Supporting Science Understanding through a Customized Learning Service for Concept Knowledge

Sebastian de la Chica, Faisal Ahmad, James H. Martin, and Tamara R. Sumner[1]

Abstract. A key educational finding from learning research is that every student brings preconceptions about how the world works to every learning situation, and that these initial understandings need to be explicitly targeted as part of an effective instructional process. Our work focuses on the design and evaluation of an end-to-end prototype of a "customized learning service for concept knowledge (CLICK)" to enable student-centered customizations by comparing learners' conceptual understandings, depicted as concept maps, with reference domain concept maps generated by analyzing digital library resources. These comparisons enable learning environments to provide customized retrieval, delivery, and presentation of educational resources drawn from digital libraries. Preliminary analysis of data collected in a study with human experts has validated our research approach and provided key insights concerning our design strategy for the natural language processing components of CLICK.

1 INTRODUCTION

Over the past two decades, cognitive research has examined the role of background knowledge, individual differences and preferred learning styles in influencing learning outcomes [1]. A key finding is that every student brings preconceptions about how the world works to every learning situation, and that these initial understandings need to be explicitly targeted as part of the instructional process. Simultaneously, there have been major demographic shifts taking place in learning populations the world over, with many classrooms containing learners from diverse cultural backgrounds and prior experiences [2]. Educators increasingly need support to customize educational content and activities to meet the needs of a heterogeneous student population [3].

In this paper, we discuss our work related to the design and evaluation of an end-to-end "customized learning service for concept knowledge" (hereafter referred to as the CLICK Service). The goal of this service is to support learner understanding of science content and to promote effective learning processes through the customized retrieval, delivery, and presentation of educational resources drawn from digital libraries. Student-centered customizations will be made by analyzing learners' work artifacts (e.g., student essays) to automatically generate a concept map depicting their existing understanding. The CLICK Service compares these student maps with "reference" concept maps that depict essential domain ideas to identify potential gaps or misconceptions in learner understanding. The CLICK Service delivers relevant digital library resources to the learner, contextually presented within a concept map, to support further student investigations in the identified areas. Our research is guided by the following research questions:

1. What are effective operations for comparing concept maps to identify conceptual gaps in student understanding of science ideas?
2. How can natural language processing techniques be used to analyze digital library resources and student essays to create concept maps that effectively depict essential science domain ideas and student understanding of science topics?
3. How can automatically generated concept maps be used to customize interactions between the learner and digital library-based learning environments?
4. How effective are customized learning interactions for concept knowledge in supporting learning processes and learner understanding of science content?

The science content focus for our work includes the US high school (grades 9-12) Earth science learning goals specified in the "Changes in the Earth's Surface" Strand Map, published by the American Association for the Advancement of Science (AAAS) and the National Science Teacher's Association [4]. This map specifies 21 nationally-recognized learning goals defining what high school students should know, or be able to do, with respect to understanding plate tectonics and weathering, building on abstract concepts such as multiple, interacting time scales, and energy and heat transfer. Student-centered customizations, such as those envisioned for the CLICK Service, are predicated on the existence of rich dynamic models of student understanding [5, 6]. Such models depict the key ideas that learners should understand, how these ideas are interconnected, and how these ideas change over time [4, 7, 8]. We will use innovative natural language processing (NLP) techniques to analyze grade-appropriate educational resources about Changes in the Earth's Surface, drawn from collections in the Digital Library for Earth System Science (www.DLESE.org), to create reference concept maps of the science topic. These reference maps model the core concepts found in these learning resources and the interconnections between these concepts. The basic assumption behind this approach is that these reference maps, computationally derived by analyzing library resources (e.g., background texts, lesson plans, classroom activities, and lab activities), will prove to be rich and robust representations of essential science concepts for a targeted topic and grade range. We will extend these NLP techniques to the analysis of student-generated essays to develop representations of current student

[1] Department of Computer Science, University of Colorado, Boulder, Colorado 80309-0430, {firstname.lastname@colorado.edu}

understandings that can be compared with the reference maps. Essays have been selected as a vehicle for capturing student understanding because writing essays is a familiar task for students. Essays also provide an appropriate form of verbal data for processing using a variety of NLP techniques. However, the CLICK Service aims to provide generalized supports for conceptual knowledge remediation in a variety of online learning environments. We will assess student learning by studying students' cognitive and behavioral processes when using the CLICK Service as compared to an existing interface for the Digital Library for Earth System Education (DLESE), and by measuring and comparing student conceptual change.

Over the past decade, there has been vocal and visible public demand in the US for improved science education across the national, state, and local levels, and a call for greater access to quality science education for all citizens [9-11]. In part, this call is being answered by the emergence of operational digital libraries devoted to science education across a range of science, mathematics, engineering and technology disciplines. Two prominent examples are the National Science Digital Library (www.NSDL.org) and the Digital Library for Earth System Education (www.DLESE.org). Both of these library efforts aim to make accessible an array of high-quality collections to serve diverse constituencies of users, from research scientists, to educators, to students, at all educational levels, in both formal and informal settings [12-14]. The outcomes of this research will provide a model for building student-centered learning environments on top of educational digital library platforms. This customized learning support represents a critical step towards making digital library resources more useful for diverse and heterogeneous student populations.

