Engaging Students With Computing And Climate Change Through A Course In Scientific Computing

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Abstract

Course-based undergraduate research (CURE) is an educational paradigm to engage students in authentic research projects as part of their classroom experience. We present a course-based undergraduate research experience (CURE) for first-year students to get acquainted with the research process and apply the skills of scientific computing to investigate publicly available information on climate change and its impacts. The course trains students in elementary programming skills and computational thinking using the Wolfram language (WL) and the Mathematica platform. The experience also provides students with an introduction to the climate change studies, secondary literature, and policy recommendations provided by the Intergovernmental Panel on Climate Change. Students apply the programming, data analysis, and information literacy skills from the course to identify and investigate climate change data to improve their research skills and engage with their peers in a collaborative research experience. The results of our pedagogical experiment are presented in the form of student survey results from the national CURE survey. We highlight student responses toward this learning experience and showcase the positive outcomes compared to results from the nationwide CURE survey of students.

Keywords: scientific computing, computational thining, first-year undergraduate, climate change, project-based learning

Introduction

Poor retention of undergraduate students in STEM fields has been implicated as an imminent threat to US economic demand in the 2012 report from the President's Council of Advisors on Science and Technology (PCAST, 2012). A key recommendation of that report was the replacement of conventional introductory laboratory courses with discovery-based learning experiences. This is expected to increase student retention and can contribute to increased persistence in the first two years of their undergraduate experience. Numerous programs have been designed to develop classroom undergraduate research experiences (Dolan, 2017; Elgin et al., 2017; D Lopatto et al., 2008; Singer et al., 2013) to fulfill the need for student retention and engagement in STEM disciplines. Many such programs have been devised in a variety of modalities from single institution single course to multi-institution collaborations and have been quite successful in increasing student engagement (Ashraf, Marzouk, Shehadi, & Murphy, 2011; Auchincloss et al., 2014; Carpenter & Pappenfus, 2009; Clark, Ricciardo, & Weaver, 2016; Dolan, Lally, Brooks, & Tax, 2008} These approaches have also been successful in directing students toward scientific careers (Eagan et al., 2013; David Lopatto, 2007; Seymour, Hunter, Laursen, & DeAntoni, 2004).

There is a wide variety of course-based undergraduate research experience (CURE) modalities and the implementation of this pedagogical tool can be an exciting and transformative teaching and learning experience ("CUREnet," n.d.). We have designed and implemented a learning experience that is based on the CURE paradigm and integrates key elements of this approach to present first-year students with an immersive and contextualized learning experience. Our approach involves training students in computational thinking, analysis of data, and applying their newly learned skills to one of the most serious issues of our time, climate change.

Climate change is now a well-regarded and established scientific fact ("IPCC - Intergovernmental Panel on Climate Change," n.d.). The scientific community has reached a consensus about its veracity and its real and measurable effects. There have been multiple attempts by academic researchers to integrate climate modeling and climate change education in mainstream courses (Carey & Gougis, 2016; Maslowsky, 2016). However, there is a wide disconnect between the scientific facts, public reporting, and understanding of these facts. The current political climate and the official US government stance on denial of climate change is in stark contrast to the generally accepted scientific standpoint. To the students that started college during the years 2016 - 2019, the differences could not be more glaring. On one hand, the US government's official stance is denial of climate change; while on the other hand students seem to be inundated with news media and much popular science literature about climate change and its impacts that are unfolding across the world. This crisis of confidence presents a unique learning opportunity to create a lasting impact.

We think it is prudent to educate the next generation in leveraging the advances in computing to analyze, interpret, and solve challenging problems that threaten our world. One potential solution is to introduce students to computational thinking that provides them with the ability to ask intelligent questions to computing interfaces and investigate the large datasets that are ubiquitous to develop insights that are only accessible by combing through large datasets.

These two themes of climate change and computational competency can be united by providing students with a research embedded experience in which computational thinking skills are applied to such problems. A solution that we have designed and implemented is an, "Introduction to Scientific Computing" course that teaches elementary computational thinking skills and provides students with the opportunity to utilize this skill in the investigation and understanding of climate change data. The course aims to provide students with an introduction to functional programming, visualization, and analysis of large-scale data. The research component of the course affords a collaborative learning experience for students in their first year of college experience. A variation of this course without the research component has been described in detail in another publication (Sharma, 2017). The primary motivation for the development of this course was to bring computational thinking and its applications to first-year students. The course design is intentionally inclusive of all potential STEM majors and without regard to previous exposure to computers and mathematics preparation. The course pre-requisites are any introductory class in the natural science disciplines taken during the first semester freshman year. Thus, the course is designed to be appropriate and most advantageous for second-semester freshman students.

