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Closed-Loop Dynamically Adaptive Educational Systems

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Abstract

We believe that our education systems are currently not capable of evolving at the rate necessary to meet the challenges presented by rapidly changing technology epitomized by Industry 4.0 and the digital transformation. Our research project goal is to pilot a learning laboratory that can be used to conduct the necessary experiments to create and apply the foundational knowledge necessary to support a dynamically adaptive educational system for university students that can meet the challenges presented by rapid change. Our research will address the following three critical areas: educational program evolution, social real-time learning, and personalized knowledge discovery. This paper describes how these three research tracks will produce generalized knowledge about feedback mechanisms that can serve as a foundation for the creation of a dynamic, self-adapting educational system impacting individual students' acquisition and application of knowledge, skills and dispositions as well as classroom curricula and pedagogy, and program outcomes and design.

Keywords: Education ecosystem; learning laboratory; AI in education; dynamically adaptive education; engineering graduate education

1. Introduction

1.1. Motivation

We believe that our education systems are not capable of evolving at the rate necessary to meet the challenges presented by rapidly changing technology epitomized by Industry 4.0 and the digital transformation. In particular, there are relatively slow, inaccurate, and incomplete feedback mechanisms between the needs of employers, students and universities at the level of program content development and evolution[1-3].

Unfortunately, much of the K-12 and post-secondary educational systems in use in the US today were developed in the 1800's to serve the social and economic needs of the second industrial revolution. The resulting educational processes in many ways mimicked the batch manufacturing processes of this technological revolution, where what you learn as a student is primarily determined by your date of manufacture (aka date of birth), following a standard process of attending lectures, reading textbooks, completing homework and taking quizzes and tests. The structures of courses and post-secondary institution departmental divisions also are based on reductionist approaches first used in industrial corporate organizations at that time. Educational pedagogies are reflective of an industrial process in which information is presented to all students synchronously, often in large, non-interactive groups.

While the existing educational organizations and strategies have been sufficient for the industrial age in which desired occupational capabilities and supporting educational objectives are changing slowly over time, they are not sufficient in today's rapidly evolving, networked, digitally transformed environment. We are entering the fourth industrial revolution which is driven by complex, massively distributed, data-driven systems. This revolution relies on data, analytics, machine learning, and modeling to constantly evolve and improve, during ever-shorter iterations. Humans are increasingly becoming an integral part of the system itself, raising the importance of the social sciences to provide context for the use of technology. As human impact increases, environmental, societal, and economic sustainability become increasingly important factors in the engineering design process. The pandemic has accentuated the need to make education more accessible in numerous modalities and their hybrid variants. Finally, these changes are taking place at an ever increasing rate, far outstripping our ability to predict the near future. While education has adopted new technologies, in many cases they have been used to replicate existing educational processes. The current, relatively static educational structures are inadequate to support the rapidly changing needs for the networked age.

1.2. Project Goal

Engineering graduate education is at the cutting edge of Industry 4.0 as advanced post-secondary education is necessary to support and advance the state of the art. The socio-technical aspects of this challenge require the contributions of a transdisciplinary team, with anthropological insights to understand the critical cultural context, educational social scientists with expertise in these systems, cognitive scientists with insights in the human process of learning, data scientists and engineers who can provide the technical expertise to support the collection of data and their subsequent analysis. We believe that due to the complexity of the education system, dynamic adaptation will require the use of the same technologies and techniques that are enabling Industry 4.0, namely the use of data-driven feedback to drive system behavior.

Research Goal: Pilot a learning laboratory that can be used to conduct the necessary experiments to create the foundational knowledge necessary to support a dynamically adaptive educational system for engineering graduate students which can meet the challenges presented by a rapidly evolving technology.

1.3. Project Focus Areas

Education is a complex ecosystem composed of numerous stakeholders including: students, educational institutions, educational administrators, curriculum developers, instructors, tutors, employers and educational technology suppliers. There are many critical decision points in the educational process for all the stakeholders as shown in Table 1 below.

