1 Introduction

The UTMOST project develops innovative models for the teaching and learning of undergraduate mathematics. This project grew out of an awareness that it was possible to create openly licensed material, including software, textbooks, and other educational resources, that would benefit a wide range of teachers and students. Bringing together individuals with experience in undergraduate teaching, textbook authors, and developers of mathematical software, UTMOST has produced educational resources including curriculum materials, classroom resources, and computer-enhanced learning environments specifically targeted at the STEM disciplines.

Initial work, supported by an NSF CCLI type II grant, successfully showed the effectiveness of such integrated materials, and resulted in preliminary versions of software, open textbooks that smoothly incorporate new technology, and several additional items that we describe below. The proposed work will build on this model in two ways: 1) more widely disseminate our advances and acquire formative feedback from early adopters of the materials; and 2) develop online tools that enable the broader STEM community to both benefit from and contribute to the resources developed through this project.

UTMOST is motivated by several challenges in the teaching and learning of mathematics.

Issue 1 Classroom demonstrations with mathematical software can greatly assist a teacher explaining a difficult concept or illustrating an example which requires more computation than is possible by hand. Because of cost or licensing terms, commercial software is not always available in a classroom, office, computer lab, or on student computers.

Issue 2 Mathematical software can significantly aid a student's efforts to understand difficult concepts. Unfortunately, the main commercial offerings are very expensive, licensing restrictions limit their portability, and competition between products fractures the market and impedes the formation of a community of users with a common purpose.

Issue 3 Traditional textbooks are expensive. For many student populations (such as community colleges), textbook costs represent a large fraction of the cost of their education. It has reached the point where some students do not purchase required texts [38][17].

Issue 4 Today's textbooks frequently fail to address the way today's students live and learn. Print versions have their place, while electronic versions offer the possibility of greatly expanded interactive applications embedded into the text. Students can use their texts on laptops, which are extremely prevalent; on tablets, which are commonplace; and their phones, which are ubiquitous and have increasingly powerful capabilities. Most textbooks do not offer low-cost electronic versions that make full use of available technology.

Issue 5 Existing course management systems are designed to be applicable to any course in any discipline. While they support some aspects of the daily interactions between students and teachers, they provide little support for the peculiarities of learning mathematics or science, such as the need to communicate using equations, or to utilize mathematical software.

Our research and development project has seven principal components, most of which incorporate the Sage computer algebra system, that directly address these five issues.

- Sage Cell Server: This technology allows web pages, textbooks, ebooks, online homework, and other instructional materials to seamlessly embed live Sage computations.

- SageMathCloud: A robust, scalable web application that provides a collaborative scientific computing environment in the cloud. Users can edit all types of files, use a command line terminal, chat or video conference, and compute with Sage.

- Textbook Authoring: An author-friendly standard for authoring textbooks and other materials in a structured way, enabling multiple output formats, especially electronic forms that utilize the SageMathCloud, the Sage Cell Server, as well as other computational tools.

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- AIM Open Textbook Initiative: An Editorial Board, composed of experienced mathematicians and authors that evaluates completed open textbooks, and also assists authors of promising open textbooks in development.
- Pedagogy and Educational Research: To gain a better understanding how a learning environment such as the one that we are proposing with the SageMathCloud influences the teaching and learning of mathematics and complements existing course management systems.
- Test Sites: Support for faculty and departments who will be early adopters of UTMOST and will provide formative feedback on the effect on their students, teaching, and courses.
- Workshops: Continuation of the Sage Educational Days workshop series, with an expansion in frequency, attendance, and geographic distribution.

2 Components of the UTMOST Project We briefly describe the components of the UTMOST project and how these address Issues 1-5. We elaborate on these items in the later sections of this proposal.

The first two components we describe are the Sage Cell Server and SageMathCloud. Both of these are based on Sage, a free open-source computer algebra system. Sage has similar capabilities to the commercial products Mathematica, Maple, MATLAB and Magma, but the fact that it is free and available in any web browser on any computer makes it attractive for both students and faculty. The wide availability of Sage addresses Issue 2, providing students easy access to a computer algebra system. Enhancements to Sage, begun in our previous UTMOST CCLI Type II grant and continuing in this proposal, address several other issues.

Sage Cell Server The Sage Cell Server is an online service that makes it easy to embed, link to, or interact with live Sage computations hosted in the cloud. Webpages, wikis, online or print textbooks, online homework systems, mobile apps, and more use this service to provide short calculations, examples, interactive demonstrations, and graded exercises. The Cell Server addresses Issues 1 and 2 through its use in the classroom and in instructor-provided material, and Issue 4 through its ability to greatly enhance textbooks.

The Sage Cell Server eliminates the start-up cost inherent in using computer algebra systems in a classroom. Typically, new users must invest large amounts of time and money in acquiring and installing software, and downloading or typing in examples. Instructors are particularly sensitive to these start-up costs for students when they evaluate how much valuable class time to devote to the mechanics of getting students up and running with a software package. Java or Flash applets make it easier for a student to get started, but often are complex for instructors to program, customize, or set up, and are not easily modified by curious students.

With the Sage Cell Server, an instructor can cut and paste a few lines into a webpage, or paste a web permalink into a textbook or email, and the students will instantly have access to a live Sage computation or interactive demonstration. The student using the Sage Cell Server sees immediate rewards for using technology and can be gradually introduced to more complicated applications. Students can spend as much time as they wish investigating more deeply, from simply modifying and running the provided commands (right in the instructor's webpage), to copying the code to a more comprehensive environment such as the SageMathCloud.

It is not necessary for all instructors to develop their own Sage Cell demonstrations. At the Sage Education Days Workshops (described below), participants learn Sage as they develop new demonstrations. During the next phase of the UTMOST project, these demonstrations will be expanded to cover standard topics in calculus, differential equations, linear algebra, and abstract algebra. These demonstrations will be *keyed to the table of contents of major textbooks*, providing an easy way for any instructor, including those who are not well-versed in Sage, to incorporate computer demonstrations into their curriculum.