We strain to clarify a subtle yet important distinguishing characteristic of this experience. Scientific Computing in a broad sense is the application of computer programming and modeling to solve scientific problems. The field is also concerned with development of algorithms, increasing efficiency of existing code-bases, design and implementation of general-purpose libraries that could be utilized in a variety of domains. However, the barrier to enter the field is quite high and students need exposure to multiple math courses, at least one programming language, and an understanding of algorithms. Our goal in this course is to provide students with an exposure to programming in a high-level language in the service of their learning goals. One of the most important elements of the course philosophy is to highlight the ubiquitous thread of computing that permeates modern scientific endeavors. The course aims to help students to become better learners and practitioners in their chosen disciplinary paths. This is achieved by repeatedly highlighting the role and power of computational thinking in solving problems. The course uses the freely available text, An Elementary introduction to the Wolfram language (Wolfram, 2017), by Stephen Wolfram, the creator of the Wolfram programming language which is at the core of the Mathematica interface.

A climate change data collection project cannot be carried out at a single institution. Thus, the usage of international databases and collaboration is needed to tackle such problems. This exposure also gets students acquainted with large collaborative approaches to solving problems of such scale. There is a large amount of publicly accessible climate change data, however, an individual needs enough technical literacy to process the information and to analyze it or consume it in a meaningful fashion. In the sense that students are analyzing data-sets with thousands of data points, this becomes their first encounter with the new field of data science and allows interesting classroom discussions on the nature of large-scale data and special considerations that must be applied for such situations.

Course Description

This course has been taught twice at Wagner College during the Spring 2017 and Spring 2018 semesters. The course started by introducing students to the problem of climate change through videos of world leaders and leading scientists talking about this issue. The timeline of the course allowed a juxtaposition of then outgoing US President Obama with the new incoming administration of President Trump. We highlighted the stark differences in the former US President Obama's public stance on climate change ("A Historic Commitment to Protecting the Environment and Addressing the Impacts of Climate Change | whitehouse.gov," n.d.) and then President-elect Trump's diametrically opposite approach to climate change science. Even at the time of writing this manuscript, the Environmental Protection Agency, EPA website page on climate change is not informative or appreciative of the problem (OEI US EPA, n.d.). The contrast with the previous administration's EPA website could not be clearer (OAR,OAP,CCD US EPA, n.d. This was a powerful pivot to get the students interested in the topic. The course had assigned readings from the Intergovernmental panel on climate change ("IPCC - Intergovernmental Panel on Climate Change," n.d.), and the Discovery of global warming (Weart, 2008). Additionally, students were introduced to the NetLogo agent-based modeling environment and modeled an elementary climate change exercise (Levy & Wilensky, 2009; Shiflet & Shiflet, 2014). The assigned readings were followed by in-class discussions and informal writing exercises. The research phase of the project sensitized students to problems associated with climate change in countries around the world. Students later commented that this aspect of the course was most impactful.

The course was taught in a 90-minute twice weekly format. The first four weeks were devoted to preparing students with baseline competency in the programming language. The students were assigned weekly homework assignments that integrated scientific concepts with programming elements to increase student awareness and utilization of programming as a skill that could positively impact their learning in other disciplines such as physics, chemistry, biology, and mathematics. After this initial burst of introduction to the language, one lecture each week was reserved for coding and programming skill development and the other lecture was utilized for in-class discussions of assigned reading on climate change issues and for other classroom activities aligned with the research goal.

The goal of the first lecture was to ensure that students appreciated the scale of the problem. We stressed the message that the programming language would empower them to access the publicly available data to contribute to their own understanding of this issue. We impressed upon students that the course is not about the nuts and bolts of programming but learning technical platforms that can be used to address high level questions. In a previous iteration this course focused on computational thinking, molecular visualization, and data analysis. The students performed short classroom projects based on their interests from the tools and approaches presented in the course. The interested reader is encouraged to follow that publication for more details (Sharma, 2017). Here, we provide a concise summary of the programming component of the course.

The course follows a workshop model in which the instructor projects the notebook (Mathematica interface) on a large screen and students replicate the code on their individual computers. This is important to get the first practice of coding and to increase student familiarity and confidence with the interface and the programming language. The basic data structure in Mathematica is a list (array). We spend at least three lectures on familiarizing students with the list data structure and performing operations. Standard operations like reversing the list, calculating mean, standard deviations, etc. are carried out to develop baseline competency. We perform simple algebra on lists and solve problems that require setting up lists for solutions. Such problems abound in scientific domains and provide a review of scientific concepts as well as the skill of expressing scientific problems into a computational framework. We intentionally incorporated problems from different domains, physics, chemistry, biology, etc. to highlight broad usage of the platform and to inspire students to use their newly acquired skill across other courses.

