Enriching STEM Education through Personalization and Teaching Collaboration

(Invited Paper)

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Abstract—Advances in databases, computational intelligence, and pervasive computing, which allow “anytime, anywhere” transparent access to information, provide fertile ground for radical changes in pedagogy. Cyberinfrastructure leveraging these technological advances can yield improvements in both instruction and learning, supporting a networked curricular model, facilitating collaboration within and among groups of students and instructors, and providing continuous access to instructional material. The trajectory followed by each student through the curriculum can be intelligently personalized, based on prior knowledge and skills, learning styles, and interests of the student, among other attributes.

We propose to achieve these objectives by developing Pervasive Cyberinfrastructure for Personalized Learning and Instructional Support (PERCEPOLIS), which serves as the centerpiece of an experiment to create a community of faculty and students over a set of campuses, focusing on STEM disciplines. While numerous distance learning methods exist, we believe that the best way to provide STEM education is to use a blended approach - one that embraces both online components and classroom mentoring by qualified faculty members. The goal is to provide high-quality STEM education for the students, while raising the skill set of the entire community through teaching collaboration.

I. INTRODUCTION AND MOTIVATION

The need for transformative change in higher education is especially pressing in Science, Technology, Engineering, and Mathematics (STEM) disciplines, where courses and curricula should keep abreast of rapid technological advances. The critical role of STEM education in the knowledge-based global economy has been articulated in Rising Above the Gathering Storm, a report issued in 2005 by the National Academies [1]. The America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science (COMPETES) Act (2007-2010) was signed into law in response to this need. However, the five-year review - Rising Above the Gathering Storm, Revisited: Rapidly Approaching Category 5, released by the National Academies in September 2010, concluded that despite stimulus funding, the quality of STEM education in the United States has worsened [2].

Recent statistics that place the United States far behind other industrialized countries in education offer further testament to the urgent need for revitalizing higher education [3].

Several principle shortcomings of current undergraduate engineering education programs were identified in Educating Engineers: Designing for the Future of the Field, a report by the Carnegie Foundation for the Advancement of Teaching. One of the main problems described is the linearity of the dominant curricular model. A networked curricular model was proposed to remedy this shortcoming. The report also emphasizes that the trajectory followed by each student through the curriculum can and should differ. The importance of personalizing this trajectory is underscored by the selection of personalized learning as one of fourteen Grand Challenges for Engineering identified by the National Academy of Engineering [4].

The predominant instructional model is also in need of a paradigm shift. The majority of endeavors undertaken by faculty members are carried out in disjoint and isolated fashion. Collaboration, at best, is typically limited to sharing of instructional content for specific courses within a program, resulting in duplication of effort, and inconsistency from one offering of the course to the next. For many schools, the lack of expertise and/or resources for effective delivery of subject matter are very pressing issues, especially in light of financial constraints that prevent hiring, training, and expansion.

This paper describes an innovative, practical, and comprehensive alternative to the traditional linear curriculum and lecture-based static pedagogy inherited from a socio-economical platform where higher education was not a necessity, but a privilege. The objective of the proposed efforts is to establish a growing community of educators who leverage shared cyberinfrastructure for teaching collaboration and personalization of STEM courses and curricula. Expected outcomes are increased enrollment, retention, and graduation rates for a diverse set of STEM disciplines, rather than any single program. The ultimate result will be a highly-qualified STEM workforce, equipped with critical thinking ability, and computational knowledge and skills well-suited to advances in technology and socio-economical needs. Figure 1 further articulates the objectives and outcomes of the project.
Increased enrollment  Improved retention  Increased graduation

Improved quality of STEM education

Achieves

PERVASIVE CYBERINFRASTRUCTURE FOR PERSONALIZED LEARNING AND INSTRUCTIONAL SUPPORT (PERCEPOLIS)

Supports networked curricular model

Teaching collaboration  Reform of teaching practices  Personalization

Support for networked curricular model

Elevating knowledge and experience  Resource sharing  Blended instruction and learning  Active and peer learning

Fig. 1. The overall objectives and outcomes of PERCEPOLIS.

**Pervasive Cyberinfrastructure for Personalized Learning and Instructional Support (PERCEPOLIS)** leverages a plethora of enabling technologies to facilitate resource sharing and collaboration across multiple disciplines and institutions. PERCEPOLIS views each course as a set of topics - some mandatory, as dictated by the curriculum to satisfy degree objectives and accreditation requirements; and elective topics that can be chosen to supplement a student’s knowledge of prerequisites, or to engage an interested student in advanced content. Once a critical mass of educational artifacts is developed, linkage of topics across courses can facilitate support of a networked curriculum - potentially eliminating redundancy.