2 RELATED RESEARCH

Concept maps can be effective representations to diagnose learner understanding and to scaffold the development of abstract science concepts. Concept maps are node-link diagrams that depict concepts and their interrelationships. In our work, nodes contain richly descriptive statements that capture robust concepts and ideas related to a domain. Prior research suggests that concept maps can offer effective encodings of complex science domain knowledge. Concept maps have been shown to be reliable representations of learner understanding and flexible models to track and assess cognitive development [15]. Recent research shows promise for the use of node and link element matching to assess student concept maps computationally [16]. In addition, learning research suggests that concept maps promote the development of macro-level understandings and more effective learning in cooperative situations, especially for low knowledge learners [17]. Our own research has shown that concept maps to support conceptual search in digital libraries encourages learners to focus more on the science content of their task, and less on the operational details of performing searches [18]. We are extending this prior research to consider whether presenting digital library resources in the context of an overarching conceptual representation can scaffold performance of the necessary cognitive skills to integrate information from multiple digital library resources into flexible and coherent mental models.

Natural language processing techniques may be employed to generate structured summaries of text documents. The problem of getting computers to produce structured text representations, such as concept maps, can be viewed as a problem of natural language generation. Fluent generation is a key component in many NLP applications including spoken dialog systems, knowledge-based tutorial systems, and machine translation systems. Over the last decade, systems that generate by summarizing have increasingly become the method of choice in domains where existing source documents contain the material needed for output documents [19]. Current approaches to summarization vary along a number of interesting dimensions including: whether they produce a summary from a single document or across multiple documents, whether they simply extract sentences from the source documents or actually synthesize sentences as output, and whether the systems are domain independent or based on a particular content domain [20]. As we will see, each of these dimensions is relevant to the problem of generating concept maps for use in the CLICK Service prototype.

The customization components within the CLICK Service extend prior research on model-based adaptive learning environments and conversational learning theory. Adaptive learning environments provide learners with tailored guidance for particular learning tasks [21]. Customization mechanisms in adaptive environments often make use of three types of underlying information models: an expert domain knowledge model, a model of current student understanding, and a pedagogical strategy model [22]. Adaptive learning research efforts using different approaches for modeling and comparing domain and learner knowledge, such as cognitive modeling [23] and semantic analysis [24, 25], have consistently demonstrated positive educational impacts.

Adaptive learning systems require a computational component capable of determining an appropriate pedagogical strategy; i.e., a means of identifying effective instructional remediations, developing appropriate system responses, and providing useful feedback to the learner [22]. Conversational learning theory provides a framework that promotes the construction of flexible knowledge structures through coherent information personalization and integration [26]. This emphasis on supporting information integration makes this theory particularly relevant to application in digital library-based learning environments. According to this theory of learning, understanding of a topic takes place as a result of a structured, focused and iterative conversation between an instructor and a learner [26, 27]. Understanding is achieved when the instructor is satisfied with the level of agreement between her own and the learner's conception of a topic, and conversational moves are motivated by differences between these conceptions. To support developing a coherent conceptual understanding of a topic, the instructor-learner conversation has to be anchored in a specific conversational domain, which is a detailed representation of the topic under study, encoded as a knowledge structure. The instructor-learner dialogue serves to construct and reconstruct learner understanding, conceptions and misconceptions about a topic. The theory outlines several types of tailored pedagogical responses – discursive, reflexive, and adaptive [28] – for furthering dialogue about student conceptions.

3 THE CLICK CONCEPTUAL FRAMEWORK

The conversational theory of learning [26, 28] guides the design of our conceptual approach. As shown in Figure 1, the learner and the learning environment engage in an ongoing dialogue that provides opportunities for the learner to take action to enhance her own understanding and for the learning environment to respond with appropriate feedback. Throughout this dialogue, both the learner and the learning environment enact interactions consistent with the conversational learning theory dialogue types, namely discursive, adaptive, and reflective interactions.

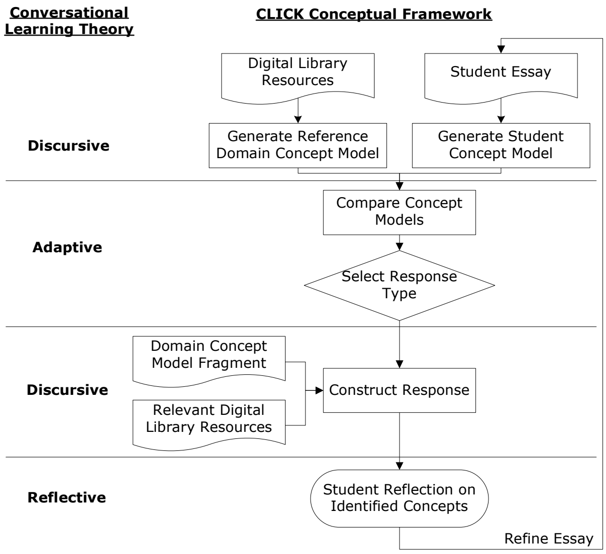

Figure 1. CLICK conceptual framework

Discursive interactions make thinking visible by externalizing internal conceptualizations for dialogue between the learner and the instructor. In the CLICK conceptual framework, digital library resources provide the necessary domain text-base to generate reference concept maps of science topics. The learning environment prepares and delivers to the learner selected fragments of its reference concept map and relevant digital library resources. Similarly, learners externalize their understanding through essays that provide the text-base to generate concept map representations of their understanding. In these interactions, the learning environment exposes its knowledge structures to the learner to facilitate thinking about science concepts, and the learner exposes her internal conceptions for assessment and feedback.

