1 Overview

In the last several decades, we have witnessed a proliferation of options in educational technology. However, despite the myriad of options, the most effective uses of technology to facilitate learning remain unclear. One obstacle to researching technology effectiveness is the increasing commercialization of data, as the value of personal data has been more widely recognized. The publishing industry, having been disrupted by openly available texts, has responded by providing assessments linked to their products, giving them control over the resulting student assessment data. At the same time, despite an abundance of openly available educational material, the paucity of available data on how students use and learn from those materials has impeded their effective use in the classroom. The absence of data-driven guidance for improving open educational content and its implementation inhibits our ability to develop educational experiences that will maximize learning.

We propose to promote the collection, analysis, and application of student interaction data through the development of a distributed educational technology framework designed to facilitate the participation of authors, instructors, researchers, and learners. This platform, the Distributed Open Education Network (Doenet), is, at its core, a mechanism for measuring and sharing student interactions with web pages and storing anonymized data in an open distributed data warehouse. We propose to develop the Doenet platform and its ecosystem of tools for (a) authoring interactive educational content, (b) conducting educational research using the content, and (c) discovering the most effective content based on the research results. We will also create and adapt existing content to be used with Doenet, conduct experiments on the effectiveness of different versions of interactive content, and work with faculty and researchers from a variety of institutions to conduct learning experiments using the Doenet platform. Our initial focus will be on mathematics, followed by expansion to other STEM disciplines.

2 Results of prior NSF Support

2.1 Duane Nykamp

Award: DMS-0847749; *Title*: CAREER: Toward a second order description of neuronal networks; *Amount*: $520,000; *Dates*: September 2009 to August 2014; *PI*: D. Q. Nykamp.

2.1.1 Intellectual Merit

During the award period, we developed a second order network (SONET) model of random networks with prescribed motif frequencies [15] and applied the results to studying influences of network motifs on synchronization of neuronal networks [26]. To capture the influence of such network structures on population activity, we derived mean-field equations for the activity of the network with complex microstructure [15] and extended those equations to networks with arbitrary low rank structure [4]. We also developed population equations for the cases when neuronal dynamics include depolarization block [10].

We collaborated on three other projects. The first involved SONET network simulations to investigate shifts in network synchrony at seizure initiation [3]. The second was an analysis of functional connectivity in developing songbirds, showing evidence of a network that develops as the birds mature and that may coordinate sequential activity during the song

[6]. The third project was modeling and analysis of links between behavioral deviations and single neuron recordings during an oculomotor delayed response task by monkeys, providing evidence for a bump attractor as predicted by working memory models [23].

2.1.2 Broader Impacts

The research has generated tools to help researchers to study interactions between network structure and dynamics. In additional to the publications, the SONET code is publicly available (`github.com/dqnykamp/sonets`). A number of groups have discussed with us how they are using the SONET code. We are aware of one publication that employs SONETs [9].

The research involved two postdoctoral scholars, two graduate students, fifteen undergraduate students, and one high school student. In particular, three undergraduate students played a significant role in the development of the SONET network. Three undergraduate students and one high school student played a key role in testing a prediction of the population equations and are coauthors on a publication [15].

Additional results from the award include: (A) a flipped biocalculus course, whose content, including videos, interactive worksheets, and online assessments, is publicly available (`mathinsight.org/thread/math1241`), (B) interactive assessments for a mathematical neuroscience course (`mathinsight.org/thread/math5447`), and (C) mathematical biology instruction for high school women during a summer camp.

Publications: See references [26, 3, 6, 23, 15, 10, 4]

2.2 Matt Thomas

Award: DUE #1712312; *Title*: Collaborative Research: Investigating Student Learning and Sense-Making from Instructional Calculus Videos ; *Amount*: $185,985.00; *Dates*: May 2017 to current; *PI*: Aaron Weinberg.

2.2.1 Intellectual Merit

This ongoing project is generating new knowledge about the effectiveness of various implementation methods for instructional videos in supporting students' productive ways of understanding foundational calculus concepts. The research project is adapting ideas from the fields of information systems and organizational studies to investigate:

- The ways students interact with video lectures, including how they pause, skip, and re-watch portions of the videos;
- The aspects of the videos students attend to - and report attending to - as they watch;
- The ways students make sense of and learn from these videos, and how this relates the other aspects described above;
- How various ways of structuring the video-watching experience can influence each of these aspects.

The analysis is yielding knowledge about the ways students interact with and learn from instructional videos and how to create effective interventions based on structuring the ways students watch these videos.

2.2.2 Broader Impacts

This project investigates the use of video lectures to teach calculus content. Videos have been proposed as a way to support active learning in classrooms and increase student success. However, there has been little research that describes how students actually interact with and learn from instructional videos. The project contributes to the understanding of how students make sense of and learn calculus from instructional videos. This investigation into various methods of structuring the video-watching experience contributes to the field's understanding of how to create and use videos as effective pedagogical tools. In addition, the project is currently producing high-quality materials for creating instructional calculus videos.

Publications: See references [21, 22]

2.3 Jim Fowler and Bart Snapp

Award: DUE #1245433; *Title*: Interactive Textbooks ; *Amount*: $180,000.00; *Dates*: September 2013 to August 2017; *PI*: Herb Clemens.

This project produced Ximera, a platform for converting LaTeX into interactive webpages on a central server.

