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Learning Science and Technology R&D: A Roadmap to the Future of Learning

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New information technology tools make it possible to implement the insights of modern cognitive science and achieve revolutionary improvements in how we teach and learn. In fact, it may not be practical to implement some of the recommendations of cognitive scientists such as discovery-based learning and individualized counseling and tutoring without technology. But, the breadth and scale of the research effort to fully realize such gains demands a significant financial investment in a carefully designed and well managed program of research. A long-term, large-scale effort is needed to develop, test, and disseminate tools for building advanced learning systems that are reliable, well-performing, easy-to-use, and scalable. We know too little about why certain information technology education and training technologies and methods do or do not work. Our understanding will be solidified only after the technologies have been developed, used, and evaluated.

The Learning Science and Technology R&D Roadmap, recently completed by the Learning Federation, details a technology roadmap for developing next-generation learning systems. The Learning Federation, a partnership among industry, academia, and private foundations to stimulate research and development in learning science and technology, worked with over seventy leading learning science and information technology researchers over a three year period to produce the Roadmap. The Roadmap defines research priorities, a development chronology, and short- and long-term milestones. While the roadmap focuses on post-secondary science, math, engineering, and technology education, its research plan should be useful to all learning markets, including K-12. The roadmap provides a comprehensive strategic view of the learning science and technologies field which can guide researchers, industry, and funding agencies as they strive for innovation in educational technology. This paper describes how the roadmap was developed and outlines the R&D priorities identified in the roadmap.

Background

Recent progress in cognitive science has resulted in key insights about how people learn, how to teach, and how progress in learning can be evaluated. We know, for example, that discovery based learning, performance based assessments, and instructional systems continually adjusted by sensitive formative assessments can contribute to learning in powerful ways.[1] Unfortunately, these practices are not pervasive in America's classrooms and training centers. Individualized instruction, subject-matter experts, and rich curricular activities are often simply too expensive. Expense and related challenges often cause both formal education and corporate training to rely on strategies that ignore the findings of learning research.

It's known that individual tutoring can improve average student performance by as much as two standard deviations (2σ) with a dramatic reduction in the distribution of outcomes.[2] But hiring an individual tutor for each student isn't practical. Technology, however, may be able to provide a mixture of artificial tutors and links to real human coaches and subject experts that may even improve on the outcomes achieved in one-on-one tutoring. A recent National Academy of Science analysis of student assessments, for example, emphasizes that the challenge of continuously gathering and evaluating complex information about students probably cannot be achieved without new information technology. The report notes that "New capabilities enabled by technology include directly assessing problem-solving skills, making visible sequences of actions taken by learners in solving problems, and modeling and simulating complex reasoning tasks."[3]

New communication tools allow students to collaborate on complex projects and ask for help from teachers and experts from around the world. Learning systems can be designed to adapt to differences in student interests, backgrounds, learning styles and aptitudes. They can provide continuous measures of competence, integral to the learning process that can help teachers work more effectively with individuals and leave a record of competence that is compelling to students and to employers. And new tools can allow continuous evaluation and improvement of the learning systems themselves. These new tools make it possible to imagine learning systems that can adapt to the background and interest of every individual, as well as efficiently move each learner to the appropriate level of expertise. Continuous formative assessments based on simulations of practical experiences will ensure that they can walk into the next stage of their education or into a demanding work environment and be productive immediately. The assessments can also lead to continuous improvements in the instructional system itself.

The Learning Science and Technology R&D Roadmap

Development of the Learning Science and Technology R&D Roadmap was sponsored by Hewlett Packard, Microsoft Research, the Digital Promise Project, the National Science Foundation, Department of Defense, the Carnegie Corporation of New York, and the Hewlett Foundation. A senior Steering Committee comprised of national leaders in learning science and information technology provided advice and guidance, and review and endorsement of the research plan described in the Roadmap. Table 1 lists the Steering Committee members. The Federation of American Scientists, a Washington, DC non-profit, provided project leadership.