Students also learned to visually represent different types of data. The standard mathematical functions, dynamic plots, parametric plots, etc. are explored in the course. Bar charts and histograms are also covered to provide students with an overview of different aspects of data presentation. The students appreciate different data representations and their appropriateness to highlight certain aspects of the data. Lively discussions on choosing data representation are routinely carried out in the classroom. In all cases the data originates from solution of a problem from one of the scientific disciplines. This builds up on previous knowledge of the core principles of Mathematica. A glimpse of the diversity of examples that we execute in class and homework assignments is provided below. These examples take advantage of Mathematica's curated research databases and the coding principles taught in the course. This approach enables students to use computational skills in their other courses and research assignments.

1. Plotting temperature data for various cities and analyzing weather trends
2. Identifying most populated cities in the USA and representing that information
3. Construction and analysis of dice games
4. Demographics and infrastructure comparison in G8 countries
5. Analysis of trends in properties of elements in the periodic table
6. Interactive plots of mathematical functions
7. Dynamic data representations

Coding Examples

This section presents three examples from the classroom to illustrate the ease of programming in the Wolfram language.

1. We demonstrate a game of throwing an eight-faced die and the number of trials needed to achieve a fair distribution of numbers. We setup an eight-faced die as a list of numbers from 1 to 8.
   a. singleDie = {1, 2, 3, 4, 5, 6, 7, 8};
   b. The function RandomChoice is used to randomly pick one option out of a list of choices supplied to the function. We perform repeated such operations to simulate a game of die throws and track the output. The output of such an experiment is easier to track visually by directly plotting the results.
   c. BarChart[Counts@Sort@Table[RandomChoice[singleDie], 10]]

d. This code fragment performs the following actions
    i. It picks a result from 10 simulated throws of the octahedral die
    ii. The Table function replaces the "for loop" that is prevalent in procedural languages. This allows the code to be extended to larger number of trials by simply chang ing the final numerical argument.
    iii. The output is sorted so that the bar chart axis represents the die faces in or der using the Sort function.
    iv. The occurrence of each die face is count ed using the Counts function.
    v. Finally, the results are plotted using a Bar Chart and the output from this experiment is shown in Fig. 1

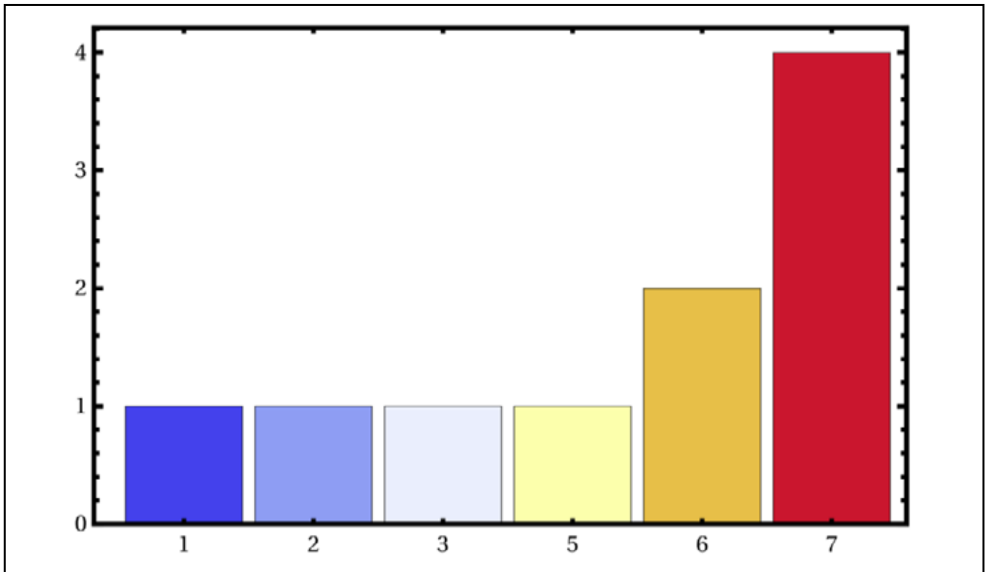

Figure 1. The results from 10 throws of an octahedral die. The vertical axis represents counts and horizontal axis shows the die face that turns up in the throw.