2.3.1 Intellectual Merit

Developing the content conversion tool provided key insights into how to transform LaTeX into other formats like HTML, and revealed the appropriate interactive primitives out of which larger student learning experiences can be built. This knowledge forms the foundation for ongoing work in educational technology. Navigating a large technical document is difficult, and by iterating on the design of the content navigator with the evaluation team, the Ximera team has produced a workable mechanism ("cards") for navigating through the textbook. Creating interactive calculus textbooks has contributed to the OER community's understanding of what is possible with open textbooks. By leveraging open standards like xAPI for recording learner events, the Ximera platform has generated knowledge about student learning. For example, the Ximera platform permitted a conceptual inventory in calculus to be deployed to Ohio State students with pre- and post-tests.

2.3.2 Broader Impacts

There have been 442,618 unique users on `ximera.osu.edu`. The project integrates research of textbook design and virtual manipulatives with the teaching of mathematics courses. The Ximera platform enhances the classroom technology infrastructure, and by making quality course material widely available, engages underserved individuals with interactive mathematics through, for example, a calculus MOOC which used the platform. The content authoring tools have been broadly disseminated as open source software on the web and through seven Ximera Workshops held in Ohio and Florida.

2.3.3 Evidence of research products

The deliverables are archived at `github.com/ximeraproject`, with a calculus course available at `github.com/mooculus`. A manuscript detailing research findings (e.g., relationship between student use of Ximera and classroom grades) has been submitted, with a second on the conceptual inventory in preparation. The 2018 Web SIGMAA address at the Joint Mathematics Meetings (JMM) highlighted Ximera, and the 2019 JMM will also include presentations on Ximera.

2.4 Jim Fowler

Award: DUE #1505246; *Title*: Open resources for the mathematics curriculum ; *Amount*: $248,724.00; *Dates*: September 2015 to September 2018; *PI*: David Farmer.

2.4.1 Intellectual Merit

The team created a robust system for collaboratively creating and curating open mathematics resources and making these open resources readily available to users, which is available at `curatedcourses.org`. Comprehensive course materials for linear algebra were developed collaboratively, and mathematicians were engaged in curating and reviewing this content; this workflow provided critical insights into what is necessary for a sustainable open infrastructure for OER, thereby bolstering the intellecutal groundwork for projects like DUE #1624634 (UTMOST: Undergraduate Teaching in Mathematics with Open Software and Textbooks). A complete metadata tagging system for topics in linear algebra was created; the tagging system advances our understanding of how linear algebra is taught. Best practices for content creation and curation were disseminated through workshops and mini-courses. Ongoing surveys are used to study the efficacy of the CuratedCourses resources in empowering faculty to adopt active learning instructional practices and the properties of OER items that make them most usable and educationally effective.

2.4.2 Broader Impacts

Active learning instructional practices have been shown to decrease the achievement gap for underserved student populations. CuratedCourses facilitates the adoption of evidence-based instructional practices by creating and curating high-quality open educational resources. During the funded period, faculty were trained on how to use OER to make room for active learning in their course design. A diverse group of workshop participants, content contributors, content reviewers, and faculty adopters participated in the project.

2.4.3 Evidence of research products

Deliverables are archived at `github.com/curatedcourses` and are live at `curatedcourses.org`. Perhaps the most significant evidence is the list of linear algebra tags at `github.com/curatedcourses` which permits other textbooks (such as those proposed herein) to be linked to each other. The publication [17] describes the project.

3 Background

Recent research has indicated that students are more successful in learning when they are in active learning environments than in traditional lecture settings [7]. These gains are particularly large among female and minority students [12, 8].

While there are many ways to create an active learning environment, the use of online resources has become a valuable tool. Flipped classrooms are one way online resources have been used, often taking advantage of online videos to deliver content which would otherwise be presented in a lecture [5]. By moving the delivery of content outside of class time, class activities can be more active. Students in flipped classrooms have been shown to outperform students in traditional classrooms, and perform better in subsequent classes [19].

One can also create active learning opportunties with *virtual manipulatives*: interactive computer widgets that students can directly manipulate to discover mathematical content. These tools have been shown to increase students' learning of mathematics content [14] and students' ability to recall information about Taylor series at a later time [20]. By blending these online and in-class activities, not only has student learning been shown to improve, but student attitudes towards mathematics have as well [24].

One such online tool which has been widely adopted is WeBWorK (`webwork.maa.org`), developed by the MAA. Such systems in which students receive immediate feedback on questions have been shown to be helpful in facilitating flipped classrooms [13], and they improve student performance and generate positive student feedback [25]. WeBWorK has been shown to be beneficial in reducing non-pedagogically-useful mistakes [18] and in providing students a better sense of what they are doing than ungraded paper-and-pencil homework [11].

4 Specific Aims

The goal of this proposal is to develop a distributed educational technology platform to run experiments that systematically evaluate the effectiveness of open source educational content. We organize the proposal around four specific aims: technology development, content development, experimental design and implementation, and data analysis. Our vision is to empower faculty to run learning experiments and locate high-quality content with demonstrated effectiveness.

4.1 Specific aim 1: Development of educational technology to underlie learning experiments

To form the basis of our learning experiments, we propose to develop a distributed educational technology platform, the Distributed Open Education Network (Doenet). Doenet will draw on our experience developing other educational technology platforms: Ximera (`ximera.osu.edu`) and Math Insight (`mathinsight.org`). Doenet's innovative focus is providing a mechanism for simple web pages to share data across the network. To help anyone create content on Doenet, we will provide tools for authors to easily create educational content that integrates interactive widgets with text, video, assessment, and feedback. The resulting content can be posted anywhere on the internet, such as directly on an author's web page, and it will be copied to other nodes on the network (even an individual user's device). For programmers who wish to develop sites with their own technology, we will develop technical standards for hooking sites into Doenet. The distributed architecture of Doenet will minimize barriers for faculty to adopt the system for both course content and learning experiments. Participation in the network will be possible without setting up a server or even maintaining a consistent internet connection. The Doenet platform will automatically record data on user interaction and store anonymized data in an open database, facilitating the analysis and dissemination of results from learning experiments.

