

Summary

Overview:

Computers are now ubiquitous in scientific research, but many researchers in science, technology, engineering, and mathematics (STEM) are still not *computationally competent*: they do repetitive tasks manually instead of automating them, develop software haphazardly, and fail to track their work in any systematic, reproducible way. This lack of foundational skills impedes their ability to do research, and prevents them from engaging with new opportunities in open and web-enabled science.

This project will train STEM undergraduates in these skills, and to assess the impact of that training on their productivity and career paths. We will do this by adapting the workshops run by Software Carpentry for researchers at the graduate level and above to undergraduates, and track their alumni over several subsequent years both to improve the training itself, and to encourage wider adoption of our model.

More specifically, we will run two-day software skills workshops each year for five years for undergraduate students taking part in that year in summer research opportunities such as the NSF's Research Experience for Undergraduates (REU) program, at or near the start of those students' time in the lab. We will additionally run at least one workshop each year specifically aimed at female students, and another specifically aimed at students from minority groups that are under-represented in STEM.

Together, these workshops will reach over 2000 students during the course of the project. Participants will then serve as the treatment population for a five-year study by a full-time professional researcher in educational assessment, who will explore the impact of this training on their careers in general, and their involvement with open and web-enabled science in particular.

Intellectual merit:

Our main contribution to knowledge will be an assessment of ways in which training of this kind can accelerate the careers of participants and the science they do. We will discover whether students who receive this training are more likely than their peers to continue to graduate school than their peers, to incorporate open science and/or web-enabled science tools and practices into their work, to choose computationally oriented research topics and/or careers, and/or to develop new computational tools and practices. We will also determine the extent to which training of this kind changes students' outlook on the practice of science itself, and whether it can help level the playing field for women and minorities currently underrepresented in computing and science.

Broader impacts:

In the medium term, this project will have broader impact through the creation and dissemination of teaching materials and practices that other educators and institutions can adopt. All of the materials produced by and for this project will be made freely available under the Creative Commons - Attribution (CC-BY) license, while the results of our studies of the program's effect will be shared with other educators through science education journals and conferences.

In the long term, the project's greatest impact will be on scientific competitiveness. Computing is no longer optional in any part of science: even scientists who don't think of themselves as doing computational work rely on computers to prepare papers, store data, and collaborate with col-

leagues. The better their computing skills are, the better able they will be to conduct world-class research that aids national economic competitiveness.

PROJECT DESCRIPTION

The Impact of Intensive Software Skills Training on Students' Scientific Careers

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1 The Problem

Scientists and engineers invented electronic computers to accelerate their work, but two generations later, many researchers in science, technology, engineering, and mathematics (STEM) are still not *computationally competent*: they do repetitive tasks manually instead of automating them, develop software using a methodology best summarized as “copy, paste, tweak, and pray”, and fail to track their work in any systematic, reproducible way.

While the World-Wide Web was created by a scientist to help his peers share information, many still use it primarily as a way to find and download PDFs. Researchers may understand that open data can fuel new insights, but often lack the skills needed to create and provide a reusable data set. Equally, any discussion of changing scientific publishing, making research reproducible, or using the web to support “science as a service” must eventually address the lack of pre-requisite skills in the general STEM research community.

Since the mid-1980s (at least), proponents of computational science have taken an “if we build it, they will come” approach to this problem. But this learning-by-osmosis approach has not borne fruit: most faculty would agree that today’s graduates are no more able to use computing and the web in *their research* than they were a generation ago. Reasons why “learning by osmosis” has not been effective include:

1. *The curriculum is full.* Undergraduate STEM programs already struggle to cover material regarded as core to their field. While many scientists would agree that more material on programming, reproducible research, or web-enabled science would be useful, there is no consensus on what to take out to make room.
2. *The blind leading the blind.* Many faculty lack computational skills themselves, and hence are unable to pass them on.
3. *Cultural difference.* Scientists and software developers have different priorities and different approaches to problem solving, which often impedes collaboration and knowledge transfer [13].
4. *Difficulty of assessing impact.* It is easy to say, “This discovery could not have been made without use of that supercomputer.” It is much harder to attribute specific advances in science to prior training in particular methods or techniques, particularly ones as young as those that facilitate open and web-enabled science.

The final, and possibly largest, issue is that *the rewards are unknown*. Open, web-based science is still in its infancy, so there is no general understanding of what people might need to know in order to incorporate it into their research careers. Since it is hard to measure something if you don’t know what to look for, or if it is so young that there hasn’t actually *been* long-term impact,

little systematic study has been done to date of whether early training in the skills needed for this new kind of science actually has an impact, and if so, how and how much. Without such feedback, there is no systematic way to improve the training programs that currently exist.

