ISPeL: A topic dependency-driven system for personalized learning

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Abstract—**In this paper, we describe the design and development of ISPeL – an Interactive System for Personalization of Learning. Central to ISPeL is topic-based authoring. A topic is a small, self-contained, reusable, and context-free content unit. Learners may study a topic provided that they have met its prerequisite dependencies. Pre- and post-tests are associated with topics. Furthermore, topics feature several practice problems to enhance student learning. A pilot implementation of three undergraduate computer science courses currently in ISPeL is also presented.**

Index Terms—**Topic-based authoring; domain ontology; personalized learning; inclusive pedagogy; engaged learning; ISPeL**

I. Introduction

Broadening Participation in Computing (BPC) is an initiative to address the longstanding underrepresentation of female, Black, Hispanic, Native Indian, and Pacific Islander populations in the computing discipline. This cherished goal remains elusive in closing the gender gap and removing racial inequities. Google commissioned Gallup to understand the structural and social barriers that underrepresented groups face, and the factors that could influence their decision to pursue computing education and careers [1]. This report details both structural and social barriers these groups face for learning computer science.

Most universities and corporations responded to recent injustices to Black people by issuing position statements that outline organizational approaches to addressing the racial inequities. Also, these institutions required their employees complete training courses on diversity and inclusion; some organizations created special units to address racial inequalities. Some ongoing efforts to bridging the gender and racial inequities include first-year experience programs, personalized academic advising, diversity in student services, on-campus living learning communities, peer mentoring, peer tutoring, and undergraduate research. Though these are noble initiatives to help close the gender and racial inequalities in computing, for a transformational and lasting change, we posit that concrete initiatives at the curricula and course levels are needed.

Inclusive pedagogy is an approach to teaching and learning [2]. Though it originally aimed at teaching and learning in K-12 education [3], it is just as relevant for higher education [4], [5]. The three pillars of inclusive pedagogy are course design, recognizing biases and mitigating their effects, and promoting a sense of belonging. Does the course design – readings, discussions, assignments, projects, and assessments – reflect the needs, perspectives, and prior academic background of a diverse array of student identities in the course? Are the instructor and students aware of implicit and explicit biases that they carry? Does the instructor have a plan and tools to mitigate the effects of such biases? Does the course promote a sense of belonging for **all** students? Does the course invite regular student participation, promote student engagement with the course, and foster a sense of belonging?

Universal Design for Learning (UDL) is one framework for implementing inclusive pedagogy [6], [7]. UDL's primary goal is to structure teaching and learning in a way that gives all students an equal opportunity to succeed. UDL offers flexibility for students in accessing and engaging the course content and demonstrating what they have learned. Grier-Reed and Williams-Wengerd [8] provide practical strategies for promoting inclusive teaching and learning by integrating universal design, culturally sustaining pedagogy, and constructivist approaches.

One facet of UDL is personalization of learning. In this paper, we discuss the design of ISPeL – a topic dependency-driven system for personalized learning. ISPeL's lofty goal is to close the academic achievement gap and increase graduation rates for all students including the underrepresented groups.

Central to ISPeL is topic-based authoring. Topics are self-contained and atomic knowledge units. A topic dependency graph captures prerequisite dependencies between topics. Since topics do not have context, topics can be strung together to achieve desired learning outcomes. Topic-based authoring promotes topic reuse and helps to realize *non-course-centric curriculum.* We have developed topics for a Discrete Structures course (among others) and hosted them on ISPeL. We have also piloted the

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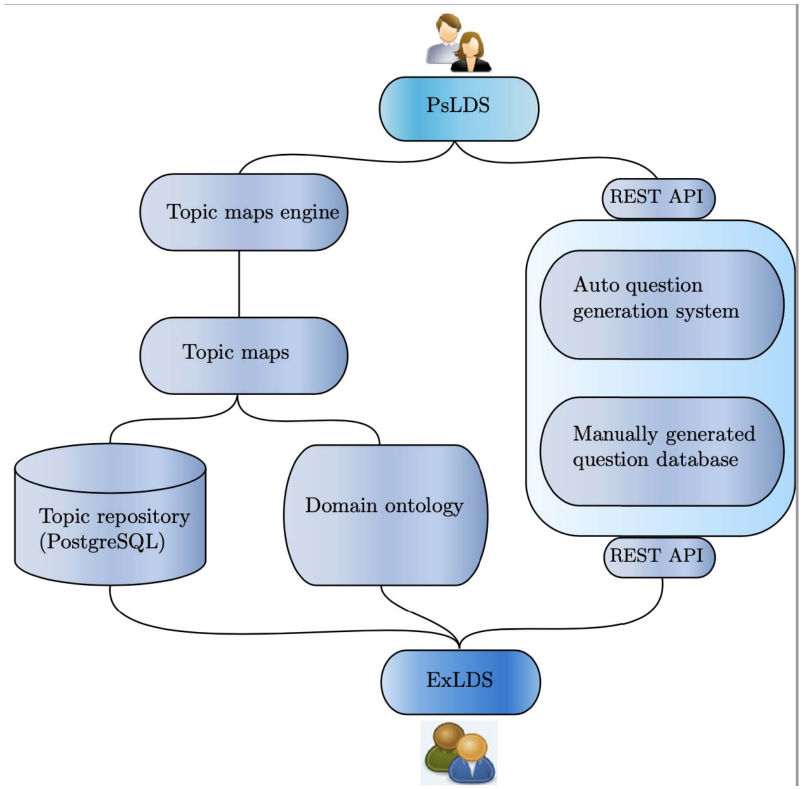