The Sage Cell Server also provides a web service for online homework systems, mobile apps, and more to use Sage remotely. For example, the WeBWorK online homework system recently incorporated an AskSage function, which allows problem writers to remotely query the Sage Cell Server each time a problem is generated to help in writing randomized problems, generating graphics, or grading student answers. Android and iPhone apps for Sage also use the Sage Cell Server to power small calculations and interactive demonstrations.

The Sage Cell Server began development during the first UTMOST grant. It is beginning to see widespread adoption—around 1500 computations are done each day from around the world. In order for the Sage Cell Server to reach its potential of being used in a substantial fraction of college math classrooms, significant work remains in scaling the service to enterprise levels. Along with these changes, we will be exploring how to create a sustainable model for widespread use. We will also improve the support for interactive demonstrations, particularly for 2d and 3d graphics.

Development of the Cell Server is led by PI Grout.

SageMathCloud SageMathCloud (SMC) is a system for scientific collaboration, with a focus on higher education. Features of SMC include the complete Sage computer algebra system (and all other open source mathematical software), a text editor, a chat system, both private and shared files, and the ability to form working groups. The instructor and students in a class can become a "group" in SMC. Students working on a project can form a "team" within the group. Both the group and the teams within the group have private space to work together on the course content, homework, and projects. These resources are available *anywhere* with a network connection *without installing any software*. Unlike most course management systems, these collaboration features have been designed into SMC from the beginning, resulting in smoothly functioning tools which directly address Issue 5 while playing a supporting role in Issues 1, 2, 3, and 4.

The SMC opens new possibilities both inside and outside the classroom. If a student has a question about Sage, the instructor or TA can view the student's worksheet from their own computer, and then give feedback by sharing their own worksheet or directly commenting on the student's worksheet. A team of students working on a project can edit a common set of files in their own private directory, reducing many barriers to collaboration. All these activities can occur whether or not the people are together in the classroom. Project Leader Beezer has held online SMC "office hours" in the evening, using the chat feature to answer questions, while being able to look at the student's work just as clearly as if they were sitting together in his office.

The seamless integration of all these features, the minimal effort required to begin work in SMC, and the inclusion of features specific to STEM education, opens new possibilities which we are excited to explore. The basic features of SMC are under development as we complete our first UTMOST grant, and we already have over 2,000 active users (unique returning visitors each week), who provide extensive feedback. Major work ahead of us includes the creation of improved infrastructure so that SMC can be made even more widely available, and improving the usability and interconnectivity of specific features. Of particular importance is our research involving the test sites, in which we will obtain data on the use of SMC by a large number of instructors in a variety of courses. SMC takes snapshots of the state of each project every 2 minutes, which provides an enormous amount of new data that we can analyze to improve the usability of SMC and its ability to support good pedagogy.

Development of the SageMathCloud is led by PI Stein.

Textbook Authoring Tools Electronic forms of textbooks hold great promise to improve on printed versions. With much lower barriers for publication they have the potential to greatly increase the supply and variety of textbooks. Technical improvements in the display of mathematical formulas and styling of web page elements, along with an increasing supply of embedded applications, make it an exciting time for creating these electronic texts.

As we mentioned in Issue 4, textbooks do not always meet the needs of current students. A specific issue we will address is the availability of good online versions of textbooks. It is well-established that students want to have traditional paper textbooks [12], [19]. But it is also clear, at least anecdotally in our observations, that students benefit from an electronic version which they can have with them at all times. It is quite difficult to view a PDF version on a mobile device, so this points to the need for an electronic version which makes better use of the Web.

We will develop tools which will allow authors to easily create interactive mathematics textbooks in a variety of output formats. We will design a simple-to-use specification that will allow authors to capture the structure of their work, and together with our conversion tools, to create print-on-demand, PDF, web page, or Sage Notebook versions that accurately represent the content and structure of what they have written. The electronic versions can host embedded audio and video, or interactive GeoGebra, Sage Cell, or CodeMirror applications, and eventually online homework questions. These improved versions of textbooks address Issue 4, and our tools will lead to the creation of more open textbooks, addressing Issue 3.

Development of the Textbook Authoring Tools is led by Project Leader Beezer.

AIM Editorial Board For many students the cost of textbooks is significant and their educational progress is jeopardized when they do not buy the required books or reduce their course load to save on book expenses. But faculty wanting to find suitable open textbook for their classes can be overwhelmed by the mass of available material, much of which is not suitable for their course. These conditions motivated the creation of the AIM Open Textbook Initiative in order to evaluate, identify, publicize, and promote open source and open access textbooks for undergraduate mathematics courses.

During the past three years, the Editorial Board developed objective criteria for evaluating open textbooks and applied these criteria to the majority of available open textbooks for mainstream university math courses. Twenty-five books have meet the Board's criteria. The books are listed on project's website with clear and concise information about each, providing valuable resource to faculty who might consider adopting an open textbook. The Board has publicized its work at the Joint Mathematics Meetings for the past three years and in articles published in the principal news publications of the American Mathematical Society [3] and the Mathematical Association of America [2].

Our experience in the first UTMOST grant has led us to an understanding of the shortcomings that are present in many open textbooks, as well as an appreciation of the work required to address those shortcomings. The Editorial Board will work directly with open textbook authors to improve the content of existing textbooks, while other members of the UTMOST team will assist authors to create online versions that incorporate appropriate technology, such as Sage Cells. These efforts will address Issues 3 and 4 by increasing both the number and the quality of open textbooks.

Editorial Board activities are led by PI Morrison.

Pedagogy and Educational Research Computer algebra systems (CAS) have long held great promise for education. CASs are currently found in many undergraduate classrooms, and there is a considerable amount of research has focused on the use of CAS in the teaching and learning undergraduate mathematics. Studies have documented the improvement in students understanding ([26], [27], [36], [40]). The use of technology allows students to avoid long tables of integrals or Laplace transforms, find numerical and graphical solutions to differential equations, visualize complicated 2-D plots and 3-D mathematical objects, and easily deal with unwieldy matrices in linear algebra. The ability to make large computations, quickly and without errors, with graphical output, can greatly aid students understanding of difficult ideas in mathematics and provides them with an incredible capacity for experimentation and conjecture.

