
# EXECUTIVE SUMMARY

**Learning Science *and* Technology R&D Roadmap**

The Learning Federation
Federation of American Scientists
1717 K St. NW Suite 209
Washington, DC 20036
T (202) 454-4685
F (202) 675-1010

www.thelearningfederation.org
thelearningfederation@fas.org

The Learning Science and Technology R&D Roadmap Executive Summary incorporates a series of technology research roadmaps, or plans, developed over a three year period by the Federation of American Scientists and the Learning Federation, a partnership among industry, academia, and private foundations to stimulate research and development in learning science and technology. The full series of research roadmaps is available at *www.thelearningfederation.org*.


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# **The Learning Federation:** Learning Science and Technology Research & Development Roadmap

# *Executive Summary*

# Learning Federation Steering Committee

## Executive Leadership

**Randy Hinrichs**, Group Research Manager, Learning Science and Technology, Microsoft Research

**Henry Kelly**, President, Federation of American Scientists

**Andries van Dam**, Vice President for Research, Brown University

## Steering Committee Members

**Ruzena Bajcsy**, Director, Center for Information Technology, Research in the Interest of Society, University of California, Berkeley

**John D. Bransford**, College of Education, University of Washington

**Gene Broderson**, Director of Education, Corporation of Public Broadcasting

**Edward Lazowska**, Bill & Melinda Gates Chair in Computer Science, University of Washington

**Elliot Masie**, President, MASIE Center

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**Donald Norman**, Co-founder, Nielsen Norman Group, Professor Emeritus, Cognitive Science and Psychology, University of California, San Diego

**Raj Reddy,** Herbert A. Simon University Professor of Computer Science and Robotics, Carnegie Mellon University

**Shankar Sastry**, Chair of Electrical Engineering and Computer Sciences, University of California, Berkeley

**William Spencer**, Chairman Emeritus, International SEMATECH Board

**Janos Sztipanovits**, E. Bronson Ingram Distinguished Professor of Engineering, Vanderbilt University

**Ann Wittbrodt**, Research and Development Manager Education Services, Hewlett-Packard Company

## Project Management

Kay Howell, Director, Information Technologies, Learning Federation Project Director, Federation of American Scientists

Kendra Bodnar, Director, Learning Technologies Project, Federation of American Scientists

Thomas Kalil, Assistant to the Chancellor for Science and Technology, University of California, Berkeley

# The Learning Federation
# Learning Science and Technology R&D Roadmap

## Introduction

### Catalyzing a revolution in how we teach and learn

With this technology Roadmap for innovation in learning science and technology, the Learning Federation charts a course toward creating revolutionary new learning environments and launching the action plan to make those real. The plan focuses entirely on identifying research that can lead directly to better learning outcomes and greater access to quality education and training for anyone with a desire to learn. It outlines a vision of what our nation could achieve with adequate investment, accompanied by a research plan that can realize that vision—a plan with clear targets, clear research objectives, clear priorities, and a management plan to ensure continuous evaluation and feedback. Put in operation, this plan will enable us radically to improve approaches to teaching and learning through information technology. Our goal is to catalyze a partnership joining companies, universities, the educational community, government agencies and private foundations to execute this plan. Information technology, used both in classrooms with well-educated and motivated instructors, and at home and in the workplace by individuals, can greatly increase the productivity and accessibility of education and training.

## About the Learning Federation

The Learning Federation was formed in 2001 as a partnership among industry, academia, and private foundations to stimulate research and development in learning science and technology. The Learning Federation has focused on developing this Roadmap, with the goal of producing a well-designed research plan that identifies research priorities, an

R&D chronology and metrics of success and a management plan for forming research teams and disseminating R&D results.

The Learning Federation is led by a Steering Committee of national leaders in learning science and information technology to provide advice and guidance, review and endorse the plan, and act as advocates on its behalf. In addition, more than 70 leading researchers, from industry, academia, and government donated time and labor to help us develop this Roadmap through their participation in focused workshops, interviews, and preparation of technical plans.

# Rationale

Emerging technologies make it practical now to approach learning in ways that theorists have advocated for many years. Unfortunately, the practices recommended by educational psychologists and cognitive scientists 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.

In a landmark series of studies, Bloom and colleagues demonstrated that one-on-one tutoring improved student achievement by two standard deviations over group instruction (Bloom, 1984)[1]. While no one was surprised to learn that one-on-one tutoring improved learning, the degree of improvement was surprising—the equivalent of improving the performance of 50$^{th}$ percentile students to that of 98$^{th}$ percentile! Imagine what an impact this could make on American society if we could replicate this across the educational enterprise. Researchers have sought to understand why such dramatic differences exist. Among the possible explanations are: individualization (that instruction can be tailored to the learner's particular needs), and instructional intensity (the number of interactions between teacher and student during a tutorial). If computers and advanced information technologies can implement even a portion of the ideal tutoring strategies, substantial learning gains should follow.