2 Proposed Work

This proposal builds on the success to date of the Software Carpentry workshops in enhancing the skills of graduate students, post-docs, and faculty. We propose to:

1. conduct formative evaluation of the impact of software skills training for undergraduates likely to continue in research careers as they progress through the early stages of those careers;
2. conduct summative evaluation of the training's overall impact on a multi-year timescale in order to improve the content and presentation of the training; and
3. disseminate the resulting curriculum widely.

We will run software-skills workshops for undergraduate students taking part each year in summer research opportunities such as the NSF's Research Experience for Undergraduates (REU) program, at or near the start of those students' time in the lab. We expect this training will help them be more productive during their research (graduate-level participants in our existing workshops typically report that what we teach saves them a day a week), and also prepare them to work in a world where all aspects of science are increasingly dependent on computing.

These undergraduates will serve as the treatment population for a five-year study of the impact of this training on their careers in general, and their involvement with open and web-enabled science in particular. In order to conduct this study, we will hire an expert in educational assessment, whose full-time work for the duration of the project will be to explore the effects of the training on workshop participants.

2.1 Workshops

We will run two-day workshops at a steadily increasing number of sites each year for four years, timed to coincide with the start of the summer influx of undergraduate research students. Each workshop will be offered to a minimum of 40 learners per site (giving us a target study population of 1440 students by year 4). The content will be tailored to meet local needs, but will be based on what is being used at that time by Software Carpentry and affiliated educational efforts. By design, it is straightforward to adapt workshop materials and contribute changes back to the Software Carpentry organization. These features enhance the portability and flexibility of the workshops, and increase the likelihood of wide dissemination beyond this project.

The home sites for investigators named in this proposal (Michigan State University, Utah State University, George Washington University, University of California – Berkeley, and University of Wisconsin – Madison) will run workshops in each of those years. Other sites will be added each year, increasing the total to 15 in year 5, which increases the size of our study population. We will focus expansion on NSF REU sites [10], but as detailed in the next section, we will also offer some workshops to other communities.

While there is, as mentioned above, considerable scope for customizing workshops to accommodate learners' prior experience and discipline-specific needs, a typical workshop devotes roughly half a day to each of these four topics:

- the Unix shell;
- version control with Git;
- programming in Python or R; and
- using SQL with databases.

What these workshops actually seek to convey, though, is the best practices a researcher needs to be *computationally competent* [16]:

- how to automate repetitive tasks;
- how to track and share work over the web;
- how to grow a program in a modular, testable, reusable way; and
- how to create, use, and share structured data.

All of the workshop instructors will have been trained and certified by Software Carpentry, and will have had experience teaching this material prior to engaging in this particular workshops. Just as importantly, all will themselves be working scientists who use these skills and concepts daily in their own research, and are therefore able both to serve as role models and to deal with unanticipated questions or challenges based on personal experience (e.g., [12]).

2.2 Increasing Diversity

In order to increase the diversity of the study population, at least one workshop in each year will be aimed specifically at female students. Software Carpentry's first such workshop, held in Boston in June 2013, attracted 120 participants; its second is scheduled for Lawrence Berkeley National Laboratory in March 2014, and at least two more will be held by the time work on this project commences (one in the United States and one in Europe). This work will build on that experience, and draw on the pool of instructors who have gained mentoring experience through those specific workshops.

Finally, we will organize workshops in years 2–5 specifically aimed at students from minority groups that are underrepresented in STEM. We are already in contact with the Computing Alliance for Hispanic-Serving Institutions (CAHSI), and with the Association of Public and Land-grant Universities' program for historically black colleges and universities (HBCUs); Software Carpentry is running its first workshop at an HBCU (Spelman) in early 2014, and we expect to have expanded these efforts by the start of this project.

2.3 Assessment

We will employ an expert in educational assessment full-time for five years to monitor and compare undergraduate participants in these workshops, participants in a subset of our regular (graduate-level) workshops, and non-participants (as a control population). As part of their work, this person will be responsible not only for collecting and analyzing data, but also for refining and extending the methods and measures used to gauge impact.

Assessment will focus particularly, but not exclusively, on the following questions:

1. Are students who receive this training more likely to continue to graduate school than their peers?
2. Are students who receive this training more likely than their peers to incorporate open science and/or web-enabled science tools and practices into their work?
3. Are students who receive this training more likely than their peers to choose computationally oriented research topics and/or careers? Are those who do not choose computationally oriented paths nevertheless more likely to incorporate the tools and practices mentioned above into their work?
4. Are students who receive this training more likely than their peers to develop new tools and practices, and/or become involved in outreach and education activities (i.e., are they more likely to become creators and leaders)?
5. Do outcomes differ between women and underrepresented minorities on one hand and non-underrepresented minorities and men on the other? If so, in what ways, and what steps are effective in correcting for these differences?
6. In what ways does this training change students' outlook on the practice of science itself?