4.2 Specific aim 2: Deployment of interactive educational content

To provide the basis for learning experiments, we propose to incorporate existing interactive content into Doenet as well as develop new content. We will add hooks to Ximera so that its content, including its interactive calculus texts, will become part of Doenet. We will convert the biocalculus and multivariable calculus content on Math Insight to a Doenet-compatible format, and similarly convert Dr. Weimerskirch's precalculus video textbook and classroom activities (`math.umn.edu/~weim0024/pre_calc_hybrid.shtml`). We will continue development of an interactive multivariable calculus text using Doenet's authoring tools. Since Doenet's authoring tools are based on PreTeXt (`pretextbook.org`), we can import content from existing open textbooks written in PreTeXt (`pretextbook.org/gallery.html`), giving us access to static content that can be used in experiments to compare with interactive content. Moreover, to encourage development of online interactive instructional content, we propose to create a peer-reviewed overlay journal for interactive content published on Doenet, providing an avenue for the recognition of authors' work.

4.3 Specific aim 3: Design and implementation of learning experiments

We will run the initial learning experiments in mathematics courses at Ithaca College, Ohio State University and the University of Minnesota. During the proposal period, we will run experiments in precalculus, calculus, biocalculus, multivariable calculus, and linear algebra courses. The experiments, including both the interaction with content as well as the assessment, will be conducted online through Doenet. In these experiments, we will examine the role of interactions with virtual manipulatives, with an emphasis on the guidance given for the interaction. We will explore conditions ranging from free, unguided exploration, in-person guidance from an instructor, guidance via computer-generated feedback, and fixed guidance via text or video. Once we have completed our first round of experiments, we will promote the use of the Distributed Open Education Network as a tool for running learning experiments. We will run a workshop helping faculty design and set up their own experiments.

4.4 Specific aim 4: Analysis of learning experiment data to measure content effectiveness

The data from learning experiments will form the basis for determining the effectiveness of different content and different approaches for using interactive material. Anonymized data from learning experiments performed on Doenet will be placed into an open database as part of the Doenet ecosystem. As learning experiments through Doenet are performed by us and others, this growing, publicly available, repository of data can be mined for insights into the effectiveness of course content. We propose to analyze this data in two different ways. The first analysis will follow directly from the design of our experiments, and will seek to understand what types of guidance lead to most effective learning via interactive widgets. We will use these results to design more effective interactive content. The second analysis will use the combined data of many learning experiments to gauge the relative effectiveness of the content on Doenet. This analysis will underlie search tools that will help instructors and learners find the most effective content for their learning goals.

5 Creating the Doenet infrastructure

Our first specific aim is to develop the educational technology infrastructure to underlie online learning experiments. We are designing the Distributed Open Education Network (Doenet) to minimize barriers for adoption by authors, instructors, educational researchers, and students, since one fundamental goal is ensuring that anyone can publish or view content, as well as analyze its data. Doenet's distributed architecture will facilitate posting content, interacting with content, and accessing data without requiring specialized servers or even consistent access to the internet. To encourage collaboration and broad ownership, Doenet is an open source project. Developing a collaborative community around Doenet will be key to its success, since a decentralized platform like Doenet requires building bridges between technicians and technologists both inside and outside of academia.

Doenet fundamentals. The decentralized architecture of Doenet will allow authors to publish content to Doenet simply by posting a web page with their content, written to be compatible with Doenet specifications (see below). Instructors and educational researchers can take advantage of content on Doenet by simply pointing students to Doenet-compatible content on the internet. When a user (such as a student) interacts with content on Doenet, their device becomes a node on Doenet, and data from their interactions is stored on their device. Assuming the user has granted permission, the data is sent to Doenet's data warehouse (and new content is potentially downloaded) whenever their device is connected to the internet. Educational researchers would have access to anonymized, or de-identified, data of users' interactions with the content, along with performance data on any assessments incorporated into the content. If a student authenticates with Doenet and gives permission for their data to be shared with an institution, an instructor will be able to import (using tools we provide) identified student data into a gradebook, such as in their institution's learning management system (LMS).

For content on the internet to be part of Doenet, the author must have either 1) used our authoring tools to create the content (the simplest option), 2) linked their page to the freely available Doenet Javascript library (requires some knowledge of how web pages work), or 3) programmed their web site to follow Doenet's rules for communicating data (for expert programmers only). When users who are authenticated with Doenet access this content, not only is data communicated across the network, the content itself will also be copied to other nodes on Doenet, ensuring consistent access even if the content on the original node becomes unavailable. Authors may register their content with Doenet if they wish for instructors and students to be able to find their content via searches on Doenet. They can also set up their pages to automatically find related content on Doenet and display links to those pages.

A key distinction between Doenet and other systems is that Doenet is designed first and foremost to be decentralized, addressing the issue that faculty often lack either the technical expertise or permission to put content or student data on an external (and often commercial) server. This barrier to adopting interactive content is often why faculty turn to commercial providers. The proposal's timeliness is buoyed by recent developments in decentralized web technology like IPFS [2] and Blockstack [1]. We propose using IPFS to distribute content without depending on a central server, and Blockstack to handle student identity and page state. A strategic investment in decentralized web technology promises to tilt the balance away from commercial publishers and back towards academic control of online curricula.