Table 1. Learning Federation Steering Committee Membership

Henry Kelly President Federation of American Scientists	**Andries van Dam** Vice President Brown University
Randy Hinrichs Group Research Manager, Learning Science and Technology Microsoft Research	**Ruzena Bajcsy** Director, Center for Information Technology Research in the Interest of Society University of California, Berkeley
John D. Bransford Department of Education University of Washington	**Shankar Sastry** Professor of Electrical Engineering and Computer Sciences University of California, Berkeley)
Gene Broderson Director of Education Corporation of Public Broadcasting	**William Spencer** Chairman Emeritus International SEMATECH Board
Edward Lazowska Bill & Melinda Gates Chair in Computer Science University of Washington	**Janos Sztipanovits** E. Bronson Ingram Distinguished Professor of Engineering Vanderbilt University
Elliot Masie President, MASIE Center	**Ann Wittbrodt** Research & Development Manager Education Services Hewlett-Packard
Richard Newton Dean of the College of Engineering Roy W. Carlson Professor of Engineering University of California, Berkeley	**Project Management:** **Kay Howell** Director, Information Technologies Federation of American Scientists
Donald Norman Cofounder,Nielsen Norman Group, Prof. Emeritus Cognitive Science and Psychology University of California, San Diego	**Kendra Bodnar** Program Manager Learning Technologies Federation of American Scientists.
Raj Reddy Herbert A. Simon University Professor of Computer Science and Robotics Carnegie Mellon University	**Thomas Kalil** Assistant to the Chancellor for Science and Technology University of California, Berkeley

The Learning Science and Technology R&D Roadmap was developed over a three year period using the methods pioneered by the SEMATECH Corporation that has built and revised a research plan for semiconductor manufacturing for over a decade. Using advice provided by experts from educational institutions, government, and industry, a series of five component roadmaps was developed, each addressing critical learning science and technology R&D focus areas. Input was solicited from a variety of disciplines, including information science, software engineering and design, cognitive science, and pedagogy.

Following is a list of the individuals who assisted in development of the Roadmap via participation in a workshop and/or as a reviewer of the Roadmap:

Clark Aldrich, SimuLearn, Inc.	Ed Lazowska, University of Washington
Robert Atkinson, Arizona State University	Alan Lesgold, LRDC, University of Pittsburgh
Eva Baker, UCLA	Marcia Linn, UC-Berkley
Marianne Bakia, Federation of American Scientists	Diane Litman, University of Pittsburgh
Sasha Barab, Indiana University	Stephanie Loranger, Federation of American Scientists
Bryan Barnett, Microsoft	Max Louwerse, University of Memphis
John Behrens, Cisco	Jean MacMillan, Aptima, Inc.
Randy Bennett, ETS	Peg Maddocks, Cisco
John Bransford, Vanderbilt	Lee Maxey, Click2Learn
Jack Bresse, Microsoft	Michael Meloth, Abion University
Lori Breslow, MIT	Jim Minstrell, Talaria, Inc.
Mark Briski, Titan Systems	Allison Moore, Vanderbilt
Barbara Buckley, The Concord Consortium	Jamie Mulkey, Hewlett Packard
John Burger, MITRE	John Newkirk, Acuitus
Janis Cannon-Bowers, UCF/IST	Paul Nichols, NCS/Pearson
Jack Carroll, Virginia Tech	Jim Olsen, Alpine Media
Howard Champion, Tech Med Inc.	Hugh Osborn, TurboKids
Ralph Chatham, DARPA	Adrian Pell, Hewlett Packard
Yakov Cherner, ATE Learning	Leslie Perelman, MIT
Dick Clark, USC	Ray Perez, Office of Naval Research
Cristina Conati, UBC	Maria Potenza, Microsoft
Albert Corbett, Carnegi Mellon	Mark Prensky, Games2Train.com
Sarah DeMark, Cisco	Carla Pugh, Stanford
Phil Dodds, ADL-SCORM	Clark Quinn, Ottersurf
Dexter Fletcher, IDA	Sowmya Ramachandran, Stottler Henke Associates
Peter Foltz, New Mexico State University	Catherine Rickelman, IBM
Casey Garhart, IBM	John Rieser, Vanderbilt
Stephen Golberg, Army Research Institute	Nora H. Sabelli, SRI
Judith Hale, Hale Associates	Elizabeth Sheldon, Sonalysts, Inc.
Sanda Harabagiu, UT Dallas	Peter Simon, Horn Interactive
Ken Hay, UGA	Kurt Squire, MIT
Gerry Higgins, Simquest	Neil Stillings, Hampshire College
Randy Hinrichs, Microsoft	Brenda Sugrue, eLearnia
Eric Horvitz, Microsoft	Bob Tinker, Concord Consortium
Larry Howard, Vanderbilt	Kurt van Lehn, University of Pittsburgh
Kay Howell, Federation of American Scientists	Ellen Voorhees, NIST
Lewis Johnson, USC CARTE	Ken Whang, NSF

