Computational Thinking in U.S. College Geography: An Initial Education Research Agenda

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Abstract

The authors summarize the outcomes of efforts to initiate a research coordination network to build capacity for computational thinking in geography education. There is a growing demand for graduates with skills in both spatial and computational (or geocomputational) thinking, but such skill sets are difficult to find. The growth of spatial data science programs are a good indicator for the significance of this growing demand. The Encoding Geography Research Coordination Network (EG-RCN) met virtually to engage in guided discussions around challenges of teaching and learning computational thinking at the college level. The main outcome of this network is the identification of an initial education research agenda to measure and address such challenges. This EG-RCN are one of the efforts under the broader Encoding Geography Initiative, which was launched by the American Association of Geographers (AAG) in 2018.

Keywords: Geography Education Research, Computational Thinking, Geocomputation, Geocomputational Thinking, Research Coordination Networks

Introduction

The geospatial services industry across both public and private sectors shows continuing innovation and growth. The presence and contributions of geographers in the geospatial services industry is critical because they provide conceptual geographic knowledge and an understanding of spatial data quality standards, which prevents misused or mishandled spatial information, misinterpretation of spatial analyses, and misinformed decision-making. There is still a demand for geographers in this industry, although employers now prefer to also see their knowledge coupled with skills in GIS, computer programming, data management, software development, or even computation, and individuals with this full breadth of skills are uncommon.

Efforts to build capacity for computational thinking in geography education come with many challenges. To initiate collaborative efforts to better understand and address these challenges, the authors formed an Encoding Geography Research Coordination Network (EG-RCN), supported by the Transformative Research in Geography Education program of the National Center for Research in Geography Education (NCRGE). This RCN was formed to initiate discussions on topics that would help inform a broader research strategy towards designing geocomputational curricula that (1) is inclusive, (2) supports teacher learning, and (3) can be measured for effectiveness.

This manuscript will provide the background and literature to show the transformative potential of an EG-RCN, and the value of the RCN framework towards building capacity and capability in geography education for computational thinking. Separate sections will outline the approach and the efforts this network accomplished to develop a research agenda. This will be followed by a section with concluding remarks.

Background

There is a growing demand for graduates with skills in both spatial and computational thinking, but they are hard to find. Their limited availability requires employers across the public and private sectors of the geospatial industry to choose between hiring a geographer, or a computer science graduate with limited or no expertise in geography and geographic information technology. The growth of data science and spatial data science programs are good indicators for the significance of this growing demand. These programs are sometimes directly funded by companies or organizations in the geospatial services industry.

2.1. Increased demand for geographers with computational thinking skills

Geographers were at the forefront of the development of geospatial technologies (e.g., GPS, remote sensing, and GIS). Geospatial technologies are now ubiquitous, integrated into our everyday lives, and central to the financial success of tech companies such as Google, Uber, and Amazon. These companies and other tech startups along with the customers and users of their platforms are generating large amounts of geospatial data by the minute. The parent company of Google, AlphaBeta, estimated that geospatial services creates approximately 4 million direct jobs and generates 400 billion U.S. dollars globally in revenue per year (AlphaBeta, 2017). There are also growing networks of "crowdsourced spatial data" collected through volunteered geographic information (VGI) or citizen science projects. These data create new challenges in terms of standards, quality, reliability, and credibility of spatial data (Goodchild & Li, 2012; See et al., 2016), but are also an indication of the value that geographic knowledge and information provide across society. In a geospatial-centric society–a society in which companies and governments run on spatial data and where the use of geospatial tools are ingrained in our daily lives, it seems that an early acquisition of geographic knowledge and of geospatial awareness are not only important for civic participation, but would also help prepare for a wide array of careers. Yet, geography is unevenly present in K-12 curricula in the U.S.