Adaptive interactions guide the instructor-learner dialogue based on the instructor's assessment of the learner's current conceptual understanding. In the CLICK conceptual framework, the learning environment compares reference concept maps to student concept maps to identify conceptual gaps and select a learner-appropriate response. CLICK response types are characterized by three key dimensions: the resource type(s) of the relevant educational digital library resources, the content of those educational resources, and the information presentation selected to provide feedback to the learner. The learning environment leverages its internal reference concept map and assessment of learner understanding to prepare and deliver a learner-appropriate response, thus engaging in adaptive dialogue.

Reflective interactions enable the learner to establish meaningful connections between her current understanding, instructor feedback and the learning task. In the CLICK conceptual framework, the learner processes the feedback from the learning environment, uses the returned digital library resources, and engages in reflective response by integrating and internalizing newly identified concepts to evolve her current conceptual understanding.

Consider the scenario where Heather, a 12th grade science student, has been assigned the task of writing an online essay on the causes of earthquakes using CLICK. CLICK has previously processed digital library resources from DLESE to construct a reference concept map of Changes in the Earth's Surface, which includes the concepts about plate tectonics shown in Figure 2.

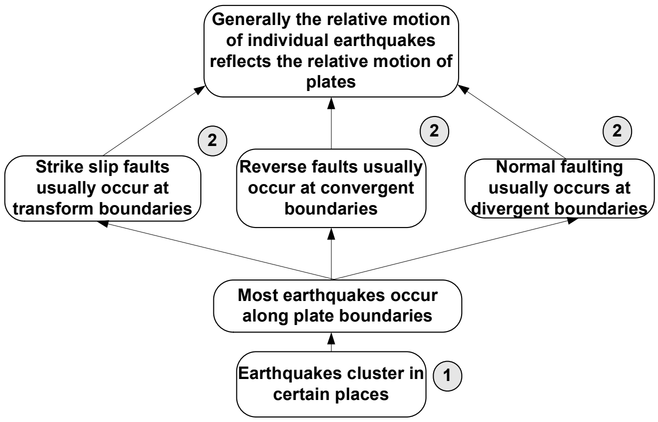

Figure 2. Partial plate tectonics reference concept map

Heather writes that earthquakes can occur all over the world and requests feedback from CLICK. CLICK analyzes and detects critical differences between Heather's essay and node 1 of its internal reference concept map. To address this misconception, CLICK presents the contents of this node to Heather as a hint. CLICK's response makes Heather reflect on the inaccuracy of her current conception. Heather remembers that there are more earthquakes in California than in Colorado. Heather explores this difference using a DLESE resource about plate boundaries suggested by CLICK. This educational resource helps Heather understand that earthquakes are concentrated along plate boundaries.

Heather continues writing her essay indicating that two plates pushing against each other cause earthquakes and that land above such plates is more susceptible to earthquakes. At this point, Heather requests CLICK to verify her conception. CLICK detects that Heather's essay closely resembles the concepts embedded in the three nodes labeled 2 in Figure 1, but she is missing the concepts that "divergent boundaries and transform boundaries also cause earthquakes". CLICK presents these fragments of the reference concept map to Heather as a suggestion for improvement, including links to access age-appropriate digital library resources from DLESE relevant to these concepts. With CLICK's assistance, Heather begins to understand the relationships between these concepts.

4 CLICK RESEARCH COMPONENTS

Our overall research agenda comprises the following key components: expert study, concept map generation, CLICK service implementation, and educational impacts assessment.

4.1 Expert study

The expert study serves to gather human data on reference and concept map representations, and processes for comparing them. The purpose of this study is three-fold: (1) to understand how human experts extract conceptual knowledge from educational resources and student work, (2) to understand the processes by which human experts compare concept maps to identify potential differences in understanding, and (3) to understand how experts select digital library resources for appropriate instructional remediations.

The study participants include science domain and instructional design experts drawn from the University Center for Atmospheric Research and the Department of Geology at the University of Colorado at Boulder. We are working with domain and instructional design experts to identify approximately 20 DLESE resources corresponding to the learning goals from the Changes in the Earth's Surface Strand Map. An equivalent number of student essays have been elicited from undergraduate students with little additional science education beyond their high school courses.

In order to understand how humans extract conceptual information from textual materials, expert participants generate concept maps for each of the selected library resources and student essays. From these concept maps, experts work collaboratively to distill a reference map synthesizing the important science concepts and ideas reflected in the resources. For concept maps to be a useful tool for identifying students' conceptual needs, processes and mechanisms for comparing the reference map and the concept maps of student essays must be identified. Thus, the expert participants compare each of the student essays to the reference map to identify gaps in understanding and to recommend the types of digital library resources that may be used by the learner to build knowledge in the identified area.

The reference map, the identified comparison processes, and the remediation recommendations will inform the design of the CLICK Service prototype. The concept maps and the reference map resulting from this study will also be used to guide the development and evaluation of the NLP algorithms used to automatically generate concept maps.