Henry Kelly, Federation of American Scientists	Mark Wierderhold, SAIC
Pat Kyllonen, ETS	Brenda Wiederhold, VR Med Ctr
Jim L'Allier, Thomson NETg	David Williamson, ETS
Andrea Lauer, IBM	Erling A. Woods, Laerdal Medical

The Learning Science and Technology R&D Roadmap is comprised of a series of five component roadmaps that detail a research plan for the following key research focus areas:

- *Instructional Design for New Technology-Enabled Approaches to Learning* - exploiting the inherent motivational aspects of games and simulations for education and training;

- *Question Generation and Answering Systems* - using what we know about question generation and question answering to design learning environments that increase learning outcomes and that facilitate inquiry by taking advantage of the benefits offered by emerging technologies;

- *Learner Modeling and Assessment* - providing continuous measures of competence that can help teachers work more effectively with individuals and leave a compelling record of competence;

- *Building Simulations and Exploration Environments* - making simulations and virtual environments easier to build and incorporate into learning environments; and

- *Integration Tools for Building and Maintaining Advanced Learning Systems* - designing development and integration tools built on a common infrastructure that bridge the gap between the complexity of web-based learning systems and the instructional design community.

Each roadmap is organized into key research topics that should collectively facilitate the roadmap focus area. Associated with each research topic is a set of tasks and subtasks that need to be accomplished. Milestones are projected for the next 3, 5, and 10 years. In order to track progress in achieving the various tasks, there are recommended metrics. The component roadmaps range from 30 – 80 pages in length, and contain between 8 – 16 tables each that present the research tasks, along with milestones and metrics, identified for the research topic. The following paragraphs summarize the research tasks presented in the component roadmaps. For more detail, the reader is encouraged to read the full roadmaps which are available at www.thelearningfederation.org.

Research Tasks Identified in the Instructional Design Component Roadmap

The Instructional Design Component Roadmap identifies research priorities for designing and evaluating simulations and games in instructional environments. Many indications exist that the prudent application of technology in learning systems has the potential to vastly improve the more elusive aspects of the educational process. The most important aspect is the motivation to learn and continue learning over one's lifetime. Clearly, computer games hold special interest to a generation who has grown up with them, and as such, they show promise as educational tools. Whether this is due to the inherent challenge built into game play, the richness of graphics presented to the user, the opportunity to interact with other users (in web-based games), the story or context in which the game is couched, or some other feature is worthy of study. Moreover, the advent (and availability) of immersive environments for entertainment purposes is likely to grow considerably in the next few years, and surely will have important applications in learning. Exploiting the inherent motivational aspects of games and simulations for education and training must be based on a sound understanding of which features of these systems are important for learning and why.

