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'Kinetic Sculptures': A Centerpiece Project Integrated with Mathematics and Physics*

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An integrated set of courses, or Integrated Course Block (ICB), developed for incoming first-year students at the Franklin W. Olin College of Engineering, is presented. Bound by a common theme of 'Kinetic Sculptures', the individual courses in this ICB are mathematics (single variable calculus and ordinary differential equations), physics (kinetics and dynamics of linear and rotational motion, thermodynamics and fluids), and an open-ended engineering project. The project part of the ICB allows students to explore the motion through the design of kinetic (moving) sculptures while utilizing the mathematics and physics concepts learned in the accompanying courses. This paper considers the 'Kinetic Sculptures' ICB from the pedagogical and epistemological points of view by presenting its implementation and discussing the results and analysis of three student surveys taken during three semesters, and seven semesters after participating in the ICB.

Keywords: first-year design experience; integrated curriculum; centerpiece project; kinetic sculpture

INTRODUCTION

IN AN ATTEMPT to address the calls for change in engineering education [1] and to support the increasing emphasis on interdisciplinary research and industry, researchers and learners strive to synthesize information and build links between distinct disciplines and fields. In engineering, this need is exacerbated by rapidly developing science and technology. However, today's engineering students still see very few connections between their science and mathematics courses and the real world [2]. Additionally, although current engineering curricula are designed for a large transfer of mathematics and science knowledge through engineering courses, the desired transfer occurs to a very small degree, if at all [3]. Moreover, high attrition rates, particularly among women and under-represented minorities, weak student engagement, and poor student performance have inspired a number of engineering schools to develop integrated programs [4–7]. It has been suggested that in addition to addressing the above problems, an integrated pedagogy should result in other advantages, such as increased stimulation of cognitive structures, avoidance of unproductive repetition, synchronization and linkage of related subjects, improved interdisciplinary thinking, and greater opportunities for students to develop teaming skills. Although many engineering programs are incorporating integration into their curricula, no single definition describes all of these programs. Many, however, are characterized by either course collaboration among faculty from different disciplines and students' enrolment in disciplinarily distinct course sets or by courses combining a set of different disciplines [4]. These aspects also characterize the integrated first-year curriculum at Franklin W. Olin College of Engineering.

A number of schools have had significant success with integrated courses. Of particular note are programs developed by various schools within the Engineering Education Coalition; these include *IFYCSEM* at Rose Hulman [8], *MSFE* and E^4 at Drexel [9, 10], *Connections* at Colorado School of Mines [11], *TIDE* at the University of Alabama [12, 13], *IMPEC* at North Carolina State [14, 15], *IMPULSE* at University of Massachusetts Dartmouth [16], new curriculum at Texas A&M [17], *Engineering First* at Northwestern University [18], among others. Assessment data from these programs suggest that integrated curricula result in improved student learning, improved retention and satisfaction, and potentially improved student performance throughout the curriculum [4, 8, 11, 19]. An additional positive aspect of curricular integration is its potential for creating learning communities, which increase student retention and satisfaction and build interdisciplinary and social links within a community [4, 11, 20, 21].

Integrated curricula are not without difficulties. While it appears that integration benefits student learning, it is also clear that there is significant room for improvement in this area. As Froyd and Ohland [4] pointed out, "despite stated intentions to help students make connections across topics and courses, none of the published assessment methodologies used for evaluation of integrated curricula have attempted to show that students are making improved connections . . . [and] no

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assessment processes and/or instruments have been developed to help define the degree to which a learner has integrated her/his knowledge". In addition, as much as integration appears desirable, relatively few schools have tried integrated programs due to institutional resistance to change and the perceived difficulties in creating integrated course blocks. Much of the work on integrated curricula has focused on the issue of surmounting institutional barriers [22].

It is notworthy that some form of a first-year design project has also become a part of many integrated curricula. Therefore, many engineering programs have placed an emphasis on developing and improving teaming, communication and design skills through the introduction of a first-year design course [18, 23–28]. A literature survey suggests that the objectives of such design projects generally fall into the following categories:

- to introduce students to the design process early in their engineering education;
- to develop student skills in working on large, open-ended problems;
- to develop student teaming and communication skills;
- to motivate students to stay in engineering.

In a few cases, first-year design is also cited as a means for students to see the connections between mathematics, science, and engineering [8, 16, 18, 29, 30]. The nature of these first-year design experiences varies greatly from school to school and from program to program. Burton and White surveyed first-year design programs at 43 different institutions, while Sheppard and Jenison reviewed first-year design curriculum in 16 different schools; among the approaches to the design projects, they found reverse engineering, case studies, design competitions, and customer-centered design [25, 26]. Moreover, in terms of Sheppard and Jenison's organizational framework, these design courses further vary in terms of 'what is taught and learned' or the 'skill/knowledge' and in terms of 'how the 'what' is taught' or the 'pedagogical approach'. Within the space spanned by these two dimensions, 'of what' and 'how' design courses can be described as 'individual-content centric'/ 'team-content centric' and 'individual-process centric'/'team-process centric' [26]. [Although many first-year design courses fit nicely into these categories, the design course we are about to describe is different in that it evolves from 'individual-content centric' to 'team-process based', thus allowing for a smoother high-school to college transition and better paced acquisition of 'how to learn' skills.]