The geospatial services industry across both public and private sectors shows continuing innovation beyond mobile GPS technologies. For example, geospatial hardware is becoming cheaper and smaller, making it possible to manufacture satellites the size of a shoebox at a low cost. This democratization of manufacturing geospatial hardware together with cheaper and unmanned rocket launches is the business model of about a dozen start-up companies who offer their service to customers who want to capture their own spatial data from space (Baiocchi & Welser, 2015). It seems all but certain that geospatial data will be generated at even higher velocity and greater variety than we are already facing. The true value of these data hinges on a workforce that is geographically knowledgeable and equipped with the skills to properly analyze spatial data (e.g. spatial thinking, geoprivacy, geoethics, and geospatial tools) while able to efficiently handle sizeable data (e.g. data structures, data mining, computing). Faced by the limited supply of people with both skillsets, many employers make the choice to fill such positions with a computer scientist or engineer, and increasingly excluding any input from geographers.

2.2. Current capacity for computational thinking in geography education

The low supply of graduates with knowledge and skills in geography and computational thinking indicates a low capacity to teach this integrated subject matter. In this section, we will provide a brief overview of existing learning pathways integrating geocomputational thinking in the U.S.

At the K-12 levels, we are still facing long-standing challenges with geography education. In 2015, the Government Accountability Office raised concerns that "throughout the country, K-12 students may not be acquiring adequate skills in and exposure to geography, which are needed to meet workforce needs in geospatial and other geography-related industries" (GAO, 2015). States vary considerably in their requirements to teach geography in the K-12 curriculum; in most states, geography is embedded within the social studies curriculum. Computer Science, on the other hand, is experiencing a growing importance within K-12 curriculum, but this is fairly recent and still in the capacity building phases of finding teachers, building a body of knowledge and testing effectiveness of curriculum. In K-12, capacity building for geography (within social studies) and computer science are separate efforts, thus it is fair to say that there are no current learning opportunities or pathways towards integrated geocomputational thinking.

At the college level, geographic knowledge, its concepts, and the unique characteristics and challenges associated with geospatial data are taught in undergraduate geography (or related) programs and are not part of the core curriculum of other programs. Computational thinking skills have not been a core component of undergraduate geography programs but some related coursework is starting to appear. A recent survey of highly-ranked undergraduate geography programs in the U.S. found that 80% of departments in their sample offer at least one course involving some type of computer programming (Bowlick, Goldberg, & Bednarz, 2017). Only a handful of programs build capacity for certificates or a specialty in geocomputation (Wikle & Fagin, 2014; Bowlick, Goldberg, & Bednarz, 2017). At the advanced undergraduate level and graduate level there is more capacity for computational thinking with courses such as computer programming for GIS, spatial database management, agent-based modeling for complex adaptive systems, geo-visualizations, or spatial network analysis. To further test this capacity, Dony et al. (2019) recorded the department code of course titles that were associated with computational thinking (e.g., courses containing words such as programming, coding, scripting, automation, Netlogo, Python, Matlab, R, JavaScript, or web mapping). The authors found that although geography programs list courses that would support the development of computational thinking, these courses are often taught outside of geography departments, and only sometimes are prerequisite for advanced geography courses. Indeed, geography students are sometimes directed to computer science departments.

During the 2018 Annual Meeting of the American Association of Geographers (AAG) sessions were organized to start discussions among educators, professionals and students around computational thinking. During these sessions, faculty and educators expressed their inexperience and lack of confidence in advising students about computational courses because they themselves lacked or avoided similar coursework when they were students. Thus, it is fair to assume that students today receive limited guidance when they are sent to other departments to acquire computational skills. These findings highlight the need to better understand effective synergies between computer science, engineering, and geography programs.

In computer science programs, capacity for spatial thinking is not built in, yet there are signs of a growing interest to build that capacity with courses such as spatial computing and spatial data science (Shekhar, Feiner, & Aref, 2016; Wang, 2016). A growing number of colleges are investing in data science programs, though when these are led by computer scientists, explicit attention to the relevant topics of spatial or geographic data are likely to be absent. A small set of geography programs have deliberately targeted these opportunities by creating new or modifying existing programs into "spatial data science," making more explicit which kinds of data will be the focus of analysis. The latter showcases the growing need for a new breed of scholars with integrated spatial and computational thinking.