A program of research is needed that aims to systematically elucidate and investigate the host of variables that will have an impact on instructional effectiveness for a particular application. In general, such an approach would be concerned with what is being taught, who the learners are, which phase of instruction is of interest, how best to teach targeted material, the context in which learning will occur, and any practical considerations that limit what can be done. One way to organize a systematic program of this sort is to construct an overriding model or framework that lays out all of the pertinent variables and the manner in which they are related. Using such a model would provide researchers with a common framework in which to conceptualize their studies and make it easier to see how individual studies (i.e., the specific variables and context being tested) fit into the larger picture. In addition, a common framework will allow research results to be more effectively integrated across factors, and gaps in understanding to be identified. The research tasks identified in the Instructional Design Component Roadmap are summarized in Table 2. The full roadmap, available at www.thelearningfederation.org, provides detailed subtasks, milestones, and metrics for each of the research tasks summarized in the table.

Table 2. Research Tasks in Instructional Design

Research Tasks	R&D Outcomes
Integrative Framework to Facilitate Generalization and Integration of Research Results	• Automated tools for classifying and identifying task demands, knowledge types and establishing instructional objectives. • Automated tools for cognitive task analysis that link task demands to knowledge types and learning objectives • Automated team task analysis capabilities that link task demands with knowledge types and learning objectives • Documentation on the nature of challenges that are typical in games and why they work
Tools for Determining and Assessing Learner Characteristics	• Prioritized list of learner characteristics to study and tools to measure and assess • Open standards software that can be embedded in third party simulations that diagnose and remediate across general, spatial, technological parameters • Automated processes for adjusting the learning environment in accordance with the learner's initial knowledge and experience • Empirical results of the relationship between goal orientation and aspects of technology-enabled learning systems across multiple subject domains/ skill classes • Embedded, open source tools to adjust curriculum/instruction based on goal orientation and content
Methods and Tools for Practice Environments	• Empirically validated strategies for developing scenarios and cases that are linked to task types and learner characteristics; these strategies will reduce time to develop effective scenarios and cases by 50% • Automated tools for assessing fidelity and authenticity based on learning goals and learner characteristics, including a library of techniques for enhancing the authenticity and fidelity of practice environments • Validated modeling strategies for creating simulated teammates and adversaries that produce achievement equivalent to human actors • Automated coaching strategies that dynamically adjust according to learner achievement and demonstrate time/cost savings and learning ability • Tools to guide design of computer-assisted collaboration in learning
Identify Features of Games that Can Be Used to Improve Learning	• Documented features of challenges crucial for motivation and learning; develop guidelines for implementing challenges across task/domain types and learner characteristics • Guidelines for developing compelling stories for learning; and develop mechanisms to assess the appropriateness of a story for learning

	• Techniques for assessing immersion and engagement; guidelines for increasing immersion and engagement in learning games • Guidelines for developing games that optimize mastery orientation in games; demonstrate optimization that reflects a 50% increase in mastery orientation • Techniques to increase motivation in games across tasks and learners and demonstrate 50% learning increases

Research Tasks Identified in the Question Generation and Answering Systems Component Roadmap

Cognitive science research has demonstrated that learning improves when students ask questions. Yet, it is well documented that most learning environments do not stimulate many learner questions. According to the estimates of Graesser and Person (1994), a typical student asks .17 question per hour in a conventional classroom and 27 questions per hour in one-on-one human tutoring.[4] In addition to rarely asking questions, many learners do not know how to ask good questions. Many classroom environments are focused on teacher monologues; in effect, students rarely observe good collaborative dialogue.

Making dialogues and questions a routine part of learning systems requires tools for managing and responding to learner queries that integrate question generation and answering capabilities. Computer tools are needed that can: answer students' questions whenever they ask them; formulate answers in a fashion that uses the specific pedagogical theory deemed most appropriate for the learner and subject; deliver quick, correct, relevant, and informative answers; and connect learners to teachers, coaches, and experts, as well as to computer-generated answers. As a longer-term goal, learning systems should have even more sophisticated facilities that diagnose student problems and provide help *before* the question is asked. For example, learning tools are needed that can:

- incorporate detailed learner profiling that keeps track of general capabilities and aptitudes of the learner and details about the history of learning episodes;
- stimulate learner questions through learning situations such as challenges, contradictions, and obstacles to important goals; and
- teach learners how to ask good questions, by direct instructions on questioning or by a person or computer that models questioning skills.