Table 1. Critical Decision Points in Graduate Education

	Program & Course Design	**Classroom Experience**	**Individual Learning**
Graduate Students	- Institution application & enrollment - Degree/major selection - Course selection - Class/instructor selection	- Determination of when and how to study - Selection of learning materials (lectures, reading, videos, etc.) - Determination of where to work to use skills	- Determination of personal interests - Development of knowledge production skills (e.g., Web search) - Selection of online resources for knowledge acquisition

	Program & Course Design	**Classroom Experience**
Academic Institution & Instructors	- Program topic and target student selection - Program learning outcomes and objectives specification - Course topic: outcomes and objectives specification - Course design: curricula, pedagogy, assessment, and curriculum mapping - Determination of which educational applications to provide to instructors - Determination of whom to admit into programs and classes - Allocation of resources, including assignment of instructors to classes, room assignments, lab, funding of TA's, tutors, graders - Determination of tuition and other educational costs	- Determination of how to present/facilitate materials - Determination of which educational applications to use in instruction - Determination of how to answer [and ask] questions and interact with students - Determination of how to update and integrate course materials - Determination of how to assess, measure, and evaluate student performance while providing timely feedback - Determination and application of grading policy

	Program & Course Design
Employers	- Determination of necessary skills for employees in the workplace - Determination of which schools to support with partnerships and funding - Determination of which schools to actively recruit students - Determination of which students to interview - Determination of which students to hire as interns, coops, and permanent employees - Determination of which programs are eligible for professional education reimbursement - Determination of which employees to reimburse for professional education

These decisions require various amounts of qualitative and quantitative information, with sometimes greatly differing lag times. While analysis of the entire educational ecosystem is beyond the scope of this project, we intend to address a range of critical decision points, with a wide range of decision latencies and contexts. The critical decision points that we aim to address are: (1) how educational institutions define programs, and design and develop courses with decision latencies in months to years. (2) how instructors and students interact to maximize engagement in the classroom with decision latencies in minutes to months, and (3) how individual students search for and access information with decision latencies in seconds to minutes. The three research focus areas are shown diagrammatically in Figure 1 and described below.

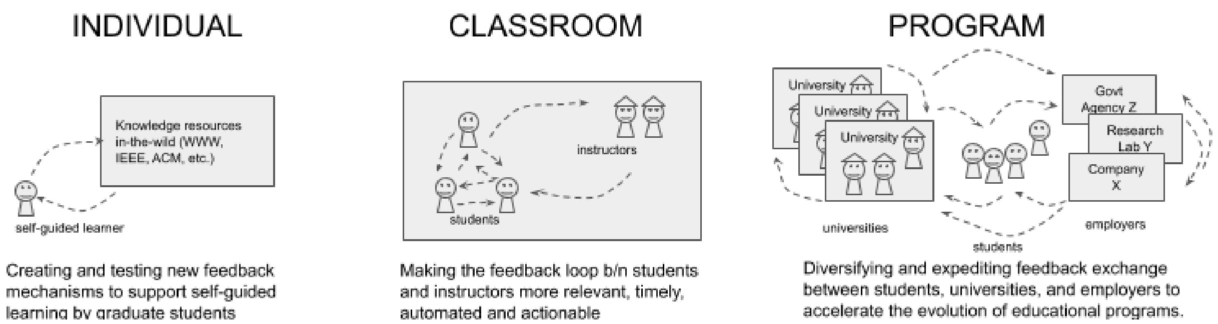

Fig. 1. The proposed research seeks to create/improve/evaluate dynamically adaptive feedback loops for individuals, classrooms, and programs.

1. Educational Program Evolution (EPE) — Existing feedback loops between prospective graduate students, employers and educational institutions rely on inadequate information and are too slow to support timely guidance for educational program development. Goal: This project will explore the means by which graduate students, educators, and employers can communicate their specific educational capabilities, desires and needs, to provide the dynamic feedback necessary to accelerate the evolution of more cohesive educational programs outcomes and curricula.