Doenet's authoring tools. We have created an initial draft of a tool for authoring interactive content using an XML format derived from PreTeXt (`pretextbook.org`). PreTeXt is a format used for numerous (primarily mathematics) textbooks. We chose PreTeXt, not only to facilitate conversion of material from textbooks, but also because it forms the basis for a semantic markup of content. By insisting, for example, that authors describe figures by their mathematical meaning, we lay the groundwork for converting materials into accessible formats that are compatible with assistive technology, moving us closer to our goal of making content available to anyone. The ability to convert material to other formats will also ensure that content will be viewable on future technology without requiring authors to change their documents. To make content authoring easier for those who may be uncomfortable writing

XML, we propose to develop a graphical authoring tool, where authors can create interactive content using a point-and-click interface that hides the XML being generated.

Data warehouse. A key feature of Doenet is the ability to communicate data from web pages that are written to be part of Doenet. Data that includes a user's identity will be stored only on the user's device, and, if they give permission, on particular servers, such as with their institution. Data stored elsewhere on Doenet will be anonymized to protect users' identities. We will store two types of data on Doenet: progress data and event stream data. Progress data includes users' responses and evaluations of those responses. Event stream data is a record of all interaction with the content.

Building upon previous platforms. The Doenet platform design resulted from our previous experience building Ximera (Drs. Fowler and Snapp), Math Insight (Dr. Nykamp), and commissioning the Minnesota Online Learning System (Dr. Weimerskirch). We are already storing and analyzing both event stream and progress data with Ximera; the primary change with Doenet will be anonymizing the data before it is stored. Math Insight contains many virtual manipulatives that are linked with assessments, which will provide the basis for some of our learning experiments (below). We've used the Minnesota Online Learning System for assessment in precalculus. Ximera is currently being used to host the videos as a part of the DUE #1712312 grant. Additionally, the event streams are being used to collect data on video watching, providing a proof-of-concept for the usefulness of analyzing event streams and providing the foundation on which tools can be built for instructors.

6 Adapting and creating content for Doenet

To achieve our second specific aim of deploying interactive educational content on Doenet, we will employ three strategies: adapting existing content, creating new content ourselves, and encouraging the development of interactive content via a peer-reviewed journal.

Adapting content into the Doenet framework. We propose to focus initially on adapting our own content from three sources: Ximera, Math Insight, and a precalculus course. Since Ximera already incorporates much of the fundamental data communication that we are building into Doenet, minor modifications to the Ximera platform will make all its content, including its interactive calculus text, available on Doenet. We propose to use the Doenet authoring tools to convert the content from the other two sources into Doenet's XML format based on PreTeXt. Once completed, the biocalculus and multivariable calculus materials from Math Insight, as well as Dr. Weimerskirch's precalculus video textbook and classroom activities (`math.umn.edu/~weim0024/pre_calc_hybrid.shtml`), will be available for running learning experiments.

The fact that the Doenet XML format is based on PreTeXt will facilitate adapting material from textbooks currently on PreTeXt (`pretextbook.org/gallery.html`). For example, there are already excellent linear algebra materials for a proof-oriented course written in PreTeXt. The copyrights to the commercial textbook *Linear Algebra and Differential Equations Using MATLAB* by Martin Golubitsky and Michael Dellnitz have been returned to the authors, who have graciously released their textbook under an open license. The team can use this source material to produce an interactive linear algebra and differential equations text for an engineering audience.

Another source of interactive content that we propose to adapt to Doenet is WeBWorK's open problem library (`webwork.maa.org/wiki/Open_Problem_Library`). This effort will be done in consultation with Alex Jordan from Portand Community College (see letter of collaboration), who has developed an approach for integrating WeBWorK into PreTeXt. We plan to develop two approaches for using WeBWorK problems on Doenet: creating an interface for problems running on a WeBWorK server and converting the problems fully to Doenet's XML format.

Developing new Doenet content. We propose to develop a new interactive multivariable calculus text in Doenet. Dr. Rogness and a postdoc have recently begun developing this text in Ximera. The initial target for the text is the University of Minnesota Talented Youth Mathematics Program (UMTYMP), a program where high school students take classes at the University of Minnesota. We propose to continue developing the text in collaboration with postdocs, migrating it to take advantage of the Doenet authoring tools. In addition to using the text in the UMTYMP course, we will create a version of the text to use in the University of Minnesota's undergraduate multivariable calculus course.

Our first foray outside mathematics will be in collaboration with Michelle Driessen, Professor of Chemistry at the University of Minnesota (see letter of collaboration). Dr. Driessen has been developing interactive content for general chemistry courses and will advise us on building tools into Doenet that would be required for chemistry courses. We propose to subsequently work with her to create content on Doenet for these courses.

We also propose to develop material for physics. Working with Andrew Heckler, Professor of Physics at Ohio State University (see letter of collaboration), we will develop content to explain vectors algebraically, geometrically, and numerically.

An overlay journal. To provide official recognition for authors' work on creating open educational content, we propose to create a peer-reviewed journal to which authors can submit their Doenet content. The journal will be an overlay journal, meaning that it will not directly host content, but instead simply point to content on Doenet. Accepted content will receive a citation and a DOI for the particular peer-reviewed version of the content, and the content can display the journal symbol to indicate its status as peer-reviewed. To ensure continued access to journal content, we will keep a copy of all published content on a Doenet node maintained by the journal.

Dr. Rogness, who recently started the Minnesota Journal of Undergraduate Mathematics, will guide the formation of the journal. In additional, we will be assisted in this effort by Sue Wick, Professor of Plant and Microbial Biology at the University of Minnesota, and advisory board member for CourseSource, an open-access journal of peer-reviewed teaching resources for undergraduate biological sciences (see letter of collaboration).