Our vision of SageMathCloud as a teaching and learning environment with the computational capabilities of a computer algebra system allows new possibilities for the teaching and learning of mathematics. From a teaching and learning point of view, the SMC fulfills many of the functions of a the typical course management system (CMS). In addition to being able to do computation using Sage (and R, Octave, IPython, etc.) and communicate mathematics using LaTeX or ASCIIMath, students and teachers can share files, grade assignments, and participate in chatrooms.

Research on how CMSs are used for teaching and learning is still developing [37]. To date, much of the research on CMSs has focused on technical issues. With test site data and other data collected during project evaluations, we have an opportunity to address some interesting research questions. For example, how do student interactions with the SMC chat environment or Sage computations influence the delivery of content? Does the using SMC change how we evaluate students? We anticipate that other research questions will arise during the course of the project.

Pedagogy and Educational Research efforts are led by PI Judson.

Test Sites In order to better understand the effects of open software and textbooks in undergraduate mathematics classrooms, we will expand the number of relationships we have with individual faculty, and include department-level relationships. Individual faculty will report on the transformations of their classes using these new materials and administer survey instruments such as the Student Assessment of Learning Goals (SALG). Departments will experiment with the use of Sage, the Cell Server, and the SageMathCloud. Besides being useful for research about the effects of our efforts, these test sites will be highly targeted component of our dissemination efforts.

Sage Educational Days Workshops Sage Days workshops, and Sage Educational Days in particular, have a unique atmosphere, which is dynamic and highly productive. They have been a key component of our previous project, winning praise from both the participants and our evaluators. We will greatly increase the frequency, attendance, and geographic diversity of these workshops as part of a much larger dissemination effort.

Workshops will address Issue 1 through the training of instructors on the use of Sage in the classroom, and Issue 4 through the development of curricular materials by workshop participants.

All of the PIs are actively involved in working with the Test Sites and organizing Sage Educational Days Workshops.

3 Project Activities

We provide more details on the components of the UTMOST Project.

3.1 Sage Cell Server

The primary purpose of the Sage Cell Server is to lower the barrier to using Sage for simple calculations and demonstrations. The Cell Server accomplishes this by providing a way to embed live Sage computations seamlessly into existing web pages, easily share simple computations and demonstrations via permalinks and QR codes, and query Sage over the internet programmatically. A popular use of the Cell Server is to embed live Sage computations into webpages—a few lines of JavaScript and HTML embed a small code editor, optionally preloaded with useful code, and an "evaluate" button (over 4,800 different web pages have embedded a Sage cell in the last 6 months). Sage Cells occur throughout PI Beezer's linear algebra textbook, as shown in Figure 1.

Our authoring tools will make it easy to create textbook with online versions that incorporate Sage Cells and other interactive features.

Other applications of Sage Cells occur in the classroom. For example, in PI Grout's class, a multiple-part problem in a PDF file has a Sage Cell permalink in the margin next to the first part. Students click on the link and their web browser opens up to a live Sage cell visualizing the situation. The next part of the problem has a hint in the margin telling how to modify the code in the Sage cell to visualize the second part of the problem. The third part of the problem has a margin note asking the student to check their work (but without explicitly telling the student how to modify the code). In each stage of the problem, the student sees an immediate benefit to using technology and is gradually guided in how to use the system in increasingly complex problems.

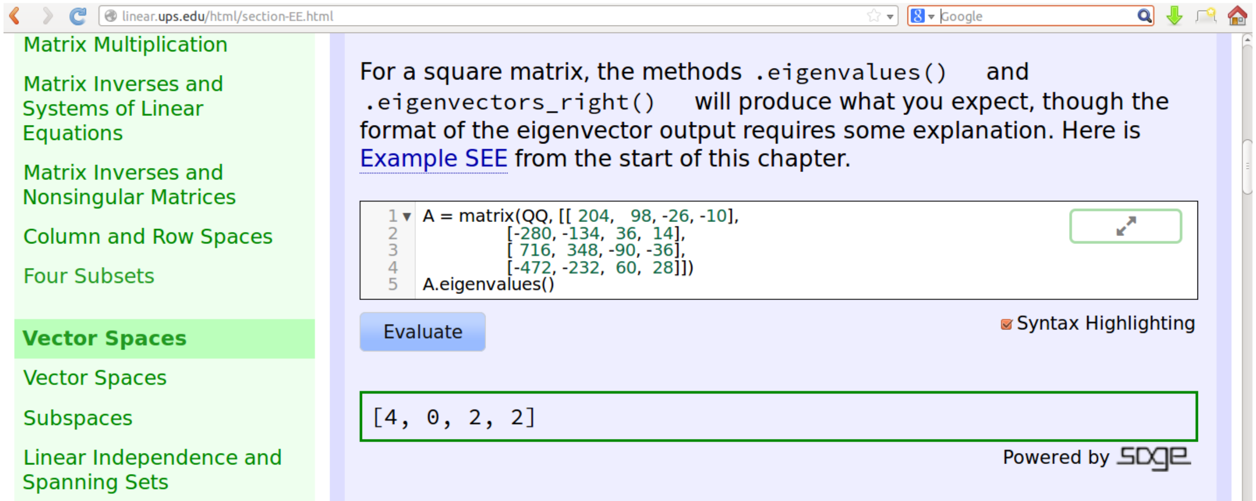

Figure 1: Executed Sage Cell embedded in online version of *A First Course in Linear Algebra*

Students can spend as much time as they wish investigating more deeply, from simply modifying and running the provided commands (right in the instructor's webpage) to copying the code to a more comprehensive environment such as their SageMathCloud account or their own copy of Sage. Since Sage is open source, advanced students can (and do) dive into the internals of Sage, implement the functionality they need, and become part of the professional mathematical community.