2. Social Realtime Learning (SRL) — Timely and actionable feedback necessary to improve effective individualized learning for engineering graduate students is often impacted by a lack of tools and a viable context to gather data, by a misalignment of timing of such feedback, and weaknesses in communication channels by which such feedback is provided. Goal: This project seeks to serve as a laboratory for experimentation, so we can better understand how to create more timely, actionable, contextualized, effective stakeholder feedback to improve learning in and beyond the classroom.

3. Personalized Knowledge Discovery (PKD) — Graduate students often guide their own learning process using a wealth of materials on the web, but lack effective feedback on what and how they should identify and learn a new domain, especially for unstructured complex topics. Goal: This project seeks to understand feedback mechanisms that help graduate students optimally search, acquire, share, and apply new knowledge in a self-guided manner.

Our three research tracks will produce generalized knowledge about feedback mechanisms that can serve as a foundation for the creation of a more dynamic, self-adapting educational system impacting individual graduate students' acquisition and application of knowledge, classroom curricula and pedagogy, and program outcomes and design. In addition to this knowledge, the learning laboratory and its base technologies will be disseminated to accelerate educational learning necessary to support Industry 4.0 and the digital transformation.

1.4. Project Approach

As described earlier, education constitutes a complex, distributed system that needs to evolve to meet the rapidly changing challenge that it faces. As such, we believe that it needs to employ the same concepts and technologies that are driving Industry 4.0, in much the same way that the earlier industrial revolution formed this education system over a century ago.

The Fourth Industrial revolution is the industrial response to the digital transformation that is dramatically changing all aspects of our lives. It is characterized by the following four fundamental design principles: (Hermann et al., 2016).

- **Interconnection** — The ability of machines, devices, sensors, and people to connect and communicate with each other via the Internet of things (IoT), the Internet of people (IoP) forming the Internet of everything (IoE).
- **Information transparency** — Enabled by the IoE, the fusion of the physical and virtual world enables a new form of information transparency which supports data informed decision making.
- **Decentralized decisions** — Based on the interconnection of objects and people as well as transparency on information from inside and outside of an organization, allowing participants to perform their tasks as autonomously as possible.
- **Technical assistance** — The technological facility of systems to assist humans in decision-making and problem-solving, and the ability to shift the main role of humans from an operator of machines towards a strategic decision-maker and a flexible problem solver.

We believe that these founding principles of Industry 4.0 are also foundational to educational programs. This paper will apply the concepts of evolving, self-learning systems that rely on data, analytics, and machine learning and modeling, to experiments in three research focus areas described earlier. The Jacobs School of Engineering (JSOE) at the University of California, San Diego (UCSD) is in the process of developing new systems engineering principles, methods, processes and tools, to meet the challenges of AI-intensive systems driving Industry 4.0. While the development of the JSOE systems engineering masters program is not the subject of this paper, it will serve as a source of technical principles and techniques, and, more importantly, as a learning laboratory for experiments in dynamically adaptive educational systems.