4.2 Concept map generation

We are casting the problem of generating concept maps for specific science domains from digital educational resources as a problem in multi-document analysis and summarization. Our second problem of generating concept map representations of individual student essays is treated as a process of information extraction through the alignment of the contents of students' essays with the appropriate reference map for the domain in question.

Most state-of-the-art multi-document summarizers [19] operate by first segmenting source documents into fundamental text units, such as sentences and paragraphs, and then grouping these units into clusters of similar units. These systems operate by first characterizing the units as a vector of features derived from a linguistic analysis of each unit. Typical features include the set or words that occur in the unit, their parts of speech, larger syntactic base phrases, syntactic structure, etc. Once the units are represented formally as a vector of features, a similarity metric [29, 30] can be employed to project the sentences into a space based on the distance between sentences imposed by the similarity measure. Based on the topology of this space a set of clusters can then be extracted. The resulting clusters are taken to represent the various topics discussed in the source documents. Roughly, these clusters will correspond to the nodes typically found in concept maps such as the ones shown earlier in Figure 2. The key tasks here include the selection/development of a suitable similarity metric and an effective clustering mechanism. A key challenge in this task, not found in most summarization settings, will be to deal with, and exploit, the fact that our digital educational resources are typical Web artifacts consisting of images, diagrams, and a potentially complex hypertext structure.

Having determined the set of concepts to be included in a concept map, the next step in our approach is to produce the text to be associated with each concept. Following most recent research on summarization, we will employ a process of first selecting sentences that are most representative of each concept and then modifying the resulting text to fit the needs of potential readers. In our setting, this second phase will focus on the constraint of producing concept maps that are appropriate for specified grade and reading levels.

Our next challenge is to identify the underlying relationships among the concepts discovered in the resources and student essays. Concept maps, of the kind we are considering, contain labeled and unlabeled binary relations between the concepts that make up the map. Our primary task here is, therefore, to create a system that can determine whether or not two concepts should be directly linked in the map, and if so what label should be assigned to that connection. Following on work applying machine learning techniques to the extraction of both content [31] and discourse [32] relations in unstructured text, we propose to apply a similar approach to this problem. A two-phase supervised machine learning approach using Support Vector Machines (SVM) [33] will be followed. SVMs are a robust and principled method for creating classifiers from labeled training data that have proven to be extremely accurate when applied to a wide variety of language-related tasks [34-37]. In the first phase, an SVM classifier will be trained to make a binary classification as to whether two concepts should be related in a concept map or not. Following this phase, an N-way classifier will be trained to classify relations according to their type. The annotated materials developed during the expert study will be used, as well as additional materials specifically annotated for this purpose, to create appropriate testing and training materials for this task.

Finally, student essays tend to be short, often lacking in well-developed discourse structure and in appropriate vocabulary for the domain under consideration. Because of these constraints, the approach taken to summarizing digital educational resources is unlikely to succeed with student essays. Instead, our approach to generating concept map representations of student essays, takes an information extraction approach to summarization. In information extraction, unstructured documents are processed by identifying specific spans of text within the documents that correspond to pre-specified slots associated with reference frames that define the topic under consideration. This computational approach mimics how educational researchers originally employed the concept map used to plan a student interview as a template to capture content knowledge elicited from the student during the actual enactment of the interview [38]. In adopting this approach, we assume that a relevant reference concept map, which plays the role of a frame, is available to the system as student essays are processed. The system will first segment student essays into coherent units employing techniques similar to those described above, and then align those units with the corresponding elements in the reference concept map.

Not surprisingly, most current information extraction systems are based on supervised machine learning approaches, where a system is trained to associate particular spans of text with particular slots through the use of annotated training data [39-42]. We will take a similar approach, where the concept maps generated from student essays developed during the expert study will play the role of our initial training material.

4.3 CLICK service implementation

We will design and implement a prototype of the CLICK Service using a task-centered design methodology [43] with teachers as design consultants. We will bring together teachers of science to explore educational practice issues related to effective conversational learning strategies. This workshop will focus on the discovery of conceptual breakdowns and appropriate remediation strategies using concept maps in education. The criteria for selecting workshop participants include instructional expertise in plate tectonics and experience integrating digital libraries into classroom practice. This workshop will elicit expert educational practice knowledge following a participatory design methodology [44] with teachers as cohorts. Workshop participants will develop rich educational use scenarios describing effective conversational interactions using concept maps with learners in the context of digital library–based instruction. These rich scenarios will be complemented with matching learning environment mockups co-designed with teachers.

The inventory of concept map operators and response types from the expert study, together with the rich scenarios and mockups from this teacher workshop, will inform our design and implementation of the CLICK Service prototype. The CLICK Service will be implemented as a web service, an architecture that facilitates integration of the Service's capabilities into diverse learning environments. Figure 3 provides the architectural depiction of the CLICK web service.

