and race inequities within the technical disciplines are also a concern, as there are still underrepresented populations among science and engineering practitioners.

These myriad of factors produce extreme pressures on academic programs, and more broadly on colleges and universities themselves. Institutions of Higher Education are increasingly being looked at to provide support for current students, to produce capable graduates, and to meet the needs of the labor markets. In order to attempt to meet these daunting goals, various aspects of the academic curriculum will need to be adjusted and formalized.

A recently completed NSF-funded project at Burlington County College, entitled "Institutional-Level Reform of an Engineering Technology Program." sought to identify critical skills and competencies needed by industry (both technical and non-technical) and to examine the means by which these competencies are incorporated into the curriculum. The current effort, of formalizing the incorporation of a principles-application approach, complete with outcomes assessments in a 'discovery-learning' model, is an extension of this earlier work.

It is expected that by helping students immediately see the relevance of the subjects they are expected to learn, and to tie in the foundational principles from the beginning, it will help to capture or increase their interest in the subject matter. This increased interest will foster a love of learning for the subject and teach students to think critically and creatively, making them more valuable in the job market.

This approach is not one of merely giving examples, but is rather a formalized approach in developing applications that foster "discovery learning" and allow students to develop a true understanding of basic principles. The extent to which the desired competencies are gained will be measured by a formalized outcomes assessment approach.

Background

The importance and application of science and engineering principles in our daily lives cannot be overstated. Materials and devices from semiconductors to microprocessors to the vehicles we drive rely on a highly sophisticated understanding of applications-based principles. With a struggling global economy on many sectors, and an increased focus on persistence and graduation rates, it behooves higher education in the United States to develop a meaningful

approach to teaching the linkage between scientific principles and the critical applications upon which we rely so heavily.

On the secondary level, formalized approaches to the incorporation of applications-type projects in technology education have been conducted. These efforts often involve assigning a specific project to a group of students, and developing various aspects of the design, development, and use of a practical item or system. One such effort has been initiated with the goal of promoting an understanding and appreciation of quality in America's schools.[3]

Other formalized secondary school project-type programs include, on the Elementary School level: "Engineering is Elementary"[4], developed by the museum of science in Boston. On the Middle School Level: "Building Math"[5], a modular curriculum for grades 6-8 mathematics studies that integrates math concepts, algebraic reasoning, and engineering through an engineering design challenge in a realistic story context. Additionally, on the Middle School level: "A World in Motion"[6], developed by the Society of Automotive Engineers Foundation, brings math and science principles to life in the context of an engineering design challenge for middle school students through highly interactive and innovative learning experiences that incorporate the laws of physics, motion, flight, and electronics. And on the High School level: "Engineering the Future"[7], developed by the Museum of Science in Boston, is a full-year engineering and technology education course suitable for Grade 9-12 students. Through four projects students learn about engineering design, manufacturing, communication, and energy systems.

On the Higher Ed level, an applications and context-based approach, in the technical disciplines, can mirror and logically extend from those in other segments of education, and other disciplines as well.

Academic programs with contextualized readings, that is reading and other academic assignments containing subject matter relevant to a particular student's interests have been shown to improve academic outcomes. For example, students interested in computer networking technology would be assigned readings dealing with factual situations pertaining to this topic. This approach to contextualization or "authentic content" is to teach skills with direct reference to real-life situations, in order to make the learning process more meaningful, and interesting, to students [8].

The formalized incorporation of an applications-based approach can be considered to be a type of "discovery learning" modality, much like that used to teach early algebra to elementary school students [9]. In such studies, analysis of data shows that students are able to build mental representations of variable, open sentences, true or false statements, the rule for substitution, etc. through exercises that enable discussion, exploration, and discovery of new concepts and ideas. Students have been observed to gain more mathematical ability from discovery learning than they do from the more passive approach of rote learning.

