PRACTICE

Undergraduate Research and Inquiry-Based Learning in Geographical Information Science: A Case Study from China

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Abstract

Undergraduate research experience is the process where undergraduates contribute to the development of a subject field through their inquiry-based learning (IBL). IBL is a student-centered learning strategy. Students work as professional scientists do, through inquiry. This article presents approaches to IBL and practices of an instructor from China for strengthening and facilitating IBL in geographical information science (GIS). Two paths were proposed for the development of the students on the basis of four modes of IBL. The practical experience was introduced in two parts: course design and IBL tool development for classroom teaching, and undergraduate mentoring outside of the classroom.

Keywords: *inquiry-based learning, undergraduate research experience, course design*

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China is striving to improve the quality of higher education and build competitive world-class universities. The Ministry of Education of the People's Republic of China has proposed to insist on "rooting in undergraduate education and promoting four returns" to accelerate the development of high-level undergraduate education. Undergraduates are the largest pool who can be trained to become high-quality professionals. Today's undergraduates will be tomorrow's scientists and the backbone of all kinds of fields. How can undergraduates best be trained and the quality of undergraduate education improved? An effective way is to encourage undergraduate students to engage in inquiry-based learning (IBL) and undergraduate research experiences (URE). The Boyer Commission (1998) proposed that research-based learning be routine for college education. Healey and Jenkins (2009) shared this view and proposed strategies to develop undergraduate research and inquiry. Walkington et al. (2011) suggested including research-based learning as early as possible in undergraduate geography courses. In this article, we present a case study of a geographical information science (GIS) teacher implementing URE and IBL approaches.

IBL is a subset of active learning (Spronken-Smith et al. 2008). It has various definitions. Generally speaking, IBL is a student-focused and student self-directed learning strategy where a student solves problems or tests hypotheses through an inquiry process similar to that done by a professional scientist. The phases of IBL include orientation, conceptualization, investigation, conclusion, and discussion (Pedaste et al. 2015). IBL has three levels of scaffolding: structured, guided, and open (Spronken-Smith and Walker 2010). Colloquially, undergraduate research experience is the process where undergraduates contribute to the development of a subject field through their inquiry-based learning efforts (Beckman and Hensel 2009). There are various approaches to research experience for undergraduates (Healey 2005; Healey and Jenkins 2018; Lopatto 2009; Prince, Felder, and Brent 2007), including courses involving research (Geschwind and Broström 2015; Howitt et al. 2010; Levy and Petrulis 2012; Moore, Hvenegaard, and Wesselius 2018; Valter and Akerlind 2010; Zimbardi and Myatt 2014), internship in research projects of their professors (Hunter et al.

2010; John and Creighton 2011; Seymour et al. 2004), student research projects with or without teacher guidance (Cantor et al. 2015; Walkington, Hill, and Kneale 2017; Yarnal and Neff 2007), academic competitions or contests (Tian 2017), academic summer camps or workshops (Buxeda et al. 2000; Falconer and Holcomb 2008; Hunter et al. 2010), and scientific expeditions (Healey and Jenkins 2009).

The Outline of China's National Plan for Medium and Long-term Education Reform and Development (2010–2020) clearly stated that "[s]tudents shall be urged to participate in scientific research; teaching in practice intensified" and that "[w]e will advocate teaching to be heuristic, exploratory, discussion-based, and participatory, and help students learn how to study" (Ministry of Education 2010, 19, 25). As one of the strategic tasks to develop world-class education with Chinese characteristics, China seeks to "innovate in the way to foster talents," to "promote inspirational, inquiry-based, participatory, cooperative ways of teaching and learning," and to "develop the spirits of innovation and the capability of practice." Wuhan University has been valuing undergraduate education and fostering students' abilities in innovation and entrepreneurship by supporting student research projects, academic contests, and field trips. Teachers here are also asked to integrate their research with teaching.

GIS is a typical interdisciplinary field characterized by a diverse body of knowledge (DiBiase et al. 2006; Wilson 2014), strong ties to application (Wikle and Fagin 2014), and rapid evolution (Egenhofer et al. 2016). The emergence of a series of new theories, new methods, and new technologies, such as NeoGeography (Goodchild 2009), big data, cloud computing, and location-based services, has overturned people's perception of traditional GIS disciplines and industries. The development of the internet has led people into an era of knowledge and information explosion that has fundamentally changed the way of acquiring knowledge. From an instructor's perspective, teaching in the old fashion of repeating what is in the textbook will no longer fulfill the needs of students, nor prepare them for the professional workplace. From the perspective of students, it is difficult to master complicated knowledge by passively receiving information from instructors. Instead, active learning through research can help students keep pace with the development of their discipline and master new theories, new methods, and new technologies, paving their way for further education and careers.