The same experiment is then conducted 100 times and finally a million times by simply changing the final numerical argument supplied to the code fragment. The result from one such experiment is shown in Figure 2. This experiment serves to highlight the functional aspects of the Wolfram language. The experiments also get students to appreciate the scale of data and the power of large data sets to uncover principles from the underlying phenomenon.

2. The periodic table of the elements is well known and is a central organizing feature in the physical sciences. We used this example to teach students to access data and analyze it programmatically using the Wolfram language curated databases. This example has the added advantage that it makes it easier for students to appreciate the applications of programming in their courses beyond this experience.
    a. We chose to highlight the second period of elements in the periodic table from Lithium (atomic number 3) to Neon (atomic number 10). The students were instructed to prepare plots of atomic radius and atomic mass for the second period elements to visualize the trend. The students learn such topics in the general chemistry course and find it easy to relate their previous experience with this activity. The atomic mass increases as we traverse from Lithium to Neon while the atomic radius decreases. This is displayed in Figure 3. The relevant coding commands to extract these properties are shown below
        i. Table[ElementData[i,"AtomicMass"], {i, 3, 10}]
        ii. Table[ElementData[i, "AtomicRadius"], {i, 3, 10}]
        iii. The function ElementData is intrinsic to the programming language and reports back specified properties for the designated atomic numbers. Here, we have extracted atomic mass and atomic radius for analysis.
    b. The students are then introduced to Pearson's correlation coefficient and compute the correlation coefficients for atomic number, atomic radius, and atomic mass. The results are then displayed in the form a matrix plot to highlight the data trends. The correlation plot shows that as the atomic number increases the atomic mass increases. The other interesting property highlighted is the atomic size across a period. Atomic size decreases as we traverse the row of elements from left to right. The correlation matrix diagram summarizes this information in Figure 4.

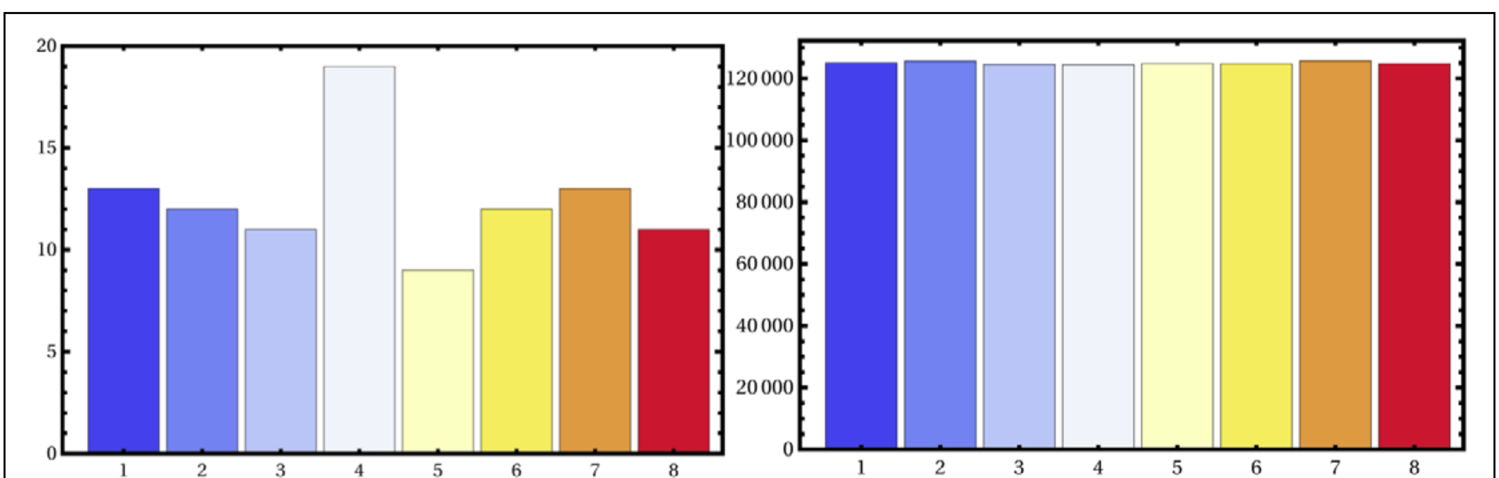

Figure 2: The results from 100 and 1 million iterations of the die throwing game. The results clearly indicate that the die appears fair in the limit of large trials. The vertical axis represents counts and horizontal axis shows the die face that turns up in the throw.