Increasing enrollment, retention, and graduation through grass-root efforts that enrich and facilitate STEM education requires attention to both teaching and learning. The intelligent personalization offered by PERCEPOLIS can be leveraged to both ends, as it facilitates sharing and navigation of and access to two possibly overlapping sets of educational artifacts: i) a set of teaching artifacts, which is accessible by the instructor; and ii) a set of learning artifacts that is intended for students. The learning artifacts made available to the students are selected by the instructor of the course, and can include as few or as many teaching artifacts as the instructor deems appropriate. Intelligent software agents will aid instructors in personalizing courses to their teaching style and view of pivotal topics, recommending an appropriate set of teaching artifacts. The learning artifacts recommended to each student for a course can be similarly personalized, based on attributes such as academic profile, learning style, needs, and interests.

As depicted in Figure 2, the proposed cyberinfrastructure will be in the form of middleware that links databases, e.g., PeopleSoft, and instructional platforms, e.g., Blackboard, Angel, currently in use at academic institutions, facilitating incremental adoption of the networked and modular curricular model at low cost. Moreover, the ability to connect tools already in use, without requiring customized computing resources, enables instructors at different academic institutions to collaborate on and exchange educational materials and information, creating an environment conducive to collaboration on both teaching and educational research.

Current efforts are focused on STEM disciplines, due to the teaching and research expertise of the authors. However, the cyberinfrastructure and personalization methodology are applicable to a broad range of disciplines. This article is not intended to compare and contrast different approaches to “personalization of courses” as advanced in the literature. It is intended to articulate the importance of personalization and networked curricula, while introducing PERCEPOLIS and enumerating its features.

**II. INTRINSIC CHARACTERISTICS OF PERCEPOLIS**

A. **Novelty**

Fundamental to PERCEPOLIS is the modular approach to course development, which allows for finer granularity in personalization. PERCEPOLIS: i) offers a teaching methodology that is more in-tune with technology savvy generation-Y and millennial college students, ii) leverages pervasive and ubiquitous computing and communication through the use of intelligent software agents, and iii) provides assessments that gauge the student's mastery of concepts at the module level and allow self-paced progression through the course.

To maintain a sense of community, advanced students who progress through the course more rapidly will serve as group leaders. This peer learning approach fosters skills such as communication and negotiation. Furthermore, the proposed cyberinfrastructure facilitates the collection of data on student performance and learning at a resolution that far exceeds what is currently available. Knowledge discovery from this rich data set can yield invaluable insights, such as the efficacy of particular instructional techniques and strategies embedded in the learning artifacts. The capabilities envisioned for PERCEPOLIS subsume currently existing technology, which includes animated textbooks and similar electronic artifacts; online
homework repositories, e.g., Sapling Learning; or standardization efforts for web-based learning, e.g., SCORM [5]. Our efforts rise to the grand challenge of personalized education.

B. Support of Cognitive Apprenticeship

A significant body of research [6] has concluded that effective learning takes place in the course of a “cognitive apprenticeship” that fosters the learner’s intellectual development [6]–[8]. Four concepts have been identified as essential to the critical examination and improvement of education; each concept represents a stage in the cognitive apprenticeship:

2) Scaffolding: provide support for emulating expert performance.
3) Coaching: providing students with deliberate, planned feedback that guides their performance from novice- to expert-level.
4) Fading: removing the scaffolding as students become more competent.

PERCEPOLIS facilitates all four stages of cognitive apprenticeship. In the modeling stage, the classroom instructor provides in-class access to an expert. The material provided as supplementary material for each module, such as solved problems, design examples, and guided exercises with “hints” are among the learning artifacts useful in the scaffolding stage. Online assessments, some of which are graded instantaneously, are examples of artifacts that facilitate coaching. Allowing the students to work on their own schedule and pace on the more advanced learning artifacts provides a gradual fading of the student’s reliance on the classroom instructor. In conjunction with the frequent and detailed feedback that PERCEPOLIS can aid in providing to the students, this allows for a “metacognitive” approach to instruction, where students define their own learning goals and monitor their progress towards them. Evidence for the effectiveness of the metacognitive approach has been documented in numerous studies, a seminal example of which is How People Learn: Bridging Research and Practice - a report by the National Research Council [9].

C. Building a Community of Educators

Mentoring less experienced faculty members who may, by necessity, be teaching courses outside of their main areas of expertise by more experienced faculty members is a powerful aspect of PERCEPOLIS. Multi-institutional collaboration will create a richer pool of teaching expertise, such that in cases where the local faculty member designated to teach the class does not have all of the required skill set (either content knowledge or teaching strategies), PERCEPOLIS can assign a faculty member from another institution to mentor the local faculty member. An important aspect of this approach is its bidirectional nature. While content knowledge is likely to be stronger at the larger universities, instructors at smaller institutions are more likely to utilize unique teaching approaches.