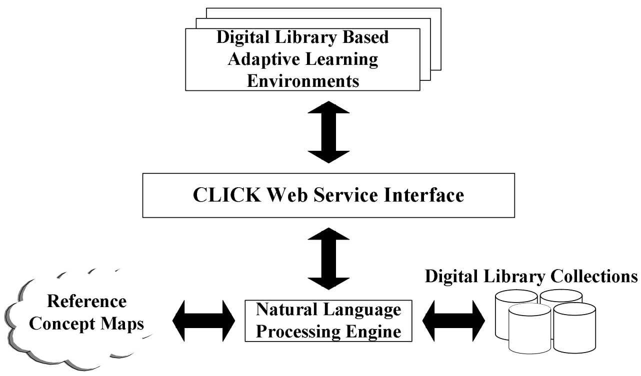

Figure 3. CLICK service architecture and components

We are building on results from our prior research, namely the technical infrastructure of the Strand Map Service [8] to model educational concepts and to dynamically generate interactive concept map representations. The Strand Map Service generates concept-browsing interfaces that support educators and learners to locate digital library resources aligned with nationally recognized learning goals. To ensure that the CLICK prototype is usable by learners, we will conduct a usability evaluation with undergraduate students. Participants will be asked to engage in think-aloud protocols [45], as they complete representative tasks based on the workshop scenarios.

4.4 Educational impacts assessment

The customized conceptual support provided by the CLICK Service may influence student learning in two ways: (1) by supporting deeper learning processes (the ways in which students seek and evaluate information), and (2) by supporting students' evolving scientific understanding (the ways in which they represent and integrate relevant content into prior domain knowledge).

Because we are interested in the rich comprehension processes in which students engage during science learning, we will use a mixed methods approach that combines quantitative and qualitative data to develop an integrated understanding of the behavioral and cognitive components of learning. Online behavioral tracking will be used to determine how learners approach a learning task. Verbal protocols will be used to provide more in-depth data on student cognition; verbal protocols are a key method for collecting and analyzing the rich cognitive data needed for studying complex learning processes [46, 47]. Finally, conceptual change also will be assessed by pre- and posttest concept maps produced by students.

We will complete a learning study that assesses students' cognitive and behavioral processes when using either the CLICK Service or an existing digital library interface from DLESE. Because each student in the study will be receiving customized remediation based on their initial conceptual knowledge, we anticipate that a total of about 20 participants will be needed to achieve the appropriate statistical power for assessment. Students initially will generate a concept map that illustrates their understanding of the domain. Student actions and verbalizations will be recorded as students use the CLICK Service or the DLESE interface to complete a series of short science-based learning tasks (e.g., Where do the deepest earthquakes tend to occur? Why?) After learning, students again will generate a concept map. Resulting data and analyses will address two important potential outcomes, specifically whether the CLICK Service can be demonstrated to promote concept-based learning processes and to scaffold science understanding. Two types of data will be used in conjunction: behavioral process data and verbal protocol data.

Behavioral Process Data. Each participant's interactions with the computer interface will be recorded and analyzed. This behavioral data will address the online learning processes used by a student. Behavioral data will be coded for type of activity (e.g., resource selection, keyword searching, concept selection, backtracking) and duration (e.g., time spent on a resource – longer engagement may lead to increased understanding). Analyses will include assessment of favored processes (e.g., most frequent activities), process variation (in a student's activities), overall time on task, and time allotted to learning behaviors.

Verbal Protocol Data. Transcribed verbal data will be separated into complex propositions [48, 49] and coded according to the type of comprehension process represented. Categories to be analyzed include paraphrasing, monitoring, elaborations, inferences, errors, revisions, and connections. These categories allow identification of more shallow versus deeper comprehension processes (e.g., paraphrasing versus inferencing). Understanding the ways in which students process, integrate, and monitor knowledge during learning will allow critical evaluation of the effectiveness of the CLICK Service in supporting science understanding. In addition, changes in the content and organization of students' concept maps will be analyzed to characterize and assess conceptual learning effects.

5 PRELIMINARY FINDINGS

We have been working collaboratively with science domain and instructional design experts in the selection of representative digital library resources on Changes in the Earth's Surface, more specifically earthquakes and plate tectonics. In addition, the experts have individually created concept maps for the selected resources. The experts have also participated in a one hour think-aloud session during the construction of a concept map. Concomitant to this expert study, we have also engaged in the evaluation of MEAD, a state-of-the-art open source multi-document summarizer [50], as the NLP tool of choice to identify concepts across selected digital library resources [51, 52].

Preliminary analysis of the verbal protocols collected during the expert concept mapping think-aloud sessions indicate that human experts bring significant "external knowledge" to bear on the construction of concept maps. Science domain experts scan the digital library resources looking for specific concepts based on their knowledge of the subject matter. This scanning behavior may result in the filtering out of significant portions of the text contained in the digital library resource. Similarly, instructional design experts are particularly mindful of concepts represented in the National Science Education Standards (NSES) [53], including both domain knowledge and information about the nature of science. For instance, while science domain experts check a digital library resource on earthquakes and plate tectonics to make sure it covers all three types of faults (i.e., divergent, convergent and transform), instructional experts also look for concepts illustrating how science is made (i.e., observations lead to models and theories).