7 Learning experiments

Our third specific aim is to use content on Doenet to run online learning experiments. The experiments will focus on different approaches to help students learn a particular concept. In general, an experiment will consist of dividing students randomly into different groups and assigning each group a different version of content. All students will receive the same pre- and post-tests, so that we can look for differences in learning gains that are correlated with the content versions. Since the assessments and most of the content will be on Doenet, anonymized data from the experiments will be stored on Doenet's open data warehouse.

Our initial experiments will focus on the influence of different types of guidance in the exploration of virtual manipulatives. We will subsequently promote Doenet as a platform for running learning experiments, including organizing a workshop to help faculty design and implement their own experiments.

7.1 Analyzing the effects of guidance

We propose to examine how learning gains from interactions with virtual manipulatives are influenced by the types of guidance for the interactions. We will perform experiments based on a lesson involving a particular manipulative. The influence of the manipulative and guidance on learning will be examined by dividing students into the following four groups:

A. Students receive instruction without the manipulative.
B. Students receive the same instruction as A, followed by free, unguided exploration with the manipulative.
C. Students are guided through an exploratory activity with the manipulative.
D. Students are guided through an exploratory activity with the manipulative and receive immediate, computer-generated feedback based on their responses.

We will run these initial learning experiments in precalculus, calculus, biocalculus, multivariable calculus, and linear algebra courses at Ithaca College, Ohio State University and the University of Minnesota. In each case, students will be assessed immediately after the activity and again after six weeks. Below are examples of the learning experiments we propose to perform.

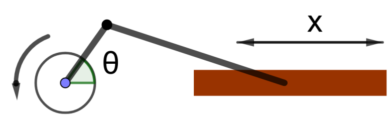

Figure 1: Sketch of a future piston motion manipulative.

Piston motion. We will examine how a piston motion manipulative (see Fig. 1) that we will create in Doenet will help precalculus students learn how to describe the complex motion of the piston. The goal is for students to learn to express the piston location as a function of the crank angle. For groups A and B (described above), students will receive a text description with or without the piston manipulative. In groups C and D, students will work through an online worksheet consisting of questions that prompt the students through the process of discovering the formula. In group C, students will receive the graded assignment the following class period, while in group D, the computer will check the mathematical answers (using the computer algebra system built into pages written with Doenet's authoring tool) and give immediate feedback. Students will be assessed with an online multiple choice instrument.

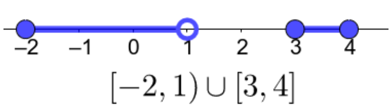

Figure 2: Sketch of a future interval notation manipulative.

Interval notation. A second precalculus experiment will examine the benefits of a tool (see Fig. 2) that we will create in Doenet where students manipulate a number line to represent the domain of a function as it automatically translates their manipulations into interval notation. Groups A and B will be presented with material on interval notation with a video lecture and accompanying readings on interval notation, including how it relates to intersections and unions. Groups C and D will be guided through an activity teaching them how to solve problems with the manipulative. Group C will receive guidance from a teaching assistant while group D will, in addition, receive immediate feedback from the computer. Students will be assessed by being asked to represent the domain of a function in interval notation and draw the set on a number line.

Approximating derivatives at a point. Once we convert a Math Insight secant slope manipulative (see Fig. 3) to Doenet so that we can gather data from student interactions, we will examine the influence of the manipulative on students' ability to approximate the derivative of a function at a point via slopes of a sequence of secant lines. Experimental conditions will include a video lecture (groups A and B) and an online worksheet guiding students through using the manipulative (groups C and D), where only group D receives immediate computer feedback. Students will be assessed with an online multiple choice instrument.

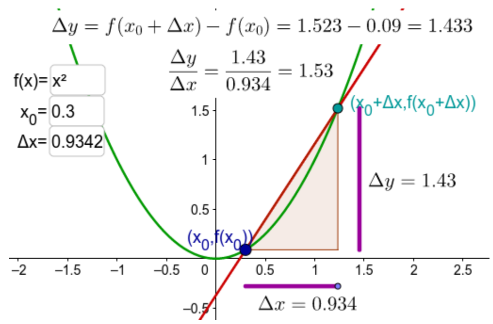

Figure 3: Snapshot of a Math Insight manipulative on secant line slopes.

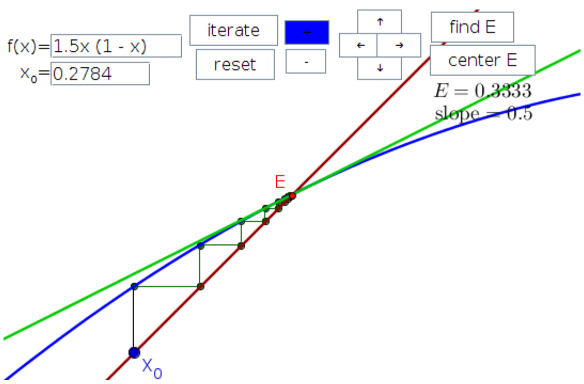

Figure 4: Snapshot of a Math Insight manipulative on discrete dynamical system equilibrium stability and tangent line slope.

Stability of equilibria of discrete dynamical systems. A learning experiment from the discrete dynamical system module of the University of Minnesota biocalculus course will focus on the stability theorem result that an equilibrium is stable when the slope of the map function is between −1 and 1. We will convert the Math Insight manipulative illustrated in Fig. 4 to Doenet. Groups A and B will watch a video that explains the main result. Groups C and D will be led through a set of online questions to discover the result, with group D receiving immediate feedback from the computer based on their progress. Students will be assessed via an online multiple choice instrument.

The line integral of a vector field. A multivariable calculus experiment will explore how a Math Insight manipulative illustrating the concepts behind a line integral (Fig. 5) aids learning when accompanied by a text describing the concepts (groups A and B) and when integrated into an online worksheet where students are directed to manipulate the applet to answer questions (groups C and D).

