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Disciplinary Learning From an Authentic Engineering Context

Catherine Langman
Illinois Institute of Technology, cnewman5@hawk.iit.edu

Judith Zawojewski
Illinois Institute of Technology, judijz@gmail.com

Patricia McNicholas
Robert Morris University, pmcnicholas@earthlink.net

See next page for additional authors

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Two mathematical modeling research questions were addressed: 1. What mathematical approaches did student-teams take when they designed mathematical models to evaluate the quality of blood vessel networks? and 2. What attributes of mature mathematical models were captured in the mathematical models that the student-teams designed? One science content research question was addressed: 1. Before and after the module, what aspects of angiogenesis did students describe when they were asked what they knew about the process of blood vessel growth from existing vessels?

Participants who field-tested the module included high school students in a summer enrichment program and early college students enrolled in four general-studies mathematics courses. Data collected from participants included mathematical models produced by small teams of students, as well as students' individual responses before and after the module to a prompt asking them what they knew about the process of new blood vessel growth from existing vessels. The data were analyzed for mathematical model type and science content by adopting methods of grounded theory, in which researchers suspend expectations about what should be in the data and, instead, allow for the emergence of patterns and trends. The mathematical models were further analyzed for mathematical maturity using an a priori coding scheme of attributes of a mathematical model. Analyses showed that student-teams created mathematical models of varying maturity using four different mathematical approaches, and comparisons of students' responses to the science prompt showed students knew essentially nothing about angiogenesis before the module but described important aspects of angiogenesis after the module. These findings were used to set up an agenda for future research about the design of the module and the relationship between disciplinary learning and authentic engineering problems.

Keywords

STEM, mathematics education, science education, engineering education, model-eliciting activities, authentic, tissue engineering

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Authors

Catherine Langman, Judith Zawojewski, Patricia McNicholas, Ali Cinar, Eric Brey, Mustafa Bilgic, and Hamidreza Mehdizadeh

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Catherine Langman,[1] Judith Zawojewski,[1] Patricia McNicholas,[2] Ali Cinar,[1] Eric Brey,[1] Mustafa Bilgic,[1] and Hamidreza Mehdizadeh[1]

[1]*Illinois Institute of Technology*
[2]*Robert Morris University*

Abstract

This small-scale design study describes disciplinary learning in mathematical modeling and science from an authentic engineering-themed module. Current research in tissue engineering served as source material for the module, including science content for readings and a mathematical modeling activity in which students work in small teams to design a model in response to a problem from a client. The design of the module was guided by well-established principles of model-eliciting activities (a special class of problem-solving activities deeply studied in mathematics education) and recently published implementation design principles, which emphasize the portability of model-eliciting activities to many classroom settings.

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Introduction

Real-world engineering problems often require problem solvers to use knowledge and methods from multiple disciplines, in addition to engineering thinking and design. Therefore, activities that bring real-world engineering problems into the classroom can address many learning goals simultaneously. However, most schools organize courses around highly prescribed disciplinary curricula. A resulting challenge is to provide convincing evidence for teachers, students, parents, administrators, policymakers, and others that exposing students in disciplinary-based classrooms to authentic engineering problems and activities can benefit their learning of conventional disciplinary content.

One way to approach this challenge is by developing an intervention focused on a real-world engineering problem, and studying the disciplinary learning that results from it. This small-scale design study, which was embedded in a long-term design research project, examines disciplinary content in mathematical modeling and science that students learned from an intervention featuring an authentic engineering context. Current research in tissue engineering was used as the basis for the module, because tissue engineering, like all subdomains of engineering, uses content knowledge and methods in mathematics and science as its foundation.

The design of the module was guided by two sets of principles: well-established principles of model-eliciting activities (a special class of problem-solving activities deeply studied in mathematics education and engineering education research) and recently published implementation design principles that encourage adapting model-eliciting activities for many different classroom settings. The module contained three parts: readings and videos about tissue engineering; a game that mimics the growth of new blood vessels from existing vessels; and a model-eliciting activity related to the readings and the game. Early versions of the module were piloted with three participant groups to hone the effectiveness of the module toward eliciting mathematical models and relevant science content from participants. After honing the module based on evidence gathered during the pilot testing, the module was field-tested with five sample classrooms of students.

Two types of data were collected from each of the five classrooms. The first type of data was collected to reveal the nature of the mathematical models students produced in response to the model-eliciting activity. The model-eliciting activity involved students working in small teams to create a mathematical model for a client to quantify and compare blood vessel growth shown in provided images. Each student-team wrote a memo to the client describing their mathematical model and how it could be applied to the image of other blood vessel networks. The memos containing the mathematical models were collected after the module. The second type of data was collected to reveal students' understandings of the science of angiogenesis (i.e., the process of new blood vessel growth from existing vessels). Before and after the module, students were asked individually to "describe what you know about the process of new blood vessel growth from existing vessels." Students' written responses to the prompt were collected at the time they were written.

Analyses of these two types of data were accomplished using the methods of grounded theory. Such methods require researchers to suspend expectations about what should be included in the data and, instead, search for ideas that repeatedly emerge from the data. Results show that student-teams designed mathematical models using four different mathematical approaches and that their models were of varying maturity. Comparisons of students' responses to the science prompt showed that before the module students knew essentially nothing about angiogenesis, whereas after the module students described important aspects of angiogenesis. The results of this study indicated that the iterative design process was coming to a close, setting the stage for future studies to scale up the use of the module. Continued work with a broader selection of participants in a wider variety of contexts can provide opportunities for further study of the relationship between student engagement in authentic engineering problems and the manifestation of disciplinary learning.

Background

The emphasis on the STEM disciplines (STEM is the colloquial acronym for Science, Technology, Engineering, and Mathematics) in US policy, curriculum development, and education over the last two decades has mainly resulted in focused improvements on mathematics and science as isolated academic areas (Breiner, Harkness, Johnson, & Koehler, 2012; Kelley & Knowles, 2016; Moore & Smith, 2014). Most pre-college curricula treat each discipline in STEM independently, with, at most, occasional cross-fertilization taking place when one of the disciplines in STEM plays a minor, supporting role to another (Bryan, Moore, Johnson, & Roehrig, 2016; English, 2016).

Despite a greater emphasis on engineering education from policy influencers, and the inclusion of engineering in some curriculum standards in recent years, student engagement in authentic engineering problems will likely come from brief interventions by individual teachers of traditional subjects like mathematics and sciences (NAE, 2010; NAE and NRC, 2014). Though a 2010 effort by the National Academy of Engineering considered the development of content standards for K–12 engineering education, the report concluded that imposing engineering education standards on the current curricular structure would prove of limited value or feasibility. The report describes other approaches, such as infusing engineering education into existing K–12 curricula standards, mapping the big ideas in engineering onto the curricular standards of other disciplines, and creating guidelines for K–12 engineering education materials, among other suggestions (NAE, 2010; NAE and NRC, 2014).

Yet, infusing engineering into pre-collegiate curricula remains a challenge, even when engineering is explicitly incorporated into other discipline-specific standards (Koehler, Faraclas, Giblin, Moss, & Kazerounian, 2013; Moore, Tank, Glancy, & Kersten, 2015). Although the Next Generation Science Standards (NGSS) (Lead States, 2013) incorporate engineering and design into a set of national science standards, not all states have adopted these progressive standards; as of September 2018, only 19 states have adopted NGSS (NSTA, n.d.). Other recent curriculum-reform efforts perpetuate this separation of subjects by treating each discipline in relative isolation. This is especially true of mathematics, where the Common Core State Standards for Math (CCSSM) (National Governors Association Center for Best Practices, & Council of Chief State School Officers, 2010) list specific competencies and objectives in each set of standards, portraying an almost complete focus on discipline-specific goals (Lesh, 2013). According to a joint report created by the National Academy of Engineering and National Research Council (2014), "One challenge of implementing both the CCSSM and NGSS is to ensure the development of discipline-specific knowledge while also supporting connections across STEM" (p. 110).