As part of the so-called "four returns" initiative, the Chinese Ministry of Education has been calling for universities to return to their remit in undergraduate education by promoting teachers' enthusiasm, commitment, and scholarship in teaching. It is a teacher's duty to focus on teaching and fostering talents. The role of the instructor is essential in URE and IBL (Dobber et al. 2017). In this article, we present a case study of a GIS teacher implementing URE and IBL approaches. The rest of the article is organized as follows: the next section introduces two approaches to IBL implementation, the following details our practice of implementing IBL both inside and outside of classrooms, and the final section concludes the paper.

Approaches to Inquiry-Based Learning

The remit of instructors usually includes teaching activities specific to a course and extracurricular student mentorships throughout research practice. Levy and Petrulis (2012) proposed four ideal modes of IBL according to who framed the inquiry and the two dimensions of whether building new knowledge or exploring existing knowledge (see Figure 1). Based on these modes of IBL, we introduce strategies for teachers to implement IBL both inside and outside the classroom.

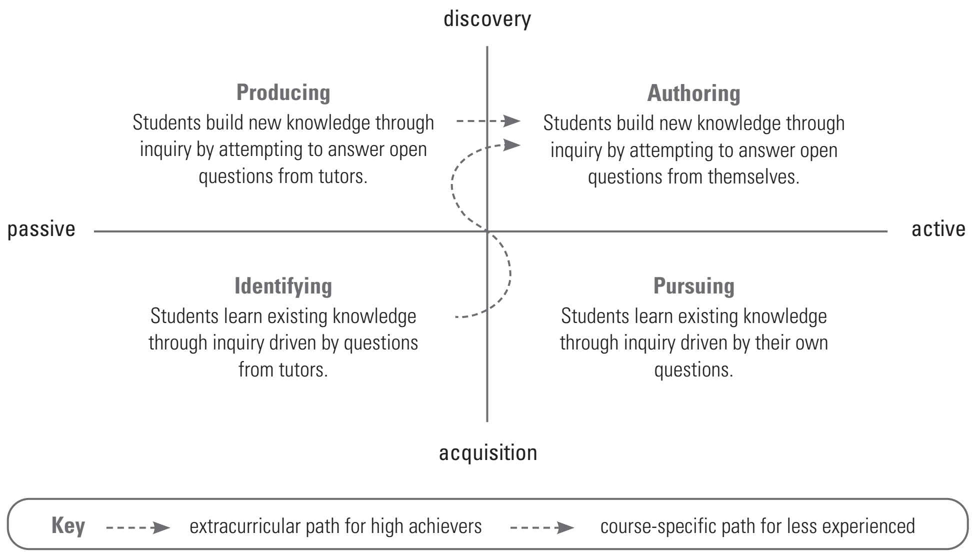
Inside the Classroom

The instructors may help students with IBL in class through course design and teaching material development. The most inappropriate approach is merely to leave a research question for students to investigate. Considering that face-to-face lecture remains the mainstream approach to teaching in Chinese universities (Shi, Ma, and Wang 2020), instructors should combine the subject content of a course with research in course design. Specifically, one can introduce the research progress, demonstrate the intermediate process of research by replicating previous work, and teach research methodology. It is also practical to organize discussion on literature retrieved by students and provide research experience in the form of homework and final projects. In other words, instructors should make full use of the teaching–research nexus model proposed by Healey and Jenkins (2009).

Because not all students are high achievers, they can use the identifying or pursuing mode of IBL, such as reproducing existing research findings. After the training in reproducing findings, students can still switch to producing and authoring modes, as long as they are willing to conduct original research. Students can follow the identifying–pursuing–producing–authoring path.

Meanwhile, IBL may need the support of appropriate tools. These tools are important for most students in geography and GIS, where quantifying basic concepts often involves massive geometric and statistical operations. For example, Tobler's first law of geography asserts things are similar to those in their vicinity, which is formally called spatial autocorrelation (SA). Moran's index is a basic metric of the SA, but its manual calculation is so tedious that students may get lost in the math. Open-source or commercial software supporting the index calculation (Bivand,

FIGURE 1. Linking Four Ideal Modes (Levy and Petrulis 2012) Through Two Suggested Paths of Inquiry-Based Learning



Pebesma, and Gómez-Rubio 2013; Scott and Janikas 2010) would facilitate student exploration of their data.