The research tasks identified in the Question Generation and Answering Systems Component Roadmap are summarized in Table 3. The full roadmap, available at www.thelearningfederation.org, provides detailed subtasks, milestones, and metrics for each of the research tasks summarized in the table.

Table 3. Research Tasks in Question Generation and Answering Systems

Research Priorities	R&D Outcomes
Tools to Stimulate Learner Questions and Questions that Stimulate Learning	• Decision aids for identifying the critical components of learning environments that stimulate question asking • Published models that predict how varying features in a learning environment change quantity and types of questions • Complete repositories of sample questions for additional new classes of learning environments
Tools to Simplify Question Asking	• Intuitive interfaces that allow the learner to correct the system's understanding of the question • Spoken language questions in open domains • Utilities for annotating images for student use in deictic reference • Automated markup of large text collections in support of question answering • Models of student knowledge to coach learners on questions that should be asked
Tools for Comprehending and Answering Learner Questions	• Natural understanding modules that perform within 10% of human interpretation of answers • Complex answers compiled, merged, and generated from multiple sources, with confidence level • Dynamically constructed answer justification sensitive to the user and session context • Learning environments selected and tailored automatically to maximize landscape of important questions • Electronic information within 2 seconds for all question categories; teacher, coach, or relevant expert response within seconds
Tools for Interpreting Learner Answers	• Software utilities and authoring tools for marking up documents in learning repository and natural language processing components • Tools for tagging and segmenting content to enable automatic matching of content to pedagogical taxonomies and educational objectives that perform as well as humans • Tools to support integration of pens, eye-trackers, gesture analysis, etc. and to interpret/evaluate visual and action modalities • Natural language understanding modules that perform within 10% of human interpretation of answers
Tools to Advance the Discussion and to Summon Teachers and Experts as Needed	• Systems capable of asking the learner major questions or presenting problems that will require major attention and conversation • Systems capable of responding to student assertions by giving feedback in a variety of forms: verbal feedback without intonation, verbal feedback with intonation, facial expressions, a visual symbol on the interface, etc. • Systems that summon teachers or experts, as needed • Systems with audio and video speech recognition and speech synthesis implemented, plus evaluation experiments to assess effectiveness • Systems that direct the learner to simulation and visual media when needed, interrupt when needed, etc.

Research Tasks Identified in the Learner Modeling and Assessment Component Roadmap

Internet technologies will reinvent assessment, because the Internet is interactive, broadband, switched, networked and standards-based[5]. These attributes facilitate automation of assessment development processes, expansion of the stimulus and response possibilities of assessment tasks, automated scoring of complex constructed responses, real-time reporting, and automated learning management. Online assessment permits real-time analysis and dynamic adaptation of both the assessment content itself and learning content associated with the competencies being measured. The same data can be used to trigger automated feedback or intervention by a human expert or intelligent agent, or to inform the decisions of a human teacher. However, as delivery and use of assessment development are automated, weak links in the non-automated processes become evident. Fuzzy practices, inconsistencies, and disconnects that have persisted for decades become obstacles to measurable progress. The theoretical underpinnings and models that drive current assessment practices will need to be articulated more precisely and consensus will need to be reached on what should be measured, when it should be measured, how it should be measured, and what should be done with the data.

The Learner Modeling and Assessment Component Roadmap identifies five R&D research tasks that will help turn the research and software, heretofore confined to research labs and proof of concepts, into scalable, extensible, integrated Internet-based learning systems. The R&D tasks identified in the roadmaps will significantly increase the validity, efficiency, utility, effectiveness, and widespread use of learner modeling and technology-enabled assessment.

The research tasks identified in the Learner Modeling and Assessment Component Roadmap are summarized in Table 4. The full roadmap, available at www.thelearningfederation.org, provides detailed subtasks, milestones, and metrics for each of the research tasks summarized in the table.