Fig. 1. The architecture of the ISPeL system. There are two modes of interacting with ISPeL: via Pre-sequenced Learning Delivery System (PsLDS), or Exploratory Learning Delivery System (ExLDS). Both use the question engine that provides automatically generated questions, as well as manually curated questions from a question bank, through a REST API. These are used as pre-test and post-test questions and practice problems for each topic. PsLDS and ExLDS also present topics that are stored in a PostgreSQL database and organized using a domain ontology, and displayed visually along with their prerequisites using the topic maps engine. Further details are provided in Sections III, IV, and V.

ISPeL/Discrete Structures course at two universities and gathered formative feedback of ISPeL from students.

We organized the paper as follows. The research that informed the ISPeL design is presented in Section II. ISPeL architecture is presented in Section III. Topic-based authoring is illustrated in Section IV. Section V describes how the topic dependency graph is developed. Implementation of the ISPeL system is presented in Section VI. Section VII concludes the paper.

II. The research that informed ISPeL design

Computer science departments which primarily serve socioeconomically disadvantaged students, rural students, and first generation college students typically have low retention and graduation rates. Much has changed in the educational environment, notably, the use of social media tools, the rapid rise of online instruction and informal learning, and the need for just-in-time and personalized learning. However, the teaching and learning practices in computing have not fundamentally changed given the above backdrop.

Recent advances in computing and communications, cognitive science, and educational technology offer unprecedented opportunities to make significant improvements to how we teach and learn in universities. For example, Ambrose et al. [9] describe seven principles grounded in learning theory and based on research evidence for college teaching. Bean [10] provides a practical guide on how to design engaging writing and critical thinking activities and integrating them into courses to encourage learners' inquiry, exploration, discussion, and debate. Carey [11] describes counter intuitive techniques based on decades of education research and landmark studies to enhance student engagement and learning.

Other evidence based educational research works include using the science of emotion to effect learning [12]; Brown et al. [13] discuss the cognitive psychology-rooted self-testing, introducing difficulties in practice questions, spacing, and interleaving the practice of one skill or topic with another as effective means for learning; Lang [14] discusses how cognitive theory techniques can be utilized to facilitate better student learning. Lastly, Agarwal and Bain [15] provide evidence-based strategies to boost learning for diverse students.

In summary, the recurring themes in the literature to improve student engagement and learning include retrieval practice, spaced repetition, interleaving, and scaffolding. Retrieval practice refers to frequently recalling what has been learned in the form of questions (ranging from factual to higher levels in the Bloom's taxonomy). In the cognitive science domain, retrieval practice is referred to as *the testing effect*.

Spaced repetition is a way to ensure that the learned information is not forgotten by revisiting the information at gradually increasing intervals. Mixing together different pieces of knowledge or forms of practice is referred to as *interleaving*. It requires integrating what is learned now with what has been learned earlier. This is often achieved by solving increasingly complex problems which require synthesizing several pieces of knowledge. Scaffolding is a general technique for enhancing learning and has multiple facets. One facet of scaffolding involves solving a problem in multiple ways to ensure understanding.

Our striving for fostering an equitable and culturally responsive learning environment led us to the design and development of ISPeL, with the above mentioned research informing the functional aspects of ISPeL.

III. ISPeL architecture

Figure 1 shows the high-level architecture of the ISPeL system. The system is driven by topics and domain ontologies, which are persistently stored. Currently, domain ontologies are limited to capturing only the prerequisite dependencies between the topics.