It should be noted that a formalized approach to incorporating applications into the curriculum is different from experiences gained through internships and co-operative education experiences. The utilization of an applications-based approach can help students decide if a career path is right for them, and help them decide which aspects of a technology career inspire them. Experiences gained in internships and co-ops are often invaluable as resume boosters but are often not formalized in their linkage to specific applications and their associated educational outcomes.

Regardless of the initial approach, the formalized incorporation of applications will have some common elements:

1) The application must have some readily identifiable significance, both in terms of functionality and economic benefit, and the underlying and reliant principles must be readily identifiable and well understood.

2) The underlying and reliant principles must be summarized in plain language and communicated with a simple figure or table, where appropriate.

3) The application and principles must have significance to an emerging student, both in future academic courses (on the undergraduate and graduate levels) and in likely career experiences.

4) The introduction and development of the application must follow a sound pedagogical approach (i.e. the inclusion of Bloom's taxonomy in defining outcomes, etc.), as well as a standardized and consistent academic outcomes measurement approach.

Applications

Two relevant applications will now be discussed, along with their important underlying principles, and how student learning can be assessed, measured, and used as feedback. Both can be summarized in plain language and communicated with a simple figure, and then the mathematics further developed.

Mathematics and Engineering

One of the best practical applications of mathematics is the application of calculus, the mathematics of motion and change, in PID (Proportional-Integral-Derivative) loop controllers. This is an application of calculus often taught in process control and industrial control courses, which should alternatively be taught in introductory calculus and other technical courses. This application readily demonstrates to students the practical application of the mathematics they are learning, and the power of mathematical constructs involving changing rates and quantities.

Figure 1 below[10] illustrates this application via the typical behavior of a controlled process. The curves from top to bottom represent a process with no control, with proportional control only, with proportional and integral control, and with proportional, integral, and derivative control, respectively.

After a step change in a load variable, a process controller, by means of a PID control scheme, acts to dampen the offset and oscillatory effects of attempting to maintain the variable about a pre-specified set point. For every action, there is a reaction, and when attempting to correct for the difference in the measured value and the desired set point, there is a danger of overshooting, or over-compensating in the other direction. The PID scheme presents the best solution to the problem of maintaining a process variable about a desired set point, directly using the principles of calculus.
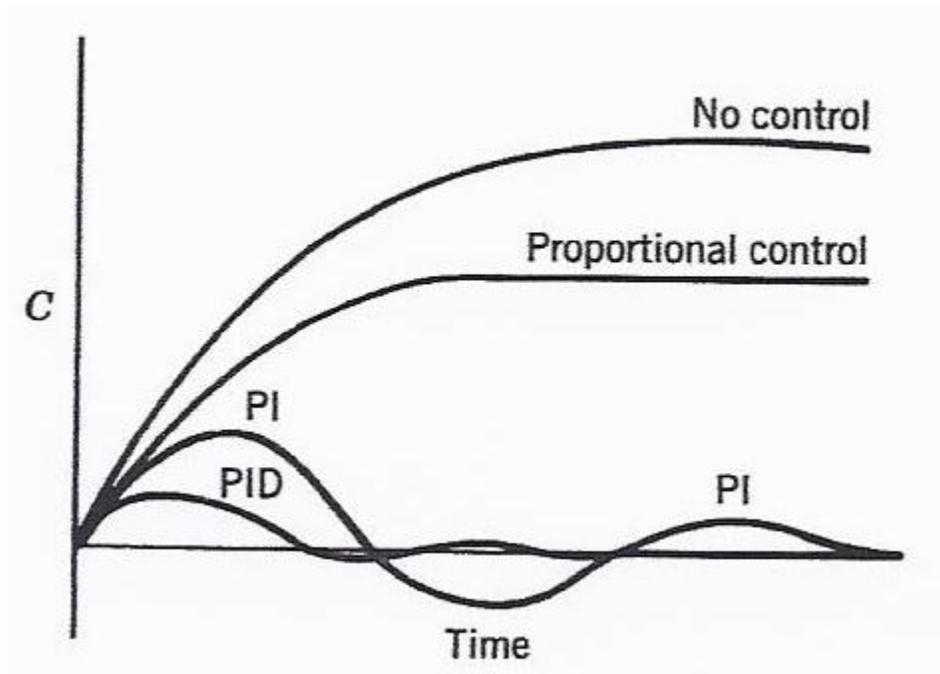

Figure 1. Behavior of a process with No control, Proportional control, Proportional and Integral control, and Proportional-Integral-Derivative control, respectively.