In short, courses that integrate more technical concepts or computational thinking into their courses are only beginning to appear in upper-level undergraduate geography curricula. Yet, much is unknown about the effectiveness of these courses for preparing students for the rapidly evolving job market. Much is also unknown about their effectiveness and the motivations of students to enroll in these courses. Geographers have voiced intimidation around computer programming, software, and web-development because of the perceived steep learning curves associated with these (Muller & Kidd, 2014). During sessions at the 2018 Annual Meeting of the AAG, students were disinclined to value the importance of acquiring computational skills. Relevant coursework is perceived as intimidating, and students were resistant to classes that could negatively impact their GPAs. This is consistent with the small fraction of undergraduate geography programs (10%) that require a computer programming course (or related) for their degree (Bowlick, Goldberg, & Bednarz, 2017). Based on this evidence, it is safe to assume that geography undergraduate students will not enroll in computational courses unless it is required for the degree or certificate they are pursuing.

Approach

This first Encoding Geography Research Coordination Network (EG-RCN) brought together different perspectives of college-level faculty and researchers who are at the forefront of building capacity for computational thinking in geography. This EG-RCN focused on geography education at the college level because this is where the capacity for geocomputational thinking currently lies, as made clear in the previous section (see 2.2). The EG-RCN (i.e. the authors) combined different experiences developing and teaching curriculum, while bringing different potential solutions to challenges in learning and teaching geocomputational courses. A few of them are already developing instructional materials that are meant to be disseminated to other geography departments. The effectiveness of this curriculum for large-scale dissemination, however, has not yet been tested.

Discussions among the EG-RCN were conducted virtually, and the objectives were to discuss a survey design to further improve the measurement of the current and future capacity for geocomputational thinking at the college level in the U.S., and to discuss how to identify diversity challenges associated with such curriculum. Central questions were:

- How can we best identify geography programs offering courses that involve computational thinking? Who can we contact to better understand departmental and institutional factors, challenges and/or barriers that led to the decision to or not to offer these courses?
- What data sources are available that can help us assess diversity and participation in geo-computational courses (student, teachers and teaching assistants)? What primary data should be collected to make assessments on diversity, broadening participation, and barriers experienced by students to enroll or succeed in these courses?

The longer-term objective of this EG-RCN is to identify experts beyond the college level and to eventually expand the network to all levels of geography education. The formation of an EG-RCN is the first stage of a planned long-term commitment to ensure that future generations of geographers and geospatial industry professionals are prepared to contribute to the national innovative ecosystem.

Outcomes

The EG-RCN identified a number of research questions that should be pursued in order to advance our understanding of computational thinking in geography education, and to measure the current capacity for it in college which would ultimately enable us to evaluate whether certain solutions are effectively building this capacity or not.

First, there is a need for a working definition of computational thinking that is more closely applicable to the discipline of geography. The most commonly used definitions of computational thinking are either a summary of computer science concepts–such as algorithmic thinking, abstraction, or decomposition (e.g., Selby & Woollard, 2013); or a statement about the ability to write solutions as a workflow executable by a computer (e.g., Cuny, Snyder, & Wing, 2010). Without a more practical definition that applies to geography it will not be possible to measure capacity or evaluate capacity building. Second, major educational challenges were shared about teaching concepts of computational thinking to geographers at the college level. Third, broadening participation of underrepresented students is an important challenge with very few working solutions so far. Lastly, a list of already existing data sources was composed that would support different research questions set forth by the EG-RCN. These four items are discussed in more detail in the next sections.

4.1. Need for a computational thinking definition applicable to geography

To measure the current capacity for computational thinking in college level geography, a first step would be to identify courses that develop such thinking. The most obvious examples of such courses are probably the "computer programming for GIS" (or related) courses. In fact, any course that involves computer programming is very likely to instill computational thinking, which is why the work by Bowlick, Goldberg and Bednarz (2017) is a good starting point to measure capacity. Computational thinking, however, is a broader skill than computer programming and can be developed without coding (e.g. Yadav et al., 2011; Lu & Fletscher, 2009). But, identifying courses that develop computational thinking without the use of computer programming becomes more challenging and requires an agreed upon, working definition of computational thinking that can be more practical in identifying what concepts, courses or skills would constitute such thinking.