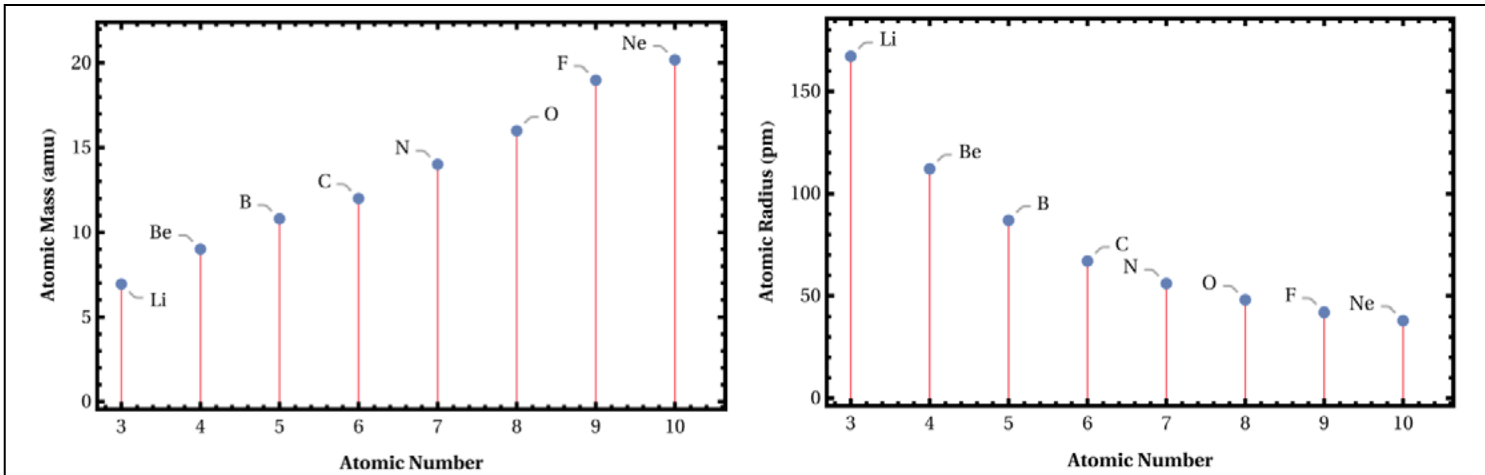

Figure 3: An exercise to plot the atomic mass and atomic radius vs the atomic number to highlight trends in the periodic table. The figure on the left shows atomic mass increasing as atomic number increases. The figure on the right shows that the atomic radius decreases as the atomic number increases in a period from left to right.

3. The final example to demonstrate the programming and curated data available in the Wolfram Language engages students to access and visualize time series of weather data for two cities in the United States. The coding commands are shown below along with their interpretation
   a. WeatherData["KPHX", "MaxTemperature", {{2017, 1, 1}, {2017, 12, 31},"Week"}]
   b. The intrinsic function WeatherData can access historical weather information including temperature, wind speeds, pressure, precipitation, etc. for most cities and localities in the US and major cities of the world. The code presented here accesses the weekly average of maximum temperatures recorded in Phoenix, AZ during the year 2017. The students compared the maximum and minimum weekly average temperatures of Phoenix, AZ with Rochester, NY to understand such time series data and to clearly see the strikingly different weather experienced in these cities. The weather data for Rochester was accessed as:
   c. WeatherData["KROC", "MaxTemperature", {{2017, 1, 1}, {2017, 12, 31},"Week"}]
   d. The maximum and minimum weekly average temperature comparisons are shown in Figure 5. The visual comparison of the temperature profiles immediately provides students with a clear sense of the severity of summer in Phoenix and the severe winter in Rochester. Students are encouraged to identify such interesting sets during class to familiarize them with the coding and to boost their confidence in identifying and visualizing such patterns.

Student Involvement and Output

Students in the course identified aspects of the climate change problem and focused their investigations on different parts of the world. Students performed extensive online research to identify reliable sources of data and its associated context. This provided a healthy discussion on information literacy and veracity of sources. The nature of the research problem brought students face to face with politically driven websites as well as scientific publications and helped to create a unique fervor in the classroom. The students felt engaged and driven to explore the effects of climate change and to impact their immediate surroundings with their zeal to spread information about this global challenge. The students worked in small groups of two or three in this project driven experiential learning paradigm. They provided regular project updates in the form of short presentations to the entire class. All students were provided an opportunity to share their critiques either directly or anonymously through the instructor. This built in a sustained culture of peer review and peer accountability in the classroom.