Our initial evaluation of MEAD involves generating summaries of sets of digital library resources on earthquakes and plate tectonics and comparing the resulting summary sentences to the concepts selected by a human annotator to represent the same set of resources. Preliminary analysis of the automatically generated concepts and the human-generated concept maps indicate a granularity mismatch between the selected concepts. Human-generated concept maps show a tendency towards depicting more complete concept networks including concept units below the sentence level, while MEAD operates at the sentence level. For instance, the concepts related to secondary waves selected by a human annotator include the following concepts:

- Secondary or S-waves
- S-Waves move through solids, but not liquids or gases
- If you and a friend have ever held a jump rope between you, you probably moved the rope up and down like a whip
- S-Waves cause the rock particles to move at right angles to the direction of the wave

Meanwhile the concepts selected by MEAD using the default feature scoring and sentence ranking algorithms and a 20% sentence compression factor includes only the following concept related to secondary waves:

- A secondary, or S wave moves through the earth causing the rock particles to move at right angles to the direction of the wave.

The default MEAD configuration attends solely to linguistic features of the input text (i.e., centroid, position, and length) and uses percent of sentences to establish the relevant length for the summary. As a result, the generated concepts lack any educational relevance or conceptual completeness awareness. For instance, while a human annotator may include concepts related to primary, secondary and surface waves, the default MEAD summary does not include any mention of primary waves. In the context of the CLICK Service implementation, such omissions would result in the generation of incomplete reference concept maps with very limited educational usefulness.

Given our initial evaluation of the MEAD summarizer and the preliminary observations from our think aloud sessions with human experts, it is clear that traditional single-pass bottom-up approaches to multi-document summarization would provide results of very limited use for online learning environments. To generate concepts from multiple digital library sources for educational purposes requires the introduction of a more sophisticated summarization approach that allows for the encoding of both domain and instructional design knowledge. Based on these findings, we are enhancing the MEAD summarizer by defining and computing a sentence scoring feature based on the pedagogical significance of the terms present in each sentence. Currently, we are considering a domain ontology [54], the NSES [53], and encyclopedic entries as the basis for this feature computation. We are expecting this approach to inject the science domain and instructional design knowledge necessary to identify the full complement of educationally relevant concepts.

Finally, all science domain and instructional design experts consistently made verbal references and demonstrated concept map construction techniques illustrating the use of a secondary notation based on layout and graphical cues consistent with expert diagramming behaviors [55]. This observation is particularly relevant because none of our expert participants had significant prior experience with concept mapping activities. Further coding of the audio and visual protocols should serve to elucidate the role domain expertise plays on the use and nature of secondary graphical notations in concept mapping for educational purposes.

These preliminary findings have also served to confirm the effectiveness of our research methods. The combination of qualitative studies with human experts with quantitative computational methods enables us to capture human expertise related to the tasks of concept map construction and student knowledge assessment and intervention design. This human expertise knowledge becomes a key aspect of our computational solutions. This approach is of particular importance in educational settings where much of the human knowledge is tacit and highly contextualized, hence extremely valuable for the construction of effective educational web services and online learning environments.

6 CONCLUDING REMARKS

The resulting CLICK prototype should serve as a model for future learning tools that can radically improve science education through individualized knowledge representation and customized remediations using digital library resources. It is widely recognized that the design of learning environments and instructional strategies can be greatly improved through a well-developed and concrete understanding of common learner conceptions for a science topic. Prior research, conducted through painstaking investigations spanning at least a decade, has developed a significant knowledge base of common student conceptions and difficulties in mathematics and physics [56, 57]. However, relatively little is known about student conceptions and difficulties in the natural sciences. This research has the potential to establish an entirely new and automatic method for identifying and representing essential science concepts that characterize deep knowledge of a targeted science topic. In addition, there are currently no automatic or efficient mechanisms for identifying student conceptual needs. This research will develop and test a fundamentally new method, using state-of-the-art natural language processing techniques, to address this important educational problem.

While the primary goal of this work is the creation of the CLICK Service, we are also pursuing the design and development of innovative online learning environments that exploit the affordances of the Service. The CLICK Service enables the emergence of innovative pedagogical approaches within digital library-based learning environments. For instance, we are designing educational scaffolds to support the construction of scientific explanations in SciNews Online, an online report writing environment for students to investigate the “science behind the news” [58], by making the generated CLICK domain and learner models open and scrutable.

ACKNOWLEDGEMENTS

This work is funded in part by the National Science Foundation through NSF Award IIS/ALT 0537194.

REFERENCES

[1] J. D. Bransford, A. L. Brown, and R. R. Cocking, "How People Learn: Brain, Mind, Experience, and School," Expanded edition ed: National Academy Press, 2000, pp. 374.

[2] U.S. Department of Education - National Center for Education Statistics, "The Condition of Education 2002," U.S. Government Printing Office, Washington, D.C. NCES 2002-025, 2002.

[3] D. H. Jonassen and B. L. Grabowski, *Handbook of Individual Differences, Learning and Instruction*. Hillsdale, NJ: Lawrence Erlbaum Associates, 1993.

[4] AAAS, *Atlas of Science Literacy*. Washington, DC: Project 2061, American Association for the Advancement of Science, and the National Science Teachers Association, 2001.

[5] A. T. Corbett, K. R. Koedinger, and W. H. Hadley, "Cognitive tutors: from the research classroom to all classrooms," in *Technology Enhanced Learning: Opportunities for Change*, P. S. Goodman, Ed. Mahwah, NJ: Lawrence Erlbaum Associates, 2001.

[6] M. Marlino, T. Sumner, and M. Wright, "Geoscience Education and Cyberinfrastructure," Digital Library for Earth System Education Program Center, Boulder, CO, Report of workshop sponsored by the National Science Foundation (NSF) April 19-20 2004.

