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Sequencing spatial concepts in problem-based GIS instruction

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Abstract

In this paper, we sketch a general framework to help educators sequence problem-based GIS instruction. This framework weaves together: (1) problem based learning with GIS, (2) cognitive load theory in problem solving, (3) the structural view of spatial knowledge, where higher-level concepts are constructed in part from lower-level concepts, (4) how the form of representation used to solve problems influences the development of spatial thinking skills.

Keywords: Problem-based learning; cognitive load theory; spatial concepts; GIS; pedagogy;

1. Introduction

Over the last two decades, the number of instructors teaching undergraduate students how to use geographic information systems (GIS) has grown significantly [1]. During this time, several major efforts have sought to provide these growing ranks of GIS instructors with materials to assist their teaching. This includes a model curriculum developed as part of the National Center for Geographic Information and Analysis (NCGIA) [2] and the more recent 'Body of Knowledge' (BoK) developed through the University Consortium of Geographic Information Science [3].

Yet despite these efforts, GIS instructors still face several major challenges when designing GIS instruction. The BoK primarily defines *what* students should or could know, but leaves it up to the instructor to figure out *how* they should come to know it. It is intended to be "an inventory of the domain, not a set of academic course outlines" [3]. Similarly, the NCGIA's effort aimed "to develop a broadly appropriate general set of materials that can be arranged and presented according to each instructor's preference" [2]. In theory, having the recommended "content" be modular and scalable is an attractive characteristic for the wide range of instructors who are charged with teaching GIS to diverse audiences

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and under varied formats and structures. Yet in practice, that modularity is difficult to manage when it comes to instructional design.

There are at least three fundamental issues of instructional design that are left up to the instructor. The first concerns the scope and sequence of the course. While the BoK identifies "core" units [3], the scope of instruction typically reflects the instructor's expertise and institutional setting [1]. The problem of how to effectively sequence the material ("Where should instruction begin?" "Should one unit logically follow another?") is largely left up to the instructor, or perhaps the author of the textbook that the instructor has chosen for the course.

A second distinct challenge, once an instructor defines the scope and sequence of a course, concerns how they deliver their instruction to students. Methods of GIS instruction tend to generate the "split personality" of GIS classes [4] stemming from the need to coordinate lecture and lab material. What are instructional methods that help students connect the general theory and concepts of geographic information *science* with the graphical user interfaces and specific operations of geographical information *systems*? The NCGIA model designed lab materials to supplement lectures and suggested that labs designed to reinforce lecture concepts could not simultaneously provide adequate technical training [2].

A third challenge left up to instructors concerns how they assess both student learning and the effectiveness of their instructional design [5][6]. This again reflects the science/system dichotomy of GIS instruction. Should instructors separate their assessment of general concepts from assessment of technical operations (e.g. a short answer or multiple choice examination on lecture content followed by a problem set related to laboratory content)? Or are there methods to assess student comprehension of general concepts through their implementation of technical operations? Similarly, how can instructors assess whether their teaching methods facilitated learning or instead made the material more difficult for students to learn?

Often, these issues of content, sequencing, and assessment occur within the context of problem-based learning (PBL). PBL has become regarded as an effective and popular format for introductory GIS instruction [7][8][9][10][11][12]. Working through problems while concurrently acquiring skills with GIS operations mimics the application of GIS to "real-world" problems, bridging conceptual and technical learning. The use of PBL and GIS together encourage robust analytical and critical thinking skills [13][14].

In classroom settings, PBL can take multiple forms within a given course, with varying degrees of problem complexity and instructor involvement. On a smaller scale, students can pursue inquiry-based activities during lab sessions, when they work on small but structured problems, designed to be "solvable" in one or more lab session. These lab exercises often complement specific theoretical material that the students would have received during recent class lecture sessions, and the exercises become the application of the knowledge through software. However, classroom management practices may dictate that the problems themselves are simplified or constrained, with prepared data and expected outcomes. These "mock" problems may be tightly planned, placing the burden of design and preparation on the instructor ahead of time, but minimizing the later likelihood of unanticipated data and software issues or questions. Their delivery and execution is highly controlled.

In "pure" PBL, the learning becomes more unstructured and chaotic, with the students in control of the process through which solutions will be identified and reached [10][15]. In this form, students are presented with the general problem or situation and then proceed to organize the strategies and methods for reaching an outcome, but that outcome is uncertain at the beginning of the process. The "authentic" problem at the center of the experience is often a real-world one, reflecting the reality of life's uncertainties, messiness, tensions, and politics. Though the learning experience may ultimately be a richly rewarding one, instructors may feel great anxiety and discomfort at their lack of control over the process and its outcomes.