A different but related challenge comes from lack of teacher competencies in teaching subject matter outside of their academic concentration (Frykholm & Glasson, 2005; Stinson, Harkness, Meyer & Stallworth, 2009; Stohlman, Moore, & Roehrig, 2012), which makes large-scale curricular cross-fertilization of STEM disciplines impractical (NAE and NRC, 2014). Though the NGSS addresses some of these considerations by including "crosscutting concepts" within each standard (Lead States, 2013), practical considerations such as identifying and planning for connections across disciplines remains difficult for many teachers (Baker & Galanti, 2017; Kelley & Knowles, 2016; Stohlman, Moore, & Roehrig, 2012; Vasquez, Sneider, & Comer, 2013).

In response to these challenges, various experts (e.g., Moore, Johnson, Peters-Burton, & Guzey, 2016; Sanders, 2009) have suggested that STEM curricular objects should identify learning outcomes in the disciplines that they claim to connect. However, few studies address disciplinary learning from STEM experiences (Barrett, Moran, & Woods, 2014; NAE and NRC, 2014). Even content area educators lament the dearth of work, such as Shaughnessy (2013) and English (2016) who each describe the documentation on mathematics learning from STEM experiences as underdeveloped and under-researched. For those few studies that do exist, the National Academy of Engineering and National Research Council (2014) indicates that the descriptions of STEM integration and guiding theory are often so limited that it becomes impossible to make generalizations from the results. The lack of research in all these areas highlights the importance of launching programs of research that establish, describe, and explain how disciplinary learning may emerge from student engagement in STEM experiences.

Experts in the field of engineering education (e.g., Kelley & Knowles, 2016; Koehler, Binns, & Bloom, 2016; Moore, Stohlman, Wang, Tank, Glancy, & Roehrig, 2014) lament the need for pre-college curricula to better prepare students to recognize the need to utilize other disciplines in their search for solutions to authentic engineering problems. To begin to address that need, this study was designed to establish and describe disciplinary learning that emerged from students' engagement in an authentic engineering problem.

Research Questions

This small-scale design study describes students' disciplinary learning of mathematical modeling and science content from a module of study based on an authentic engineering context.

Mathematical Modeling Research Questions

To understand the nature of the mathematical models that student-teams designed in response to the module, two research questions were posed:

1. What mathematical approaches did student-teams take when they designed mathematical models to evaluate the quality of blood vessel networks?
2. What attributes of mature mathematical models were captured in the mathematical models that the student-teams designed?

Science Content Research Question

To understand what students learned about science content, one research question was posed:

1. Before and after the module, what aspects of angiogenesis did students describe when they were asked what they knew about the process of new blood vessel growth from existing vessels?

Research Setting

Kelly (2013) identified optimal conditions for small-scale design research, including the following: when existing instructional materials are not available; when teachers' knowledge and skills are unsatisfactory; or when educational researchers' knowledge of the content and instructional strategies or instructional materials are poor. Grounded in Kelly's recommendations, the module was designed to: provide pre-collegiate students with an innovative mathematical modeling experience in the context of tissue engineering; enable teachers to guide students in unfamiliar areas of modeling ambiguous situations and teach the concept of angiogenesis; and forge a new path where little prior educational research exists.

The National Academy of Engineering and National Research Council (2014) recommends that "researchers need to document the curriculum, program, or intervention in greater detail, with particular attention to the nature of intervention and how it was supported" (p. 137–138) in order to contribute to the growing body of literature on STEM education. Therefore, provided below is a considerable effort to fully describe the module design process and the curricular module that resulted. This section also describes the participants whose work samples were collected during field-testing of the module for this study, as well as the types and quantities of data collected.

Module Design Process

Creation of the module followed design-based research methodology, as described by Amiel and Reeves (2008), Burkhardt and Schoenfeld (2003), and others, wherein a practical problem is analyzed by researchers and practitioners and an initial curricular object under design is produced based on existing design principles, which is then subjected to iterative cycles of piloting with real students and revision. Meetings between tissue engineering researchers and educational researchers and practitioners (i.e., the authors of this paper) included discussions of real-world tissue engineering research (e.g., Artel, Mehdizadeh, Chiu, Brey, & Cinar, 2011), which provided the source material for relevant science content and mathematical modeling tasks to be developed into activities and readings for students. Using well-established principles for model-eliciting activities (Lesh, Hoover, Hole, Kelly, & Post, 2000) and recently published principles for implementation of design activities (Langman, Zawojewski, & Whitney, 2016), a first draft of the module was produced. Iterative cycles of piloting, observation of students' responses to the activities, and revision based on students' responses were conducted, until the evidence suggested that both sets of principles were satisfied. The module was then ready for late-stage design field-testing and formal data-gathering, which is reported in this study.

Source material for the module

The source material for the module under study came from the authentic mathematical modeling of angiogenesis by research engineers and scientists, as summarized in a previously published scientific research article about tissue engineering (i.e., Artel, et al., 2011). Discussions between the module designers and the authors of the tissue engineering research article, along with the article itself, helped illuminate many of the fundamental concepts of tissue engineering. These concepts were originally described in seminal publications on tissue engineering by Langer and Vacanti (1993) and Vacanti and Langer (1999), as well as recent contributions to the field by Brey (2014) and Artel and colleagues (2011), and are summarized as follows.

Tissue engineering and regenerative medicine are a combined field that seeks to develop clinical methods to replace, reconstruct, or revitalize tissue that has been damaged, is defective, or is missing (for example, wounds that won't heal in diabetic patients). The central premise of tissue engineering is that engineers create structures (called "scaffolds") that could support tissue growth in the shape that they want the tissue to grow. The scaffolds are made with holes in them (called "pores") and are smeared with tissue cells, then implanted into a mammal. The blood vessels from the mammal's muscle grow through the pores and toward the cells on the structure, providing the vasculature necessary to nourish the cells with oxygen and nutrients, and to remove waste so that the cells can proliferate. As the tissue cells grow into functioning, vascularized tissue, the scaffold slowly dissolves away into harmless substances, much like dissolvable sutures. A central challenge to tissue engineering is the creation of better scaffolds to promote the growth of blood vessel networks, which is necessary for viable tissue growth.

Many properties of scaffolds can be manipulated in experiments (Brey, 2014; Artel, et al., 2011). For example, scaffolds can be made with pores that are either uniformly distributed or randomly distributed through the scaffold, then studied to determine which distribution yields a better blood vessel network and, thus, higher tissue growth (Mehdizadeh, Somo, Bayrak, Brey, & Cinar, 2013). Artel, and colleagues (2011), in their article on tissue engineering research, described experiments in which scaffolds created to have pores of different diameters were implanted into rats, given time to grow a blood vessel network, and then examined to determine which diameter of pores yielded viable blood vessel networks (Artel, et al., 2011). Computer simulations were designed to help predict possible outcomes of the experiments. The simulations show a series of images of blood vessel networks, grown into scaffolds with different pore sizes over a four-week period (Artel, et al., 2011). Artel and colleagues (2011) described both the experimental results and the simulation results in their article.

Artel and colleagues' (2011) simulation results showed blood vessel growth in scaffolds with different pore sizes. Their article described creating scaffolds with pores of different diameters as a way of dividing up available space within a scaffold (i.e., the area of the scaffold was always 800 microns x 800 microns, but within that region there could be 36 pores of diameter 135 microns each, or nine pores of diameter 270 microns each). The goal was to determine which division of space within the scaffold would produce a blood vessel network that covers the most available space and has the most connections between vessels, thus reaching the most tissue cells.