In the equation below, e = the error between the set point and measured value, T_i = the integral time, T_R=the reset time, and T_D= the derivative time. K_C = the overall gain of the controller (as differentiated from that of other process components)

The equation for the three mode controller then, with terms representing proportional, integral, and derivative corrective inputs, respectively, is:

$$p = K_C(e + \frac{1}{T_R} \int_0^t e \, dt + T_D \frac{de}{dt})$$

This introductory application of calculus plainly illustrates the effect, on some relevant process, of trying to hold an important variable around a set point, and how an understanding of mathematics makes this possible. Mathematical proportional influence, mathematical integral influence, and mathematical derivative influence are shown to work in concert to produce a controlled result, which would otherwise be impossible to achieve.

In keeping with the scheme described above:

1) <u>Readily identifiable significance</u>-Many important processes, where devices are intended to be used and operated at a desired level, rely on PID loop controlling, including driving a car or manufacturing chemicals or materials.

2) <u>Summarized in plain language and communicated with a simple figure</u>-For every action there is a reaction. If a process control variable moves in the direction of a desired set point, it will invariably overshoot, or remain far away from the desired set point, without PID loop control tuning.

3) <u>Significance to an emerging student</u>-This application is important for all students who will ever take a calculus course (all engineering, science, and technicians) and be expected to apply the principles learned, as well as those whose employers will expect them to understand and control or tune such processes. The range of employers includes food, chemicals, mechanical devices, and many others.

4) <u>Pedagogical approach</u>-Appropriate outcome statements will include:

At the end of this lesson, students will be able to:

• Employ the principles of calculus in a physical process.

• Demonstrate the utility of mathematical principles on the control of a relevant process.

• Predict cost and schedule savings as a result of employing efficient control methodology.

<u>Science and Mathematics</u>

A second relevant application involves the equilibrium concentration of vacancies, a type of defect, in crystal structures. This application illustrates the thermodynamic limitation of solid

crystalline systems being formed with 100% purity. The application of this science, that is thermodynamics, and mathematical principles limits the functionality of solid state materials and the semiconductors that rely on them, as well as the appearance of ornamental diamonds. For example, diamonds are sold with consideration toward the criteria of the four C's: Color, Clarity, Cut, and Carat. The first two criteria speak directly to the defect concentration in the crystalline structure.

Figure 2[11] demonstrates how the free energy of a crystalline system changes with increasing defect concentration. In the figure, the linear top curve represents the change in free energy associated with an increasing number of defect vacancies. The bottom curve represents the effect on free energy as a result of adding or mixing vacancies into the crystal matrix. In the equations shown, N = the number of atoms, n = the number of vacancies, ΔH_V = the change in enthalpy associated with the vacancies, ΔS_V = the change in entropy associated with the vacancies, k = Boltzmann's constant, and T = temperature.