Despite the large differences between various approaches, *most design projects are relatively small scale* lasting from one class session to five weeks and are expected to occupy a small fraction of student time. There are a number of reasons why projects may be limited in scale: tight limits on the amount of course time allocated to the project (e.g., one credit hour design course), a stronger focus on the design process and management thereof [31], a desire to complete multiple projects, for example small discipline-specific projects [30, 32].

For the small number of cases when first-year design projects are larger in magnitude, students often interact with clients [33] as a way of introduction to the open-ended, ill-structured nature of design problems. Such projects typically stress design theory, project management, and occasionally ethics. In some cases, design is driven by vertical integration, i.e., first-year students working with juniors or seniors on a large design project [34, 35]. Like customer-driven design projects, this approach has the advantage of introducing students to 'real' problems [36, 37].

Whether large or small, many first-year design projects intentionally *include little technical content*. Rationales for this lack of emphasis on technical content include a desire to focus on the design process itself, a necessity to avoid discipline-specific work before students have selected a major, and the assumption that students' backgrounds are too limited to allow more substantive projects. For example, Columbia University's first-year project uses toy design as a theme, because while "most first-year students lack technical knowledge, and many are disillusioned about the engineering profession after being submerged in first-year mathematics and science courses, . . . virtually all students are toy experts having had at least 17 years of experience with toys of varying levels and complexitites" [38].

In short, although frequent, first-year design projects appear to be thought of as *antidotes* to boring and alienating physics and mathematics lectures [39], rather than as *motivators* or *reinforcers* for the material taught in these courses. Unfortunately, in the cases when science and mathematics content is indeed motivated and reinforced through the design project, the latter is often a small-scale 'add-on' (e.g., egg drops). It is also noteworthy that first-year projects often address calls for design and teamwork early in the curriculum, but rarely push the need for interdisciplinary thinking or improve the learning of core STEM (Sciences, Technology, Engineering and Mathematics) disciplines [40]. Furthermore, at many schools, the very idea of first-year design has not yet entered the curriculum; rather Introduction to Engineering courses frequently consist of short modules, in which faculty members from different departments lecture about their specific discipline. Unfortunately, such courses often earn the nickname Sleep 101 [41].

Our approach is to provide the archetype integration of discipline-specific topics in mathematics and physics accompanied by a large open-ended design project that teaches teamwork, research, computer aided design (CAD) and fabrication techniques. The general theme of the project is chosen to allow students significant flexibility in selecting a specific design of interest to them, but also to use, motivate, and reinforce the knowledge acquired in the corresponding mathematics and physics courses. We consider these projects as 'centerpiece' since they serve the role of a centerpiece in the first-year engineering experience.

In this paper, we describe one of our integrated course blocks that was implemented during the first academic year of the Franklin W. Olin College of Engineering (2002–2003). First we describe the individual courses, their specific learning objectives and topics. Then we show how the topics of these three courses are sequenced and integrated throughout the semester. We then show the progression of work (prototypes and analysis) done by one of the kinetic sculpture teams during this semester. Finally, we conclude by sharing student feedback taken via three surveys containing a mixture of open-ended and Likert scale questions that allow for quantitative and qualitative analysis. The surveys were taken while students were going through the experience, and afterwards—three and seven semesters after their experience, in the summer following students' sophomore year and in the spring semester of their senior year, respectively. We also share our observations, experiences, and lessons learned while delivering the 'Kinetic Sculptures' integrated course block. In what follows we adopt McKenna *et al.*'s [2] framework by discussing both pedagogical and epistemological aspects of the ICB. While doing so, we will address the issue of large-scale projects, integration and student learning, possible gender difference in attracting students into integrated engineering activities, and the ability of such activities to affect student desire to remain in the engineering program and to pursue engineering career.

PEDAGOGICAL ASPECTS

Intended to foster student collaboration, crossing disciplinary boundaries, and application of student knowledge to real engineering problems, a first-year integrated course block, or ICB, taught at the Franklin W. Olin College of Engineering is a symbiosis of three components—Mathematics, Physics, and an Engineering Project—taught by a multidisciplinary faculty team. An interesting feature of Olin's first-year curriculum was students' ability to *choose* between three ICB themes offered each semester. In the Fall of 2002, 'Kinetic Sculptures' was one of these themes, where students explored art and motion, while learning mathematics and physics content as well as mastering design, modeling, simulation and other skills. In order to understand the functioning, goals and the results of the whole ICB, it is critical to understand each of its components as well as the way these components were integrated. Below we describe three individual courses comprising ICB with their corresponding goals and learning objectives, the integration of these three courses, and an example of one team's effort in the ICB.