Outside the Classroom

The instructors may guide students to participate in various scientific research practices outside the classroom, such as undergraduate innovation and entrepreneurship projects, major-related competitions, the instructors' own research projects, and field expeditions. Usually, the students participating in such activities are high achievers. Therefore, high targets should be set for them, for example, winning in competitions or publishing research papers. Instructors should treat these undergrads as they would doctoral students and advise them to perform authentic research. This coincides with the idea of high quality for both research experience and work, as emphasized by Walkington et al. (2019). The mode of IBL should be shifted from producing to authoring, and the inquiry type should be changed from structured to open. In the initial stage of structured producing, instructors should design appropriate topics that match the strengths of students to facilitate a smooth start for the students. At the same time, instructors should teach research methods and skills, such as programming, English reading and writing, and data analysis. Instructors need to supervise the entire process. Once the students achieve some results, they can switch to authoring mode and open inquiries.

Implementation

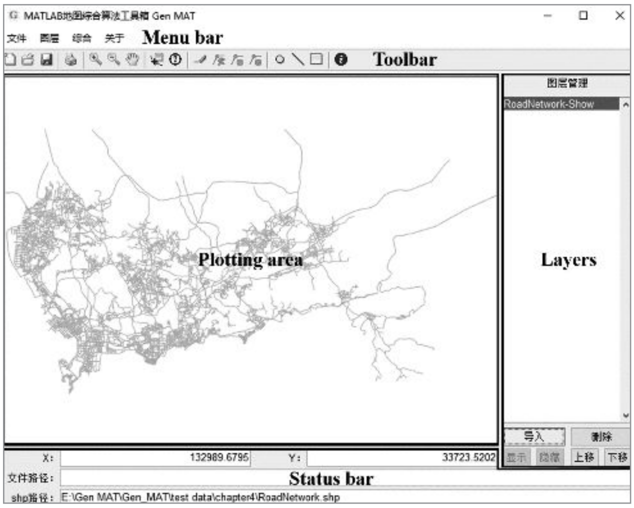
In this section, we present our practice of the two approaches of IBL. With IBL in mind, we developed a course and a learning tool for the classroom and also mentored undergraduates outside the classroom.

Course Design

MATLAB is a 1.5-credit course for second-year cartography undergraduates featuring multiple modes of research–teaching nexus. In the first week, students are asked to gather and summarize research articles using MATLAB for cartography and GIS topics, which is research-led in nature. They are then shown how to reproduce the results of a sample publication in the following week, which is research oriented. From the third to the seventh week, MATLAB programming concepts and topics are covered, with two assignments linking programming concepts of graphics and toolboxes to the research frontier of information visualization and automated map generalization. At the end of the course, students discuss with the teacher on the literature they found, as a research-tutored experience, in preparation for their research-based final projects to solve practical or scientific problems using MATLAB (Tian et al. 2020).

According to our survey on research-related skills before ($N = 47$, 93.6% response rate) and after ($N = 37$, 97.3% response rate) this course, students reported significant gains in several aspects, as measured by the Survey of Undergraduate Research Experiences Tools (Lopatto 2004) with Cronbach's alpha reliability of 0.92 (before) and 0.94 (after). They developed better understanding of the research process ($P < 0.01$), the ways scientists think ($P < 0.01$) and tackle real problems ($P < 0.01$), and the way to construct knowledge ($P = 0.02$). The course improved their research skills including literature reading ($P = 0.04$) and scientific writing ($P < 0.01$). Students also learned the ethics ($P = 0.01$) and independence ($P = 0.05$) in research, felt more connected to the learning community ($P < 0.01$), and became more tolerant to obstacles ($P = 0.04$).

FIGURE 2. Graphical Interface of Map Generalization Algorithm Toolbox



Students had a limited grasp of programming skills at the beginning. Considering this fact, we developed GEN_MAT, a MATLAB toolbox of map generalization algorithms, to assist students in inquiry learning (Figure 2). Forty-two map generalization algorithms from Li's monograph (2006) and mainstream GIS journals were implemented (Wang et al. 2017). With our toolbox, the students could reproduce the execution results of algorithms from the literature they read, which enables them to learn intuitively and compare their actual outputs with the literature. On this basis, the students could also find problems in existing algorithms using alternative testing data.