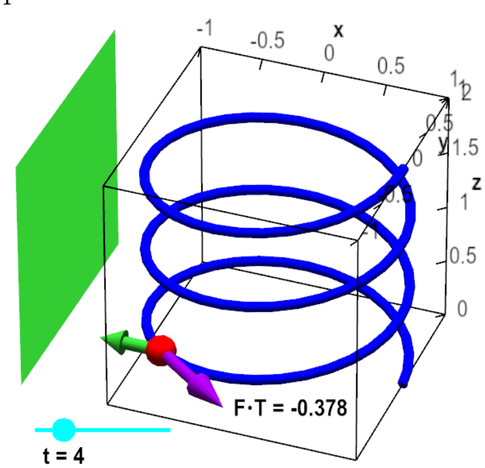

Figure 5: Snapshot of a line integral manipulative on the relationship between vector field and tangent vector.

Linear algebra. Building on the content created under CuratedCourses (DUE–1505246), experimental modules in linear algebra will examine guided inquiry into eigenvalues and eigenvectors, supplementing the work of Plaxco, Zandieh, Wawro [16] with online content, virtual manipulatives, and assessment.

7.2 Promoting learning experiments

Using our experiments as examples, we will subsequently promote Doenet as a platform for instructors to run their own learning experiments. Our goal is to increase the number of faculty who critically evaluate how different choices in employing content influence student learning in their classrooms. We designed Doenet to lower barriers for performing learning experiments and will promote creating discrete experiments covering single topics so that creating and implementing an experiment will not require a significant investment.

To further assist faculty in creating learning experiments, we will organize a four-day workshop for about 12 participants who are interested in these experiments. In this workshop, we will step faculty through the process of creating an experiment, discuss strategies for integrating experiments into a course, and demonstrate how to obtain data from Doenet's data warehouse. Michelle Driessen and Andrew Heckler have already expressed interest in running such experiments, and we anticipate we can make the process simple and attractive so that others will want to join. As an additional incentive, we will award small stipends to faculty who perform learning experiments on Doenet during the proposal period.

8 Data analysis

Our fourth specific aim is to measure the effectiveness of content on Doenet. We will take advantage of Doenet's open data warehouse that stores anonymized data from user interaction with content on Doenet, including data from learning experiments. As this data will be publicly available, the growing repository of data can be mined for insight into content effectiveness. We propose to analyze data from individual learning experiments to answer questions posed in the context of the experiment and also analyze aggregate data over multiple learning experiments to gain additional insight into the relative effectiveness of the content.

Individual experiments. The key data for analyzing our learning experiments will be the event stream data from user interaction with the content combined with progress data that shows students' performance on the assessments. By comparing the progress data from the assessments as a function of group, we can determine any effect of the manipulative alone (comparing groups A and B), any effect of a guided activity using the manipulative (comparing groups B and C), and any effect of additional guidance due to immediate, computer-generated feedback (comparing groups C and D). We can gain additional insight into potential explanations for observed differences by analyzing the event stream data. We will look for differences in how students interacted with the manipulative as a function of experimental condition (i.e., group), and how computer-generated feedback influenced how students progressed through the activity. If we can correlate certain behaviors (from event stream data) with subsequent performance (from progress data), we may both identify behaviors that are associated with higher performance and identify characteristics of activities that are associated with those behaviors. Such insights could suggest modifications for more effective interactive content that we could test with further experiments.

Finding effective content. The accumulation of data from many learning experiments in Doenet's open data warehouse leads to the potential for developing measures of the relative effectiveness among similar content. If we can detect that one activity tends to lead to higher performance on assessments than another activity, we can assign a higher effectiveness score to the first activity. By analyzing data from the repository, we propose to investigate the potential of such content effectiveness measures. We seek to provide tools to help instructors and students find content for their learning goals. We will explore adding content effectiveness measures into the algorithm for determining results for searches of Doenet content, where a higher effectiveness measure leads to higher placement in the results.

9 Advisory board

Advisory board. To help guide our development of educational technology and learning experiments, we have formed an advisory board of five senior mathematicians:

- Rob Beezer, Professor of Mathematics at the University of Pouget Sound and creator of PreTeXt,
- Deborah Hughes-Hallett, Professor of Mathematics at the University of Arizona,
- Kevin Knudson, Professor and Chair of Mathematics at the Univeristy of Florida,
- Benjamin Wiles, chief data officer at Clemson University, and
- Brian Winkel, Professor Emeritus of Mathematical Sciences at the United States Military Academy and Director of SIMIODE.

Each year, the advisory board will hold one phone meeting with the co-PIs, where we will discuss progress and plans for the development of Doenet, its content, and learning experiments. (See letters of collaboration.) We will use their input to help shape our plans.

10 Security Team

Discussions with computer security professionals have led us to understand that standards for data on an open distributed network such as Doenet have not been established. For this reason, we will commission a team of security professionals to create a report on recommended procedures and protocols for Doenet. The team will primarily focus on two issues: (A) how to minimize the possibility that user identities will be discoverable from the open anonymized data warehouse and (B) how to best securely transmit data with identifiable user information to designated servers without any central control over the individual pages from which the data originates. Establishing such procedures and protocols will help assure institutions that may be wary of adopting an open distributed solution such as Doenet for their classes.

The security team will work with Jason Nowell from the University of Florida (see letter of collaboration), who has experience engaging with the technologists at a large public institution to address student data and FERPA concerns with implementing Ximera's online homework. Jason will advise on policy concerns around adopting online education technology that isn't supported by a commercial third party.