The students were provided with peer research mentors to assist them with their coding and research questions. This was by far the most impactful feature of the course, for both the students and the peer research mentors. The peer mentors were chosen for their success in the course in the previous year. The peer mentors were sophomore students for each iteration of the course. We noticed a marked increase in responsibility and maturity from the peer mentors over the course of the semester. The peer mentors in Spring 2018 led the application process for the students to apply to a regional scientific conference,

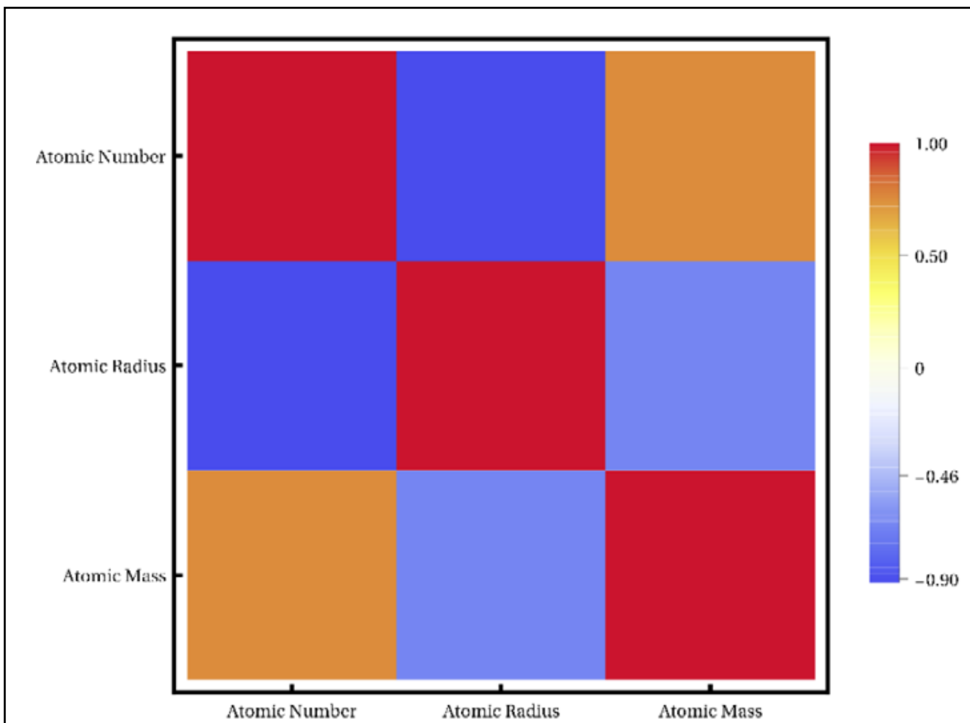

Figure 4: Correlation matrix plot for three properties of elements of the second period of the periodic table of elements.

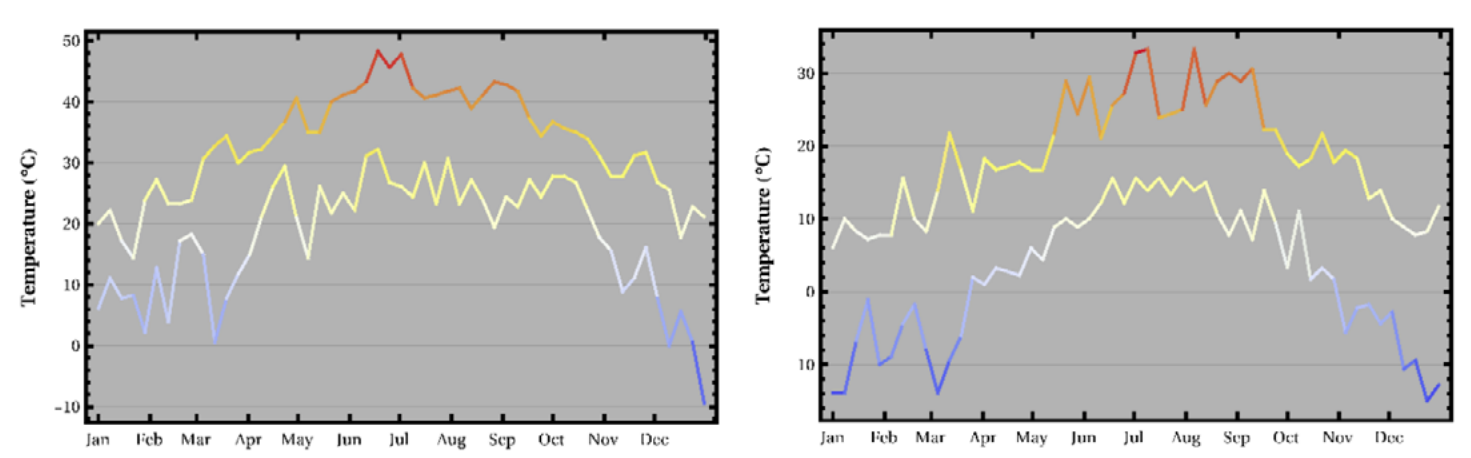

Figure 5. A comparison of averages of weekly maximum and minimum temperatures in Phoenix, AZ and Rochester, NY for 2017. The picture on the left shows the weekly average of maximum temperatures with Phoenix temperatures above that of Rochester. The picture on the right shows the weekly average of minimum temperatures for the same locations.