The center curve G=f(n) shows mathematically the summation of the effects of the top and bottom curves. By gaining an understanding of this application, students are taught that a certain concentration of defects in the crystal lattice actually lowers the free energy, up until some maximum, before the effect of the top curve takes over and causes an increase in the free energy of the entire system.
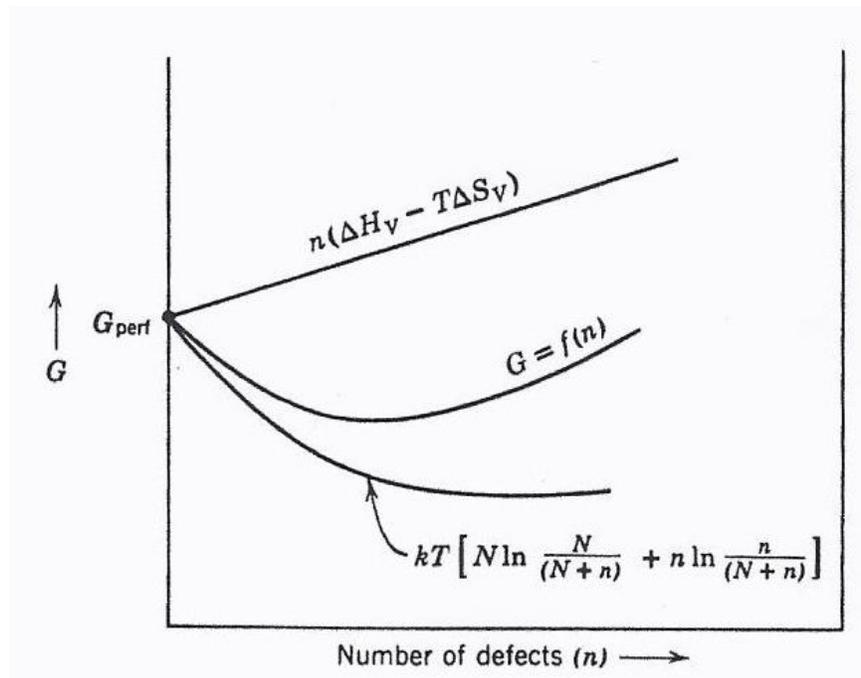

Figure 2. The composite effect of the change in free energy of a crystalline system with increasing defect concentration.

Therefore it is observed, and mathematically demonstrated, that the introduction of vacancies actually lowers the free energy of the system until a finite equilibrium concentration is reached, and then causes an increase in free energy. This means that the thermodynamic effects illustrated in the figure above will limit the purity of a crystalline material, and that 'perfect' crystals cannot be made, at least not without a great deal of effort and expense.

In keeping with the scheme described above:

1) <u>Readily identifiable significance</u>- The purity of materials directly impacts their properties, including chemical, electrical, and mechanical properties.

2) <u>Summarized in plain language and communicated with a simple figure</u>- Solid crystalline materials, of which important devices from microprocessors to medical sensors are made, cannot be made 100% pure due to thermodynamic limitations.

3) <u>Significance to an emerging student</u>-Any solid crystalline material will have properties that depend on crystal purity.

4) <u>Pedagogical approach</u>-Appropriate outcome statements will include:

At the end of this lesson, students will be able to:

•Relate the presence of crystal defects to an equilibrium free energy of the solid system.

•Interpret the effects of crystal defects on an entire material system.

•Relate the concepts of crystal purity to any material system where purity and defect concentration affect subsequent properties and use.

•Understand the value added in creating specialized facilities such as clean room manufacturing plants, and the often limited return on investment.

The two applications described above have been integrated into the curriculum, on a pilot basis, of an introductory material science and engineering class (EGR-212), during the 2012 Spring semester, at Burlington County College. The computer control and automation example, with the application of calculus in PID loop control, has been incorporated within lessons on process control and stoichiometry control. The crystal defects example, with the application of thermodynamics and the lowest energy state observed with a finite concentration of defects, has been incorporated within lessons on crystallography and mechanical properties of materials. Students are assessed through embedded questions in exams and quizzes that are specifically created to gauge their understanding of these relevant topics. Assessment collection and analysis are currently ongoing.