The two-pronged approach of the proposed efforts aims for improvements in both learning and teaching. Efforts related to teaching center on mentoring of less-experienced (with a particular topic, or teaching in general) faculty, by those with greater expertise. This approach has been shown to improve both the instructor’s experience and the quality of her/his teaching [10]–[13]. Mandernach et al. [14] have shown similar effectiveness for mentoring of online instructors. The use of technology in mentoring has been a useful tool for cost-effective communication between mentors and instructors. Gentry et al. [15] discuss three successful technology mediated approaches to mentoring studied in the literature; namely, technology-enhanced professional development coupled with access to a mentor, electronic mail, and online discussion forums. PERCEPOLIS goes beyond these tools to provide an intelligent platform for sharing and navigation of teaching resources, where pervasive computing is utilized to personalize the resources (including mentoring) recommended to an instructor, based on needs, preferences, and teaching style.

D. Support of Blended Learning

The PERCEPOLIS community enables blended learning, where the classroom instructor has the choice of using online,
computer-mediated instruction to supplement traditional classroom activities, as well as supporting personalized enrichment material for the students. Blended learning is an emerging phenomenon well-suited to the learning styles and expectations of today’s students, who are digital natives [16].

E. Support of Peer and Active Learning

The peer and active learning opportunities offered by in-class activities can strengthen interpersonal skills and facilitate interaction among students. PERCEPOLIS allows the instructor to make use of online forum tools in existing course management platforms to initiate and scaffold both asynchronous, written group activities (discussion boards) and synchronous, live team negotiations (voice boards, online conferencing tools). These activities can be monitored by the instructor, advanced students serving as peer leaders, or both. The involvement of peer leaders will help students build leadership skills, strongly valued by the future employers. Furthermore, the engagement of multiple STEM disciplines exposes students to interdisciplinary applications of the topics they study - tangible motivation for learning the material.

The ability of the instructor to utilize computing technology to support rich educational content has the added benefit of facilitating the accommodation of differences in learning styles. The average learner retains about 20% of what is heard, 40% of what is seen and heard, and 75% of what is seen, heard, and performed [17]–[19]. A traditional classroom setting mainly offers visual and auditory content; print or video-based distance study does the same. The ability to provide tactile content, whether in reality, in a classroom setting, or through remote access and virtual reality, is especially helpful in the modeling stage of the cognitive apprenticeship, but can also be exploited to increase the efficacy of other stages. Furthermore, the predominant learning style of a student can be assessed and used in personalizing courses and curricular trajectories for each student. The ability to track the perusal of educational content by each student allows more accurate determination of his/her learning style [20].

III. DESIGN OF PERCEPOLIS

PERCEPOLIS views a degree-granting program as four sets of entities: i) instructors, I; ii) (teaching) mentors, M; iii) students, S; and iv) courses, C. An instructor, \( i \in I \), has expertise in one or more subjects. A mentor, \( m \in M \), is a faculty member with a high level of expertise in one or more areas. A student, \( s \in S \), is studying towards a degree and is required to take courses from \( C \), in an orderly fashion, to satisfy degree requirements. Each \( c \in C \) represents a course in the curriculum, and is tagged as required or elective. The courses are interrelated, per the structure of the curriculum.

Each of \( I, M, S, \) and \( C \), respectively, is represented by a community of software agents that communicate and negotiate with each other according to the defined tasks, e.g., recommending a personalized set of teaching (learning) artifacts to each instructor (student), and in effect, personalizing his or her experience of a course (or curriculum). Mentors are assigned to courses as required. As described in Section III-A, we use a modular approach in the development and delivery of courses, so that each course \( c \in C \) can be viewed as a collection of interrelated topics, where the degree of connectivity among topics can vary from course to course.