Connecting the source materials with curriculum standards

Density and comparisons of quantities are typically taught in middle school and high school, so it seemed possible to present students with essentially the same modeling challenge that the engineers faced when evaluating the different blood vessel networks: Which pore size resulted in the "best" blood vessel network? The expectation was that many students would apply appropriate mathematics that they had already learned in order to answer this question. Specifically, we expected students to "define appropriate quantities for the purpose of descriptive modeling" (CCSS.MATH.CONTENT.HSN.Q.A.2) and "apply concepts of density based on area in modeling situations" (CCSS.MATH.CONTENT.HSG.MG.A.2). Further, mathematical modeling is a central standard in CCSSM, and the problem-solving nature of the model-eliciting activity within the module attends to cross-cutting mathematical practices under CCSSM.

Artel and colleagues' (2011) tissue engineering article also served as a source for identifying science content that could be taught at the high school level. Specifically, angiogenesis (defined as the process of new blood vessel growth from existing vessels) and key features of blood vessel networks, situated within basic knowledge of the cardiovascular system, can be mapped to curricular goals in the life sciences. Within the NGSS high school life sciences standards, core ideas in the Structure and Function topic strand include learning that "systems of specialized cells within organisms help them perform the essential functions of life" (HS-LS1-1) and "multicellular organisms have a hierarchical structural organization, in which any one system is made up of numerous parts and is itself a component of the next level" (HS-LS1-2). Additionally, critical reading of scientific texts adapted for the classroom is included in one of the eight science and engineering practices described in the NGSS for grades 9–12 (Practice 8, Lead States, 2013).

Using design principles to guide module design

The decision to design the module around a model-eliciting activity (sometimes abbreviated "MEA") was made early in the design process, because MEAs have been shown to be successfully implemented in mathematics, science, and engineering classrooms, as well as adaptable for students of many ability levels. MEAs are a special class of problem-solving activity in which students work in teams of three or four to express, test, and revise a mathematical model in response to a real-world problem from a client. These activities are guided by well-established design principles, and have been used and researched extensively in mathematics education for bringing students' previously learned mathematics content to the fore (Lesh & Doerr, 2003). They have also been used in engineering education research for engaging students in iterative cycles of expressing, testing, and revising a solution to a problem (Diefes-Dux, Hjalmarson, Bowman, & Zawojewski, 2006). More recently, MEAs have been adopted into STEM education (Baker & Galanti, 2017; English & King, 2015).

MEAs fit within the definition of problem-solving lessons given by Swan and Burkhardt (2014) as lessons that "are not primarily about developing understanding of mathematical ideas, but rather about students developing and comparing alternative mathematical approaches to non-routine tasks for which students have not been previously prepared" (p. 14). MEAs are novel or non-routine problems with solutions that are not immediately known, which usually involve quantifying qualitative information (Lesh & Doerr, 2003).

During model-eliciting activities, students create their own mathematical models in response to a novel problem. Research into cognition and problem-solving has established that when students are presented with a novel situation, they "try to apply knowledge, skills, and specific strategies from other, more familiar domains" (Perkins & Salomon, 1989, p. 22). When students are presented with a novel situation that requires a mathematical solution, they naturally draw from the pool of mathematical knowledge, skills, and strategies that they have previously learned. As such, there is no formal teaching of mathematical content; rather, students bring previously learned mathematical content to bear on the problem, sometimes in creative or surprising ways. Since students work in groups to design their mathematical models during an MEA, their mathematical knowledge, skills, and strategies are continuously externalized, which is why MEAs are sometimes called "thought-revealing" activities (Lesh & Doerr, 2003; Lesh, et al., 2000).

MEAs are designed following six principles that signify key features of elicited students' responses (Lesh, et al., 2000), shown in Table 1.

MEAs are often supported by additional learning activities and materials to ensure that the problem context is accessible to all students. Examples of additional learning activities that accompany model-eliciting activities include readings, videos, games, and/or readiness questions. These additional learning activities tap students' prior knowledge, skills, life experiences, and interests; address the academic needs of students; contain disciplinary knowledge related to the problem context; and enhance the students' engagement with the mathematical modeling task. A different set of principles signifies key features of learning activities that support the students in designing models (Langman, Zawojewski, & Whitney, 2016), shown in Table 2.

Piloting early drafts of the module

Early drafts of the module underwent three cycles of pilot testing and revision to identify whether the design principles in Tables 1 and 2 had been satisfied. Each cycle was comprised of the following: piloting the module with participants; collecting data in the form of observations, field notes, and informal participant interviews; analyzing the data for alignment between the enacted module and the

Table 1
Principles for designing model-eliciting activities (from Lesh, et al., 2000).

Principle	This principle ensures that modeling task requires the problem-solver to . . .
Model Construction	create a mathematical model to address the needs and purpose of a given client
Reality	use the mathematical model to solve a realistic problem
Generalizability	create a model that approaches the situation in a way that is transferable, shareable, easily modified, and/or reusable
Self-Assessment	evaluate their progress as they work on the problem
Construct Documentation	document explicitly how the problem solver is thinking about the problem and model at the conclusion of the problem-solving session
Effective Prototype	create a model that can be used as a prototype or metaphor for other similar situations in the future

Table 2
Principles for designing implementation supports (from Langman, Zawojewski, & Whitney, 2016).

Principle	This principle ensures that the supporting learning activities . . .
Familiarity	help students relate to, and care about, the context of the problem
Prerequisites	target critical vocabulary, concepts, and contextual information appropriate for the students and educational context
Accessing Complexity	help students productively engage in designing a mathematical model for a complex, intellectually challenging situation
End-in-View	help students to keep present in their thinking what their final product might be
Alternative Perspectives	provide opportunities that put students in the position of taking an alternative perspective on their mathematical model

design principles in Tables 1 and 2; and revising the module using the analysis to guide the revisions.

Participants in these cycles of pilot testing were selected by convenience. The first pilot testing occurred with teachers from community colleges and pre-service teachers in a professional development workshop, who were asked to engage in the module as their students would. Revisions based on this pilot testing led to the next draft, which was then piloted with high school students from an urban parochial high school in an honors-level biology class. The module was revised again and piloted with a college-prep biology class at the same parochial high school.

All of the principles described in Tables 1 and 2 guided the revisions of the module and were incorporated into the teacher notes for implementation, with emphasis on the Module Construction Principle and Construct Documentation Principle from Table 1, as well as the Prerequisites Principle from Table 2. After the third pilot testing, observations and field notes evidenced that about 80% of participants produced at least primitive "mathematical models" (i.e., having some features of mathematical models, such as identification of variables and quantification methods). This indicated that the MEA designed as the centerpiece of the module satisfied the Model Construction Principle shown in Table 1. About 80% of participants were also able to create a document (in the form of a memorandum to a client) describing their model, satisfying the Construct Documentation Principle in Table 1. About the same percentage of participants articulated facts about angiogenesis when prompted (either verbally or in writing), evidencing that the Prerequisites Principle of Table 2 was also satisfied, so that the students' understanding of angiogenesis could be studied more formally.

Description of the Module for Use in Field Tests for the Study

The module used in field tests for this study had three parts, each of which took one or two class periods.

Part 1. Readings and videos

The first part of the module used several media, which, together, described the work of Artel and colleagues (2011). These media included: a one-page newspaper-style story about the social and historical relevance of tissue engineering, including a famous photograph of a mouse with an ear growing on its back; a one-page description of the science of angiogenesis and the science of scaffolds; a video obtained from a cell biology textbook (Alberts, et al., 2009) showing an animation of angiogenesis; and an excerpt from a video obtained from a research study showing the fusion of two blood vessels and resulting blood flow (Herwig, et al., 2011). The media was followed by a classroom-based question-and-answer session. The time allotted for the first segment was about 60 minutes, or one class period.