The Sage Cell Server enables a variety of instructional techniques for incorporating technology in the classroom. An instructor can easily create and demonstrate a live example involving sliders, buttons, interactive 2d and 3d graphics, combined with sophisticated mathematical algorithms, on a publicly-available webpage or online textbook. An instructor can explore an example in front of a class, click a button to display a QR code on the projector screen sharing the demonstration, and students with mobile phones and a commonly-available QR code app can take a picture of the code on the projector from their seats and instantly have their own live copy of the demonstration for a group activity.

Our main development priorities are (a) making it securely and robustly scale to enterprise levels and (b) continuing to develop better interactive capabilities. Currently, the Sage Cell Server handles about 1,500 computations each day. Going forward, in order to handle, say, 1,000,000 computations each day, we will need to implement several enhancements including: a distributed database for permalinks, a larger load balancing architecture, enhanced testing and security, and an updated infrastructure which will enable us to deploy upgrades without any down time. This work will be performed in conjunction with the development of the SageMathCloud.

A second focus in our proposed development is better interactive capabilities. We have experimented much in this area our first UTMOST grant, and current web technologies are rapidly maturing to allow greater and greater interactivity. We will work with other major open source projects like IPython and Matplotlib to push these boundaries even further. For example, web browser technology is just maturing to the point where we can have rich input like interactive graphs, drag-and-drop images, 2d matrices and tables, and sliders and buttons in the *input*.

3.2 SageMathCloud and Course Management SageMathCloud (SMC, cloud.sagemath.com) combines open source technology for cloud computing with mathematical software (e.g., web-based Sage and IPython worksheets) to make online mathematical computation easily accessible. People can collaboratively use mathematical software, author LaTeX documents, use a full command line terminal, discuss in a chat window, and edit complicated computer programs, all using a standard web browser with no special plugins. The core design goals are collaboration, availability, and reliability. The current dedicated infrastructure should easily handle well over a thousand simultaneous active users, and we plan to scale up to tens of thousands of users as demand grows (about 180 users sign up each day right now). Also, the site receive about 5000 unique visitors each week, with an average visit duration well over an hour.

Most open source mathematical software is pre-installed into SMC, and users can also install their own copies of proprietary software, if desired. Instructors are able to provide these resources to their students with no preparation and no overhead. Students, faculty, and teaching assistants then have a common place to compute, write, discuss and collaborate. The only requirement is a modern device with a connected web browser.

We will add functionality to SMC to better support using SMC as a tool for teaching an undergraduate or graduate course. Enhancements will include a facility to tie together a collection of projects and supplementary material for a course. An instructor will create a course project, then add information concerning the students and TAs in the course, and (optionally) link the SMC course project to a campus-wide course management system such as Blackboard, Moodle or Canvas. SMC then creates private projects for each student in the course, with the student and instructor as collaborators, projects for the TAs, and a single big common course project that is shared by all. Tabs to access some of those features can be seen in Figure 2.

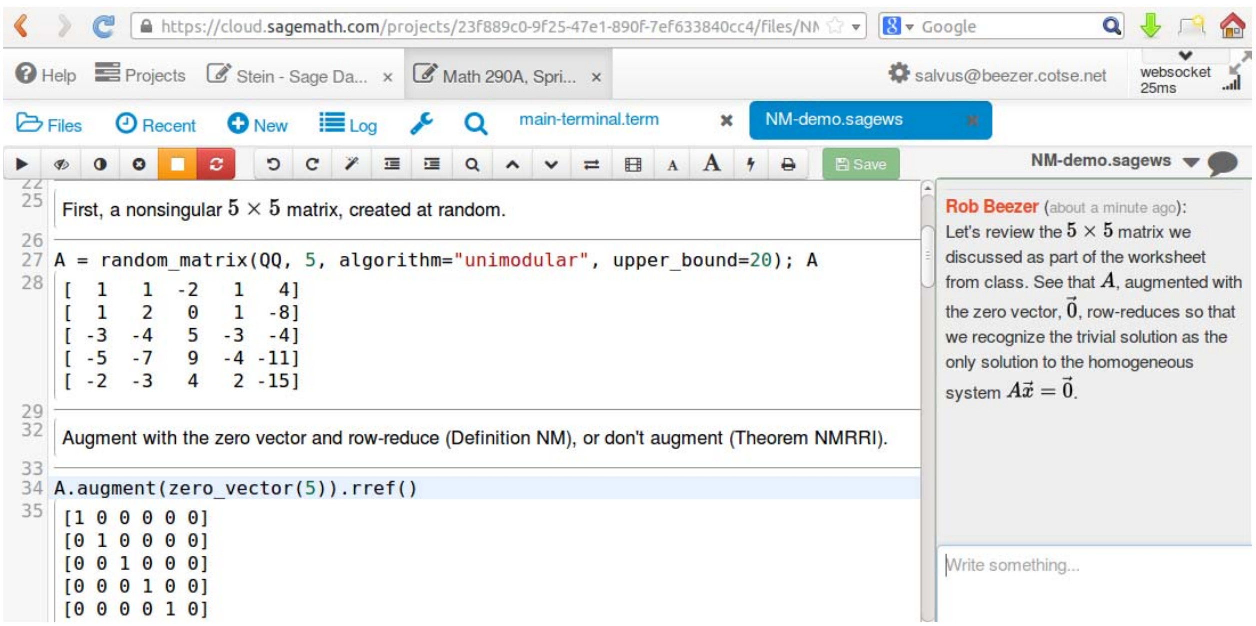

Figure 2: SageMathCloud with Sage worksheet and chat window

The instructor can share files (e.g., notes, homework, videos, etc.) with the students, just with a single click. Conversely, to gather files back from all students, the instructor specifies a directory and a deadline, and at the deadline all relevant files (such as completed homework assignments) are copied to the directory. Finally, the instructor can "return" the graded homework within the SMC. Some parts of the grading process may be done manually, and others could be automated, leveraging the extensive power of Sage and the SMC environment. Grades could be entered directly into SMC, and then securely transferred to the linked course management tool.

The display for a course will show a list of the student projects indicating current and historical activity in each. If a student appears to be having trouble (e.g., having many errors in Sage or LaTeX, or clicking a "help" button), the instructor could visit their project and chat with the student while also seeing exactly what the student is doing (via document synchronization) and has done (via the snapshot history). For example, we recently incorporated WebRTC-based peer-to-peer video chat into SMC. An example in the SMC (using text chat, not video) is in Figure 2.