Learners navigate the ISPeL topic universe in two different ways: Pre-sequenced mode, using the Pre-sequenced Learning Delivery System (PsLDS) component, and Exploratory and discovery mode, using the Exploratory Learning Delivery System (ExLDS) component. A domain expert (e.g., a course instructor) determines the sequence in which the topics should be learned and declaratively creates a web application using the *Topic maps* and *Topic maps engine* components. This application is delivered through the PsLDS subsystem of ISPeL. In the exploratory and discovery mode, the learners are on their own and engage in exploratory learning by navigating the ISPeL topic universe. This functionality is provided by the ExLDS subsystem. In the exploratory mode, learning of a topic is constrained only by the prerequisites for the topic. A topic may require one or more other topics as prerequisite knowledge.

Through both modes of learning, ISPeL provides learners opportunities to internalize what they are learning through pre-test and post-test questions, and practice problems. ISPeL features on-demand auto-generated questions as well as questions drawn from question banks. The questions are available through a REST API.

IV. Topic-based authoring

As indicated earlier, a topic is a small, self-contained, reusable, and context-free content unit. Topics can be aggregated to form higher-level learning units. The fields that comprise the topic are:

1) topic-id (a system-wide unique identifier)
2) topic-name (a self-describing short name)
3) topic-prerequisites (topic-ids of other topics that form prerequisites for the topic under consideration)
4) topic-keywords (one or more terms that can be used to search for topics)
5) topic-content (detailed topic description)

Topic content for a topic named *set definition* is shown in [16]. Only the *topic content* is shown and other meta-data about the topic – ID, prerequisite topics, and keywords – are not shown. The latter are not directly visible to the learners. The meta-data is used for navigating the topic universe and to search for topics.

One of the greatest challenges to topic-based authoring is the identification of topics. Deep domain expertise is essential for this task. Our manual approach, shown in Figure 2, involves coming up with a list of topics and their dependencies by drawing upon the domain knowledge. It is essentially an incremental and iterative process. In the tabular form (Figure 2), it is hard to detect errors in topic dependencies. To reduce and eliminate errors, we visualize the dependencies using a topic dependency graph, which is discussed in the next section.

V. Topic dependency graph

Dependencies between the topics are modeled as a Directed Acyclic Graph (DAG). Vertices in the DAG correspond to topics and the directed edges between them correspond to prerequisite dependencies. For example, a directed edge from vertex v_1 to v_2 denotes that the topic corresponding to the vertex v_1 is a prerequisite for the topic corresponding to the vertex v_2. A topic can have multiple other topics as prerequisites. Likewise, a topic can be a prerequisite for multiple other topics.

An interactive topic dependency graph for a subset of the topics for an undergraduate course in Discrete Structures is available at https://rpubs.com/gudivada/708133. The topics encompass set theory, functions, relations, and (limited scope) discrete probability. A learner can zoom in/out and pan the graph. One way to explore the ISPeL topic universe is to use the DAG as an user interface. By clicking on a vertex, the ExLDS component of the ISPeL system will take the learner directly to the topic.

VI. ISPeL implementation

ISPeL system implementation is in alpha phase. The current version has limited functionality and is available at https://ispel.cs.ecu.edu/. The courses hosted on ISPeL include Discrete structures, Organization of programming languages, and Digital image processing/ Computer vision.

The topics are authored using the R Markdown language. Interactive elements are embedded using R lan-

Topic ID	Topic Name	Parent Topic IDs (comma seperated)	Relationships (total number, direction, name)	Si
Relations				
ds:relations:relation-definition	relation-definition	ds:functions:function-definition, ds:set-theory:cartesian-product	2,c2p,ds:functions:function,prerequisite-dependency;c2p,ds:set-theory:cartesian-product,prerequisite-dependency	
ds:relations:inverse-relation	inverse-relation	ds:relations:relation	3,c2p,ds:relations:relation,prerequisite-dependency,p2c,ds:relations:relation,inverting-a-relation, c2p, ds:relations:relation, is-a	
ds:relations:relation-composition	relation-composition	ds:relations:relation	3,c2p,ds:relations:relation,prerequisite-dependency,p2c,ds:relations:relation,composing-relations, c2p, ds:relations:relation, is-a	
ds:relations:reflexive-relation	reflexive-relation	ds:relations:relation	3,c2p,ds:relations:relation,prerequisite-dependency,p2c,ds:relations:relation,reflexive-property, c2p, ds:relations:relation, is-a	
ds:relations:irreflexive-relation	irreflexive-relation	ds:relations:relation	3,c2p,ds:relations:relation,prerequisite-dependency,p2c,ds:relations:relation,irreflexive-property, c2p, ds:relations:relation, is-a	
ds:relations:symmetric-relation	symmetric-relation	ds:relations:relation	3,c2p,ds:relations:relation,prerequisite-dependency,p2c,ds:relations:relation,symmetric-property, c2p, ds:relations:relation, is-a	
ds:relations:antisymmetric-relation	antisymmetric-relation	ds:relations:relation	3,c2p,ds:relations:relation,prerequisite-dependency,p2c,ds:relations:relation,antisymmetric-property, c2p, ds:relations:relation, is-a	

Fig. 2. Subset of the domain ontology. Each topic has a unique identifier, a name, a list of prerequisite topics, and a list of keywords.