Part 2. A game

The second part of the module demonstrated how a set of rules could be used to represent blood vessel growth over time. This was accomplished with a two-player paper-based game. In the game, each player acted as an existing blood vessel that must grow to form a blood vessel network on the same two-dimensional grid. The roll of a six-sided die determined how the blood vessel would grow. For example, if a player rolled a "1," then the player could grow any part of their blood vessel network one increment

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forward (away from their main blood vessel). A roll of a "3" would mean that a player could move one increment diagonally away from any part of the blood vessel network.

Points were earned for the final blood vessel network based on features that scientists and engineers look for when measuring actual networks of blood vessels: amount of blood vessels grown (density of the network); number of connections between distinctly growing vessels (interconnectedness of the network); and length of the longest blood vessel (depth of invasion). Time allotted for the game was 30–60 minutes, followed by a question-and-answer session highlighting features of blood vessel networks.

Part 3. A model-eliciting activity

The third part of the module was a model-eliciting activity, during which students worked in teams of three or four to interpret, evaluate, and compare blood vessel networks grown in scaffolds. Teams were provided a memo from an engineering director who needed a procedure for measuring (or scoring) blood vessel growth in images attached to the memo, and a demonstration of how to apply the procedure to the images. The memo emphasized that the procedure should be applicable to any image of a blood vessel network. Terms to describe qualitative aspects such as "healthiest," "amount," and "best" were purposely left undefined, which offered opportunities for students to quantify qualitative situations by developing definitions, identifying assumptions, and providing rationales.

The images attached to the memo were photocopies of the published simulation results in the tissue engineering research article (Artel, et al., 2011). The images showed two-dimensional 800 micron x 800 micron regions with lines representing existing blood vessels, one on the top and one on the bottom of the region. The space between the blood vessels showed uniformly spaced circles, representing the pores in the scaffolds. The ratio of the area of region made up of scaffolding to the area of the region containing pores was roughly the same for each image, except for a control that showed what blood vessel growth would look like without any scaffolding. Lines representing new blood vessel growth began at the two existing blood vessels and extended or branched in the pores in the general direction of the center of the image. Results were included for four different pore sizes (four different circle diameters) that showed the progressive change in the new blood vessel growth over the course of four weeks, for a total of 16 images (one image per pore size per week). The time allotted for the model-eliciting activity was one 90-minute class period or two 60-minute class periods, depending on the class.

Samples

Convenience samples (called Samples 1, 2, 3, 4, and 5, respectively) were obtained from five classrooms of high school and early college students.

Participants

Participants in Sample 1 were high school students who chose to field-test the module as part of a program about biomedical engineering within a summer enrichment program. Entry into the summer enrichment program required students to be entering their junior year in high school and to have completed at least one algebra course and one geometry course, with plans to take Algebra 2 during their junior year. Participants in Samples 2, 3, 4, and 5 were early college students enrolled in general studies mathematics courses, tailored for students in a pharmacy technician associate degree program, business majors in associate's and bachelor's programs at a suburban satellite campus, and students in associate's and bachelor's degree programs such as liberal studies, business, and culinary arts. The mathematics content listed in the course descriptions for these general studies mathematics courses could be found in a high school Algebra 2 class.

Sample size

Students in all five classrooms were given the option of participating in this study, participating in part of the study, or voluntarily withdrawing at any time, following human subjects research protocol. Consenting participants who were not in attendance for all parts of the module were excluded from the data pool.

For a mathematical model to be included in the mathematical modeling dataset, all students who worked on the mathematical modeling team that created the model had to consent to participation in the study and all students who worked on the team had to be present for all parts of the module.

For the science dataset, consenting participants had to submit both a "before" and an "after" response to the prompt to be part of the data pool. Thus, a total of 67 pairs of responses collected from Samples 2, 3, 4, and 5 were used as the science dataset. Written responses were not collected from Sample 1 before implementation; rather, all students in Sample 1 were verbally polled for prior knowledge of angiogenesis before the start of the module. Written responses were collected after implementation from 18 students in Sample 1 who consented to participate in the study. Trends in the post-implementation responses from students in Sample 1 were explored, but treated as a separate data set from the other four Samples, since pre-implementation responses were not obtained.

These factors significantly reduced the number of mathematical models that could be included in the dataset, and the number of paired "before" and "after" responses that could be included in the science dataset. Table 3 shows the final size of each sample.

Instructors

For consistency in implementation, one of the coauthors of this paper assisted during all field tests. A high school physics teacher working for the summer enrichment program

Table 3
Sample size.

Data Type	Sample 1	2	3	4	5	Total
Mathematical models	9	7	8	3	1	28
Paired science "before" and "after" responses	0	18	32	8	9	67

led the instruction for Sample 1. A mathematics professor and curriculum chair at a regional university taught all four general studies mathematics courses for Samples 2, 3, 4, and 5, and co-authored this paper. During field-testing with Sample 3, a second coauthor of this paper also observed the implementation.

Implementation

In response to time constraints of the different classrooms, minor variations in the implementation of the module occurred over the five field tests. Changes that occurred after field-testing the module with Sample 1 included the following. The video was edited to remove parts not directly related to the module or which proved too complicated for an introduction. The reading was revised from one long, informative passage to two separate, short, engaging passages: a newspaper-style article about tissue engineering and a short informative passage about the science of blood vessel growth. A set of questions were written to help standardize and speed up the question-and-answer session. Also, consistent with verbal prompts given during the field test with Sample 1, small edits were made to the wording of the game's objective, rules, and scoring. Graphics that were drawn on the board during Sample 1's field test were also added to the game instructions received by students. These minor changes helped reduce the amount of time that students needed to learn how to play the game.

After field tests with Samples 2 and 3, the number of images accompanying the model-eliciting activity was reduced in anticipation of different time requirements for the classes in Samples 4 and 5. Instead of receiving 16 images (i.e., four images for each pore size that show the progressive development of the network over four weeks), teams in Samples 4 and 5 received just four images (i.e., one image for each pore size of the final network after four weeks). By reducing the number of images that students received, the amount of time it took for students to understand them was reduced. Students still had the opportunity to create mathematical models for comparing the density of blood vessel networks.

Mathematical Modeling

Data Analysis, Results, and Discussion

The research questions concerning the nature of mathematical models designed by student teams called for identifying the model type (mathematical modeling research question 1) and the model maturity (mathematical modeling research question 2). "Model type" provides information about specific mathematical approaches or mathematical tools used by students in their models. "Model maturity" contributes to an understanding of the students' mathematical modeling capabilities, providing a snapshot of the model's stage of development. Further, model maturity may be considered a type of engineering education goal. One might think of creating mathematical models as a type of engineering design, where one would expect that more mature models result from those teams who engage in iterative cycles of model creation, testing, and revision. For an introduction to the role of mathematical model development as a central theme in engineering education, see Zawojewski, Hjalmarson, Bowman, and Lesh (2008).

To answer the mathematical modeling research questions, mathematical models created by student-teams were collected. The models were analyzed for model type using methods borrowed from grounded theory; then, the models were analyzed for model maturity using an *a priori* coding scheme. The coding schemes for model type and model maturity, along with examples of four models collected during the study, are presented below. Then, the results of applying these coding schemes to all models are reported and discussed within the broader context of educational research and design.

Data Collection

Data source

During the module, each team of three or four students produced a written memo that contained their mathematical model in response to the task from the model-eliciting activity. That task was to create a way to measure and compare the density and connectedness of blood vessel networks from images provided, as described above.

Quantity of data collected

A total of 28 memos, each of which contained one student-team's mathematical model, were collected from all five samples and pooled for analysis. Each memo was assigned a unique number identifying the classroom from which it originated and the student-team that produced it.

Table 4a
Mathematical model type coding scheme.

Model Type	The mathematical model . . .
Area	quantifies the amount of blood vessels in a sample by estimating the area of regions within the sample that contain blood vessels
Counting	creates a way to count occurrences of one or more variable attributes of blood vessel networks
Change-Over-Time	quantifies and describes the change in some attribute of blood vessel growth over time for each sample
Subjective Scoring	assigns a value to one or more aspects of a blood vessel network and makes use of the resulting quantities to rank, order, sample, or score them

Table 4b
Mathematical model maturity coding scheme.