SageMathCloud was initiated towards the end of the UTMOST CCLI grant, and has been under very active development since. There is an ongoing commercialization effort through University of Washington, motivated by many users who have requested more compute power, disk space, or the option to host their own installation. We envision a sustainable service that builds on open source tools for communication and protocols, and for computation. Some level of service will always be freely available. To provide higher levels of service and guarantees of availability, individuals and institutions will purchase subscriptions and support contracts. We will experiment with this "freemium" model of sustainability by providing support contracts for our test sites.

3.3 Textbook Authoring Textbooks are highly structured documents. They are meant to be read, and then reread, and then consulted again later as a reference. Interconnections among the information contained in a textbook is reflected by an author's cross-references. We do not read these books straight through, as if they were novels. Electronic textbooks offer much more effective ways of navigating, and learning from, this structured material. They also allow for embedded interactive computational tools (such as Sage Cell, Geogebra, CodeMirror) along with embedded media such as audio and video. Electronic versions can be viewed on a variety of devices and can be transported easily. Books offered commercially typically reserve or control the right to make copies, negating or diminishing many of the advantages of an electronic format.

Textbooks with open licenses can take full advantage of electronic formats, though few authors have all the technical skills to produce these texts in effective formats. We will design and implement a system for authors to author textbooks, which allows them to concentrate on the *content*, rather than *presentation* and *production*.

We have extensive experience producing mathematics textbooks, and other materials, in multiple output formats, such as print, PDF, web pages, Sage notebooks, iPython notebooks and SMC worksheets. Through a great deal of experimentation, we are convinced that eXtensible Markup Language (XML) is the appropriate syntax for capturing the *structure* and *content* of a scholarly document. Then the eXtensible Stylesheet Language (XSL) in the hands of a single expert, can transform the writings of many authors into accurate, effective, and aesthetically pleasing formats (plural), including those not yet imagined. No other markup language offers the possibility of a simple, flexible and powerful system for describing and preserving the structure of a document and converting it to arbitrary output formats.

Our XML application will be designed by authors, for authors. For anyone who already understands LaTeX it will be easy to learn quickly. The syntax for mathematical expressions will continue to be the same as LaTeX, which can then be rendered in the traditional way as print, or with MathJax for electronic formats. All of the technical aspects of an electronic book (MathJax, HTML, CSS) will be encapsulated in the conversion routines, along with the technical aspects of embedding interactive applications or media. The result is that it is easy for authors to embed interactive computational tools, such as instances of the Sage Cell Server.

We have begun work on this system with initial support from the Shuttleworth Foundation. A handful of individuals are helping develop the system by writing homework notes, solution manuals, study guides, monographs, and textbooks using the limited capabilities present now. These authors find it extremely liberating to be freed from thoughts about presentation and production when writing, and focus on an author's job — creating content. It is the high quality of the resulting output, and the simplicity of producing it, which draws them in and motivates them to learn a new approach to authoring. There remains a lot of work to do, especially in allowing for some customization of the output, and supporting new users with documentation and assistance.

An example of what is possible is Project Leader Beezer's textbook *First Course in Linear Algebra* [8]. From the XML source, the book is available in print, PDF, and HTML, and the

HTML has 579 embedded Sage Cells. The XSL transforms which produce those various versions can be used on *any* book written in XML. This will be an enormous benefit to other authors.

At the start of this project we were concerned that the transition to XML may be difficult for authors. However, we have recently developed a tool for converting existing LaTeX to HTML and XML. We applied this tool to the source of PI Judson's abstract algebra textbook. The resulting HTML averaged fewer than one error per section, all of which were easy to fix by hand. This facility greatly decreases the start-up cost to authors who wish to make use of the XML tools we are developing, making us confident that we will see wide adoption.

We will be successful if we can expand this system to accommodate all of the structure authors need for their projects and provide high quality conversions to the most popular output formats. If the design of the XML application is done carefully and thoughtfully, then others will become involved and contribute conversions to other formats, or with alternative styles. We hope to create a community of users with successful projects, which will in turn attract others to become users.

3.4 American Institute of Mathematics Open Textbook Initiative The AIM Editorial Board sees a common need for a stronger editorial presence to ensure a consistent and professional tone throughout open textbooks. Most authors need, and benefit from, editorial help. This is one area where there is a large gap between open textbooks and professionally published texts. Similarly, creating effective and attractive graphical content requires technical abilities that not every open textbook author possesses.

Open textbooks also need communities to foster their development and expand their reach. It is not enough for an author to place a PDF version of the book on a website and wait for it to be discovered and adopted. To be successful a book needs an ecosystem made up of contributors, coauthors, and instructors using the book, along with infrastructure such as a website with information about the versions available, how to purchase a hard copy, errata, means to identify errors, make comments, suggest improvements to the author, and adoption lists.

But it is too much to expect individual authors to perform all the tasks desirable for a robust textbook environment. Of the twenty five books now on our approved list there are several that can be improved with some dedicated editorial work. We will employ three editors, each working 120 hours over the summer, collaborating with the authors, and focusing on individual books and whatever is most vital to improve them. This could be copy editing (particularly for the books that were not once commercially published), checking exercises and solutions, adding exercises, improving or adding graphics, embedding Sage cells, arranging for on-demand printing, gathering data on course adoptions, conferring with instructors who have used the books, making connections to a homework system, and expanding and improving websites.

The Editorial Board will also continue to evaluate open textbooks.

3.5 Pedagogy and Educational Research Computer software, especially computer algebra systems (CAS), are now widely used for the teaching and learning of mathematics. Currently, CAS are widely found in the undergraduate classroom and a considerable amount of mathematics education research has focused on the use of CAS in learning undergraduate mathematics. A good example of how technology has changed the curriculum can b e found in an undergraduate ordinary differential equations course. Most differential equations cannot be solved explicitly, but technology has enabled teachers to incorporate a qualitative approach in the courses that they teach [13].