Eastern Colleges Science Conference ("Eastern Colleges Science Conference | ECSC," n.d.). All student groups from the course were accepted to present their research and the peer mentors traveled with the students and mentored them to present platform talks at the conference. This was a significant experience for the students. Some of the student projects are outlined below to provide an overview of student work in the course:

1. Deforestation in the Amazon and Global warming: Students tracked the falling tree cover in the rainforests and connected it to the reduced carbon storage. They also connected the deforestation rates to political upheavals in the region.
2. Global sea level measurements: History, status, and impacts. This project tracked the impact of climate change on sea levels and glacier loss. Students prepared powerful data visualization and narrative to support their interpretation of the status and future impact.
3. Analysis of climate change and its predicted impact on Japan and surrounding areas: This project focused on Japan and covered the political leadership and climate tracking data from Japan. Students were surprised to discover Japan's leadership vis-à-vis the US lethargy in the fight against climate change.
4. Analysis of hurricanes in North America and Asia: Students analyzed the number and severity of hurricanes since 1900s to the present. They analyzed the impact of hurricane activity on the number of fatalities and injuries in Asia with those in the United States.

Figure 6. A word cloud diagram to highlight word frequency in student reflections about the course.

These final presentations from the course are available in the Supporting Information. We requested our students in Spring 2018 to provide a free text response about their experiences in the course. We present a word cloud summary of their responses in Figure 6. The themes of research and conference were predominant in their description of the course and their reflection. The final presentation at a scientific conference became a central focus for the students and the class responded to the challenge as a unit.

Assessment and Discussion

The assessment was carried out through the CURE survey (David Lopatto, 2010). The CURE survey offers a comparison of learning benefits between course experiences and undergraduate research experiences. The pre-course survey collects student data based upon demographic questions, reasons for taking the course, level of experience on various course elements, science attitudes, and learning style. The post-course survey parallels the pre-course survey and includes additional questions that focus on student estimates of learning gains in specified course elements, estimates of learning benefits that parallel questions in the Survey of Undergraduate Research Experiences (SURE) surveys (D. Lopatto, 2004), overall evaluation of the experiences, and science attitudes. The central focus of the course was to introduce students to the research experience, build a self-identity as a researcher, and to inculcate a positive attitude about Science. We have presented a selection of elements from the survey results and comparisons to the national CURE survey in

Question	Students from this course		Students in the CURE survey		Standard deviation	
	Spring 2017 (N = 17)	Spring 2018 (N = 9)	Spring 2017 (N = 11,029)	Spring 2018 (N = 8,892)	Spring 2017	Spring 2018
Tolerance for obstacles faced in the research process	3.37	4.75	3.70	3.69	1.00	1.00
Readiness for more demanding research	3.42	4.38	3.63	3.61	1.04	1.04
Ability to analyze data and other information	3.58	4.75	3.88	3.89	0.96	0.96
Skill in how to give an effective oral presentation	3.42	4.71	3.41	3.35	1.21	1.24

Table 1. The means shown for the benchmark are for all CURE participants, regardless of course. The scale is 1 to 5, with 5 being the largest gain.

Table 1. The post-course learning gains consists of 21 items; however, we specifically chose to highlight four questions that are aligned with the course goals. For example, the survey also includes questions on laboratory techniques, primary literature, etc. which were not applicable to our course and we did not include those in the manuscript. The entire survey is available in the Supporting Information.

The chosen elements represent the crux of the course and demonstrate improvement in the learning gains experienced by the students. The second iteration of the course benefited from the experience gained by the instructor during the first run of the course. Since, our student population involved first-year students, we wanted to emphasize skills that would be useful to them during their entire undergraduate education. Hence, the course focused on regular project updates in the form of short oral presentations, data analysis, and programming skills.

There is an increase in student reported metrics across the board in the Spring 2018 cohort. The second cohort also had a lower enrolment and that translated into more individualized attention and mentoring. The survey results are highly encouraging and show improvement in the course delivery and execution. The addition of a trip to a regional conference for students to present their projects became an unexpected highlight of the course and turned out to be a great motivator for student engagement and eventual success in the course.