Attribute	The mathematical model . . .	In the mathematical models collected from this module, examples included . . .
Identifies reasonable variables	identifies variable(s) relevant to the context of the problem and with the potential to be quantified	"amount of blood vessels," "length of blood vessels," "connections"
Identifies need to quantify variables	uses mathematical vocabulary that indicates a need to assign a quantitative value to the variables	"measure," "compare," "count," "average," "sort"
Details how to quantify variables	provides step-by-step or algorithmic description of quantitative approach	"estimate the length of each blood vessel by measuring a straight line from one end point to the other"
Identifies need to synthesize variables	uses vocabulary that indicates a need to combine variables that have already been quantified	"combine the score for the longest vessel with the score for the amount of connections between blood vessels"
Details how to quantitatively synthesize variables	provides a method for deciding which variables need to be combined and then combining them, or explaining why the method described already synthesizes the variables	"add the scores for each variable together"
Details how to use model to make a decision	provides a statement about how applying the method to the data given (and/or any future data) leads to a decision	"based on our method and the images given, we recommend you choose a pore size of 160 microns because . . ."

Data Analysis

Mathematical Model Type Coding Scheme

Using the methods of grounded theory described by Glaser and Strauss (1967), and Strauss and Corbin (1998), the development of a coding scheme for model type began by suspending preconceptions about what mathematics should be contained in the student-teams' models. Two authors, working independently, examined each mathematical model. They then discussed their interpretations of the mathematical approach used in the model, citing evidence from that model. As more models were examined and discussed, definitions of the mathematical model types emerged. These definitions were refined through iterative cycles of examining the models, gathering evidence, and using that evidence to adjust the definitions, until the definitions stabilized. The resulting coding scheme is shown in Table 4a.

Model Maturity Coding Scheme

MEAs require students to quantify qualitative information and to handle several different types of qualitative and quantitative information, which must be taken into account at the same time (Lesh & Doerr, 2003). It is not enough to merely describe the mathematical approach used by student-teams when analyzing their mathematical models; attention must also be paid to what information student-teams chose to take into account and how they related different types of information within their models. Therefore, an initial, *a priori* coding scheme was proposed based on attributes that, in the authors' experiences as educators and researchers, constitute a mathematical model. The coding scheme was refined through repeated application to the mathematical models, with thorough efforts to disconfirm aspects of the coding scheme. The resulting coding scheme is shown in Table 4b.

Applying the coding schemes to the data

The mathematical models were analyzed one at a time using the coding schemes shown in Tables 4a and 4b. Two authors, working independently, coded each model for type and maturity. The authors then compared their codes for each model, discussed discrepancies, and came to consensus on the code. The process was repeated until all models were coded. Some models combined features of two of the model types shown in Table 4a. Such models were referred to as "hybrid" models and coded as both model types.

Examples of student-teams' mathematical models coded for mathematical model type and mathematical model maturity

The student-teams' mathematical models, presented in Tables 4c, 4d, 4e, and 4f, were chosen to exemplify each of the model types that emerged from the data, as well as the

Table 4c
Example of coded model—"Area" type.

"Choose a sample. Separate the sample into circles that have blood vessels in them. Ignore circles that do not have blood vessels in them. Count the number of circles that have blood vessels in them. Multiply that by the area of each circle. Compare them."	Identifies reasonable variables	√
	Identifies need to quantify variables	√
	Details how to quantify variables	√
	Identifies need to synthesize variables	
	Details how to quantitatively synthesize variables	
	Details how to use model to make decision	√

Table 4d
Example of coded model—"Change-Over-Time" type.

"1. Measure the rate at which the length of each stalk is growing on a weekly schedule. 2. Measure the rate at which the intersections are growing on a weekly schedule. 3. View the density of the ending results. The highest density within the pores means that the blood can flow more easily. Take steps 1–3 to determine the growth efficiency, number of intersections for more blood flow, and number of new blood vessels."	Identifies reasonable variables	√
	Identifies need to quantify variables	√
	Details how to quantify variables	√
	Identifies need to synthesize variables	√
	Details how to quantitatively synthesize variables	
	Details how to use model to make decision	√

Table 4e
Example of coded model—"Counting" type.

"Using the printed copies of the images, we can:	Identifies reasonable variables	√
1. Measure with a ruler the length of the blood vessels between connections.	Identifies need to quantify variables	√
2. Measure the length of the images widthwise.	Details how to quantify variables	√
3. Count the number of connections.	Identifies need to synthesize variables	√
4. Lastly compare all of these values with the control group.	Details how to quantitatively synthesize variables	
We support the scaffold of 160 micrometers because it is most like the control."	Details how to use model to make decision	√

Table 4f
Example of coded model—"Scoring" type.

"To calculate the healthiness of any given sample, observe the sample or samples in Week 4. Once in Week 4, use the following five-step system. Each step assigns one point. If all steps apply, assign five additional points. The sample with the highest point value will be your healthiest sample. Steps: 1. Endothelial cells—1 point each. 2. Continuous blood vessel extension—1 point. 3. Blood vessel connections—1 point each. 4. Connections in the center, if multiple—1 point. 5. Combination of steps 1–4 will receive 5 additional points."	Identifies reasonable variables	√
	Identifies need to quantify variables	√
	Details how to quantify variables	√
	Identifies need to synthesize variables	√
	Details how to quantitatively synthesize variables	√
	Details how to use model to make decision	√

variation in mathematical maturity. The models were drawn from Samples 1, 3, 4, and 5, respectively.

Methods of analyzing coded data for trends in mathematical model type and mathematical model maturity

Once all models were coded for mathematical model type, the number of models of each type was tabulated. After all models were coded for model maturity, the number of times each of the attributes in the model maturity coding scheme appeared was counted.

Results

Mathematical model type

Twenty-eight memos were collected, and the mathematical models described in those memos were analyzed for model type. Twenty-two of the models used a single approach: ten models were subjective scoring; ten were counting; and there was one each of area and change-over-time. Four of the models combined two mathematical approaches: One combined counting and scoring; one combined area and counting; one combined area and change-over-time; and one combined counting and change-over-time. Though other combinations of model types to create hybrid models were possible, only these four hybrid types appeared in the dataset. Two memos collected lacked any clear mathematical development of any kind and were deemed to be "no model"; thus, 26 of the memos were coded with a model type. Both of the "no model" memos came from Sample 2 and included verbal descriptions of the progression of blood vessel growth for each of the scaffolds over four weeks (viewing the images similarly to the change-over-time models) but made no clear attempt to identify or quantify reasonable variables. Note that Samples 4 and 5 were only given one sample image of blood vessel growth for each of the four pore sizes at week four of the simulation and, thus, could not possibly generate a change-over-time model.

Mathematical model maturity

Even though a mathematical model may have a low barrier entry from a mathematical perspective, the final model generated could be mathematically mature. Generally, the models identified variables (26 out of 28 models) and a need to quantify variables (25 out of 28)—the procedural, routine aspects of mathematical modeling. Twenty-one of the models also described using a mathematical model to make a decision and provided some evidence describing how to do so, showing an awareness of the purpose of mathematical modeling.

The Mathematical Model Maturity Coding Scheme (see Table 4b) shows a distinction between recognizing the "need-to" and describing the "how-to." Recognizing the need to quantify a variable is distinct from describing how to do the quantification; likewise, recognizing the need to synthesize variables is distinct from describing how to synthesize the variables. Perhaps not surprisingly, the data indicate that explicitly describing the "how-to" is more challenging than indicating the "need-to." Twenty-five of the models addressed the need to quantify variables, but only 13 models gave clear instructions on how to do such quantification. Similarly, 13 models identified the need to synthesize variables, but only five provided details on how to do such synthesis.