11 Team roles

Drs. Fowler, Snapp, and Nykamp will lead the development on Doenet educational technology. Dr. Thomas, assisted by an undergraduate student, will lead the design and analysis of learning experiments. Dr. Rogness will spearhead the journal and, in collaboration with postdocs, develop multivariable calculus content. Dr. Weimerskirch will focus on developing content and experiments for precalculus. Drs. Thomas, Fowler, and Snapp will develop content and experiments for calculus and linear algebra. Dr. Nykamp will develop content and experiments for calculus and biocalculus.

12 Timeline

The following table summarizes the timeline for this proposal.

<table>
<tr><th>Year 1</th><th>Year 2</th><th>Year 3</th><th>Year 4</th></tr>
<tr><td>Create authoring tool</td><td colspan="3">Enhance authoring tool</td></tr>
<tr><td></td><td colspan="3">Develop Javascript library and communication rules</td></tr>
<tr><td>Security team report</td><td colspan="3"></td></tr>
<tr><td colspan="2">Create protocols for data warehouse</td><td colspan="2">Fully implement data warehouse</td></tr>
<tr><td colspan="2">Migrate content to Doenet</td><td colspan="2"></td></tr>
<tr><td colspan="4">Develop interactive content on Doenet</td></tr>
<tr><td>Create learning experiments</td><td colspan="3">Run learning experiments</td></tr>
<tr><td colspan="2"></td><td>Learning experiment workshop</td><td>Community-run experiments</td></tr>
<tr><td colspan="2"></td><td colspan="2">Data analysis for content effectiveness</td></tr>
</table>

13 Measurable outcomes

We will measure the success of Doenet with the following outcomes.

1. The development of authoring tools that simplify creation of interactive content
2. The number of authors adopting Doenet for creating interactive content
3. The amount and diversity of content on Doenet and the number of courses using it
4. The number of faculty running learning experiments on Doenet
5. The ability to distinguish content effectiveness from data in the data warehouse
6. The ability to use data to increase content effectiveness

14 Intellectual merit

This project will generate new knowledge about the effectiveness of different activities for learning concepts online. In particular, we will investigate the benefits of virtual manipulatives as well as the influence of the support given to students as they navigate the activities. We will create tools to enable faculty to develop their own educational experiments and generate new knowledge. Through the analysis of the data generated by the project, we will discover ways in which students interact with online materials, and look for correlations between those interactions and learning gains. Knowledge gained from this analysis will aid in the development of more effective online learning activities and will help us build tools that instructors and students can use to locate the most effective content. As the data will be stored in an open data warehouse on Doenet, any educational researcher can probe the data to generate additional knowledge on how students learn through online activities.

15 Broader impacts

Lowering barriers to participation. The Distributed Open Education Network (Doenet) is designed to reduce barriers to the development and access of online content and learning experiments. Its distributed architecture will facilitate participation without requiring a server or complicated setup. We will create authoring tools to streamline the task of setting up a web page to be part of Doenet and provide mechanisms for programmers to connect more complicated web sites to Doenet. Since when accessing a Doenet page, a user's device becomes a node on Doenet, the user can interact with the content, including assessments, even when the device does not have access to the rest of the network. Content and data can be exchanged between the device and other Doenet nodes during the moments the device is connected to the internet. Our focus on semantic markup for the Doenet authoring tool lays the groundwork for converting materials into accessible formats that are compatible with assistive technology, moving us closer to our goal of making content available to anyone.

As we develop the Doenet ecosystem, we will consult with a wide range of individuals to ensure that its tools meet the needs of different types of institutions. The co-PIs represent the perspectives of large public institutions and a private liberal arts college. Alex Jordan will share a community college perspective, and advisory board member Brian Winkel represents a military academy. Mary Sylvia Ebai Tambe, a former graduate student from the University of Minnesota (see letter of collaboration) will advise on developing Doenet to meet the needs of instructors and students in her home country Uganda and other parts of Africa.

Reducing the financial burden on students. We are designing Doenet as a publicly available resource. We will openly license Doenet's source code as well as the content and learning experiments that we develop. By stimulating the development of high-quality open content, we will help students save money on textbooks and learning materials. It turns out that, when relying on publishers for content and learning tools, the move toward online content can increase the required expenses of students. Students can find themselves in a course where the only option for completing coursework is through purchasing access to publishers' learning tools, placing on students a significant and unavoidable financial burden. By creating and encouraging the development of open, high-quality online content, we can give instructors options that will save students a considerable amount of money.

A large reach. Doenet has the potential to reach large numbers of people. The courses at the co-PI's institutions in which we propose to employ Doenet enroll each year over 10,000 undergraduate students, along with nearly 100 high school students in the UMTYMP course. As we promote the use of Doenet in other institutions and in other scientific disciplines, those numbers could grow significantly. As Doenet content and data will be publicly available, the reach of its content extends beyond students enrolled in courses employing Doenet. Already Ximera and Math Insight are visited by over two million users in a year with daily visits from more than one hundred countries. As the distributed nature of Doenet will lead to a larger range of content, we expect that its reach will surpass that of our individual web sites.

Promoting effective learning. The use of online materials has grown in recent years for both practical and pedagogical reasons. With online content, students can receive immediate feedback, allowing for faster self-assessment of understanding, and they can directly interact with materials through tools like virtual manipulatives. We seek to direct enthusiasm for online content into focused experiments that evaluate and improve the effectiveness of online educational activities. Our goal is to develop a large community that seeks to discover the most effective approaches for promoting learning with these activities. By making tools, content, and experiments freely available and accessible through Doenet, instructors and students worldwide can use these resources, modify them to suit their own needs, and share their improvements. As interactive materials and classes have been shown to be particularly effective for women and minority students, compared to lectures [7], the availability of high-quality and engaging online activities will help give everyone the best opportunity to learn.