This researcher will also explore ways in which our engagement with students changes the outlook and work practices of their peers and faculty supervisors (i.e., whether there is knowledge transfer sideways and upward), and at the effectiveness of the community building and dissemination activities detailed in the next sections.

As with our work to date (discussed below), assessment will use both qualitative and quantitative techniques. On the qualitative side, we will conduct a series of interviews over the five-year period of the study to see how attitudes, aspirations, and activities change. Quantitatively, we will measure uptake of key tools such as version control as a proxy for adoption of related practices, as well as exploring more traditional measures of research success such as progression to graduate school and publication/citation rates.

Our findings, and any new methods or measures developed, will be shared with other researchers through publication in peer-reviewed journals and high-profile conferences, as discussed below.

2.4 Community Building

We will employ one graduate student part-time at each participating site each year to provide technical support to workshop participants, and to act as an anchor for a Hacker Within-style grassroots group at that site. These community liaisons will not be study subjects, but will help us stay in touch with students who are (a key requirement for any longitudinal study).

Separately, the Mozilla Science Lab will focus part of its ongoing community engagement efforts on the students who have taken part in our workshops during both the remainder of their undergraduate careers and afterward in order to ensure that they become part of the broader open science community. This may include helping the students organize and run workshops of their own in subsequent years, connecting them with other open science projects, introducing them to potential graduate supervisors who understand and value their new skills and outlook, etc.

As a subordinate part of their work, the researcher employed by this project will assess the effectiveness of these local organizers. In particular, they will explore whether seeding activity in this way leads to the formation of self-sustaining grassroots groups, and if so, what activities those groups develop on their own, how (and how effectively) they share discoveries with each other, the extent to which alumni of this program stay engaged with these groups, and whether the presence of these groups has a demonstrable impact on students' career paths in general, and their engagement with open and web-enabled science in particular.

While it will not be feasible to bring all of the students participating in a given year's workshops together physically, we will organize and run virtual conferences toward the end of their research term to give them an opportunity to present their work to one another, discuss what they have learned, and build peer-to-peer connections. These conferences will also provide an opportunity to introduce participants to new forms of scientific "publishing", including blogging, the creation of screencasts and demonstration videos, and other methods that may not yet exist.

2.5 Curriculum Development and Dissemination

We will employ one instructional designer part-time during each of the study's first four years to create new material, and to improve existing material based on feedback from workshop participants and the assessment program. Here, "creating material" may include both designing and implementing new domain-specific learning modules, and translating existing materials into new forms, such as video recordings of lectures or auto-graded quizzes for self-paced instruction. This work will be done in consultation with educators at participating institutions in order to encourage incorporation of those materials into existing curricula.

All of the materials produced by and for this project will be made freely available under the Creative Commons – Attribution (CC-BY) license. The instructional designer will work with the Mozilla Science Lab and affiliated groups to share these materials, and the results of our studies of the program's impact, through science education journals, conferences, and other channels. Specifically, we plan to publish articles in:

- *Science Education*
- *Physics Education*
- *Journal of Computers in Mathematics and Science Teaching*
- *American Scientist*

and at the following conferences:

- the Special Interest Group on Computer Science Education (SIGCSE) of the Association for Computing Machinery, Inc. (ACM)
- the International Conference on Physics Education (ICPE)
- the Association for Biology Laboratory Education (ABLE)
- the Society for Industrial and Applied Mathematics (SIAM)'s education session at the Joint Mathematics Meeting
- the Education Training and Workforce Development Division's track at the American Nuclear Society (ANS)'s annual meeting

The dissemination of this project's curriculum has strong potential to be high. Workshop materials are all open access and flexible, thus they can be readily adopted by others. Adapting workshop materials is low cost and does not require special equipment. Workshop materials are structured

such that they can scale to the size and application of interest to a particular group. The Software Carpentry infrastructure provides support in the form of materials and people. Anyone using workshop materials can directly contribute changes and feedback, which both increases buy-in and improves the materials organically. And finally, local chapters of The Hacker Within create a natural ecosystem of support for workshop participants, their peers, and faculty.

As a subordinate part of their work, the researcher employed by this project will assess the extent to which curriculum developed during this program is taken up by other educators (particularly those who think of themselves as scientists first and computationalists second), and their perception of its utility. Mid-point results of this evaluation will be shared with the instructional designer in order to allow evidence-based improvement of the materials.