The toolbox brought the students closer to research. With the help of GEN_MAT, the students changed from passive learning to active learning, improved understanding, upgraded practical skills, gained a better grasp of map generalization, and developed a certain interest in programming (Wang et al. 2017).

Undergraduate Mentoring

Based on the situated learning theory and the collaborative apprenticeship model (Glazer and Hannafin 2006; Lave and Wenger 1991), we proposed an apprentice model to mentor GIS undergraduates (Tian 2017). The model consists of five phases: (1) Preparation phase: Asking students whether they were interested in research and assigning research topics according to the interests, knowledge, and abilities of students. (2) Introduction phase: Introducing the problem-solving method in computer science, which is to define a question in the concept layer, to design a solution in the logic layer, and to implement an idea in the physical layer. (3) Development phase: Cooperating with students to conduct research. (4) Proficiency phase: Evaluating research conducted independently by students, and suggesting improvements. (5) Mastery phase: Training students to be new instructors who are capable of providing mentorship assistance to the instructor or independently mentoring a new student.

Based on this model, the first author of this study instructed and co-authored 40 articles and one monograph with undergraduate students. Undergraduate students he mentored won the following awards and contests: three Excellent Bachelor's Degree Thesis Awards of Hubei Province (2013–2015), three Excellent Bachelor's Degree Thesis Awards of Wuhan University (2017–2019), three first prizes and seven second prizes in SuperMap University GIS Contests, one second prize in the Esri GIS Software Dev Contest, three second prizes in National College Student Paper Competitions in Surveying and Mapping Technologies, and a second prize for Excellent Students' Paper Competition at the 26th Geoinformatics Conference (organized by Chinese Professional in Geographic Information Systems). Some of the mentored undergraduates continued to pursue further studies at the following universities: University College London, University of Pennsylvania, University of Wisconsin–Madison, and University of Minnesota. Table 1 lists representative outcome of some of our students.

The instructor and students have formed a community of practice, which significantly improved students' research skills, self-confidence, cooperation, and expectations of graduate studies (Tian 2017). Students have developed skills and mindsets of research, ranging from academic reading and writing to experiment design and result interpretation. During the process of inquiry, students get to know the work of prestigious researchers and exchange ideas with peers and mentors, which draws them closer to scholarly community. With an early taste of research, students also find themselves more confident to pursue further discovery, cutting-edge technology, and practical problem solving in graduate study. The instructor received an award for education excellence in 2019 from the International Association of Chinese Professionals in Geographic Information Science.

Conclusions

IBL is an important signature pedagogy in many disciplines (Spronken-Smith 2013). This article explains two approaches to IBL and presents our practical implementation of both approaches as a GIS instructor and teaching assistants from China. IBL benefits both the academic development of students and professional development of instructors. Issues revealed in our IBL practice are the lack of the necessary skills for inquiry and the willingness to engage in inquiry on the student side. Hence, our first recommendation is to raise student awareness and motivation to become a critical thinker actively rather than to receive figures and facts passively from instructors. Another recommendation for instructors is to make every