Science Content

Data Analysis, Results, and Discussion

The science content research question asked for identification of aspects of angiogenesis present in students' responses to the prompt. Answering this research question was accomplished through: examination of a collection of individual students' responses to a prompt before and after the module; development of a coding scheme containing emergent aspects of angiogenesis identified by students in their responses; repeated testing and refinement of the coding scheme; and application of the stabilized coding scheme to all responses. Comparisons between what students knew before and after the module helped determine which aspects of angiogenesis were learned during the module.

Data Analysis

Data sources

Before and after the module, students individually responded in writing to the following prompt: "Describe what you know about the process of blood vessel growth from existing blood vessels."

Method for developing the coding scheme

To develop a coding scheme, we used ideas from grounded theory (Glaser & Strauss, 1967; Strauss & Corbin, 1998). The central tenet of grounded theory is that researchers suspend preconceptions about what should be contained in the data and, instead, trust in the emergence of concepts from the data collected. Therefore, rather than creating a rubric containing the "right" response to the open-ended prompt, each written response was searched for the concepts students described.

This approach was applied through iterative cycles of examining each response, identifying aspects of angiogenesis that emerged, and creating common definitions for each aspect of angiogenesis. Additionally, an ongoing active search for ways to disconfirm identified aspects of angiogenesis (Erickson, 1986) ensured that the emerging codes were, in the end, well-defined and robust. Each definition underwent an iterative cycle of defining, testing, and revising, which involved at least two authors independently applying the evolving definitions to student work, comparing results, and discussing discrepancies in order to increase the precision and clarity of the definition. These definitions were collected into a scheme that could be applied to every written response. Each definition (or "code") was assigned a number and compiled into a list.

Once the coding scheme stabilized (i.e., at least two authors independently applied each definition to student work to determine whether the definition was present, then compared results and agreed at least 80% of the time), the finalized coding scheme was applied to the entire dataset. The aspects incorporated into the coding scheme are shown in Table 5a and referred to herein as the "Aspects of Angiogenesis Coding Scheme." Excerpts from students' responses illustrating each of the aspects are also provided in Table 5a.

Applying the coding scheme to responses and creating a "score" for each response

After the Aspects of Angiogenesis Coding Scheme was developed, all of the students' responses were pooled and the Aspects of Angiogenesis Coding Scheme was applied to each response. Two authors, working independently, studied each response to determine whether the response contained enough contextual evidence to show understanding of the intent of each code in the Aspects of Angiogenesis Coding Scheme.

Each aspect of angiogenesis present in a response received a "1" for that aspect of angiogenesis, so long as the aspect was not associated with a misconception. Totaling up the number of aspects present in any response produced a "score" to indicate the number of aspects of

Table 5a
Aspects of Angiogenesis Coding Scheme and excerpts illustrating each aspect.

Code	Aspect of Angiogenesis	Excerpt from Students' Responses
1	An existing blood vessel	"The process starts with *an existing blood vessel* . . ."
2	A cell in distress	"A *cell in distress* sends out a hormone called VEGF . . ."
3	Cells need oxygen and nutrients and a way to be rid of waste	". . . when *cells are in distress and are in need of oxygen and other nutrients* . . ."
4	A signal, chemical, hormone, Vascular Endothelial Growth Factor, or VEGF	". . . a *hormone* called *VEGF* . . ."
5	Endothelial cells or special cells where new blood vessels can grow	". . . blood vessels begin to sprout from *an endothelial cell* . . ."
6	Connections between new blood vessels to form a pathway for blood flow	". . . blood vessels *connect* to one another so blood can flow . . ."
7	The cell releases a signal	"The *cells send out a signal and releases (sic) some chemical.*"
8	The signal reaches an existing blood vessel or an endothelial cell	"The *chemical is received by the end. (sic) cells* . . ."
9	Endothelial cells are on or line the inside of existing blood vessel	". . . *endothelial cells on existing blood vessels* . . ."
10	The signal prompts endothelial cells to sprout a new blood vessel	"The *chemical* is received by the end. (sic) cells and *allows the blood vessels to start growing*."
11	The new blood vessel grows toward the distressed cell	". . . new blood vessels *which sprout out towards* the cells in distress . . ."
12	A new blood vessel	". . . *new blood vessels* which sprout . . ."
13	A hollowing out of the new blood vessel or formation of a lumen so blood can flow through the vessel	"After blood vessels connect, they *hollow out* so blood can flow through them . . ."

Note. Italics are used within the excerpt from the student response for emphasis. Underlining is used to differentiate one code from another code.

Table 5b
Example response coded for Aspects of Angiogenesis (after implementation).

Response	Coded Aspect of Angiogenesis	Score
"A *cell in distress*[2] sends out[7] *a hormone*[4] *called VEGF*, which causes the formation of[8] *new blood vessels* towards the cell in distress. The *new blood vessels*[12] sprout from[10] *endothelial cells.*[5]"	(2) *Cell in distress* (4) *A signal, chemical, or hormone (the technical term use is "Vascular Endothelial Growth Factor" or "VEGF")* (5) *Special cells are places to start the growth of new blood vessels* (7) The (distressed) cell gives off (or releases) a (chemical) signal. (8) The (chemical) signal reaches (or is received by) a nearby existing (host) blood vessel or endothelial cells. (10) The (chemical) signal prompts starter (endothelial) cells to sprout (or grow) a new blood vessel. (12) *New blood vessels, new blood vessel network, or new blood vessel sprouts*	7

Note. Superscript and underlining are used to identify the coded aspect of angiogenesis.

angiogenesis present in the response. An example of a coded response is shown in Table 5b.

To complete the coding of the entire dataset, two authors each randomly chose five responses from the pooled responses, coded those five responses, then exchanged the batch of five responses with each other for additional coding. After studying each response independently and assigning a score, the authors compared results for each response, and in the few cases (less than 20%) where the authors differed, discussions continued until a consensus on which aspects of angiogenesis were present in the response was achieved. This process was repeated until the Aspects of Angiogenesis Coding Scheme had been applied to all responses by two authors independently, consensus had been reached, and each response had a score.

Method for comparing responses before and after the module

The scores on the 67 pairs of responses collected from Samples 2, 3, 4, and 5 were examined to determine if and by how much scores increased from before implementation to after implementation. For each sample individually, and for the pool of responses, mean scores on responses collected before implementation were compared against means scores on responses collected after implementation using paired *t*-tests and standardized change.

Results

Examples of paired responses drawn from Samples 2, 3, 4, and 5, respectively, of the "before" response and the "after" response from the same student are shown in

Table 5c
Sample paired responses.

"Before" Response	"After" Response
I don't know anything about blood vessel growth.	Blood vessels are lined with endothelial cells. Then VEGF is a chemical that is released as a signal to the other blood vessel to connect to send oxygen. The process of blood vessel growth is called angiogenesis.
I really don't know anything about blood vessels growth. I think something happens where a blood vessel is split? I am not sure how they grow or form.	I now know that endothelial cells are the start of a new blood vessel. They react to chemicals called VEGF. The longer the blood vessels grow, the number of connections within the blood vessel and the number of endothelial cells that start a new blood vessel. All of these are signs of healthy blood vessel growth.
Blood vessels grow as needed. If the body is growing physically then you will need your blood vessels to grow in order to transport more blood to and from the heart.	I know that vessels transport blood cells. These blood cells are needed all over the body. Vessels are "told" to grow in certain directions by VEGF. The VEGF is a distress call to the vessels and therefore causes the vessels to reach out and grow toward the signal.
I do not have any knowledge about the process of blood vessel growth.	Blood vessels are lined with endothelial cells that respond to a signal (VEGF) sent from a cell that is in distress. When the VEGF signal is received the endothelial cells release new blood vessels that travel to the distress cell to assist with the healing process.