2.6 Project Management

Prof. Slaybaugh will be responsible for overall project management and reporting. The educational assessment expert hired by this project will report directly to her. Prof. Slaybaugh will be assisted by Dr. Huff, who will manage and coordinate the graduate student assistants at each site.

Dr. Wilson and the half-time instructional designer hired by this project will be responsible for preparation and publication of learning materials. Dr. Wilson will also provide instructional training for the graduate student assistants and other participants in the project on an ongoing basis.

Workshop operations (such as finding instructors and arranging their travel) will be handled by Mozilla staff who are performing these duties for the Software Carpentry program more generally.

3 Related Work

3.1 Theoretical Positioning

Our theory of action is straightforward: if students are explicitly taught these skills in a way that makes them seem both useful and important, they are likely to begin using them in day-to-day work, which will create a positive feedback cycle leading to them acquiring more (and more advanced) skills on their own, which in turn will result in them being more likely to engage in open and web-enabled scientific activities that would otherwise have been unknown, incomprehensible, or out of reach. Using the terminology of [9], our work is therefore primarily *design and development research*: we are attempting to develop solutions to achieve related to student engagement and mastery of specific skills, drawing on existing evidence (from our graduate-level workshops) to design and iteratively develop interventions, and ready to begin collecting data on the feasibility of implementing solutions in typical delivery settings.

3.2 Research

Studies of how scientists use computers and the web have found that most scientists learn what they know about developing software and using computers and the web in their research through osmosis and word of mouth [5, 11]. In our experience, most training meant to address this issue:

- does not target scientists' specific needs (e.g., is a general "Introduction to Computing" class shared with students majoring in other areas);

- only covers the mechanics of programming in a particular language rather than giving a complete picture including data management, web-enabled publishing, the “defense in depth” approach to correctness discussed in [3], or the other foundational skills laid out in [16]; and/or
- jumps to advanced topics such as parallel computing before scientists have mastered the foundations. (Most research on scientific computing, such as [7], does the same.)

3.3 *Software Carpentry*

Software Carpentry [2, 15] is the largest effort to date to address these issues. Originally created as a training program at Los Alamos National Laboratory in the late 1990s, it is now part of the Mozilla Science Lab’s efforts to help scientists take advantage of ways in which the web can change the practice of science today, and invent new ways tomorrow. Over 100 certified volunteer instructors delivered two-day intensive workshops to more than 4200 people in 2013 alone.

Software Carpentry’s curriculum and teaching practices have been refined via iterative design, and are informed by current research on teaching and learning best practices. Its instructor-training program [1] introduces participants to a variety of modern teaching techniques (e.g., peer instruction, active learning, and understanding by design), to concepts underlying these techniques (e.g., cognitive load theory), and to topic-specific work by computing education researchers (see [4], [6], and the first third of [14] for overviews.) One example of how they translate theory into practice is their insistence on live coding during teaching as a way of demonstrating and transferring authentic practice to learners.

Software Carpentry has been assessing learning outcomes and retention since the beginning of its Sloan Foundation funding in January 2012. The first round of assessment included both qualitative and quantitative assessment by Dr. Jorge Aranda (then at the University of Victoria) and Prof. Julie Libarkin (Michigan State University).

Dr. Aranda surveyed and interviewed participants, observed a workshop, and analyzed screen-casts of participants working through a programming assignment. He found significant increases in participants’ understanding and use of shell commands, version control tools, Python, and testing techniques. Perhaps more importantly, participants reported better proficiency with software tools; greater concern for issues of provenance and code quality; better strategies to approach software development; and new research questions that have become accessible thanks to an increase in participants’ software development skills.

Prof. Libarkin performed a more detailed assessment of participants in a workshop held there, which was attended remotely by students from the University of Texas at Austin. 85% of participants reported that they learned what they hoped to learn, 81% changed their computational understanding, and 96% said they would recommend the workshop to others.

An attempt to scale this up in 2013 was set back by personnel changes, but systematic follow-ups with past participants in workshops have now been resumed, and we expect to be able to present preliminary results by mid-2014.

3.4 The Hacker Within

The Hacker Within (THW)[8], was founded by graduate students in nuclear engineering at the University of Wisconsin to provide a forum for sharing scientific computing skills and best practices with their peers. As it matured as a student organization, it attracted students from many scientific disciplines and academic levels. THW conducted bi-weekly seminars and developed a series of short courses addressing programming languages C++, Python, and Fortran, and best practices such as version control and test-driven code development, as well as basic skills such as UNIX mobility. This curriculum was delivered primarily as interactive short workshops on campuses and during scientific conferences. Many previous founders of the Hacker Within have since become instructors with Software Carpentry and a new generation of THW graduate students has begun to emerge in their place. In 2013, new branches of THW were begun at the University of Melbourne and the University of California - Berkeley.