The ability to make large computations, quickly and without errors, with graphical output, can greatly aid students understanding of difficult ideas in mathematics and provides them with an incredible capacity for experimentation and conjecture. However, we rarely see a seamless integration with the curriculum. To accommodate competing commercial systems that divide the market, textbooks typically offer supplements for several different CAS, or they are technology-enhanced with generic sidebars. Licensing restrictions for campus use, the expense of personal copies, and underpowered hardware often mean that students can only work with commercial software in campus labs. Some institutions are unable to afford the cost of building such labs for their students.

There have been efforts at seamless integration of technology and specific curricula (e.g., calculus [46]). An example of such an experiment is the Calculus & Mathematica project, which generated much excitement in the early 1990s and had demonstrable success in helping diverse students learn more effectively [1], [41]. However, today its use seems limited to the two institutions where it originated [39], [48]. Likewise, the use of interactive Java applets to support teaching mathematics (such as [5][14][28]) does not seem to have been widely adopted. The undergraduate curriculum has not seen the broad transformative effect of these powerful tools for increasing the learning and understanding of mathematics.

We propose an approach that will integrate open source software, open textbooks, and open curricular materials into a single learning environment and will complement more general course management systems (CMS) such as BlackBoard or Desire2Learn. Much of the research on CMSs to date has focused on technical issues. Research on how CMSs are used for teaching and learning is much less developed. To understand how CMSs are used for teaching and learning, we can divide how they are used into categories: transmitting course content (Level 1), evaluating students (Level 2), evaluating courses and instructors (Level 3), creating class discussions (Level 2), and creating computer-based instruction (Level 3) with the most used categories being Level 1 and the least used being Level 3 [37]. Project UTMOST and SMC offers a unique opportunity to collect data on how these categories influence each other. We propose the following research questions.

- Does using a comprehensive environment for the teaching and learning of mathematics such as SMC to deliver content, encourage class discussions?
- If students and instructors take advantage of SMC and interact at a high rate, does this lead to the creation of new instructional materials (either by student or instructor) such as a Sage worksheet describing how to plot phase planes in an ordinary differential equations course?
- Does SMC encourage computer-based instruction or computer-based assessment of students?

We can also ask if students are more likely to choose a course that uses open source textbooks and software? During the course of Project UTMOST, we anticipate that these research questions may be modified or other interesting research questions will appear. Since SMC can be configured to capture student and instructor interactions and other information, we have a unique opportunity to collect data on the teaching and learning of mathematics. In addition, we will have a great deal of data from the project evaluation.

3.6 Test Sites As part of our CCLI grant we selected faculty from eight institutions to experiment with Sage and open textbooks in their courses. We will expand this program in number and scope. We will give stipends to individual faculty who will work within the context of their own courses, and faculty who will work as liaisons with entire departments. The application process will require explicit departmental authorization, and will ensure that we include individuals and departments from Postsecondary Minority Institutions.

SageMathCloud will grow into a complete environment for supporting courses with computational aspects. Departments that wish to become involved will receive an annual support contract.

Individuals and departments will encourage students to participate in reporting their experiences through the Student Assessment of Learning Goals (SALG) and other survey instruments. Faculty will submit reports about the effects on their courses. These faculty will be required to participate in Sage Educational Days workshops.

3.7 Sage Educational Days Workshops Sage Days Educational Days workshops have been held at the University of Washington campus in Seattle each of the past three summers for three full days in early June (and another is scheduled for June 2014). They have proved a popular and productive way to exchange and refine ideas among faculty using Sage in their classrooms, and for faculty new to Sage to join a network of supportive colleagues. They have given the UTMOST PI's both constructive suggestions for improvements and the inspiration to innovate. Conversely, they are an excellent vehicle for disseminating the work we have done. There has also been a concurrent Sage Developer workshop focusing on tools and procedures relevant to undergraduate education (with some intersection between the groups).

We are proposing to increase the annual frequency of these meetings from one to two, with an increase in attendance per workshop from thirty to forty-five, and with greater availability of travel support for participants. While we may continue to meet in Seattle annually (given the concentration of Sage developers in that area), we will also be able to spread out geographically across the United States to be more available to faculty in other parts of the country. Some may be held in proximity to, or as part of, the January and Summer mathematics meetings, or regional MAA meetings.

Much of the focus of our CCLI grant was on supporting faculty. We would like to proceed now to carefully consider the effects of our work on students. So the themes of these workshops will put a greater emphasis on pedagogy and the role that computation and alternative textbooks have on students' learning.

Our outside evaluators have received many supportive comments from participants, and the evaluators have encouraged us to broaden the size and scope of these workshops. We will be successful if we can broaden participation, both in absolute numbers and in terms of geography and types of institutions represented. We will also be successful if we can expand the scope of the topics and discussions to center more on outcomes for student achievement.

4 Broader Impacts The UTMOST project has a wide range of broader impacts.

The Sage Cell Server improves STEM education through its ability to enhance classroom teaching by providing ready-to-use computer demonstrations of advanced mathematical concepts. The Sage Cells are easy to modify, allowing students to easily explore complicated concepts. Sage Cells have the potential to benefit the vast majority of lower-level mathematics courses.

The SageMathCloud also enhances STEM education through its ability to create a collaborative learning environment that is specifically designed to support the needs of courses involving a significant mathematics component. The SageMathCloud also has broader impacts by enhancing the infrastructure for research in the STEM disciplines.

The Textbook Authoring Tools and the Editorial Board contribute by both improving the integration of technology into existing textbooks, and enabling the creation of new high-quality open textbooks. These efforts enhance the education opportunities for all students in the STEM disciplines, and in particular contribute to the creation of a diverse workforce by lowering the barrier for low income students.

The Sage Education Days workshops directly contribute to instructor development through training in the use of Sage in the classroom, and through the development of a catalog of demonstrations (Sage Cell interacts) which will be made freely available to all students and instructors across the world.

In addition to the above benefits which have wide impact, through the test sites involved in this project, UTMOST will directly benefit 30,000 students in 250 courses at 90 universities through the entire project.