Table 5d
Scores on responses before implementation and after implementation.

	"Before" Scores			"After" Scores			
Sample	*N*	*M (SD)*	95% CI	*N*	*M (SD)*	95% CI	Change
2	18	0.17 (0.38)	0.18	18	3.72 (1.96)	0.91	9.27
3	32	0.03 (0.18)	0.06	32	3.22 (2.60)	0.90	18.03
4	8	0.13 (0.35)	0.24	8	3.38 (2.72)	1.89	9.19
5	9	0.11 (0.33)	0.22	9	4.78 (3.31)	2.16	14.00
all	67	0.09 (0.29)	0.07	67	3.58 (2.56)	0.61	12.14

Note. N = number of participants, M = mean, SD = standard deviation, CI = confidence interval, Change = standardized change.

Table 5c to illustrate the change in the quality of responses from individual students before and after implementation of the module.

The maximum possible score was 13, which would indicate that the response contained all 13 aspects identified in the Aspects of Angiogenesis Coding Scheme (Table 5a). In each sample, the lowest "before" score was zero and the highest "before" score was one, evidencing that students knew little about angiogenesis before the module. In two of the four samples, the highest "after" score was nine; in the other two samples, the highest "after" score was seven. Students in Sample 1 only submitted responses after implementation. The highest "after" score from Sample 1 was ten.

Mean scores increased from before implementation to after implementation

The mean scores for responses collected before the module were essentially zero for every sample, as shown in Table 5d. The mean scores after the module were greater than zero, showing an increase from what students' self-reported knowledge of angiogenesis before and after the module.

For all 67 pairs of responses in the dataset, a paired t-test to compare the "before" scores ($M = 0.09$, $SD = 0.29$) to the "after" scores ($M = 3.58$, $SD = 2.56$) also showed a significant increase in scores that cannot be attributed to sampling error, $t(66) = 11.16$, $p < 0.00001$. Confidence intervals and standardized change scores (computed as Change = $[M_{after} - M_{before}]/SD_{before}$ and reported in Table 5d) also indicate an increase in scores for each sample that submitted responses before and after implementation (i.e., when the standardized change score exceeds one standard deviation).

Students in Sample 1 were verbally polled before the module and reported no knowledge of angiogenesis, so it is reasonable to think that their "after" scores showed an increase in self-reported knowledge of angiogenesis ($M = 5.06$, $SD = 2.84$, 95% CI = 1.31, $N = 18$).

Discussion

The small-scale study reported here was intended to identify what mathematical models and science content students learned from a module under development in the context of a larger design research project. Amiel and Reeves (2008); Cobb, Confrey, diSessa, Lehrer, and Schauble (2003); and Kelly (2013) encourage such small-scale, local design research as one of the steps that precedes branching out to large-scale field-testing of educational materials with broader populations or conducting efforts to establish "global" theory of how educational innovations work. Cobb and colleagues (2003) indicate that conducting smaller design experiments within design research projects in real classrooms produces valid and useful intermediate findings that, over iterations, lead to the development of increasingly robust curricular objects. In this case, data collected from the iteration of this study's module showed evidence that students produced mathematical models and identified important aspects of angiogenesis, suggesting that the module had achieved the goal of producing disciplinary-based learning. On the other hand, many confounding factors present in classroom-based research make it impossible to attribute these particular aspects of students' learning entirely to the design of the curricular object. Therefore, limitations to consider include the realities of school-based sampling, natural variations in implementation across teachers and classes, and classroom-based data collection.

Discussion of Results

Mathematical modeling

Student engagement with the authentic engineering problem in this module resulted in most student-teams (26 out of 28) designing mathematical models of various types and of varying maturity. With respect to mathematical model type, student-teams more frequently produced models using mathematics that had relatively lower mathematical barriers to entry. Out of the 28 models collected and analyzed, area models were much less frequent (three, including two hybrids) than counting models (11 including two hybrids) and subjective scoring models (10). This phenomenon is consistent with the findings of Swan and Burkhardt (2014) in research on non-routine problem solving. They report that when faced with complex, non-routine problems, students tend to tap mathematics that they have long known compared to that which has been recently learned, raising one of the challenges of integrating authentic engineering-themed curriculum into mathematics classrooms. Swan and Burkhardt (2014) explain the mismatch between the mathematics students spontaneously think to bring to bear on non-routine problems and the mathematics being taught at the same time in the classroom:

> More normally, students are given 'problems' immediately after being taught the relevant content and method. They are thus, in effect, illustrative exercises in using the just-taught material. In the sense described here, however, problem solving involves recognizing and selecting, from your whole mathematical toolkit, tools appropriate for the problem. This in turn involves building and using connections with other contexts and with other parts of mathematics. Problems are therefore more difficult than a well-defined exercise involving similar mathematical content. So, for a problem to present a challenge that is comparable to a routine exercise it must be technically simpler, involving mathematics that was taught in earlier grades and has been well-absorbed by the student. (p. 4)

Tasks that are descriptive of a goal state, such as a mathematical model, but which are not prescriptive of the paths students must take to reach it, may tap the same mathematical content in many different types of students—although the content may vary in maturity. Carmona and Greenstein (2013) showed this phenomenon by testing the same MEA on two radically different groups of students (40 third-graders and eight science post-baccalaureates) and examining the models that each participant group produced. Carmona and Greenstein found that, despite the radical difference in level of schooling between the participant groups, certain types of mathematics used in the models emerged in both groups. The difference, however, was in the level of sophistication and manner in which the mathematics was used.

In our study, where all participants were assumed to be roughly at the same level of mathematics schooling due to their enrollment in courses with similar mathematics content, models that used more familiar mathematical concepts were not necessarily the most mature ones. The evidence revealed that about half of models designed were relatively immature, regardless of model type. This finding possibly illuminates a problem in the implementation of the module. Perhaps student-teams were not afforded adequate opportunity to encounter alternative perspectives (see the Alternative Perspectives Principle in Table 2) or to use those alternative perspectives to revise attributes of their own mathematical models. This issue might be resolved by incorporating a public "reporting out" by various student-teams concerning their approach to designing a model around the halfway point of the modeling session. Such an intervention might prompt student-teams to consider pros and cons of their current models. A different explanation may be that students' prerequisite knowledge and skills or the complexity of the task (see the Prerequisite Principle and the Accessing Complexity Principle in Table 2) were not adequately activated by the design of the readings, video, or game, and that such inadequacy caused students to take more time to understand the model-eliciting activity and less time to develop their models.

Science content learning

"Coding *is* analysis" (Miles & Huberman, 1994, p. 56), meaning that the codes in the Aspects of Angiogenesis Coding Scheme emerged from the data, and therefore, the codes themselves provide a *de facto* view into what students reported having learned about angiogenesis. In other words, the Aspects of Angiogenesis Coding Scheme, taken on its own, provides evidence that students learned important aspects of angiogenesis during their work in the module. The significance tests provide some evidence that the increase in mean scores from before the module to after the module did not happen by chance. This analysis, along with the increase in scores before and after the module described by the changes in the spread and central tendency of the data, seems to indicate that students learned the information captured in the Aspects of Angiogenesis Coding Scheme as a result of their experience in the tissue engineering module.

With respect to the *practical* significance of the increase in scores from before to after the module, what students included in their written responses to the open-ended prompt was limited to what they spontaneously thought to report. The goal of the testing prompt was to find evidence of what students described about angiogenesis from the module during a relatively early stage of curricular development. Results revealed some aspects of student thinking about angiogenesis but perhaps not a complete picture of what students knew after the module, since students were not prompted toward any of the details captured by the Aspects of Angiogenesis Coding Scheme. What students wrote in their responses would likely be a lower bound estimate of what they actually know. Therefore, the so-called maximum score of 13 (i.e., the score if the response contained all 13 aspects of angiogenesis captured in the Aspects of Angiogenesis Coding Scheme) is higher than what would be expected in any response. Despite this limitation, some students produced detailed responses about angiogenesis, which, we can reasonably speculate, were based on their experience with this module.