Individual courses

I. Mathematics

The mathematics course was divided into two half-semester blocks: calculus and ordinary differential equations. The calculus portion covered topics in single variable calculus, such as techniques in integration, applications of integration, parametric representation, series and sequences (the text was *Calculus: One and Several Variables* by Salas, Hille and Etgen). The ordinary differential equations portion of the course centered on first-order equations and the solution to constant coefficient second-order equations, with a focus on categorizing conservative and dissipative systems, concluding with resonance phenomenon (the text for this portion was *Elementary Differential Equations and Boundary Value Problems* by Boyce and DiPrima). The learning objectives for the entire course were:

1. to solve standard textbook-level problems by analytical means;
2. to apply multiple concepts in the solution of a more sophisticated problem, which may be derived from a scientific or from an engineering application, and
3. to mathematically model and solve a problem from science or engineering and to report the results in the original problem context, either through presentation or through a written report.

The first two learning objectives were addressed through problems found within the textbooks by reinforcing problem-solving technique (per objective 1) and by learning synthesis (per objective 2). Objective 3 was addressed through a separate independent assignment, in which the students investigated difference equations and determined numerically an approximation to Feigenbaum's constant through a series of questions posed in Boyce and DiPrima.

II. Physics

The physics course provided an introduction to classical mechanics, fluid mechanics, and thermodynamics. The course covered kinematics, Newton's laws, particle dynamics, momentum, work, energy, rotational motion, statics, oscillations, fluid statics, Bernoulli's equation, and the laws of thermodynamics. Although there exist a large number of introductory calculus-based physics textbooks, for this particular course, we used University Physics by Reese.

The general objectives of the course were:

1. to provide an understanding of fundamental physical principles and an appreciation for when, where and how they are applied in every day life and in engineering;

2. to provide basic skills necessary for understanding of physical principles on the qualitative and quantitative basis and to use this understanding in solution of problems with practical applications;
3. to provide basic data collection and analysis skills, and
4. to provide appreciation for physics and how it relates to other disciplines.

By and large, our goal in this course is to share the excitement of discovering the material universe at its most basic levels and to equip students with the basic knowledge and analytical skills necessary to become an engineer and a scientist.

Engineering project

According to Olin College's curriculum description, it is the explicit role of the project to have "student teams identify and define problems, assess opportunities, apply technical knowledge, demonstrate understanding of contextual factors, muster appropriate resources to solve problems, and apply skills such as teamwork, communication and idea generation'. [42] As such, the project course allowed students to tackle an open-ended engineering problem with 'real-world' applications early in their careers. The scope of the project was chosen to reinforce and motivate the accompanying mathematics and physics content while providing the theme of 'Kinetic Sculptures' for the whole ICB experience. To support this early undertaking, students are given explicit instruction in how to use the College's library and personnel resources to research answers to technical and non-technical questions, to generate mechanical CAD drawings of all system components, to fabricate these components in the machine shop, and to solve problems in teams.

At the beginning of the semester, student teams chose sculptures of interest and wrote proposals describing the reasons for why their proposed projects are interesting in terms of their design, reasonable in scope, and adequate in terms of content. Throughout the semester, students designed and built kinetic (moving) sculptures modeled the motion of the sculptures, and compared the modeled motion with that of the actual sculpture they built. The sculptures were required to be completely mechanical and to use a dropping weight as a power source. There were also size, cost and safety constraints that must be met in the design process.

The project work happened in three distinct phases. First, students formed semester-long teams. They brainstormed and worked out ideas for their sculptures as a team, while also consulting with their mathematics and physics instructors about the relevant topics and feasibility of mathematical and scientific modeling and simulation. In this phase, students received instruction on researching information in the library, teamwork, and Solidworks CAD drawing. Students also presented written abstracts of their proposed work that went through several iterations.

Next, students worked on modeling the behavior of the sculptures while they learned the basics of using the woodworking shop. Students refined their sculpture ideas by building crude prototypes (from paper, cardboard or existing toys) to get a better idea of how their sculptures would function. In this phase, the mathematics and physics instructors were also available to help students derive the correct models for their sculptures. This phase ended with the deliverable of a proposal that described the aesthetic effect that the students wanted to achieve, the mechanical evaluation of the sculpture motion, a budget and timeline for building and testing their final product.

The final phase of the project was implementation. Students constructed the sculptures (often in several prototypes) to implement their vision. At the end of this phase, students presented their sculptures to an external panel of engineers, scientists, mathematicians and sculptors, describing the aesthetics, the mechanisms, and the functioning of their sculptures.

The integration of the courses

In delivering the 'Kinetic Sculptures' ICB, we adopted two models of integration.