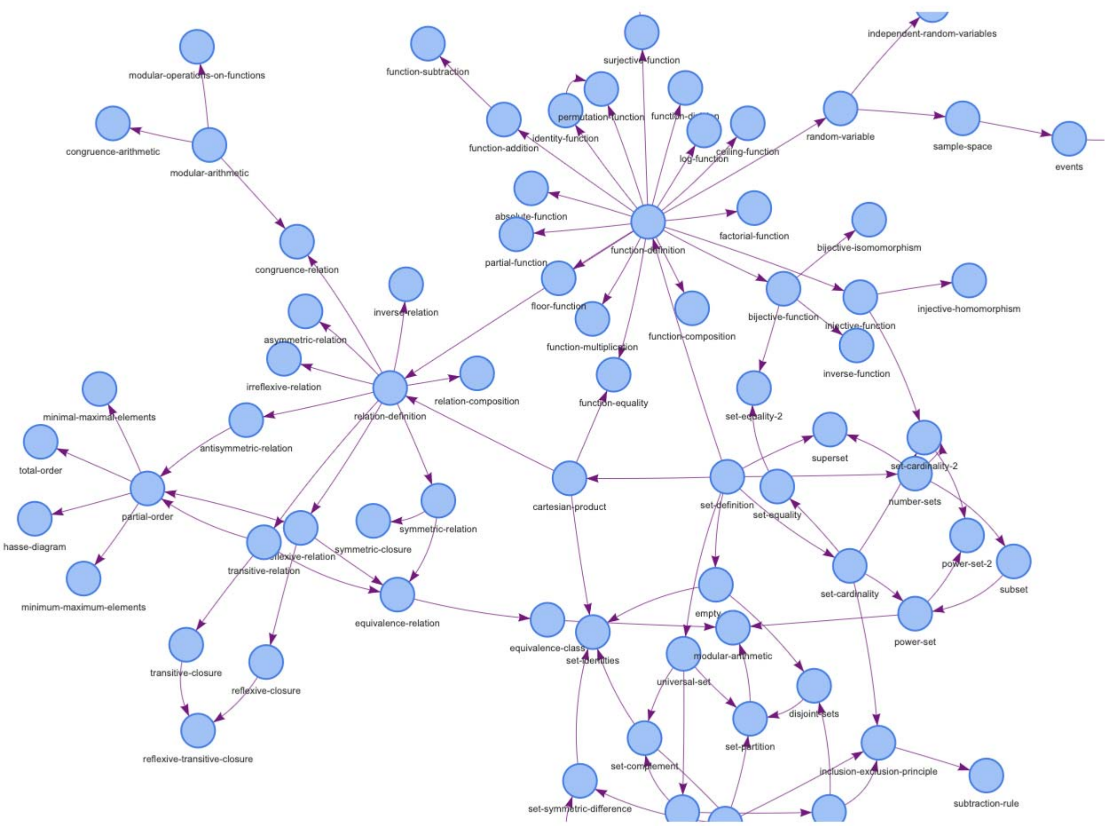

Fig. 3. The topic dependency graph. Each topics is represented as a vertex/node in the graph with the topic name listed next to it. The incoming edges represent the prerequisites for the topic, whereas the outgoing edges indicate which topics have this as a prerequisite. Users of the system can zoom in and out to narrow in on a specific topic and select it, or to view the big picture of how the topics are organized.

guage packages including ggplot2, plotly, shiny, and htlwidgets (see https://rpubs.com/gudivada/709139).

VII. Conclusion

ISPeL is a system for the personalization of learning. Central to ISPeL is topic-based authoring. Topics are authored using interactive content elements to promote student engagement and learning. ISPeL also features pretest, post-test, and practice questions to enhance learning through retrieval practice. We expect a fully functional ISPeL system by the end of the current year.

Though ISPeL is developed for computer science courses, its use is not limited to computer science learning. The key is to identify the domain topics at the right level of granularity and author them using the ISPeL topic template, ISPeL can be used across the domains.

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