5 Evaluation Formative and summative evaluation will be conducted at different phases of the project to address questions about the effectiveness of the project in creating and implementing the UTMOST model and Sage-enhanced materials for undergraduate mathematics teaching and learning. Dr. Judson will coordinate internal evaluation data-gathering, and will serve as the liaison to external evaluators from the University of Colorado at Boulder. The evaluation questions include:

1. What aspects of the Sage-based tools and open materials are beneficial to instructors, what challenges do they face, and what kinds of support do they need in integrating these to mathematics teaching?

2. How do instructors use and apply the Sage-integrated curriculum materials, and how do these benefit (or fail to benefit) their teaching of mathematics?

3. How do the tools and materials impact instructors' content knowledge, pedagogical content knowledge, classroom instructional practice, and their students' learning?

Information will be gathered on both the processes and outcomes of the project at different stages. Formative components will focus on monitoring the quality of project activities, enabling the project to make mid-program corrections and plan for future development. Summative components will focus on the impact of the project on instructors' instruction and student learning at the test sites. Instructors and classrooms will be sampled, taking into account instructor interest and local institutional cooperation.

5.1 Study design The study design includes pre- and post-surveys, follow-up surveys included in yearly self-reports, and sampled interviews of participating instructors. In addition, students will answer an online post-survey focusing on their experiences and gains in learning mathematics, including their classroom use of the Sage-enhanced materials. The design is informed by previous evaluation studies on professional development, education, and workshops in STEM fields [15], [16], [36], [42], [47] and on student outcomes of active instructional methods in undergraduate mathematics [24], [25].

Pre-survey Registration surveys for the Sage Education Days workshops will collect demographic and contact data for participants, as well as information about their awareness of workshop topics. The survey will also gather information about participants' classes, institution, current teaching practices, and pedagogical needs.

Sage Education Days workshops The two Sage Education Days workshops each year will include evaluator observations and brief daily surveys at the end of each day; these data will be summarized by the evaluator each day and presented to the facilitators that evening. This process will allow the next day's agenda to be fine-tuned to maximize effectiveness. At the end of each workshop, a final survey will be implemented, gathering overall feedback about the workshop and asking about participants' plans for using the model and Sage- enhanced materials to help guide later components of the study. A report will be generated summarizing the evaluation data collected for each workshop (from registration, daily, and final surveys). Evaluation information from each workshop will inform the design of subsequent workshops in the project, allowing ongoing refinement and improvement over the course of the program.

Follow-up survey and reports After using the model and Sage-enhanced materials for one year, the internal evaluators will have the participants file a report on their implementation, including some follow-up survey questions. They will report their use of the model and Sage-enhanced materials in their own classrooms and their future plans. Additional data on implementation will be gathered by the project team during site visits; they will conduct student focus groups using a protocol co-developed with the evaluators.

Student learning assessment Student learning will be evaluated after the first year of implementation with a post-survey based on the NSF-supported SALG instrument (DUE-0920801) [45]. This will provide information on student outcomes as well as formative feedback for the instructors using the model and Sage-enhanced materials in their classroom. A mathematics-specific version (SALG-M) has already been validated and used in a large evaluation study, and is sensitive to differences by student group and classroom practice [24], [35]. An enhanced version of this instrument was developed during the first UTMOST grant and incorporated Sage-specific questions into the SALG-M instrument.

Follow-up interviews Based on instructor and student responses on other measures, a sample of instructors will be interviewed to study factors that affect their success in implementing Sage-enhanced materials. The interviews will explore classroom use of the model and Sage-enhanced materials, impacts on instructional practices, and instructors 'perception of students' response.

5.2 Management and dissemination The evaluation will be led by Ms. Susan Lynds from the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado at Boulder, who has been an evaluator for dozens of NSF, NOAA, and NASA STEM projects. Dr. Sandra Laursen will provide consulting on the evaluation; she is co-director of Ethnography & Evaluation Research (E&ER) at the University of Colorado at Boulder, and has extensive experience evaluating large mathematics and science education projects.

Lynds and Judson will collaborate with project members and partner institutions to conduct the evaluation study. Dr. Judson and the project PIs will conduct site visits to partner institutions to observe and document the use of Sage-enhanced materials. Dr. Judson will have primary responsibility for extracting information from the site visits and workshop data to feed back to developers to improve the technology and classroom resources. Surveys and interview protocols will be prepared and conducted by Lynds and Judson. They will analyze all data and will prepare an annual report to document the evaluation activities and results. This will provide formative evaluation feedback to the project PIs and participating instructors to inform design decisions and mid-program corrections. A final report will gather results after the implementation of the tools and materials by all groups of instructors. These findings will be shared also with the broader mathematics education community through a presentation and a coauthored article about the impacts of using CAS-integrated materials in teaching and learning undergraduate mathematics.

6 Results from Prior NSF Support

Title, Award *Collaborative Research: UTMOST: Undergraduate Teaching of Mathematics with Open Software and Textbooks*, CCLI Type II (Expansion), DUE-1022574, $525,000, September 2010 to August 2013, with one-year no-cost extension to August 2014.

Results: Intellectual Merit Many new ideas resulted from our CCLI grant. The Sage Cell Server was developed by PI Grout and his students as an innovative way to provide Sage computations in a wide variety of situations. Towards the end of the grant, PI Stein began work on the SageMathCloud, a huge undertaking that will provide a robust and more collaborative replacement for the Sage Notebook. This development work was motivated in part by our experiences with our test sites. PIs Judson and Beezer successfully created electronic versions of their textbooks, with interactive Sage components embedded.

The AIM Editorial Board, under PI Morrison, has been very well received. Authors of open source textbooks now view a recommendation from the board as important for the success of their textbook projects. The board has also done an excellent job of making mathematics faculty aware of the existence of open textbooks and best practices when selecting an open textbook. Sage

Educational Days workshops have proven to be a very popular format for exchanging pedagogical and technical information. Our test sites have provided invaluable advice about the use of open software and open textbooks in their courses, and have provided quantifiable information via the Student Assessment of Learning Goals (SALG) surveys.