The first model consisted of a symbiosis of the so-called 'sequenced' [43] and spiral learning. The 'sequenced' learning involved rearrangement, sequencing, and coordination of the topics offered in the individual courses to complement one another whenever possible, such that "similar ideas [were] taught in concert while remaining separate subjects" [44]. This coordination of topics is shown in Table 1. It is important to note that in addition to sequencing some topics, a number of concepts in mathematics and physics were delivered via spiral learning methodology. For example, simple harmonic motion was brought up initially in the physics curriculum in the fifth week, and it was used again later in the tenth week of the mathematics curriculum. For this concept, the spiral methodology proved valuable to the students in their synthesis of the mathematical and physical concepts that were addressed during the semester.

The second model involved a synthesis of 'webbed' and 'integrated' learning methodologies, as described by Fogarty [43]. This methodology involved the physics and mathematics faculty actively participating in the project during proposal, design and modeling of student sculptures. In the 'webbed' methodology, the 'Kinetic Sculptures' theme was used as a base for one-on-one faculty-student team mentoring, allowing the students to understand how to view the same real problem from a variety of different perspectives (e.g., mathematics, physics and engineering) and teaching to see connections between various seemingly disparate ideas from different fields. Additionally, the use of 'integrated' methodology

Table 1. Sequence of course topics in mathematics, physics and project courses

Week	Mathematics topics	Physics topics	Project topics
1	Separation of Variables, Conic Sections, Polar Coordinates	Measurement, Units, Dimensional Analysis, Vectors, 1D Kinematics	Library Research, Information Sources
2	Sequences	2D Kinematics, 3D Motion, Relative Motion, Circular Motion, and Cylindrical Coordinates	Methods of Group Brainstorming Team Contracts, Personal and Team Dynamics
3	Integration with Disks and Washers, Integration with Shells, Theorem of Pappus, Centers of Mass, Surfaces of Revolution, Centroids of Curves and Surfaces	Newton's Laws of Motion, Weight and Normal Force, Tension, Friction, Gravitation, Gravitational Force, Mass of the Earth	Introduction Solidworks, drawing shapes, extrusions, campheres
4	Work Pressure Fluid Force, Improper Integrals, Infinite Series, and Integral Tests	Hooke's Law, Springs, Simple Harmonic Motion, Pendulum, Small Angle Approximation, Work Done by Various Forces, Conservative and Non-Conservative Forces, Geometrical Interpretation of Work, Kinetic Energy	Solidworks: sweeping functions, splines, drawing a sphere
5	Ratio and Root Tests, Absolute and Conditional Convergence	Potential and Kinetic Energy, Gravitational Potential Energy, CWE Theorem, Conservation of Mechanical Energy, Paradoxes, Power, Energy Considerations for Simple Harmonic Motion, Forced Oscillations, and Damped Oscillations, Normal Modes, Resonance, Natural Frequencies, Musical Instruments	Fabrication: Using the Panel Saw, Miter Saw, and Band Saw
6	Taylor Series, Power Series, Differentiation and Integration, Binomial Series	Gravitational Potential Energy, Escape Velocities, Bound and Unbound Orbits, Circular Orbits, Various Forms of Energy, Energy Diagrams, Momentum, Conservation of Momentum, Impulse Momentum, Collisions	Fabrication: Using the belt and spindle sanders, routing
7	Basic Models, Direction Fields, Classification, Linear Equations, Integrating Factors	Center of Mass, Rockets, Vector Product, Angular Momentum, Spin and Orbital Motion, Kepler's Laws, Elliptical Orbits, Satellites, Change of Orbits	Proposal Writing: Introductions, Proposed Approach, Timeline and Budgets
8	Modeling, Linear vs. Nonlinear, Autonomous Equations, Existence and Uniqueness	Angular Momentum and Torque for a Motion of a Single Particle, Rotating Rigid Bodies, Moment of Inertia, Parallel Axis, and Perpendicular Axis Theorem, Rotational Kinetic Energy, Fly Wheels, Neutron Stars, Pulsars, Conservation of Angular Momentum, Spinning Neutron, Stars, Stellar Collapse, Torques, Oscillating Bodies, Hoops, Rolling Motion, Precession, Gyroscopes, Torsional Pendulum	Fabrication: Joining Techniques, Finishing
9	Homogeneous, Constant Coefficient Second-Order Equations	Solids, Static Equilibrium, Stability, Rope Walker, Elasticity, Young's Modulus, Fluid Mechanics, Pascal's Principle, Hydrostatics, Atmospheric Pressure, Over Pressure in Lungs and Tires, Archimedes' Principle, Fluid Dynamics, Bernoulli's Equation	Presentations: Deciding what to present, use of slides, timing a presentation
10	Fundamental Solutions, Complex and Repeated Roots of the Characteristic Equation	Basics of Waves, 1D Waves, Sound Waves, Doppler Effect, Binary Stars, Neutron Stars, Black Holes	Group Design Session: Faculty work with individual teams on specific team questions
11	Non-homogeneous Equations: Undetermined Coefficients and Variation of Parameters	Thermodynamics	Design Review
12	Variation of Parameters, Engineering Applications	Kinetic Theory	Writing a Final Report: Contents of a report, role of appendices, knowing the correct audience, review process, etc.
13	Forced Vibrations, Resonance, Qualitative Analysis of First-Order Systems	The Second Law of Thermodynamics, The Engine The Carnot Cycle, Entropy	Dry Run of Final Presentations
14	Review	Review	Final Design Presentation: Outsider reviewers help to evaluate student results