TABLE 1. Selected Research Outcome of Students

Authors	Title of work	Year	Source/Award
Liao (B.S. 2022), Y. Wang (B.S. 2016), Ren (B.S. 2016), Tian	Identifying The Relationship Between Air Quality and Road Network Cellular Pattern in China	2021	International Conference on Geoinformatics
Yu (B.S. 2017), Huang (B.S. 2017), Cheng (B.S. 2018), Tian	An Arcmap Plug-In for Calculating Landscape Metrics of Vector Data	2019	*Ecological Informatics,* Vol. 50, pp. 207–219
Tian, Yu (B.S. 2017), Ren (B.S. 2016), Lei (B.S. 2016)	Network-Scape Metric Analysis: A New Approach or the Pattern Analysis of Urban Road Networks	2019	*International Journal of Geographical Information Science,* Vol. 33, pp. 537–566
Yan (B.S. 2017), Tian, Ren (B.S. 2016), Xiong (B.S. 2015)	Mining Co-Location Patterns of Hotels with the Q Statistic	2018	*Applied Spatial Analysis and Policy,* Vol. 11, pp. 623–639
Tian, Fang (B.S. 2016), Y. Wang (B.S. 2016), Ren (B.S. 2016)	On the Degree Correlation of Urban Road Networks	2018	*Transactions in GIS,* Vol. 22, pp. 119–148
Y. Wang (B.S. 2016), Tian, Yu (B.S. 2017), Ren (B.S. 2016), Wu (B.S. 2017)	GEN_MAT: A MATLAB-Based Map Generalization Algorithm Toolbox	2017	*Transactions in GIS,* Vol. 21, pp. 1391–1411
Zhou, Tian, Xiong (B.S. 2015), R. Wang (B.S. 2016)	Point Grid Map: A New Type of Thematic Map for Statistical Data Associated with Geographic Points	2017	*Cartography and Geographic Information Science,* Vol. 44, pp. 374–389
Zhou, R. Wang (B.S. 2016), Mai (B.S. 2017), Tian	Spatial and Temporal Patterns of Air Quality in the Three Economic Zones of China	2016	*Journal of Maps,* Vol. 12, 156–162
Tian, Song (B.S. 2015), F. Gao (B.S. 2015), Zhao (B.S. 2015)	Grid Pattern Recognition in Road Networks Using the C4.5 Algorithm	2016	*Cartography and Geographic Information Sciences,* Vol. 43, pp. 266–282
Monograph			
Tian, Liu, Ren (B.S. 2016), Yu (B.S. 2017), Lei (B.S. 2016), Fang (B.S. 2016)	Pattern Recognition and Analysis of Urban Road Networks: Theories and Methods	2018	Surveying and Mapping Press, Beijing
Awards			
Zhang (B.S. 2013)	A New Method for Radial Pattern Recognition in Road Networks	2013	Excellent dissertation of Hubei Province
M. Li (B.S. 2014)	Cluster Analysis of Vessel Trajectories in Taiwan Strait	2014	Excellent dissertation of Hubei Province
Song (B.S. 2015)	A Machine Learning Approach to Grid Pattern Recognition in Road Networks	2015	Excellent dissertation of Hubei Province
Yu (B.S. 2017)	Network Landscape Metric Analysis: A New Approach to Cellular Pattern Analysis in Urban Road Networks	2017	Excellent dissertation of Wuhan University
Cheng (B.S. 2018)	Public Transit Accessibility Analysis Based on Big Trajectory Data	2018	Excellent dissertation of Wuhan University
Liu (B.S. 2019)	A Neural Network Retraining Approach to Cloud Detection in Remotely Sensed Imagery	2019	Excellent dissertation of Wuhan University
Cheng (B.S. 2018)	2010 China Population Map Series	2018	First prize of cartography group in 16th National College GIS Contest
Ren (B.S. 2016)	Network Functionality Oriented Stroke Building in Road Networks	2015	Second place of student paper competition at Geoinformatics 2015 Conference
Liao (B.S. 2022), R. Li (B.S. 2021), Ye (B.S. 2021)	Exploring Association Between Urban Road Network Patterns and Air Quality	2020	Second prize in 12th National College Student Paper Competition in Surveying and Mapping Technologies

(*table continues*)

TABLE 1. (cont.)

Authors	Title of work	Year	Source/Award
R. Li (B.S. 2021), Liao (B.S. 2022), Mei (B.S. 2022)	Visual Analytics of Spatiotemporal Patterns in Air Quality of 367 Chinese Cities	2020	Second prize in 12th National College Student Paper Competition in Surveying and Mapping Technologies
Liu (B.S. 2019), X. Li (B.S. 2020), Y. Gao (B.S. 2021)	A Neural Network Retraining Approach to Cloud Detection in Remotely Sensed Imagery	2019	Second prize in 11th National College Student Paper Competition in Surveying and Mapping Technologies

effort to create opportunities for students to learn research or inquiry skills, which can help research-ready students gain valuable experience. The final recommendation is to exercise patience when working with students. Hands-on tutorials are highly likely to engage students into the IBL process by removing technical or other obstacles for them.

Higher education is a multidisciplinary field (Tight 2013). Professor Shulman (Shulman 2001) once said, "Each of us in higher education is a member of at least two professions: our professional field as well as our profession as an educator." As instructors in the field of geography, we should be involved in educational research (Hill, Walkington, and King 2018) and return to our duty of teaching by loving it, studying it, and being devoted to it. We should also reflect frequently and pay more attention to students. Instead of solely caring about our own research projects, we need to prioritize the development of students. More non–education-major instructors should also engage themselves in educational research and help students benefit through their action research, thereby enriching research in education.

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