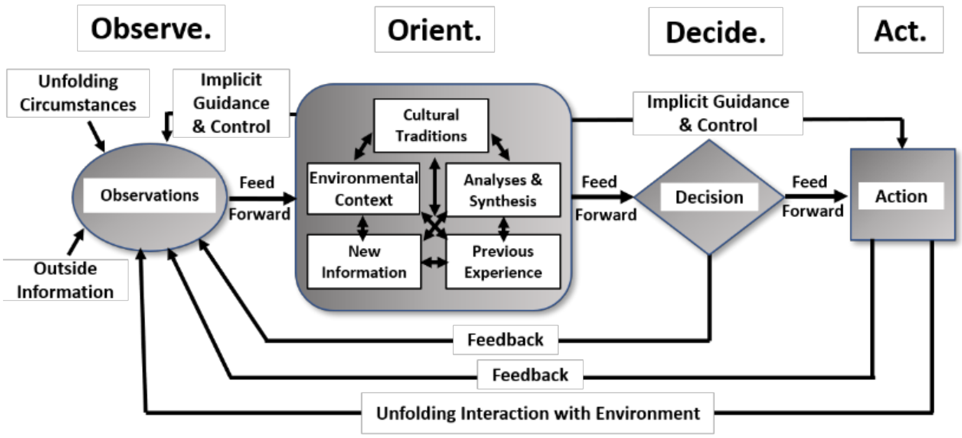

Figure 2: Observe, Orient, Decide and Act (OODA) Loop (after John Boyd)

While the research focus areas are quite different in many dimensions, a similar OODA (Observe, Orient, Decide, Act) loop analysis, as shown in Figure 2, will be applied to each case. Methods of addressing these issues will be researched and solutions will be formulated, developed, prototyped, tested and evaluated, thus forming additional feedback loops that can be used to monitor the performance of the additions to the system. This evaluative system is discussed in more detail in the following section Performance Assessment/Project Evaluation in this proposal.

2. Educational Program Evolution

2.1. Research Objective

Currently, there are a number of feedback mechanisms between university programs, students, and their prospective employers. The Accreditation Board for Engineering and Technology, Inc. (ABET) serves as the means by which US educational institutions receive feedback on their engineering programs, but its scope and use is very limited in graduate programs, and the review process and cadence is quite lengthy. U.S. News & World Report rankings have grown to be the default means by which students search for academic programs, employers scout for students, and universities assess their program's competitiveness. However, this feedback is problematic with respect to graduate education as it is based solely on 5-point peer assessment scores. Graduate engineering studies cover a wide range of topics, so it is difficult to gauge the relative strengths and weaknesses of a graduate academic program and how these match with a student's or employer's interests.

Objective: Create feedback loops by which educators, students and employers can communicate their specific educational capabilities, desires and needs, to provide the dynamic feedback necessary to accelerate the evolution of educational programs.

2.2. Research Hypothesis and Description

Hypothesis: A non-profit website can be developed that presents specific graduate engineering program information which, accompanied with interactive analytic tools, can assist students, educators, and employers to efficiently and effectively make education, program and employment decisions.

This research will focus on the discipline of Systems Engineering which is extremely broad, ill-defined and rapidly changing. In addition, the value of US NEWS feedback is of limited value in this area. As Systems Engineering (SE) was quite recently added to the category of Industrial/Systems/Manufacturing Engineering (ISME), many universities added ‘Systems’ to their masters degrees titles, often without changing the curricula to support this discipline. While the primary focus is on US academic institutions, this research will be open to international educational institutions to ensure exposure to global systems engineering curricula and trends, increasing the size of the addressed educational ecosystem.

The research platform for this work is a collaborative online environment in which systems engineering educators can interact with employer partners and students to define, create, and exchange curricular and pedagogical resources to enhance educational impact. This website provides a portal where students and practitioners can self-assess their systems competencies, determine the matches and gaps that they might have with desired positions, and based on this information select relevant academic and educational resources. Universities can use this information to assess their program suitability with selected industrial, government, and academic positions, as well as provide benchmarks with other academic programs. Employers can assess academic programs based on their needs, and contact willing students and practitioners for employment opportunities. Through this transparent communication, best matches can be found and the discipline of systems engineering can evolve to meet the emerging needs of the systems communities. Underlying the collaborative effort is a desire, while preserving the uniqueness of systems engineering programs that speak to particular varieties of students and professions, to enhance commonality among programs where it is beneficial, and establish a dynamic interactive community thereby enhancing the value of all the programs. The development of this site is currently being sponsored by the International Council on Systems Engineering (INCOSE) under the Systems Engineering Education Ecosystem (SEEE) project and will be in place by the spring of 2022[4].