during the one-on-one faculty-student teamwork, allowed for further examination of common concepts, skills and attitudes that overlap different disciplines. This is the place where the true integration of the mathematics, physics and project courses occurred: (1) a custom approach to mentoring and learning the material pertinent to individual projects allowed students to further their interdisciplinary knowledge and understanding of specific topics relevant to their chosen work; (2) individual attention to student projects from an interdisciplinary faculty team allowed students "to see interconnectedness and interrelationships among disciplines" while motivating the learning of and reinforcing the relevance of the mathematics and physics content [44].

Results

The student projects varied from 'liquid clock' to 'flying' ping-pong balls to a silo [45]. Here we show the progress of one of our student teams, 'The Juggler', as an example of the results that we have seen in the ICB.

This student team decided to design 'a juggling machine', shown in Fig. 1, that consisted of "a spinning armature [with] five arms, each of which [had] a rotating cup at the end used to pass balls around as the armature rotated. Once at the top of its path, a mechanical pin caused the cup to tip thereby dropping the ball it carried into the cup two positions forward on the sculpture. This cup had to rotate around to be in the right place at the right time to catch the ball . . ." [45]. The design involved a cycle of balls dropped and caught as the sculpture rotates through. Students believed that "this continuous motion will produce an aesthetically pleasing visual effect [while] demonstrating both circular and parabolic motion of particles", the material they learned in the mathematics and physics portions of the ICB.

The students built a quick prototype of this sculpture, shown in Fig. 2, using paper cups and tinker toys to get a feel for how the project might

Fig. 2. Initial tinker-toy-prototype for the juggling kinetic sculpture.

work. Interestingly enough, as they hand-spun the prototype, the sculpture was able to catch a few of the balls. This gave the students immense hope that they would be able to get the idea working correctly if they could obtain a constant rotary speed for the sculpture.

The students then worked on modeling the motion of the sculpture and computing the necessary rotary speed of the sculpture. This involved modeling the initial speed of the ball just as it is being released from the cup, the ball's trajectory upon leaving a cup, and the position of the forward cup when the ball finishes the trajectory. Figure 3 shows the drawing that the students used to illustrate the parameters in their equations.

The students then built a more accurate prototype of their sculpture using a Lego® motor as a power source for the sculpture. With this device, they were able to drive the sculpture at the computed speed and alter this speed to do testing to see if the theory was inaccurate.

Despite its ambitiousness, the students' impressive design, modeling and fabrication resulted in a functional sculpture; however, reliability and

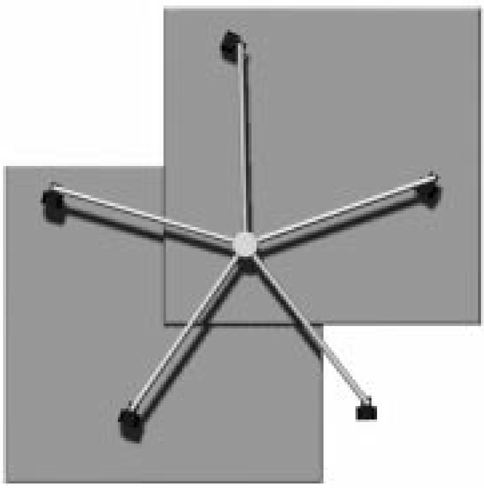

Fig. 1. Initial concept for the juggling kinetic sculpture.

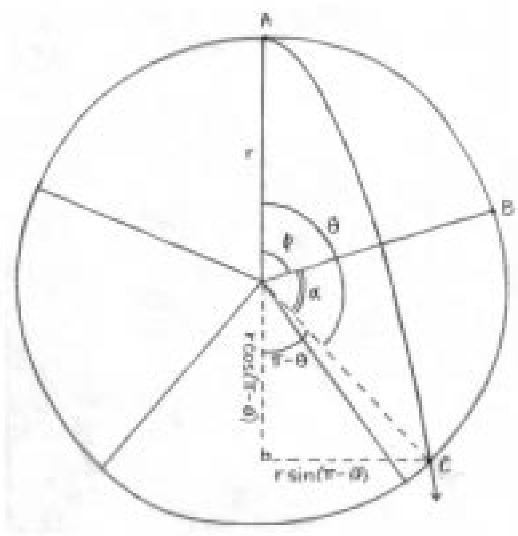

Fig. 3. Diagram showing variables used in the team's mathematical model.

Fig. 4. Final prototype of the juggling kinetic sculpture.

reproducibility remained the two issues that students wished they had more time to work on. For example, the motor was underpowered for turning the sculpture arms due to all of the frictional losses that students were unable to account for in their early calculations. Although disappointed with not being able to complete a 'perfect' sculpture, students found incredible pride in their work and a sense of accomplishment. It was the process of creating the sculpture that students reported mattered to them the most.