Results: Broader Impacts Approximately thirty faculty attended each of our Sage Educational Days workshops, and in turn they each teach many students and work with colleagues in their departments. We had formal relationships with eight mathematics departments as part of test sites program. Our test sites included participation from Postsecondary Minority Institutions.

With open source software and textbooks readily available on the internet, it can be difficult to know the magnitude of the impact. The SageMathCloud, despite being beta-quality software, is attracting over 175 new accounts per day. The Sage Cell Server powers a wide variety of electronic resources. For example: a mathematics textbook from Poland (in Polish) is conceived as an electronic textbook and has embedded demonstrations powered by the Sage Cell Server [34].

All of our indicators: downloads of Sage source code or binaries, traffic at servers for Sage Cells, account creation and project access at the SageMathCloud, and reported adoptions of Sage-enhanced textbooks, indicate wide use of our software and materials.

Selected Publications and Presentations The first UTMOST grant has produced articles [2], [3], talks [10], [7], [43], and poster presentations [30], [31], [32], [33].

Research Products Our research products include publicly accessible software: the Sage Cell Server [21], [22], SageMathCloud [44], Sage Interact Database [23], and MathBook XML [11]. In addition we have produced Sage-enhanced textbooks [29], [8], and textbook evaluations [4].

7 Personnel

The UTMOST team consists of six mathematics faculty and two experienced evaluators of STEM education initiatives. The six faculty together have many years of experience teaching undergraduates at a wide range of institutions, four are active Sage developers (including its founder), three are authors of open textbooks, all have significant mathematics research experience, and one specializes in mathematics education research. Working together, they have the wide range of complementary experience and skills that have made UTMOST a success.

Robert A. Beezer Dr. Beezer, Professor of Mathematics at the University of Puget Sound, is an undergraduate teacher with thirty-six years of experience, an active researcher in algebraic graph theory, one of the first open textbook authors, and a Sage developer. The past four years he has presented courses on Sage at the African Institute for Mathematical Sciences in Cape Town, South Africa. He began writing his open source linear algebra textbook in 2004, began using Sage in 2007, and began contributing code in early 2009. He will lead the technical aspects of designing a tool for authoring structured scholarly documents. That work was initiated with support from a Shuttleworth Flash Grant in Summer 2013. He will also be involved with testing and classroom evaluation of SageMathCloud, novel applications of the Sage Cell Server, and the work of the Editorial Board. He will serve as Project Director.

Jason Grout Dr. Grout, Assistant Professor of Mathematics at Drake University, is an undergraduate teacher, an active researcher in combinatorial matrix theory and graph theory, and a Sage developer. Dr. Grout designed and led the implementation of the Sage Cell Server with a team of students. He also has worked extensively in implementing interactive technologies used in many classroom materials. Dr. Grout uses Sage in research and in teaching, and has given numerous presentations, tutorials, and workshops on using Sage in the classroom. Dr. Grout will continue to lead the development effort on the Sage Cell Server.

Thomas W. Judson Dr. Judson, Associate Professor of Mathematics at Stephen F. Austin State University, has thirty-six years of teaching experience. He has taught at the University of Portland, the University of Puget Sound, and Harvard University. Dr. Judson conducts research in mathematics and mathematics education and is the author of a successful open source undergraduate abstract algebra textbook. He has experience in working with diverse groups both in the US and abroad and has worked extensively with undergraduate mathematics teachers, pre-service and inservice high school teachers, and graduate teaching assistants. Dr. Judson will work with Dr. Beezer to to implement authoring tools for producing textbooks and other documents in multiple formats as well as producing Sage-enhanced materials. He will also work with Dr. Laursen and Ms. Lynds to guide research and evaluation efforts for the project.

Kiran S. Kedlaya Dr. Kedlaya, Professor of Mathematics at the University of California, San Diego, has research interests in number theory, algebraic geometry, and applications to computer science. He has been involved for many years in the development and promotion of Sage for use both in research and education.

Susan Lynds Formative and summative evaluation will be performed by Susan Lynds, a program evaluator and associate scientist at the Cooperative Institute for Research in Environmental Sciences (CIRES) at the University of Colorado at Boulder. Ms. Lynds has conducted internal and external evaluation studies for programs funded by the NSF, the NOAA, NASA, the U.S. Department of Education, and the U.S. Department of Agriculture. She holds an M.S. in science education from Oregon State University and has over ten years of experience in qualitative and quantitative methods of evaluation. She has evaluated for effectiveness dozens of teacher professional development programs, scientist and journalist workshops, curriculum development projects, informal science education programs, and online resources.

Sandra Laursen Dr. Laursen leads research and evaluation studies of higher education and career development in science, engineering and mathematics (www.colorado.edu/eer). Several recent projects have addressed student outcomes of inquiry based learning in mathematics and faculty development in college mathematics, with support from NSF and the Educational Advancement Foundation. Laursen and Lynds have previously collaborated on evaluation of UTMOST faculty workshops and university outreach programs.

Kent E. Morrison Dr. Morrison, Professor Emeritus at California Polytechnic State University, San Luis Obispo, is now affiliated with AIM, where he directs the AIM Editorial Board. During his career at Cal Poly, including nine years as department chair, he was notably involved in efforts to improve student retention and degree completion, articulation with the California Community Colleges, inter-disciplinary curriculum and pedagogy for math, science, and engineering students, career development for young faculty. At the same time he maintained an active research agenda across many areas of mathematics with some topics coming from senior projects or summer REU programs. At AIM he remains active in his own research, maintains the Institute's website and local network, and seeks to improve the social infrastructure of mathematics at all levels.

William Stein Dr. Stein, Professor of Mathematics at the University of Washington, will contribute to this project in both a development and managerial role. Stein has been a driving force over the last fifteen years in applications of computation to research in number theory. As founder and director of the Sage project (sagemath.org), he has experience managing large working groups and working with students on a wide range of projects. He also designed and implemented SageMathCloud. He will involve students and others in funded work on SageMathCloud and the goals of this project.

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