When a student, \( s \), is required to take a course, \( c \), an agent, \( A_{sc} \) is created to represent the student in that course. \( A_{sc} \) acquires information about the student’s profile and determines the student’s academic background, interests, and accumulated prerequisite knowledge, among other required information. \( A_{sc} \) interacts with the agents of course modules to identify a personalized trajectory of modules and learning artifacts for the student. Furthermore, \( A_{sc} \) ensures that the student peruses required material - notes, sample programs, exercises, and the like. PERCEPOLIS also creates a course agent, \( A_{cs} \), which represents the personalized course, \( c \), for the student, \( s \). \( A_{cs} \) interacts with the agents of the instructors to identify the most knowledgeable instructor for the personalized course for this student (assuming that more than one instructor is available). If only one instructor is available for the course, a single instructor agent \( A_{ic} \) will interact on behalf of the instructor with all student agents. The student’s agent, \( A_{sc} \), then alerts the student to timelines, class schedules, learning/discussion schedules, project deadlines, appointments with the instructor, and corresponding preparations. The instructor identified is represented by an agent, \( A_{isc} \), who ensures that the student meets all requirements for each mandatory module, and collaborates with \( A_{cs} \) to ensure that the student is supplied with all required course material. \( A_{isc} \) also informs the instructor about the progress of the student and alerts the instructor whenever the student is progressing too slowly or too rapidly.

A. Modular Course Development

As described in Section I, the modular approach to course development is fundamental to PERCEPOLIS. Each course is viewed as a set of mandatory and elective topics, where each topic is associated with educational (teaching and/or learning) artifacts, which can include experiential artifacts intended to reemphasize key issues through hands-on individual and group projects. The experiential artifacts are dynamic, as their contents can be determined based on topics that a majority of the students in a given class find challenging or confusing. Figure 3 illustrates a sample environment for a course on design and analysis of algorithms.

The learning artifacts that comprise a course are self-contained, allowing for self-paced perusal and designed to promote active, rather than passive learning. Self-assessment questions at the end of each module can take a variety of forms, including objects to be “dragged” into place, and multiple-choice or short-answer questions. The most interactive learning artifacts are the design challenges, in which the student must make decisions and respond to “hints” and other feedback in order to find a solution for the problem at hand. Graphics and animation can be used to demonstrate complex concepts. Text, narration, charts, and diagrams can be used to reinforce concepts during animation.
Some topics require prior knowledge; if the student does not have this background, he/she will be able (and expected) to peruse learning artifacts associated with the prerequisite topic. Assessments that gauge the student’s mastery of concepts at the topic level are used to allow self-paced progression through the elective, and at the discretion of the instructor, the mandatory material. If these assessments indicate that a student has already mastered the basic concepts of particular topic, more advanced learning artifacts related to that topic will be recommended to him or her. To maintain a sense of community at the class level, advanced students are encouraged to serve as leaders of group activities. This peer learning approach fosters “soft” skills, such as communication and negotiation.

Figure 4 depicts the possible trajectories of a student through one topic of a course. The figure also demonstrates the student tracking process as incorporated in the topic. Each topic reinforces background knowledge and provides options to study more advanced concepts and/or to gain missing basics.

To summarize, modular course design offers:
- Adaptability/flexibility: to a certain extent, course contents can be personalized based on the needs and interests of both the students and the instructor.
- Continuity: the modular approach to course design, combined with the ability to personalize the contents of a course, allow greater continuity in the curriculum, while satisfying the needs of some students without sacrificing the needs of others.

### B. Blended Learning and Instruction

Common experience shows that online availability, e.g., through a course management system such as Blackboard, of lecture notes and other instructional content generally leads to low class attendance by students. Even students who continue to regularly attend classes may become inattentive in the classroom and passive in any discussions that take place. Furthermore, there is increasing expectation that the course coverage and examinations must be limited to whatever is available online, and any topics discussed outside of class should not be covered on the tests. Periodic examinations and pop quizzes (though extremely unpopular among the students) can be used to address this problem to some degree, but are becoming harder to implement, due to large class sizes.

We seek to adopt a new teaching practice that is attuned to advances in technology, is interactive and motivates active class participation, enforces continuous learning, and fosters interpersonal skills that may be neglected in a traditional classroom. To achieve these objectives, we propose to modify the traditional lecture-based teaching environment, by supplementing the standard lecture notes in the teaching artifacts with examples and solved problems that the instructor can use during class time to hold the student’s attention and encourage class discussion. The examples will be technology based, e.g., utilize animation. In addition we apply a blended approach to learning and instruction by providing students with a rich set of learning artifacts that are personalized to take advantage of the students needs and optimal learning styles.

We expect that these artifacts will result in classes that are more dynamic, supporting the following features:
- Students are required to peruse specified learning artifacts before class. Group study (facilitated by experiential learning artifacts) is highly encouraged.
- The combination of the learning artifacts and support for
online communication tools such as discussion boards allows students to share their concerns and questions with their peers and the instructor.