Similar feelings were experienced by other teams working on their kinetic sculptures. At the end of the course, all student teams presented their work to a panel of outside reviewers. This panel consisted of two practicing artists, an engineer, a physicist and a chemist. The panel was to ask the following three questions pertaining to each team presentation.

- What did you think about the students' presentation of their sculpture, simulations and modeling?
- What do you think about their design process?
- What advice would you give this student team or individual students on the team?

Overall, the reviewers were impressed with what the students had accomplished in their first semester. Specifically, the reviewers overwhelmingly felt that all of the student teams did an excellent job in their design processes and of presenting their sculptures. We received a wide variety of answers to the second and third questions. In many cases, the reviewers correctly identified an aspect of the design process that should have been done sooner (e.g. building a crude prototype). The students when asked to reflect on their own design process made many of these same observations.

We feel that 'Kinetic Sculptures' engineering project has been an exceptional education experience for the students in that they have been able, in many cases, to correctly identify improvements to the process they have just experienced.

EPISTEMOLOGICAL ASPECTS

Data sources and methods

The data, collected over four academic years, includes three surveys combining the Likert scale and open-ended questions. The first of these surveys was designed and conducted by the College assessment officer during the students' first semester at Olin while they were taking the 'Kinetic Sculptures' ICB. The other two surveys were designed by the authors of the study and conducted in the summer after the students' sophomore year and during the last semester in the College. These measures have been collected from the 'Kinetic Sculptures' ICB population comprising 20 students; the gender break down in the class being 13 (65%) women to 7 (35%) men including 2 Asian–American men and 1 Hispanic man. The response rate for all three surveys was in the 75–100% range.

Our data analysis included both quantitative and qualitative strategies to address the following questions:

1. What is the role of a large-scale ICB project?
2. Do students learn mathematics and physics better because of the project?
3. Does the theme of the ICB have a special appeal to women and if yes, what is it and does it affect women's learning of the pertinent material?
4. What is the role of the ICB in student feelings about the courses and desire to remain in engineering program and to pursue engineering career?

Qualitative analysis was based on the answers to open-ended survey questions. Following collection of data, we wrote analytical memos to assist in identifying emergent themes. We next created narrative summaries around identified themes. These summaries were also used when analyzing quantitative findings to the extent that such quantitative analysis was possible on a small population studied. Both quantitative and qualitative findings were used to determine whether there are any significant correlations between the pedagogical aspects described above and the student perceptions of how well they learned in the ICB environment and their resultant desire to pursue engineering degree and career.

Summary of findings

When analyzing the data, it was important to bear in mind that the majority of students report coming to Olin College with high expectation of the ICB role in their education and a preconceived notion of what ICB would and should be like.

Both men and women felt that the ICB "*would be the 'workhorse' of [the] project-driven curriculum*". In fact, it was this 'revolutionary concept' of ICB that brought many students to Olin and instilled in them a belief that the ICB would "*help [them] to become a better engineer by tying concepts together*".

In what follows, we will briefly discuss our findings with respect to such aspects of the ICB as individual courses, coordination and integration of the material between the courses, ICB theme, teamwork, 'do-learn' and 'hands-on' environment, the motivating/reinforcing role of the project, supporting role of mathematics/physics courses, and 'real world' connections. We will also report our findings about the effects of these ICB aspects on student feelings about the integrated course block as well as student desire to remain in an engineering program and pursue engineering careers.

On average, students reported that, while taking the 'Kinetic Sculptures' ICB, they found all three ICB courses to be equally important to their learning. This is an interesting fact that may partially attest to student maturity, particularly in view of the fact that students also reported that the 'do-learn' and 'hands-on' environment, provided for the most part by the project portion of ICB, to be more important than their courses. Students also rated integration of the courses within ICB to be equally as important although they did not specifically care whether there was significant coordination of topics between the courses. Teamwork was also rated very highly as one of the more important aspects of the ICB. There was no statistical difference between the responses of men and women to these questions.

However, gender differences were found in student responses to the questions related to whether the project motivated the learning of mathematics and physics: women found the project much more motivating than men ($p = 0.035$). [In our comparative quantitative analysis, we used an unpaired Student's t-test to compare the means of the responses of men and women. These numbers were used as a qualitative guideline in our quasi-quantitative analysis, given the small number of respondents.]