After a thorough review of existing systems engineering and engineering competency frameworks, interviews with industry, and anticipation of the future needs of the discipline[5-9], this research has tailored a systems engineering taxonomy[4] that is a superset of the INCOSE Systems Engineering proficiency framework[9]. An iterative approach will be taken to update and modify this framework based on data gained through prototyping exercises with the three stakeholder groups. Self-reporting processes will be developed with crowd-sourcing evaluation to ensure the validity of the information without obtrusive overhead to ensure both validity and timeliness. Professional organizations, research centers and informal personal networks will be utilized to provide motivation for participation in this research project. Extensive data will be recorded from all stakeholders through the iterative research process, and evaluated to address the aforementioned research questions.

The stakeholders are students with an interest in systems engineering graduate education, the employers of graduate students with systems engineering skills, and the academic community. We will reach students through the INCOSE students outreach programs. The INCOSE Corporate Advisory Board (CAB) will be used as a means to reach the employers of graduate systems engineers. In the US, there are 94 academic programs that are rated by US NEWS who will be reached through INCOSE and the Systems Engineering Research Center (SERC) UARC. In addition, the Worldwide Directory of Systems Engineering and Industrial Engineering Programs will be utilized to provide contact to 307 institutions which support relevant programs on a global basis.

A number of online metrics will be used to determine the success in proving the research hypothesis and addressing the primary research questions in the project in the areas of ability to communicate university program content, ability to communicate position availability, use of profile information, and program impact. These data will be captured digitally from the website and analyzed on an ongoing basis, providing iterative feedback and updates to the entered profiles and website capabilities.

2.3. Impact

The initial impact will be on the systems engineering academic community. To date, there are no easy means by which to compare systems engineering masters programs. Transparency is expected to influence the enrollment decisions of students into masters programs and the outreach activities of employers. Both of these actions, along with exposure to the curricula focus areas of top programs, will influence considered change in academic programs. The foundational knowledge from this research will enable the adoption of this approach by other graduate engineering disciplines providing effective feedback to the evolving needs of STEM education.

3. Social Realtime Learning

3.1. Research Objective

Modern institutional learning environments commonly rely heavily on minimally refreshed, statically presented curricula. Written materials are commonly stored as static PowerPoint files, and converted to PDF for portability to students (diversity and socio-economic factors impact whether students even have access to PowerPoint software). Most studies have found that PowerPoint has "no measurable influence on course performance and minimal effect on grades"[10], although students give higher ratings to slide-based courses for self-efficacy[11] and to their instructor[12] for using slide-based methods in the classroom. Furthermore, research indicates that static curricula, with few interactions between instructors and students, reduces the number and quality of formative feedback opportunities for learners, and negatively impacts student learning outcomes[13].

Objective: (1) To test mechanisms by which the value of continuous, near real-time interactions and feedback between stakeholders in the graduate learning ecosystem (instructors, students, alumni) can be made more contextually relevant, timely, automated and actionable, and whether doing so will improve individual outcomes and the collective educational experience; (2) To test mechanisms using automated machine learning models to dynamically augment the experience of stakeholders to drive improved performance outcomes.

3.2. Research Hypothesis and Description

Hypothesis: By reducing the latency of feedback, binding feedback more closely with the relevant context, and augmenting human feedback with automated machine learning (ML) techniques, we can improve the timeliness and value of actionable feedback in various stages of the teaching and learning lifecycle. Such closed-loop improvements will drive an increase in the quantity and/or quality of timely positive change, and subsequently increase the mutual engagement between instructors and graduate students which has been shown to improve learning outcomes[14-17].