Table 4. Research Tasks in Learning Modeling and Assessment

Research Tasks	***R&D Outcomes***
Establish Models of Content Expertise, Competency, and Pedagogy	• Map content/competency models and agree on a shared core model and terms • Map pedagogical models and agree on a meta model and terms • Task analysis methodology and software that reflect the core content model and enables automated generation of tasks to elicit and measure those skills

Tools for Automated Modular Assessment Design, Development, Delivery, and Analysis	• General assessment object architecture with standard item/task templates for measuring particular types of knowledge and skills, with rules for generating the content of the variable slots in the templates and rules for scoring alternative types of responses. • Authoring tools to automate creation, storage, and assembly of components • Tools and mechanisms for scoring and aggregating data from multiple sources • Integration with learning environments and data tracking/reporting systems
Multidimensional Learner Models and Measurement Methods	• Validated multidimensional learner models and their components and guidelines for when to use more and less elaborate learner models • Tools to support insertion of monitoring capabilities into multiple learning systems • Tools to specify analysis and actions based on particular levels of mastery and motivation • Decision-aids for choosing different types of measurements and level of detail based on context, budget and purpose
Tools for Reporting and Use of Assessment and Learner Modeling Data	• Decision-aids/rules for personalizing feedback, and guidance and personalization of content • Authoring tools for specifying rules and triggering feedback customized to individual needs • Authoring tools that enable dynamic assembly of feedback segments and support a variety of feedback media, including text and spoken language • Real-time generation of reports from multiple databases • Data structures and application program interfaces (APIs) for transfer of data
Web services Infrastructure for Integration of Software Applications and Services	• Specification of the architecture, with APIs to connect component software applications, for example, authoring tools or reporting services, that reflect generally accepted standards • Prototypes to validate integration of component services (authoring, scoring, analysis, maintenance of learner models; reporting) ready for integration • Validate integration of component services • APIs for integration with other e-business services

Research Tasks Identified in the Building Simulations and Exploration Environments Component Roadmap

Research has demonstrated that simulation environments are powerful learning tools that encourage exploration by allowing learners to manipulate parameters and visualize results. In academic settings, simulations can enhance lectures, supplement labs and engage students. In the workplace, simulations are a cost-effective way to train personnel. Synthetic or virtual environments can support games, exploration, and assignments with clear goals or challenges. Such environments, if well-designed, can motivate learners to meet the goal, thus sustaining their eagerness to build the needed skills. The research challenge is to better understand how to use simulations and synthetic environments to improve learning outcomes, while making them easier to build and incorporate into learning environments.

The Building Simulations and Exploration Component Roadmap identifies four key research topics, summarized in Table 5 that collectively should enable simulations and virtual environments to improve learning outcomes. The full roadmap, available at www.thelearningfederation.org, provides detailed subtasks, milestones, and metrics for each of the research tasks summarized in the table.

Table 5. Research Tasks in Building Simulations and Exploration Environments

Research Tasks	***R&D Outcomes***
Interoperability for Integration into Learning Environments	• Common network software architecture with standard protocols that govern the exchange of information about the state of each of the participants in the simulation • Common underlying architecture for maintaining information about the state of the environment related to a particular simulator • Adoption of unified ontology by communities of simulation developers • Development of a STEP-like 3D modeling environment that can be used for modeling dynamic interactions and organic shapes
Reuse, Certification, and Maintenance of Components	• Established procedures for peer review and validation of results against experiments • Easy, valid methods for tracking of the provenience of data and methods and identification of authors • Procedures for bug reports and reliable version control • Standards for the "metadata" used to identify the data and software • Methods and tools to ensure that appropriate credit is given to authors