The difference between the responses of men and women was even more dramatic when looking at the question of the importance of the 'Kinetic Sculptures' theme to their learning, with women indicating the theme was relatively more important ($p = 0.024$) . It is worthwhile pointing out that for a non-negligible minority of students (~20%), the 'Kinetic Sculptures' ICB theme was not their first choice as they would have much rather joined "*a much more engineering-sounding*" ICB theme, which seemed to "*have an actual use and the potential to make something useful*". Therefore, the seeming ability to choose an ICB theme, while having a positive influence on the student majority who joined the 'Kinetic Sculptures' ICB by choice, had a negative effect on those students who were forced into this theme. Not surprisingly, men reported seeing less relevance of the ICB to 'real life' then did women, although there were no statistical differences between these responses of the students. Thus, students' *a priori* perception about the ICB and its applicability to 'real life' colored their experiences before joining and while taking the ICB. Students also reported that due to the lack of "*real worldliness*" in the project part of ICB, their interest in it was "*dulled*" and they gravitated toward "*getting a challenging math and physics class*". Therefore, pedagogical and curricular linking mathematics, physics, and project through the use of ICB lead to an approach that appealed to all of the students—those that found the project more motivating and those that found the theory interesting.

In terms of student-driven integration of the material, when asked whether they were able to connect various concepts from mathematics and physics to their project work and to integrate all ICB concepts while taking the courses, students overwhelmingly responded that although they were somewhat able to do so, "*things just did not line up for them*". In fact, students who struggled with the mathematics and physics material did not quite see the utility of modeling, while well-prepared students felt "*left out of the loop due to the boredom in mathematics and physics*". Additionally, at the beginning of the ICB, students felt that there was no clear direction regarding their own role in integrating the material led to confusion and frustration; students also felt that at the time they were simply not mature enough. Women scored higher on this measure than men.

When asked similar questions about whether students were better prepared to do their future work as a result of the 'Kinetic Sculptures' ICB, the responses were not unlike those above: students felt they were somewhat prepared to tackle their upper-class work but not overwhelmingly so. Interestingly, women scored lower on this measure. Our data indicates that although less satisfied and seeing fewer connections between the ICB courses and ICB utility, in their future Olin careers men seemed to benefit preferentially more from participating in the ICB. Women, on the other hand, reported that they mainly benefited from individual courses rather than from the integration of the courses within the ICB.

The students from the 'Kinetic Sculptures' ICB were very positive about their experiences and utility of their experiences when recalling them seven semesters after the ICB. The overwhelming majority of the students felt that the open-ended nature of the project was '*extremely useful*'. A typical comment about this follows along the lines of what one male student reported: "*It seems like by the time we finish Olin, we have specialized in doing open-ended projects. The earlier the introduction to that, the better. After all, it seems like if you can't do an open ended project* *successfully, you're sunk*". However, the majority of women also felt that "*while [they] like the idea of open ended projects, this project was too open-ended for the first semester—[students] weren't mature and experienced enough to be able to carry it out. [They] would have preferred a more constrained project initially, with more open-endedness in the subsequent semesters*".

Students felt similarly about the semester-long nature of the project. Overwhelmingly, students felt that they "*need to have [this experience] under their belts*" as early in their college career as possible. In fact, students felt that the more experience they get in doing long-term projects early on, the easier it gets when they are working with their capstone projects. Students found the length of the project useful and necessary in their learning. In fact, when asked whether they would have benefited more from short projects, a typical student response followed what this young man said: [A series of] "*Small projects [is] good because it spreads out the risk of a project not working. It also clarifies the learning objectives . . . [However, the idea of long-term projects] fits better with the Olin experience*". While another student summarized his experiences by stating: '*I would hope that semester-wide projects of this nature would continue for first-years, even if the [ICB] aspect of it is no longer incorporated. For me, it was the one thing that 'woke me up' from my high school mindset and made me realize that I was going to have to work really hard to get things done. . . . I very much enjoyed the project and the [ICB]*'. Overall, having well-organized projects, whether longer or shorter in scope, with timelines and deliverables seemed to be the single most important comment pertaining to the project length.

We feel that our study yielded the most interesting results pertaining to students' perception of the role of teamwork in their ICB experiences and later in their Olin careers. Students had a chance to talk about teamwork formally through a designated part of the project course and then had an opportunity to work on this skill throughout the semester while working on their projects. Some students found the formal portion of the course to be very valuable in working with team members. Other students felt that the teamwork part of the course was common sense and didn't understand why we were spending time talking about it. In subsequent team-based courses, students had an opportunity to further see the importance of teamwork and became more curious about ways of dealing with certain personality clashes that they may have not had experienced in their initial teams. It was not until the end of their last semester at Olin that students recollected about just how important their first semester experiences were to them. In the words of one female student, "*The teamwork aspect of this project was a huge learning experience for me and something I took with me throughout my Olin career*". This sentiment was shared equally by men and women who took the ICB.

Owing to the perceived lack of utility of the project, students felt that their experience in the 'Kinetic Sculptures' ICB was only somewhat motivating in their desire to stay in the engineering program and pursue an engineering career. Additionally, the experience in the ICB was often mixed up with students' overall first-year first-semester experiences, whereby negative overall experiences lead to a desire for a different career. However, as these two young women put it, "*It was the first time [student] really understood what engineering was'* while *'the ability to be very hands-on, to machine, and to design definitely got [students] through the tough part of the math and physics. Keeping engineering 'fun' was more important*". Following with the above pattern, e.g. although men benefited more from the ICB and project, on average, they also reported to be less likely to stay in an engineering degree or career than women, and also more likely to switch to a different degree and career in engineering than women.