It is important to note that the national results are aggregated from a wide variety of institutions and includes schools renowned for their selectivity and high research activity. Our institution is a small liberal arts focused institution and not identified as a high research activity or STEM dominated school. We were pleased to see that our assessment results compare favorably with national averages. This may suggest the suitability of the current model to provide students without any previous research or computer programming experience with an impactful learning experience.

The CURE survey also provides four questions in the post-course survey to serve as an overall assessment of the course. We summarize the overall assessment of the two iterations of the course in Table 2. It is interesting to note that across the national landscape such courses seem to resonate strongly with students. This should be encouraging to instructors interested in incorporating such an experience in their classroom. Overall, students seem to indicate that such courses are a good mechanism to learn about the subject matter as well as the process of scientific research. Such experiences also engage the student body to think in more collective terms and see their fellow classmates as collaborators.

However, there are some limitations with this approach. The initial student reluctance to sign up for such a course may be significant, especially if the students have not seen such courses in the institution. A possible solution is to solicit support from colleagues across departments to generate student interest for such an experience. We believe that even though our class sizes were small, they are representative of niche courses at small liberal arts schools and we are optimistic that other practitioners will find satisfactory success in their implementations. A limitation of the CURE approach for traditional laboratory-based courses is the added expense for reagents and/or supplies. Integrating computational approaches to the CURE experience provides a low-cost alternative to providing such experiences to students at institutions with limited resources.

Another caveat with designing a course in this framework is the choice of in-class learning examples and homework assignments. The instructor needs to intentionally highlight applications of computational thinking instead of focusing on traditional topics taught in Computer Science courses. We believe that modulating course content in this fashion was crucial to the achievement of learning goals witnessed in our courses.

Conclusions

We have developed a model to engage freshman students in the learning and application of computing skills to societal problems and the associated scientific background to provide an engaging and research-driven learning experience. Our initial implementation of this model to analyze climate change data as a classroom-based research project seems to have met most of the learning objectives. The course is modular, and the big-data aspect

Question	*Students from this course*		*Students in the CURE survey*		*Standard deviation*	
	Spring 2017 (N = 17)	Spring 2018 (N = 9)	Spring 2017 (N = 11,029)	Spring 2018 (N = 8,892)	Spring 2017	Spring 2018
This course was a good way of learning about the subject	4.00	4.88	4.12	4.18	0.95	0.92
This course was a good way of learning about the process of scientific research	3.95	4.88	4.20	4.26	0.93	0.87
This course had a positive effect on my interest in science	3.79	4.25	3.97	4.06	1.10	1.04
I was able to ask questions in this class and get helpful responses	4.00	4.63	4.17	4.25	0.97	0.93

Table 2. These four questions serve as an overall assessment of the course. The scale is 1 (strongly disagree) to 5 (strongly agree). These questions are only on the post-course survey.

makes it highly versatile to be applied to courses outside the traditional science courses. Our students reported high levels of satisfaction with the learning experience in formal teaching evaluations as well as through informal discussions about the pedagogy implemented in the course. Student assessment of achievement of learning goals in our courses agree favorably with results from a national cohort in the CURE survey. The results from the national cohort in the CURE surveys and our experience indicates that students view such learning experiences positively despite the inherent challenges. We strongly believe that such approaches have the potential to engage students and provide them with skills that will be beneficial to their overall undergraduate educational experience.

List of Abbreviations:

CURE: Course based Undergraduate Research

STEM: Science, Technology, Engineering, and Mathematics

WL: Wolfram language

CDF: Computable Data Format

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Availability of data and materials

A selection of student final presentations is available as CDF (computable data format) files. These files can be opened with the freely available Wolfram CDF Player (https://www.wolfram.com/cdf-player/). The full-text of the CURE survey report for both iterations of the course are also provided.

Authors' contributions

AKS designed and implemented the study. MH and VP served as Peer Mentors for the two iterations of the course. MH and VP assisted in preparation of figures for the manuscript. All authors read and approved the final manuscript.

Ethics approval and consent to participate

All students participated willingly and voluntarily in the study.

Competing interests

The authors declare that they have no competing interests.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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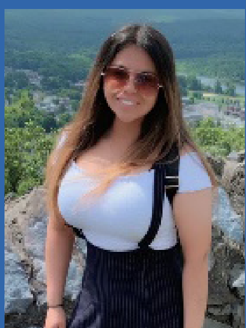

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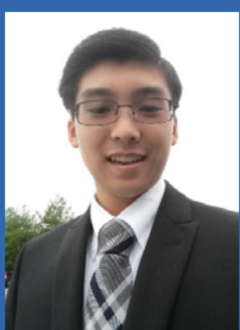

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