Limitations

Two limitations of this work are related to the use of real classrooms as a research setting: sampling and implementation. A third limitation for this study concerns assessment, specifically the prompt that was used to gather information about what students reported they knew about angiogenesis.

Sampling and participants

Instructors volunteered to be in the study because they believed that the content of the module addressed a curricular need for their course or program in a viable way. However, while all students engaged in the authentic engineering experience, the results of this study are limited to participants who volunteered to have their data included in the samples to be analyzed. This limitation, which is always part of real classroom-based research, could lead to a misrepresentation of what mathematics and science was learned by all the students in the class. The potential for misrepresentation might especially be observed in the mathematical modeling dataset. Mathematical models produced by student-teams were omitted from the study in cases where *any* student on a team exercised the right to not have their work in the study. As a result, only a small number of mathematical models were collected for the study and examined, compared to the total number of models produced by student-teams who engaged in the module. Observations and anecdotes from the instructors indicate that more sophisticated and diverse models were created than what could be reported here.

Implementation

Implementation variations in classroom-based studies emerge for many reasons. In this study, an attempt was made to somewhat stabilize the potential effect of instructor variation by including at least one of the design-researchers as co-instructor. In early stages of design research, the dual role of design-researcher and co-instructor is acceptable (Kelly, Baek, Lesh, & Bannan-Ritland, 2008) and, in fact, enables designers to bring vivid implementation experience to the revision of the curricular object. Our attempt to stabilize instructor effect across participating classrooms enabled an enhanced focus on the effectiveness of the module design, while backgrounding potential instructor-based variation. The minor revisions in the module's implementation across samples emerged primarily to accommodate for the varying lengths of time available to test the module in different classroom settings. While the results indicate that students across samples did indeed produce mathematical models and describe important aspects of angiogenesis, subsequent scale-up phases of the design research process to include greater diversity of instructors in more varied settings would enhance claims about the module's generalizability.

Assessment

The forms of assessment used in early phases of design study serve a different role than gathering of data to move students toward a predetermined fixed point (Kelly, Baek, Lesh, & Bannan-Ritland, 2008). This is particularly evident in the open-ended science prompt we used: "Describe what you know about the process of new blood vessel growth from existing vessels." This question was intended to obtain a broad-brush understanding of aspects of angiogenesis in students and was useful in establishing that students were acquiring science content as a result of their engagement.

However, due to its open-ended nature, what students reported was likely a lower bound of what they actually comprehended. Further, the Aspects of Angiogenesis Coding Scheme only captured what students chose to write down and did not capture significant detractors (i.e., artifacts found in student responses that evidenced common misconceptions or misinformation). Though we can report that these significant detractors were relatively few, further analysis would be necessary to categorize them and make sense of them in the context of the Aspects of Angiogenesis Coding Scheme.

One of the significant limitations of this approach was that scores may not be comparable across samples within the dataset. That is, for example, one response with a score of 4 may not be identical to another response with a score of 4, in terms of what is comprehended about angiogenesis or the relative quality of the responses. To some extent, this limitation is to be expected, as any testing prompt rarely captures every aspect of student thinking (DeBoer, Abell, Gogos, Michiels, Regan & Wilson, 2008), whether it is unstructured and open-ended, structured and closed-ended, or somewhere in between. Nevertheless, other assessment methods could help to eliminate this limitation.

Future Directions

The purpose of design-based research in general is two-fold: (1) to enhance the viability of the module by increasing the number of students and teachers who can use it and (2) to develop (reusable) principles for similar curricular products (Amiel & Reeves, 2008). In particular: What would be the next steps needed to establish the viability of this module for broader audiences and wider contexts? What principles could emerge from further research with this and similar modules to help establish a way to design authentic engineering modules that give rise to disciplinary learning?

Enhancing Viability of the Module

The more generalizable this module is to varied school-based circumstances, the more viable it would be for adoption. Given that the module, at this iteration, was found to elicit mathematical model development and learning of science concepts on the part of students, next steps would be to plan for scaling up—that is, to produce evidence of its effectiveness in broader circumstances. Such endeavors would include seeking a broader diversity of students and teachers, enhancing the supports for implementing the module across varied settings, and enhancing the persuasiveness of evidence of science learning.

Evidence from a greater diversity and number of students would increase the viability of the module. A more compelling case for using the module with mathematics and science students could be made by associating student demographics with student outcomes to specifically address what might be expected in, for example, urban and rural settings, and English-language learners. Evidence from a broader diversity and number of teachers can also enhance the viability for the future adoption of this module. In particular, documentation concerning the background of teacher expertise, the context of the teachers' classroom settings, and the nature of teachers' professional development prior to implementation, juxtaposed alongside student outcomes in the disciplinary learning, would help future adopters plan for their own implementation.

Simultaneously with scaling up the student and teacher populations, subsequent iterations in the design research process can target improved development of implementation guidelines (i.e., "teacher edition notes"). The potential for adoption would be improved by providing teachers with stable insights about what might happen during implementation, what types of supports students may need during the experience, and what to expect in student products. Important questions concerning discipline-based teachers' capability and comfort with integrating science or mathematics in their own classroom (e.g., Stinson, et al., 2009; Stohlman, Moore, & Roehrig, 2012) can be addressed using small design experiments embedded in design research. Such studies can explore questions such as: What additional mathematical modeling supports do science teachers need to implement the module? What additional science concept supports do mathematics teachers need to implement the module?

Adoption of this module by science teachers, in particular, would become more viable by offering compelling assessment evidence and tools that would be better aligned with classroom goals tied to specific expected curricular outcomes. Given the above-described limitation of the science prompt used in the current study, other means of assessment could be designed that more closely align with different levels of science knowledge by using Bloom's Cognitive Taxonomy (Bloom, et. al., 1957), or by using a version of it adapted for science education (e.g., Anderson & Krathwohl, 2001) or biology education (e.g., Crowe, Dirks, & Wenderoth, 2008). Developing such assessments, and providing data from field tests using these assessments, would more clearly situate the learning from the module in the literature of science education research and would provide a more complete picture of what students learned about angiogenesis from the module. Improving the science learning assessment tool could become the object of design research in its own right.

Establishing Design Principles for Pre-Collegiate Authentic Engineering Experiences

Transferring the world of authentic engineering into compelling pre-collegiate classroom experiences poses a number of challenges, and strategies for dealing with some of those challenges may generalize across curriculum development efforts. For example, simplification of real engineering problems is necessary to enable access by pre-college students, but such a quest is wrought with questions about what and how to simplify the engineering problem in a way that stays true to the actual content and context. The work in this study revealed at least some of the challenges of this type of work. One example that resulted in a potential generalized strategy concerns how to address pre-requisite disciplinary knowledge. In this tissue-engineering module, meaningful student engagement was dependent on prior knowledge of the circulatory system. A decision was made during the design phase of the module to assume that high school students would have learned about the circulatory system during their elementary and middle school years. Anecdotes, observations, and notes drawn from the research design cycles confirmed that prior learning about the cardiovascular system had some effect on students' understanding of the introduction to angiogenesis in the module. In the cases where lack of understanding of the circulatory system was evident, we found it created a barrier to understanding new ideas about blood vessel growth as presented.

A proposed principle to explore might be: "Identify and establish the extent to which assumed prerequisite understandings are actually in place for a population." Then, the design research process could be planned to include small-scale experiments that establish the extent to which the assumption is warranted, and/or whether a supplement resource is needed for some students. Even small steps that lead to focused improvements in the design and implementation of modules that use authentic engineering problems to design STEM experiences for mathematics and/or science classrooms would be a great contribution to the field.

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