Navigation of Exploration Environments	• Immersive 3-D networked simulations with no perceivable latency for multiple users of moderately complex visual simulations on simple clients • Techniques to navigate simulations and visualizations at different levels of detail • Feature-based navigation and scene management • Simulations of a full range of instruments that are interoperable with synthetic environments • Noninvasive and accurate tracking that sense and react to the user and the user's environment • Human 3-D holomers that allow merging of motion capture and diagnostic imaging modalities to completely describe human movement • Complex force feedback (haptics) displays that run on the desktop
Integrating Simulations and Exploration Environments into Learning Environments	• Model scalability for use at many levels of resolution and complexity • Virtual game worlds composed of customizable, intensive, user-specific niches, blurring distinctions between reality and synthetic environments • Multi-player, multi-educational resources available anywhere, anytime through any internet-connectable interface • Predictive computer-based modeling and simulation that can substitute for many aspects of physical testing and experimentation

Research Tasks Identified in the Integration Tools for Building and Maintaining Advanced Learning Systems Component Roadmap

As specifications and standards to support web-based system-directed learning systems have been built, the means for creating interoperable and robust instructional content have emerged. Unfortunately, current specifications have defined a technically complex infrastructure that is unfriendly to instructional designers. This Roadmap identifies development and integration tools to bridge the gap between the complexity of web-based learning systems and the instructional design community. The Roadmap identifies three research priorities: tool architecture, shareable content objects, and metadata. A major challenge is the development of a stable delivery platform that can scale broadly and be incrementally built upon. The research tasks identified in the Roadmap are summarized in Table 6. The full roadmap, available at www.thelearningfederation.org, provides detailed subtasks, milestones, and metrics for each of the research tasks summarized in the table.

Table 6. Research Tasks in Integration Tools for Building and Maintaining Advanced Learning Systems

Research Priorities	R&D Outcomes
Course Building Tools	• Extensible model for how tools and services might interconnect and self-discover • Enabling formats and standards
Shareable Content Objects to Simplify Use	• Content creation tools designed for instructional designers that hide technical implementation • Tools that seamlessly integrate varied content types for non-technical authors • Seamless search and access to digital assets • Tools that support merging content formats including static, interactive, stream-based, and active, and examine the authoring, integration and deployment issues • Integration tools for combining disparate media types
Tools and Services to Assist in Application of Metadata	• Implementation guidelines for developers in different domains • Tools to map semi-automatically across domains and determine impact on content developers • Tools to automate the application of metadata to all levels of content, perhaps through intelligent analysis by agents • Methods to connect current and emerging intelligent search and retrieval services that use learning metadata with increasingly complex services and information
Tools for Collaborative Building and Maintenance of Learning Environments	• Documented requirements of tools that support various pedagogical and theoretical approaches; tool examples that support the models • Rules-based sequencing approaches capabilities for non-technical designers • Tool strategies for creating "mini context" templates for reusable compound learning objects that can support many different communities of practice (e.g., Higher Ed, Training, Performance Support, etc.) • Search strategies to enable "real time" assembly of content based on learner profiles, mastery, subject, etc.

Conclusion

The Learning Federation Learning Science and Technology R&D Roadmap provides a comprehensive description of promising research in learning science and technology R&D that could enable dramatically improved approaches to teaching and learning. The Roadmap describes both basic research and highly applied efforts to build tools, design software, and develop courses using the products of this research. The research outlined in the Roadmap is designed to ensure a continuous flow of carefully evaluated instructional components, instructional strategies, and tools adaptable to multiple contexts, including university and corporate learning. Developing the software tools and systems described in the Roadmap will be like other software development efforts: difficult, labor-intensive, and expensive. Tools to decrease the level of effort are desperately needed. A key goal of the applied research explored in the Roadmap involves creating a useable range of interoperable, well-performing, extensible software tools that can lower the cost of entry for educational materials and systems.

The scale and scope of the research effort proposed in the Roadmap are unprecedented in education. It will require a new partnership combining the talents and resources of government, industry, and private foundations. By articulating a vision of next-generation learning systems, the Learning Federation Learning Science and Technology R&D Roadmaps should stimulate discussion and help guide investments in this important area of research.

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