References

[1] Muneeb Ali, Jude C Nelson, Ryan Shea, and Michael J Freedman. Blockstack: A global naming and storage system secured by blockchains. In *USENIX Annual Technical Conference*, pages 181–194, 2016.

[2] Juan Benet. IPFS - content addressed, versioned, P2P file system. *CoRR*, abs/1407.3561, 2014.

[3] B. Beverlin II, J Kakalios, D. Nykamp, and T. I. Netoff. Dynamical changes in neurons during seizures determine tonic to clonic shift. *J Comp Neurosci*, 33:41–51, 2012.

[4] P. Campbell. *Dynamical implications of network statistics*. PhD thesis, University of Minnesota, 2014. (http://hdl.handle.net/11299/166958).

[5] Emily Cilli-Turner. Measuring Learning Outcomes and Attitudes in a Flipped Introductory Statistics Course. *Primus*, 25(9-10):833–846, 2015.

[6] N. F. Day, K. L. Terleski, D. Q. Nykamp, and T. A. Nick. Directed functional connectivity matures with motor learning in a cortical pattern generator. *J. Neurophysiol*, 109:913–923, 2013.

[7] Scott Freeman, Sarah L Eddy, Miles McDonough, Michelle K Smith, Nnadozie Okoroafor, Hannah Jordt, and Mary Pat Wenderoth. Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences*, 111(23):8410–8415, 2014.

[8] David C Haak, Janneke HilleRisLambers, Emile Pitre, and Scott Freeman. Increased structure and active learning reduce the achievement gap in introductory biology. *Science*, 332(6034):1213–1216, 2011.

[9] Y. Hu, J. Trousdale, K. Josic, and E. Shea-Brown. Motif statistics and spike correlations in neuronal networks. *J. Statistical Mechanics*, P03012:1–51, 2013.

[10] C. Kim and D. Q. Nykamp. The influence of depolarization block on seizure-like activity in networks of excitatory and inhibitory neurons. *J. Comp. Neurosci.*, 43:65–79, 2017.

[11] P Gavin LaRose. The impact of implementing web homework in second-semester calculus. *Primus*, 20(8):664–683, 2010.

[12] Mercedes Lorenzo, Catherine H Crouch, and Eric Mazur. Reducing the gender gap in the physics classroom. *American Journal of Physics*, 74(2):118–122, 2006.

[13] Jean McGivney-Burelle and Fei Xue. Flipping calculus. *Primus*, 23(5):477–486, 2013.

[14] Patricia S Moyer-Packenham and Arla Westenskow. Effects of virtual manipulatives on student achievement and mathematics learning. *International Journal of Virtual and Personal Learning Environments*, 4(3):35–50, 2013.

[15] D. Q. Nykamp, A. Compte, D. Friedman, S. Shaker, M. Shinn, M. Vella, and A. Roxin. Mean-field equations for neuronal networks with arbitrary degree distributions. *Phys. Rev. E*, 95:042323, 2017.

[16] David Plaxco, Michelle Zandieh, and Megan Wawro. *Stretch Directions and Stretch Factors: A Sequence Intended to Support Guided Reinvention of Eigenvector and Eigenvalue*, pages 175–192. Springer International Publishing, Cham, 2018.

[17] Sarah Eichhorn David Farmer Robert A. Beezer, Petra Bonfert-Taylor and Jim Fowler. Curatedcourses: A fine-grained educational repository demonstrated with linear algebra resources. *IMAGE*, (60):26–27, 2018.

[18] Vicki Roth, Volodymyr Ivanchenko, and Nicholas Record. Evaluating student response to webwork, a web-based homework delivery and grading system. *Computers & Education*, 50(4):1462–1482, 2008.

[19] Larissa B Schroeder, Jean McGivney-Burelle, and Fei Xue. To flip or not to flip? an exploratory study comparing student performance in calculus i. *Primus*, 25(9-10):876–885, 2015.

[20] Matthew Thomas and Jason Martin. Virtual Manipulatives, Vertical Number Lines, and Taylor Series Convergence: The Case of Cody. In *Proceedings of the Twentieth Annual Conference on Research in Undergraduate Mathematics Education*, 2017.

[21] Aaron Weinberg, Jason Martin, Matthew Thomas, and Michael Tallman. Failing to rewind: Learning from instructional videos. In *Proceedings of the 40th Annual Meetings of the North American Chapter of the International Group for the Psychology of Mathematics Education*, 2018.

[22] Aaron Weinberg, Jason Martin, Matthew Thomas, and Michael Tallman. Investigating Student Learning and Sense-Making from Instructional Calculus Videos. In *Proceedings of the 21st Annual Conference on Research in Undergraduate Mathematics Education*, pages 1670–1671, 2018.

[23] K. Wimmer, D. Q. Nykamp, C. Constantinidis, and A. Compte. Bump attractor dynamics in prefrontal cortex explains behavioral precision in spatial working memory. *Nature Neuroscience*, 17:431–439, 2014.

[24] Balarabe Yushau. The effects of blended e-learning on mathematics and computer attitudes in pre-calculus algebra. *The mathematics enthusiast*, 3(2):176–183, 2006.

[25] Ryan Zerr. A quantitative and qualitative analysis of the effectiveness of online homework in first-semester calculus. *Journal of Computers in Mathematics and Science Teaching*, 26(1):55–73, 2007.

[26] L. Zhao, B. Beverlin II, T. Netoff, and D. Q. Nykamp. Synchronization from second order network connectivity statistics. *Front Comput Neurosci*, 5:28, 2011.