4 Broader Impact

We believe this work will have significant impact in several related areas.

1. *Enhance economic competitiveness.* Computing is no longer optional in any part of science: even scientists who don't think of themselves as doing computational work rely on computers to prepare papers, store data, and collaborate with colleagues. The better their computing skills are, the better able they will be to contribute to the research that underpins the nation's economic competitiveness.
2. *Improving STEM education for everyone, not just participants.* By creating and validating high-quality open access teaching materials, and the methods used to deliver them, this project will enable improvement in STEM education for everyone, everywhere, not just for participating students and participating institutions.
3. *Improving STEM education tomorrow, not just today.* As noted in the introduction of this proposal, most of today's efforts to transfer computational skills to STEM researchers and connect them with 21st Century innovations in how science is done are flying blind: there is effectively no feedback from long-term impact to instructional action. By creating and validating such a feedback loop—i.e., by showing scientists how to apply science to their teaching—this project will demonstrate how STEM education can be continuously improved.
4. *Improve participation in STEM by women and underrepresented minorities.* The disproportionately low participation of women and some minority groups in STEM is well documented, as is the fact that computing is one of the least diverse fields within STEM. This second fact creates a vicious circle: people with weaker computing skills may be less competitive in research than their peers, which reduces their participation in activities viewed as non-core, which in turn results in them having weaker skills. This project will strive to break this cycle by giving at-risk students an opportunity to “level up” in a supportive environment, and by connecting them with mentors who can serve as role models.

5 Career Management Plan

The graduate students who are serving as mentors for the undergraduates at the different universities will each be paired with a local faculty mentor. The faculty mentor will meet regularly with the graduate student to discuss and problem solve any issues that the graduate student or undergraduates are having, and to provide active mentoring on how to train students in computational approaches.

In addition to engaging with the graduate students on their mentoring of the undergraduates, the faculty mentors will also serve as a mentors for computational aspects of the graduate students' research and careers. In many areas of science, computationally-minded students are located in labs where the PIs do not have strong computational backgrounds. This means that they do not have a mentor to teach them about good computational practice in research. In addition, they do not have someone to discuss computational careers with, thus limiting their exposure to career paths outside of academia. Because the faculty mentors will have strong computational backgrounds themselves, they can fill this void for computationally-minded students.

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Data Management Plan

Human Subject Data

This project will collect human subjects data consisting of background demographics (including age, gender, ethnicity, field of study, and prior computing experience), career information (including undergraduate and/or graduate education, publication histories, and industrial experience), and degree and kind of participation in open and web-enabled science projects and communities. This data will be used to determine what impact the training provided by this project has on participants' careers and productivity.

The demographic data will be collected from questionnaires and interviews administered by the PI and student/postdoctoral researchers associated with this project, and will be entered into an electronic database. Since this data will be from human subjects, approval for human subjects research will be obtained through the University of California - Berkeley Review Board. To ensure confidentiality, each subject will be assigned an arbitrary code, which will be associated with all data relating to that subject. One file that contains the correspondence between subject names and codes will be kept in an encrypted password-controlled file accessible only to the PI and assessment researcher. The de-identified electronic data will be preserved on DVDs and external hard drives.

If requested, access to the de-identified data will be provided by contacting the principal investigator. Data will in principle be available for access and sharing as soon as is reasonably possible, normally not longer than one year after publication of the data. The data will be preserved for at least three years beyond the award period, as required by NSF guidelines.

We do not anticipate that significant intellectual property issues involved with this data will arise. However, in the event that discoveries or inventions are made in direct connection with these data, access to the data will be granted upon request once appropriate invention disclosures and/or provisional patent filings are made. The data acquired and preserved in the context of this proposal will be further governed by the University of California - Berkeley's policies pertaining to intellectual property, record retention, and data management.

Educational Materials

All of the educational materials produced by and for this project will be made freely available under the Creative Commons – Attribution (CC-BY) license. These materials will be placed in a publicly accessible version control repository, and also made available for download from the Software Carpentry web site in widely-used formats, including (but not limited to) HTML pages, PDF documents, and slide decks compatible with common presentation tools. Authorship and contribution will be tracked to ensure that contributors are credited for their work. If participating institutions show sufficient interest, we shall also provide materials in formats compatible with current and emerging e-learning standards such as SCORM and the Experience API.