Below are two of the most commonly used definitions of computational thinking:

- "Computational thinking refers to the thought processes involved in expressing solutions as computational steps or algorithms that can be carried out by a computer." (Cuny, Snyder, & Wing, 2010; Aho, 2011).
- "Computational thinking is an activity, often product oriented, associated with, but not limited to, problem solving. It is a cognitive or thought process that reflects: the ability to think in abstractions; the ability to think in terms of decomposition; the ability to think algorithmically; the ability to think in terms of evaluations; and the ability to think in generalizations." (Selby & Woollard, 2013).

These definitions are not practical at helping identify specific concepts, courses, or skills that are taught in geography and that qualify as computational thinking. Although this EG-RCN could develop such a definition, it was deemed more opportune to invite input from the geographic community rather than limit the consensus to the perspective of the seven authors. The authors did, however, build a short, initial list of course titles that could serve as examples of college-level geography courses (across the geography spectrum) that would likely develop some computational thinking:

- Geospatial Technologies and Society
- Digital Geographies / Digital Earth
- Critical Issues in Human Geography–The Social Power of Algorithms
- Python Programming for GIS
- Spatial Modeling with Matlab
- Web-mapping with JavaScript
- Emerging Technologies in Remote Sensing
- Complexity modeling with NetLogo
- Spatial Computing

Defining computational thinking as it applies to the geography discipline will need broader input from the community and–rather than finding clear consensus; it will likely be an iterative process of input and learning within our discipline.

4.2. Educational challenges with computational thinking at the college level

The authors identified main educational challenges that relate specifically to teaching and learning computational thinking (note that the working definition that was used by the EG-RCN is the list of courses identified in the previous section, see 4.1).

First, mastering and retaining any skill requires regular practice. Yet, exposure to computational thinking commonly happens during only one semester, in just one course. In other words, college level geographers are not given the opportunity to learn such thinking gradually. Second, it is uncommon to find faculty who have received formal training in computational thinking or computer programming when they were students. This causes faculty to react in one of two ways: some are not willing to teach other skills or concepts than the ones they were taught, while others are willing to teach new skills and concepts but expect and need to receive training and support to teach the skills they were not taught. Third, creating curriculum that involves geospatial technologies or spatial data analysis can be extremely time-consuming because significant updates are required regularly. Additionally, faculty often are given the suggestion to teach such courses using a wide array of examples to ensure student's interest and to be more inclusive. Developing curriculum, labs, and assignments that require wide ranging data sources, methods, and questions, is not an easy task. This adds additional time to the time spent updating curriculum. Fourth, the introductory GIS courses are becoming more popular on college campuses and are now commonly attracting non-geography majors. This means that a portion of teaching time has to be devoted summarizing basic concepts of geography to non-majors, rather than spending that teaching time progressing to more advanced geography or computational concepts. In general, it is very challenging to meet the needs of students in a class with students of different backgrounds and skill-level. Finally, some students still do not own or have access to a personal computer, which is a barrier to be successful (or enrolling) into courses that require or teach GIS, or computational skills.

To further investigate these challenges, it is important to invite input from the broader community, from faculty at different stages in their careers, and from faculty at different institution types (e.g., community colleges, R1 universities, teaching colleges). The EG-RCN identified possible solutions to a few of the challenges listed above, which would need to be measured and tested for effectiveness:

- Create computational or spatial thinking “plug-ins” or “micro-insertions”: Identify courses along the geography (or related) curriculum where computational thinking can be inserted (e.g., intro to geography, spatial thinking) or along CS curriculum where spatial thinking can be inserted (e.g., spatial databases, data science).
- Make sure computational thinking is a component of the degree requirement: Look among the required courses for a geography (or related) degrees and make sure at least one exposes students to computational thinking. If none of them do (or not sufficiently), “micro-insertions” could be a first step.