Unfortunately, designing and conducting effective PBL-GIS instruction is challenging and outcomes often fall short. Geography workforce surveys indicate that employers find recent graduates unprepared to problem-solve [16]. Some instructors may perceive that they are engaged in *problem*-based learning when they are in fact providing a *project*-based learning activity, and this exacerbates the likelihood that their instructional design will not align well with their learning outcomes.

This paper links PBL-GIS instruction with cognitive studies of problem-based learning in order to help instructors consider issues related to the sequencing of problem-based instructional materials. Our main objectives are to briefly discuss:

- What makes problem solving with GIS intrinsically difficult to learn?
- How can instructional approaches make problem-based learning with GIS more effective?
- What may make problem-solving with GIS intrinsically difficult?

"Solving" a problem requires understanding its variables, parameters and circumstances, and anticipating how those will interact in reaching a desired outcome: a solution that represents a change from the current state to a desired end. Of course, in reality "problems" are often subjective, ambiguous, temporally limited, and a matter of scale. The more realistic and authentic a problem is, the more likely that multiple, interdependent, and intermediate steps are required to reach an acceptable change of state or solution.

In GIS, typical problems that a student might address include estimating where a flood would impact a settled area, or identifying how a plant or animal's home range might by modified by climate change, or comparing data collected within a Census boundary (such as a tract) with data collected for the same locale but at a different geographical extent (such as a zip code area). Each of these situations 1) requires a multi-step solution, and 2) necessitates that students understand and apply core geographical concepts (such as distance and diffusion).

Faculty who teach GIS in higher education often learned the technology during their own graduate research years and perhaps while studying advanced GIScience topics that are esoteric and beyond the scope of a typical undergraduate introductory course [17][1]. When tasked with designing curricula, few instructors have had opportunities to think about how the problems are understood by novices and how, during this learning process, students must apply their knowledge of core concepts in order to proceed towards a solution. Essentially, all "problems" are likely to be regarded equally as "problems." An instructor is most likely to differentiate them based on what data sets are used, or what GIS operations are being covered. Explicit qualitative attention to the other characteristics of the problem itself (how it is presented, how the nature of its data sets assume prior knowledge of those data models, how the problem must be broken down to be tackled and how that tackling would vary by problem, how its solutions may be dependent on choices made during intermediate steps, etc.) is often bypassed for the sake of software skill acquisition.

We are gathering strategies that reduce the difficulty of problem-based learning based on research in cognitive load theory (CLT) [18][19]. A major focus of CLT concerns student learning of problem schemata, cognitive structures that allow problem solvers to recognize categories of problem states based on their possible solutions or allowable moves [18]. Student acquisition of problem schemata may be affected by three general sources of cognitive load: (1) the *intrinsic* load, or the intrinsic complexity of the problem domain; (2) the *extraneous* load resulting from the design of the instructional material; (3) the *germane* load, resulting from activities that facilitate the acquisition of schemata into long-term memory [20]. Problem-based instruction should be designed to manage these three sources of cognitive load in order to facilitate the learning of problem schemata.

Solving problems with GIS is an intrinsically complex undertaking. Students must learn and appy general spatial concepts (e.g. location, distance, hierarchy), general concepts of spatial representation and analysis with GIS (e.g. raster, vector, buffer), and concepts of spatial representation and analysis that are specific to particular GIS platforms (e.g. the concept of 'extract' may vary by vendor). In addition, students must also attend to thematic concepts that are specific to the problem domain (e.g. hydrology, ecology, economics). Several lines of research suggest that instructors may reduce this intrinsic complexity of solving problems with GIS by carefully attending to the sequence of instruction.

Spatial conceptual knowledge appears to have an inherent structure to it that may offer guidance for sequencing instruction. Several researchers [21][22][23][24] have suggested spatial knowledge consists of primitive concepts (e.g. identity, location, magnitude) from which more complex concepts (e.g. distance, angle, direction, boundary, etc) can be derived. There is preliminary evidence that a scope and sequence for understanding spatial concepts may exist [25][26][27]. GIS instructors should appreciate how this information may affect and inform curricular problem design. If spatial concepts themselves have inherently cumulative properties in terms of their complexity, should problems be designed in various steps and stages which take that into account? For example, if a function associated with distance, such as distance decay, is indeed a more complex concept, then problems involving the measure of phenomena through buffers and other distance operations could be more systematically structured, either within the sequence of a single lab exercise or within the sequence of a semester course.