As part of this research in online learning, we have developed a teaching platform called 'SlideSpace', that has served as a living laboratory for experiments into human interactions in a learning environment[18]. The system captures anonymized data related to content creation, user interactions, content consumption/distribution, and study habits, To date, we have used this experimental data for statistical analysis to: (1) understand how users interact with learning systems, curriculum, and each other - in live and time-shifted scenarios; (2) identify opportunities to develop enhanced features that improve the human experience and outcomes of our stakeholders; and (3) identify and test new mechanisms to make learning systems more accessible. By June 2022, the system will have been used in four courses (over fifteen sections) in the JSOE with approximately 1250 students. Key components of this program include: (1) an advanced system for creating and presenting curriculum (in class and online), (2) real-time polls (without hardware or setup), that automatically captures in-class and student responses, (3) real-time in-class drawing and annotations, (4) real-time time-encoded chat capability which captures Q/A interactions during a class session, (5) automatic time-encoded voice transcription of materials discussed, synchronized with curriculum, (6) live coding environment for software classes, (7) time-encoded student note-taking capability, (8) a student-driven discussion system, and (9) automated tagging and searching system (statistical classifiers).

This research topic will focus on the means by which immediate feedback can be captured, stored, analyzed, categorized, and shared with stakeholders in ways that improve performance indicators. This research will build on and contribute to prior work to provide a more effective learning environment for instructors and students. Techniques include: (1) categorizing aggregated student searches related to course content and transcripts, for use in proactive responses by ML recommendation engine; (2) aggregating student end-of-session feedback as an indicator of localized student perceptions of learning; (3) mining student contributed content in chat, discussions, and transcripts to identify problematic course content, and notify instructors of potential misalignment of expected learning outcomes.

Our evaluation strategy will rely on automatically generated control groups, where participants in different cohorts will receive different feature sets. To measure the effectiveness of how well a feature drives performance objectives, end-of-term performance direct measures will be correlated against feature sets and usage patterns, using statistics, ML, and several human measures. Our intention is to identify which features drive intended outcomes, along with identification of key behaviors and interactions. In our experience, a ten-week term in a course with fifty or more students can produce sufficient data for statistically significant results. Part of our research will also include an investigation into the means by which we conduct experiments, and the nature of the data we gather, in order to improve the capabilities of the platform to better serve our research needs.

3.3. Impact

This work should provide foundational knowledge that can have a major impact on the active pedagogy practiced in the classroom. This work will evaluate and identify methods and interactions in a social learning environment that drive engagement and improved performance measures for students and instructors. This research should also advance the state of the art in meaningful education technology, and make such technology easy to use, inexpensive, and accessible to everyone. Finally, this research will continuously improve the "living laboratory" capabilities of our platform that enhance our ability to test, measure, and conduct experiments in pedagogy, curriculum development, and real-time teaching and learning.

4. Personalized Knowledge Discovery

4.1. Research Objective

Both during and long after students finish their graduate education, individuals develop their own strategies for learning and consuming the vast resources available online. Web Search is nowadays integral to how graduate students learn, work, and collaborate. It provides a powerful way to browse the largest repository of knowledge — the World Wide Web — to learn and discover new information about topics of interest. However, it poses three key challenges: (1) People who lack knowledge of a particular domain or well-defined goals generally struggle to articulate useful search terms: they have not yet learned domain-specific language that could help them translate their fuzzy goals into concrete queries[19-21]; (2) Search systems do not have visibility into the student's goals, task workflows, and existing knowledge that could help make exploratory search more effective and personalized[22-23]; (3) Most search tools assume that search is a solitary, single-session, single-user activity. Therefore, it remains a challenge to coordinate exploration and synthesis of information across sessions, devices and collaborators[24-25].

Objective: Test the extent to which novel, individualized, technology-enhanced feedback systems improve graduate engineering student learning by optimizing their ability to acquire relevant information through automated search..

4.2. Research Hypothesis and Description

Hypothesis: Web search can be enhanced by developing technologies using a combination of text mining and automated machine learning to gain insight into a learner's objectives and history, which will help individuals learn new search terms, explore topics more broadly, and create connections across multiple learning sessions.

This project will focus on building novel computational and interaction techniques that integrate web search into the user's workflow. These include techniques that: (1) recommend queries, based on patterns and gaps in notes taken and previous searches to help individual graduate students unfamiliar with a domain get started with their knowledge discovery process; (2) mine past searches and contributions to task-related documents to infer prior experience and task progress, with the aim of promoting reflection and reducing coordination costs across sessions. This research will build on and contribute to prior work to make search more personalized, context-aware, and cumulative with the aim of not only helping searchers find the most relevant piece of information quicker, but also broadening and diversifying their knowledge discovery process to promote serendipity and unexpected creative connections.