Yet, further strategies need to be investigated to address educational challenges. The EG-RCN identified a research agenda with the following research questions:

- What can be done to expose geography students to computational thinking in a more gradual way, without any overhaul to the current curriculum?
- What can be done to better showcase and clarify to geography students about the benefits of computational thinking skills?

Finally, outside the U.S., in Western European countries especially, the integration of computational thinking in undergraduate geography seems to be more widespread already. Learning from capacity building efforts and challenges in other countries may provide useful information, despite differences in educational contexts.

4.3. Challenges to broaden participation

The long-term implications of an EG-RCN would be most significant if it could achieve the broadening of participation from underrepresented students in geography and STEM. Little is known about the diversity of students in geography coursework that involves computational thinking, or any motivations held by those who do enroll. There is, however, substantial evidence of an overall underrepresentation of women and minorities in geography programs and in GIS professions. According to data from the AAG's annual survey of U.S. geography departments (AAG, 2017), white, non-Hispanic students accounted for 75% of all geography undergraduate students in 2016, while the proportion of white, non-Hispanic undergraduates in all degree fields was only 55%. African Americans comprised 14% of all undergraduate students in 2016, but only 3.7% of geography students. Hispanic/Latino and Asian students were also significantly underrepresented in undergraduate geography programs relative to all degree programs. Geography undergraduates were also considerably more male-dominated than the overall student population, accounting for 62% of all geography students versus only 44% of students from all degree fields in 2016 (AAG, 2017). Based on the underrepresentation of women and minorities in geography programs it is fair to assume that this pattern would be consistent among students enrolled in computational courses offered by these programs.

There are far-reaching consequences of this underrepresentation of these groups among geographers and especially in the more technical GIS discipline. In 2015, Mazur and Albrecht published the first substantial piece of empirical research on women in the GIS profession. In surveying almost 500 women in GIS, the authors conclude that although women are not as grossly underrepresented as in the overall tech industry, they are likely underrepresented in certain sectors and positions. For example, the authors found women are underrepresented in the private sector of the GIS industry. The authors further point out that women perform more analysis than computer programming tasks and are underrepresented in positions that require managerial or highly technical skills (Mazur & Albrecht, 2015). These impacts on the STEM workforce and on the advancement of scientific knowledge highlight the need for simultaneous efforts to build capacity for computational thinking and to broaden participation.

The authors identified a known strategy to increase students' interest and retention in courses that involve computational thinking. That is, to provide hands-on exercises and examples of interest to a wider range of undergraduate geography majors. However, most courses lack this breadth because of a faculty's expertise in one area of geography. Developing hands-on exercises and curriculum from other subfields of geography is time consuming and requires that particular expertise (see 4.2). Consequently, a long-term EG-RCN would be well-positioned to motivate faculty to share their use-cases, data, and curriculum content with the purpose of broadening and retaining participation in these courses.

4.4. Data and measurement of computational thinking in geography

Being able to measure progress in terms of capacity building for computational thinking in geography will require the use of data, and where necessary; the collection of new data. The EG-RCN identified a few already existing data sources that would be helpful in measuring current and future capacities for such thinking in geography:

- Following the method used by Dony et al. (2019), geography program websites are a good resource of data. They usually provide course listings and degree/certificate requirements, however, from the course title alone it is difficult to assess whether a course is developing student's computational thinking or not.
- Geography program chairs are knowledgeable about their degrees and requirements, and about the need and plans for new curriculum.
- Alumni surveys can provide information about careers students were able to develop, about whether they require computational thinking in their career, and which courses they think helped develop this skill.
- Some geography programs have formed formal or informal partnerships with computer science departments. It would be valuable to survey departments about such partnerships and their level of success.
- Course teaching evaluations would be interesting to analyze in order to better understand the challenges associated with this curriculum. Additionally, teaching assistants and instructors can be surveyed to ask them about student challenges and barriers to learning.