Seven semesters after experiencing the 'Kinetic Sculptures' ICB, students found it to be very positive and helpful. The following statements summarize the thoughts of many former 'Kinetic Sculptures' students: "*I think project classes in general are a crucial way to get students interested in and excited about studying engineering . . .'* and '*. . . the project course definitely provided a way for us to use what we learned in physics and math to solve a real problem, which helped me stay interested in what I was studying. I definitely appreciated when math and physics came together and presented the same problem in different ways—I think I understood that material better*". In addition, students cited such strengths of the ICB as its ability to give students self-motivation, ownership of ideas, empowerment, ability to work one-on-one with faculty to learn the detailed mathematical and physical derivation and concepts, taking responsibility, planning, and using creativity, among others.

CONCLUSIONS

'Kinetic Sculptures' ICB was an interesting educational experience both for the instructor and for the students involved. The ICB did succeed in achieving several different goals. In particular, we found that despite the difficulties of running a large-scale ICB project, students find it beneficial in preparation for their senior capstone projects and for their future careers.

However, we found that it is crucial to choose the right level of 'open-endedness' to avoid early disappointing experiences when the projects fail. A few extra constraints on the design of the kinetic sculptures could have helped to define the design so that the students would be more likely to finish the projects and learn the relevant project skills. For example, a common power source designed by the entire class may have been a unifying project, teaching students initial design, modeling, building, and team-working skills, while also constraining design of the individual kinetic sculptures. It is especially important to be careful with the scale of the project so that students can have time to appreciate the connection of the project to mathematics and physics content. A class where students have freedom to perform an open-ended design work that is unique to each student team, allows students to share their design, modeling, and building experiences with other teams. This further leads to opportunities for peer instruction and consecutive development of connections between the project, mathematics and physics—a skill learned from other teams.

Further, open-ended design experience allows students to see themselves as engineers and understand the utility of theoretical analysis in their design work. However, projects and instruction must be done carefully and should be used only where the analysis adds value to the project. In other words, when in a time crunch, students are not interested in modeling their sculptures for the intellectual curiosity. They want to see that modeling will save them time in building their sculptures.

It is clear that students need to experience large-scale open-ended projects as early in their engineering programs as possible. Although during their first semester of engineering education students may not have sufficient technical background and significant maturity and sophistication, they appreciate a "*freedom to explore and learn, . . . ability to talk with other people in the class, gain ideas and inspiration from others, and do 'design reviews' during presentations*". Students also perceive this first-time project as an opportunity that presents real "*reasons' to learn things like SolidWorks, Working Model, LaTeX, and other things that come in very handy later on*". Finally, the complexity and ambitiousness of the early projects that students choose offers a lot of opportunities for failure, which students treat as "*a very good thing, [since they] learned a lot from failure*". To this end, a success of the project and the ICB in the whole depends, to a large degree, on availability of resources and faculty time. We strongly believe that with the appropriate resources and faculty guidance, even the more complicated first-semester projects may become successful.

We also believe that the integration of mathematics, physics and engineering helps students with different learning styles better grasp the material. Traditional mathematics and physics instruction is based on a logical progression of material. For some students this works very well. However, for other students, who tend to memorize equations to be used in the examinations and do not feel any real intuition to these equations, the traditional learning environment is not very efficient. Such students did particularly well during the 'Kinetic Sculptures' project, which allowed them to begin to grasp the intuitive nature, the underlying assumptions, the strengths and limitations of the pertaining equations and modeling.

Our experience with the 'Kinetic Sculptures' theme indicated that this theme has a special appeal to women students, both in terms of attracting them to engineering projects and keeping their interest in the relevant work. It was clear, however, that first-year engineering students are not sophisticated enough to independently see the connection of this theme to engineering practice; therefore, it needs to be spelled out for them what the usefulness of this project may be to an engineer-apprentice.

It is clear that the ICB, in general, and the 'Kinetic Sculptures'-themed ICB, in particular, may play a very important role in the students' feelings about their coursework and their desire to remain in the engineering program and pursue engineering careers. However, some further adjustments need to be made in the functioning of this ICB in order to make it more successful. Based on our experiences and findings, we determined that students like learning the process and having the opportunity to participate in an open-ended design experience. In addition, students feel that the integration of the courses is extremely valuable when done well. However, the "*key to all of this [is] the availability of professors outside of the classroom*". The main drawback to this approach is the time commitment required for faculty to team-mentor the individual projects.

We still have more work to do to understand how best to deliver this material when students discover that they are in need of the information.

We feel that the 'Kinetic Sculptures' ICB was an altogether successful experiment. It is our belief that if steps above are taken to mitigate the difficulties that we have encountered, a use of such an integrated course block in the future may be of even greater benefit to students. Given the high transferability of this theme and the whole ICB, we also feel that this experiment may be easy, useful and interesting to perform in other colleges and universities.

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