The methodology of formalizing an applications-based approach, described above, can be further developed to include other relevant applications of mathematical and scientific principles. Some

additional applications, presented to give readers food for thought for incorporation into mathematics and technology-based courses include: the use of variable frequency drives for the industrial control of three phase motors, the difference in heat transfer rates between electric immersion and steam jacketed process equipment, the measurement of dynamic mass flow, and the importance of turbulence in industrial mixing applications. Each of these additional applications can be incorporated into the curriculum by communicating to students the readily identifiable significance, by summarizing in plain language and communicating with a simple figure, by identifying the significance to an emerging student, and with well-defined outcome statements.

Outcomes Assessments

The axiom "What gets measured gets done" is perhaps more true in Higher Education than it is in industry. However, measurements of student learning are oftentimes more difficult than simply measuring the number of failures in a batch.

When specific learning principles are measured, overall course grades do not carry enough resolution to tell the required story. For example, a student may earn a grade of A in a course, but may still not have grasped and mastered a particular concept. In order to measure learning of a particular concept, student performance regarding that one concept must be probed. This often entails 'embedding' questions and problems that are carefully tailored to probe critical thinking skills pertaining to the concept of interest, and grading and compiling these results individually.

The Accreditation Board for Engineering and Technology (ABET) defines assessment as:

"one or more processes that identify, collect, and prepare data to evaluate the attainment of student outcomes and program educational objectives. Effective assessment uses relevant direct, indirect, quantitative and qualitative measures as appropriate to the objective or outcome being measured. Appropriate sampling methods may be used as part of an assessment process"[12].

In general, outcomes should be written with a consideration of Bloom's Taxonomy[13] which will include an appropriate range of competencies probed including Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation. Additionally, the learning outcomes must be framed in terms of the goals that are expected of students, as in the two examples given above.

The above-described assessments should be part of a standardized assessment plan that will include the following steps:

1) Determine intended learning outcomes to be assessed using internal, and where possible, external benchmarks.

2) Develop two varied assessments for each outcome assessed and a criterion for success for each.

3) Conduct assessments and collect data using qualitative or quantitative analysis.

4) Develop an improvement plan to address weaknesses and strengths.

5) Implement the improvement plan into the operations.

Challenges and Next Steps

In order to alter Higher Education curricula to have an increased focus on applications, for the benefit of students, several key elements must be in place. First, faculty must be supportive of the new approach. With a sound outcomes assessment plan in place, it will be readily apparent what elements of the program need to be changed. Therefore, trying something new will not bring the dreaded stigma of being 'stuck' with a poor approach, i.e. one that is not aligned with the expected academic outcomes, but rather the process will allow constant feedback and continuous improvement.

Instructor training is also another consideration. For faculty who have never worked in industry, or are not comfortable with the chosen applications, training and coaching must be provided. Any stigma associated with such mentoring can be dispelled by communicating consistently that such mentoring is part of the applications approach. A useful source of this mentoring, and an integral part of the continuous improvement approach, is the reliance on an industrial advisory board. This board can provide vital feedback and support to keep the applications relevant and meaningful to students.

Finally, embedding carefully designed questions into an exam or project, and then assessing and compiling parts of such questions can be more work than a traditional example/exam-based approach. However, unless this level of commitment is demonstrated by faculty, which it often is, key elements of the measurement of learning outcomes will not be possible

The next steps involved in this effort include the incorporation of the initial two applications described above further into the curriculum of science, engineering, and technology-based courses at Burlington County College. Student performance in each foundation course will be assessed, as well as subsequent student performance and progress in later, more advanced, courses.

It is a major thesis of the current work that student success will be beneficially impacted through the incorporation and demonstration of real-world examples using mathematical and scientific principles. Measures of student success, as measured by student interest, program perseverance and degree attainment, and employment and career success will be continuously measured on a

longitudinal basis. Burlington County College already collects data regarding these measures through it's ABET (Accreditation Board for Engineering and Technology) continuous improvement processes as well as through various student survey mechanisms such as the CCSSE, SENSE, and Noel-Levitz surveys.

Acknowledgements

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