The EG-RCN further discussed data sources that would help measure impacts in terms of broadening participation in geography (see 4.3), and particularly in more computational aspects of geography:

- Demographic data at the course level can be available via Diversity Offices and Enrollment Offices (or related) on college campuses. They would provide valuable data about the demographics of students who enroll in geography courses and how they compare to courses that involve computational thinking.
- Collecting data on the demographic diversity at the university level can be a benchmark to compare to the demographic diversity of geography programs and to the courses involving computational thinking.

Based on these outcomes, the EG-RCN developed a data collection instrument that would help in measuring the current capacity for computational thinking in college geography.

Conclusion

At the college level, geography departments are increasingly offering certificates in Geographic Information Systems (GIS), some of which include advanced-level courses that involve computer programming. These courses necessarily involve aspects of computational thinking, but so far GIS programs have been focused more on quantitative reasoning than on fostering computational thinking. Only a few geography departments have designed their GIS certificates or curricula in a way that deliberately encourages and expects students to acquire spatial computational thinking skills, and these are recent efforts. Because institutional transformations to modernize the geography curriculum in higher education are only beginning to appear, much remains unknown about the effectiveness of these efforts to prepare students for the workforce or for graduate education. To improve our understanding of challenges, barriers, and effectiveness, this EG-RCN identified (1) the need to develop a working definition for computational thinking specific to the geography discipline, (2) the main challenges associated with teaching such new curriculum, (3) the main challenges with broadening participation, and (4) a few data sources that would be valuable to start collecting.

The long-term implications of an EG-RCN would be most significant in terms of broadening participation in geography and STEM. There is substantial evidence of an overall underrepresentation of women and minorities in geography programs (AAG, 2017) and in GIS professions (Mazur & Albrecht, 2015). Integrating computational thinking–a concept most commonly associated with the discipline of computer science, which has its own inclusivity challenges; might worsen geography's challenges to broaden participation. These highlight the need for simultaneous efforts to build capacity for computational thinking and to broaden participation. A known strategy to increase students' interest and retention in courses that involve computational thinking is to provide hands-on exercises and examples of interest to a wider range of undergraduate geography majors. Developing hands-on exercises and curriculum from other subfields of geography, however, is time consuming and requires that particular expertise. An EG-RCN could be well-positioned to support this challenge by creating a network of faculty that can share their use-cases, data, and curriculum content.

Another important discussion has been about the development of more gradual learning paths in geocomputation. Most geography programs either do not have the capacity for teaching any computational curriculum or have one course in which students are expected to learn advanced topics and concepts in

GIScience, and to learn a computer programming language (often for the first time). “Plug-ins” or “micro-insertions” of computational curriculum in other courses of their program may expose all geography students and also lay a foundation for a gradual learning pathway. An EG-RCN could compile a number of such micro-insertions adoptable by any geography program.

The overarching goal of this EG-RCN was to inform a research strategy to design geo-computational curriculum that (1) is inclusive, (2) supports teacher learning, and (3) can be measured for effectiveness. These three objectives each respond to a specific recommendation from the Road Map for 21st Century Geography Education Project (Bednarz, Heffron and Huynh, 2013).

- Inclusive Geo-Computational Curriculum. This objective responds to the research recommendation to “develop instructional materials that use teaching strategies to engage all learners in meaningful explorations of geography” (Recommendation 3).
- Geo-Computational Curriculum that supports teacher learning. This objective responds to the research recommendation to “design instructional materials to be learning tools for teachers” (Recommendation 4).
- Geo-Computational Curriculum that can be measured for effectiveness. This objective responds to the research recommendation to “develop and fund extensive research and evaluation in geography instructional materials and professional development” (Recommendation 8).

We expect this initial project to set the stage for a longer-term research agenda around these broader objectives, and to help identify individuals with complementary expertise who are committed to pursue longer-term objectives as well. The longer-term objective of this EG-RCN is to identify experts beyond universities to expand the network to all levels of geography education. In expanding this network, (1) the diversity and its members should be monitored, (2) the list of affiliated institutions should aim to reach each U.S. state, and (3) the population each institution is serving should be documented.

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