- The class period then is dynamically organized to address major issues raised by students and enhance their understanding of subject matter in the learning artifacts.
- To encourage independent learning and reflection and enforce continuous involvement, at the beginning of each class period, students are quizzed based on the key concepts of the topic they have been asked to study. The remainder of the session will be devoted to addressing students’ questions, and discussing and analyzing the more complex concepts.
- Traditional periodic homework assignments and projects will be introduced and supported by learning artifacts. Both online and traditional examinations will continue to be utilized to reinforce learning and determine the students’ overall mastery of course concepts.
- To maintain a sense of community within the class, students who already know the material on a topic will be given a learning artifact on a related, but more advanced topic and will be asked to take part in class by leading discussions on some of the more advanced concepts.
- Finally, some of the examples in the teaching and learning artifacts will be designed to encourage, promote, and reward group activities and instill missing basics such as leadership, communication skills, and ethics.

In summary, our view of the classroom is an environment conducive to experimentation and discovery, which can be tailored to focus on topics considered pivotal by the instructor.

C. Intelligent Access Tools

We leverage our research in multidatabases, mobile agent technology, pervasive computing, and mobile data access systems to develop middleware that serves as global information sharing cyberinfrastructure [21]–[25]. The middleware is positioned on top of existing database and course management systems, and allows anytime, anywhere intelligent and transparent access to learning artifacts that comprise the courses of a curriculum. Our research within the scope of global information sharing, multidatabases, and multimedia data processing has resulted in the design and implementation of an intelligent search engine, denoted as the Summary Schemas Model (SSM) [24], [25], that supports automatic identification of semantically similar/dissimilar data that have different/same names and representations in a wired or wireless platform. The model uses word relationships, i.e., hypernym, hyponym, synonym, defined in a standard thesaurus such as Roget’s, to automatically build hierarchical metadata of local access terms exported from underlying local databases. The embedded dynamic nature and bottom-up design approach of the SSM makes it particularly suitable for extending the scope of this proposal beyond a single discipline or educational unit. The summary schemas concept will be used to develop a semantic network and semantic metadata that integrate course modules, and hence courses, within and across multiple curricula.

Furthermore, with the aid of the navigational tools and imprecise content-based search capability of the SSM, users, e.g., students, instructors, and advisors, can browse through learning artifacts from a range of courses and curricula to determine an appropriate learning trajectory. The choice of the SSM stems from: i) its ability to perform semantic search and imprecise queries; ii) the small size of its metadata; which it automatically generates; iii) its robustness and efficiency.

In the context of PERCEPOLIS, the SSM metadata hierarchy, at the root level, represents the curriculum, e.g., CS and CpE curricula, with semantic terms that specify...
curriculum objectives and content requirements. We mainly utilize the computational and software facilities available in participating organizations and UNIX-based operating systems. The relational data model will be used to model course topics. Local data sources can be built on top of various database management systems, ranging from Microsoft Access to PeopleSoft. As a security measure, provisions will be made to provide different access capabilities to different classes of users, e.g., students, administrators, or course developers, based on their individual profiles. All artifacts developed in the course of the proposed work will adhere to Sharable Content Object Reference Model (SCORM) [5] standards to facilitate interoperability with other educational platforms, and the navigational tools will be cognizant of SCORM metadata, to allow query of artifacts external to PERCEPOLIS.

IV. CONCLUSIONS

The concept of modular offering of courses, in a limited fashion, was implemented in a senior/graduate computer architecture course with an enrollment of seventeen (mainly graduate) students. The course was composed of seven distinct modules. Three sets of questionnaires were given to the students throughout the course; at the beginning, middle, and end of the semester. We are in the process of analyzing the results. In general, the students appreciated the modular approach; common complaints were due to i) unfamiliarity of the students with the new teaching approach and expectations, and ii) the frequency of examinations and testing.

The goal of the PERCEPOLIS project is to create a community of faculty and students, supported by powerful cyberinfrastructure that facilitates a) the provision of diverse educational opportunities to students and b) the mentoring of faculty who may, by necessity, be teaching courses outside of their main areas of expertise. To reach these goals, the PERCEPOLIS cyberinfrastructure utilizes teaching tools, animation techniques, and remote access to information to present the same information in different ways and accommodate differences in learning styles; allow self-paced, private, and flexible perusal of learning artifacts; and make more efficient use of resources, potentially lowering costs for both students and institutions.

Furthermore, the proposed efforts can enable a shift to professional practice, rather than technical skills, as the focus of educational efforts; by providing a rich set of teaching and learning artifacts, facilitating more efficient use of class time, and encouraging active and peer learning. Finally, PERCEPOLIS can be used to increase the efficacy of student advising, by providing the advisor with information at the topic, rather than course level; and allowing him or her to leverage the intelligent personalization and pervasive computing capabilities of the cyberinfrastructure to guide the efforts of the student.

REFERENCES