[7] AAAS, *Benchmarks for Science Literacy*. New York: Project 2061, American Association for the Advancement of Science, Oxford University Press, 1993.

[8] T. Sumner, F. Ahmad, S. Bhushan, Q. Gu, F. Molina, S. Willard, M. Wright, L. Davis, and G. Janee, "Linking Learning Goals and Educational Resources through Interactive Concept Map Visualizations," *International Journal on Digital Libraries*, vol. 5, pp. 18-24, 2005.

[9] AAAS, *Science for All Americans*. New York: Project 2061, American Association for the Advancement of Science, Oxford University Press, 1989.

[10] NRC, "Transforming Undergraduate Education in Science, Mathematics, Engineering, and Technology Education," National Research Council, National Academy Press, Washington, DC 1999.

[11] NSF, "Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology," National Science Foundation, Arlington, VA NSF 96-139, 1996.

[12] M. Marlino, T. R. Sumner, D. Fulker, C. Manduca, and D. Mogk, "The Digital Library for Earth System Education: Building Community, Building the Library," *Communications of the ACM*, vol. Special Issue on Digital Libraries (May), pp. 80-81, 2001.

[13] NSDL, "National Science Digital Library Progress Report: Fall 2000 - Summer 2003," NSDL, Boulder, CO September 2003.

[14] L. L. Zia, "The NSF National Science, Technology, Engineering, and Mathematics Education Digital Library (NSDL) program: New projects and a progress report," *D-Lib Magazine*, vol. 7, 2001.

[15] J. Novak and D. Musonda, "A twelve-year longitudinal study of science concept learning," *American Educational Research Journal*, vol. 28, pp. 117-153, 1991.

[16] B. Marshall and T. Madhusudan, "Element matching in concept maps," presented at Fourth ACM/IEEE-CS Joint Conference on Digital Libraries, Tucson, Arizona, 2004.

[17] A. M. O'Donnell, D. F. Dansereau, and R. H. Hall, "Knowledge Maps as Scaffolds for Cognitive Processing," *Educational Psychology Review*, vol. 14, pp. 71-86, 2002.

[18] K. Butcher, S. Bhushan, and T. Sumner, "Multimedia displays for conceptual search processes: Information seeking with strand maps," *ACM Multimedia Systems Journal*, pp. In Press, 2005.

[19] D. Radev, E. Hovy, and K. McKeown, "Introduction to the special issue on summarization," *Computational Linguistics*, vol. 28, pp. 399-408, 2002.

[20] I. Mani, *Automatic Summarization*. Amsterdam, Netherlands: John Benjamins, 2001.

[21] G. I. McCalla, "The search for adaptability, flexibility, and individualization: Approaches to curriculum in intelligent tutoring systems," in *Adaptive Learning Environments: Foundations and Frontiers*, *NATO ASI Series*, M. Jones and P. H. Winne, Eds. Berlin Heidelberg: Springer-Verlag, 1992, pp. 91-121.

[22] B. P. Woolf, "Towards a computational model of tutoring," in *Adaptive Learning Environments: Foundations and Frontiers*, *NATO ASI Series*, M. Jones and P. H. Winne, Eds. Berlin Heidelberg: Springer-Verlag, 1992, pp. 209-231.

[23] J. R. Anderson, A. T. Corbett, K. R. Koedinger, and R. Pelletier, "Cognitive tutors: lessons learned," *The Journal of the Learning Sciences*, vol. 4, pp. 167-207, 1995.

[24] T. K. Landauer and S. T. Dumais, "A solution to Plato's problem: the latent semantic analysis theory of acquisition, induction, and representation of knowledge," *Psychological Review*, vol. 104, pp. 211-240, 1997.

[25] D. Wade-Stein and E. Kintsch, "Summary Street: Interactive computer support for writing," *Cognition and Instruction*, vol. 22, pp. 333-362, 2004.

[26] G. Pask, *Conversation, Cognition and Learning: A Cybernetic Theory and Methodology*. Amsterdam - Oxford - New York: Elsevier, 1975.

[27] B. Scott, "Conversation theory: A constructivist, dialogical approach to educational technology," *Cybernetics & Human Knowing*, vol. 8, pp. 25-46, 2001.

[28] D. Laurillard, *Rethinking University Teaching: A framework for the effective use of educational technology*. London and New York: Routledge, 1993.

[29] K. McKeown, J. Klavans, V. Hatzivassiloglou, R. Barzilay, and E. Eskin, "Towards multidocument summarization by reformulation: Progress and prospects," presented at 16th National Conference on Artificial Intelligence (AAAI-99), 1999.