We have created an initial prototype, as a Google Chrome plugin, which individual students can choose to install on their personal computers and which will give them a place to take notes as they conduct exploratory search on open-ended topics. As the student conducts a search process and adds notes, clips, URLs, and other details to notes, the plugin will offer a set of query suggestions based on patterns and gaps in the learner's notes and previous searches. The system mines the users' notes and prior searches to implicitly infer a person's interests, current knowledge, and potentially undiscovered information to inform query suggestions. The system will leverage state-of-the-art natural language processing (NLP) algorithms to mine contextual information from notes (and eventually other task-specific documents) and map these onto semantic vector representations in order to create a learner profile that models what has and has not been already covered in their notes and previous searches.

To evaluate this strategy of providing query suggestions based on notes, we will conduct a quasi-experimental within-subjects study where participants will search on two different exploratory topics. Participants will use the enhanced plugin for one topic and then standard web search for the other. To measure the effects on search behavior and knowledge discovery, we will track the number of queries issued and the amount and breadth of information added to the notes (using a combination of computational and human coding approaches), and the overall change in individual knowledge and application (by creating and validating pre-post knowledge assessments for each topic domain).

Lessons from this study will also inform how we might build on this technology to help students learn more effectively across sessions. The assumption here is that learning new, unstructured complex topics takes time, often days or weeks, to gather and synthesize information to form an overall understanding of a domain. This next stage of research will explore strategies to help students a) recall and reflect on their prior sessions by quickly summarizing aspects of both process and content, and b) provide indicators about the order and possible directions for learning subsequent topics within a domain. This kind of session-level guidance can operate like a curriculum within a formal educational program, but geared towards supporting personalized knowledge discovery at a self-guided pace.

4.3. Impact

The knowledge gained from this research will provide the foundation for life-long, self-guided, personalized learning that is enabled by the access of information from the web. This work provides examples of co-learning between human and machine, evaluating approaches that try to identify learner goals and adapt the informational environment to those needs. Finally, the learning laboratory can be readily disseminated to support outside researchers and graduate students through the use of a robust technology (e.g., Chrome plugin) that can be downloaded by anyone who wants to use it to guide their own learning. We plan on making the code and experimental results available as open-source to allow other researchers to build on our work.

5. Conclusions and Future Work

The impact of this program should extend well beyond graduate engineering, to all forms of education. The knowledge gained from the Educational Program Evolution research can be extended to provide feedback in any education program which currently lacks transparency with its critical stakeholders and enable education to be responsive to the needs of the communities in which the graduates will contribute their skills.

The knowledge gained by the Social Real-time Learning research can find application in almost any educational environment providing insights in how feedback can be used to improve curricula and pedagogy, as well as the instructor's ability to deliver it to a diverse student body, transforming the classroom into a social environment in which students partner with the instructor to provide a learning experience that is optimized for all. Finally, the knowledge gained from the Educational Program Evolution research can be extended to improve feedback in any education program in which there is a lack of transparency and enable education to be responsive to the needs of the communities in which the graduates contribute their skills. Initial prototypes in all three of these areas will be in evaluation at the time of this paper's publication.

The concepts underlying the Personalized Knowledge Discovery research are broadly applicable to anyone who is using the internet to access information. The development of the individualized web search technology also has potentially far reaching effects in securing personal data and information for the use of their owner, rather than being aggregated by large, profit-incentivized corporations. This technology can enable people to determine what they will see on the internet based on their own personal needs, rather than having an external entity decide this for them.

All areas of research in the project provide exemplars and foundational knowledge of how access to advanced forms of AI and data analytics can provide a partnership between human and machine, enabling an optimization of human potential.

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