Designing instructional sequences of technical concepts may be guided by careful consideration of problem structure and the sequence of transformations a student must employ to solve the problem. CLT may be particularly relevant for GIS instruction because of the transformational structure of problem-solving with GIS [28][29]. When solving problems, students must learn to use GIS operations to transform data through various intermediate states in order to reach a desired goal state. CLT suggests that the more intermediate steps that a problem has, the greater the strain on working memory to keep all of the variables organized and the greater the challenge to anticipate how they will continue to interact with one another as solution states are envisioned. This work has identified methods for sequencing material based on task classes [30] and strategies for chunking problems based on the length and goal-structure of solutions [29]. An example from GIS instruction would be to introduce distance and reclassify operations prior to introducing a buffer operation.

A third thread tying sequence to instruction concerns the level of guidance provided by the instructor during problem solving. CLT research has shown that teaching through worked examples, where the instructor presents students with a problem and its solution prior to having students solve problems independently, can facilitate learning by novices more effectively than pure problem-solving, where the student must discover a solution with little or no guidance [18][33]. However, as a student gains expertise in a domain, problem-based learning often becomes more effective than worked example instruction [34][35]. It would be useful for GIS instructors to understand how to structure the transition from worked-example to pure problem-based instruction based on student learning research from other topical domains [36][37].

Knowing how problems need to be understood and deconstructed to be solved, and accomplishing that goal in an efficient manner, is an indicator of “expert” knowledge [39]. Researchers have previously paid attention to how novice/expert knowledge varies with such topics as map projections [40], but this understanding has not been placed in the context of PBL-based instruction. We expect this to be a significant issue with respect to how GIS itself affects problem-solving, and we are evaluating whether addressing it through problem restructuring, sequencing, and spatial concepts may ameliorate learning by novices. We also believe that novel instructional approaches and strategies may address this issue.

How can instructional approaches make problem-based learning with GIS more effective?

This portion of our research focuses on extraneous sources of cognitive load stemming from the design of instructional materials with which students interact while learning. With problem-based learning, in addition to the intrinsic complexity of the given problem, a student must simultaneously mediate between the graphical interface of the software platform and the media of instructions [41]. This is further complicated when GIS instruction is being delivered online, a growing trend in higher education overall [42]. Managing GIS software concurrently with instructions, whether those instructions are coming in the form of a hard copy tutorial book sitting on your physical desktop, or a digital tutorial on your virtual desktop, or verbal instructions from the instructor in the classroom, is consistently challenging. Thus better understanding of the design of instructional materials that involve multiple loads of verbal and visual information [43] is one of our ongoing objectives.

One variable for mediating these issues that we wish to learn more about is the benefit of using visualizations at different stages of the learning process. This is known to be an important pedagogical strategy in PBL-based STEM learning [44][45], but it has not yet been well-studied in GIS instruction. Blaser et al. [46] have suggested that multiple modalities of visualization aid in many stages of problem-solving with GIS. For example, the act of sketching out of problems (e.g., how the data are combined, transformed, and interacts) provides helpful guidance for selecting GIS operations. Using additional and alternative elements such as timelines may also be effective in supporting problem-solving [47].

A related approach to learning that has proven effective in other STEM disciplines is the use of physical models [48][49]. Geographers have long used globes (or oranges, or tennis balls) in classrooms to illustrate concepts of latitude and longitude, or map projections, but the use of physical models in GIS instruction is fairly uncommon. One simple GIS example of an effective approach is to have students sketch a hillside, and then build its model of clay. Viewing this hillside model from overhead, through a screen or net mesh of varying "pixel" sizes, is a very effective means to illustrate the GIScience concept of raster data resolution. Then, placing the model in a container and filling it with water to different levels is a clear representation of how contour lines are derived from digital elevation models (DEMs).

The effectiveness of these visual methods for teaching spatial concepts will likely be sensitive to the level of learner expertise. Empirical evidence in CLT has shown that strategies aimed to facilitate schema acquisition among beginners may increase extraneous cognitive load and impede learning for more advanced students [35]. Future research should elucidate the learning levels when visualizations enhance student learning and the levels when particular visualizations, such as diagramming problem solutions, become busy work.

2. Conclusion

This paper briefly introduced a framework that connects cognitive load theory to problem-based learning with GIS in order to help instructors consider strategies for sequencing instruction. The intrinsic complexity of learning how to solve problems with GIS may be alleviated by sequencing spatial concepts from simple to complex, by chunking GIS operations to facilitate schema acquisition, and by sequencing the degree of instructional guidance from worked examples to more exploratory problem-solving. Designing instructional materials that aim to reduce extraneous cognitive load should also give attention to sequencing issues. Visual methods of instruction hold promise to facilitate schema acquisition by novices, but their effectiveness will likely be influenced by the learning level of the student. While calling attention to the importance of sequence in problem-based instructional design, this framework also points toward a potentially rich research domain that intersects research on student learning, spatial thinking, and problem-based instruction with GIS.

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