[30] D. Radev, H. Jing, and M. Budzikowska, "Centroid-based summarization of multiple documents: sentence extraction," presented at ANLP/NAACL 2000 Workshop on Summarization, 2000.
[31] Z. Zhang, "Weakly-supervised relation classification for information extraction," presented at CIKM '04: Thirteenth ACM conference on Information and knowledge management, Washington, D.C., 2004.
[32] D. Marcu and A. Echihabi, "An unsupervised approach to recognizing discourse relations," presented at 40th Annual Meeting of the Association for Computational Linguistics (ACL'02), Philadelphia, PA, 2002.
[33] V. Vapnik, *The Nature of Statistical Learning Theory*. New York, NY: Springer, 1995.
[34] T. Joachims, "Transductive Inference for Text Classification using Support Vector Machines," presented at 16th International Conference on Machine Learning (ICML '99), Bled, Slovenia, 1999.
[35] J. Mayfield, P. McNamee, and C. Piatko, "Named Entity Recognition using Hundreds of Thousands of Features," presented at 7th Conference on Natural Language Learning, Edmonton, Alberta, 2003.
[36] S. Pradhan, W. Ward, K. Hacioglu, J. Martin, and D. Jurafsky, "Shallow Semantic Parsing Using Support Vector Machines," presented at Human Language Technology Conference/North American chapter of the Association of Computational Linguistics (HLT/NAACL), Boston, MA, 2004.
[37] D. Zhang and W. S. Lee, "Question classification using support vector machines," presented at 26th annual international ACM SIGIR conference on Research and development in information retrieval (SIGIR '03), Toronto, Canada, 2003.
[38] J. D. Novak and D. B. Gowin, *Learning how to learn*. New York, New York: Cambridge University Press, 1984.
[39] R. McCall, "PHIBIS: Procedurally Hierarchical Issue-Based Information Systems," presented at Conference on Architecture at the International Congress on Planning and Design Theory, New York, 1987.
[40] A. McCallum, D. Freitag, and F. Pereira, "Maximum entropy markov models for information extraction and segmentation," presented at Seventeenth International Conference on Machine Learning, Williamstown, MA, 2000.
[41] E. Riloff, "Automatically constructing a dictionary for information extraction tasks," presented at Eleventh National Conference on Artificial Intelligence, Washington, D.C., 1993.
[42] S. Soderland, "Learning information extraction rules for semi-structured and free text," *Machine Learning*, vol. 34, pp. 233-272, 1999.
[43] C. Lewis and J. Rieman. (1993). *Task-centered User Interface Design: A Practical Guide*. Retrieved December 16, 2004, from http://hcibib.org/tcuid/
[44] P. Ehn, *Work-Oriented Design of Computer Artifacts*, 2nd ed. Stockholm: arbetslivscentrum, 1989.
[45] C. Lewis, "Using the "Thinking-aloud" Method in Cognitive Interface Design," IBM Thomas J. Watson Research Center Yorktown Heights, NY 10598, Research Report RC 9265 (#40713), 2/17/82 1982.
[46] M. Chi, "Quantifying qualitative analyses of verbal data: A practical guide," *Journal of the Learning Sciences*, vol. 6, pp. 271-315, 1997.
[47] K. A. Ericsson and H. A. Simon, *Protocol Analysis: Verbal Reports As Data*, Revised Edition ed. Cambridge: MIT Press, 1993.
[48] M. Chi, N. d. Leeuw, M.-H. Chiu, and C. LaVancher, "Eliciting Self-Explanations improves understanding," *Cognitive Science*, vol. 18, pp. 439-477, 1994.
[49] W. Kintsch, *Comprehension: A paradigm for cognition*. Cambridge: Cambridge University Press, 1998.
[50] D. Radev, T. Allison, S. Blair-Goldensohn, J. Blitzer, A. Celebi, S. Dimitrov, E. Drabek, A. Hakim, W. Lam, D. Liu, J. Otterbacher, H. Qi, H. Saggion, S. Teufel, M. Toper, A. Winkel, and Z. Zhang, "MEAD - a platform for multidocument multilingual text summarization," presented at Fourth International Conference on Language Resources and Evaluation (LREC 2004), Lisbon, Portugal, 2004.
[51] Utah State Office of Education. (August 7th, 2000). *Earthquakes*. Retrieved April 10th, 2006, from http://www.usoe.k12.ut.us/curr/science/sciber00/8th/earth/sciber/surface3.htm
[52] M. Pidwirny. (February 2nd, 2006). *Fundamentals of Physical Geography (2nd Edition)*. Retrieved April 10th, 2006, from http://www.physicalgeography.net/fundamentals/chapter10.html
[53] NRC, *National Science Education Standards*. Washington, DC: National Research Council (NRC), National Academy Press, 1996.
[54] R. Raskin. (Jan 26th, 2006). *Semantic Web for Earth and Environmental Terminology (SWEET)*. Retrieved April 20th, 2006, from http://sweet.jpl.nasa.gov/ontology/
[55] M. Petre, "Why Looking Isn't Always Seeing: Readership Skills and Graphical Programming," *Communications of the ACM*, vol. 38, pp. 33-44, 1995.
[56] H. Pfundt and R. Duit, *Bibliography. Students' alternative frameworks and science education*, 3rd ed. Kiel, Germany: Institute for Science Education at the University of Kiel, 1991.
[57] A. Schoenfeld, "Learning to think mathematically: Problem solving, metacognition, and sense making in mathematics," in *Handbook of research on mathematics teaching and learning*, D. Grouws, Ed. New York, NY: McMillan Publishing Company, 1992, pp. 334-370.
[58] S. de la Chica, T. Chichirico, P. Le, J. Sun, and H. Khan, "Online science news in the classroom: Human computer interaction design issues," presented at Ed-Media 2005, World Conference on Educational Multimedia, Hypermedia and Telecommunications, Montreal, Canada, 2005.