Indeed, several learning systems have already demonstrated impressive learning gains.

*For the first time in history, technology exists that can make vastly improved learning systems routinely available. But we can achieve this goal only by undertaking a long-term, large-scale effort to develop, test, and disseminate tools for building advanced learning systems.* The positive prospects have been marred by false promises and gross underestimates of the task's complexity. There's no question that improving learning systems is one of the most difficult, and most important, research challenges facing the nation today.

Given an aggressive and successful program of research, computer simulations could let learners tinker with chemical reactions in living cells, practice operating and repairing expensive equipment, or practice marketing techniques. Simulations could make it easier to grasp complex concepts and transfer this understanding quickly to practical problems. New communication tools could enable learners to collaborate on complex projects and ask for help from teachers and experts from around the world. Learning systems could adapt to differences in student interests, backgrounds, learning styles, and aptitudes. They could provide continuous measures of competence, integral to the learning process. Such measures could help teachers work more effectively with individuals and leave a record of competence that is compelling to students and to employers. And new tools could allow continuous evaluation and improvement of the learning systems themselves.

Some of these objectives require difficult but straightforward extensions of known technologies or adapting to learning goals the design concepts that have succeeded in business or research. Others will require fundamental advances. A successful research strategy must begin with the clearest possible vision of what is being attempted, and a strategy for managing research that invites and tests a wide range of approaches. The strategy must also be rooted in experience. New learning systems must be tested in practical ways, working with real students and teachers. The successes and failures of these tests will provide essential guidance for future research.

Sophisticated computer software is essential for implementing most of the new objectives— software ranging from simulations of biological processes to systems designed to answer questions using automated systems, with live instructors and experts. Without high-quality software tools, practical tests of advanced instructional concepts are impossible. With poor or amateurish software tools it is difficult or impossible to determine whether the concept or the implementation has failed the student.

Developing these software tools and systems will be like other software development efforts: difficult, labor-intensive, and expensive. Building these specialized tools is far beyond the capacity of most instructional designers. Tools to decrease the level of effort are desperately needed. A key goal of the applied research explored in the Learning Federation 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 research Roadmap are unprecedented in education. It will require a new partnership combining the talents and resources of government, industry, and private foundations. Current investments in learning science and technology are fragmented and often discontinuous, both within and across public and private sectors. There are many players in the learning technologies space, no dominant companies or standards, and the application markets are extremely diverse and disjointed. The total national investment in education and training is approaching one trillion dollars, yet the nation is probably investing only about $50 million in basic research or $200 million in applied research—most of this in the Department of Defense.

While more funding is essential, a special research management approach is equally important in order to build the needed research teams and focus the research. The research program should be built around a clearly articulated set of goals that are constantly debated and updated. The work must be divided into manageable programs built around clear, tightly integrated objectives. A disciplined process must be put in place to develop and continuously revise these objectives. And there must be a process for establishing clear research priorities—and the flexibility to tailor research investments to meet many different needs.

The Learning Federation was formed to focus this diverse community by fostering communications and a common purpose among the players while influencing research by identifying where intellectual effort is most likely to bear fruit. It is meant to motivate a new investment, and provide a first draft of a management plan to guide investments when new programs begin. Following the model of other successful research ventures, we will adopt a regular system of reviewing goals and priorities.

# The Research Roadmap

This research plan was built using methods pioneered by the SEMATECH Corporation, which for more than a decade has built and revised a research plan for semiconductor manufacturing. Using advice from panels of experts from companies, universities, government research facilities, and others with unique expertise, a series of five component roadmaps was developed, each addressing critical learning science and technology R&D areas. Expert input was solicited during a series of specialized workshops, consultative meetings, and interviews. We designed the roadmapping process to encourage discussion and debate throughout the relevant communities, including the nation's leading researchers in the learning sciences, software designers, private sector and educational personnel.

The roadmaps provide an assessment of the R&D needs, identify key research questions and technical requirements, and detail the chronology of the R&D activities over the next five to ten years. Each roadmap also articulates long-term goals and shorter-term benchmarks. Collectively, by articulating a vision of next-generation learning systems, these roadmaps provide a comprehensive strategic view of the field, which can guide researchers, industry, and funding agencies as they enable continued innovation in educational technology.

The R&D roadmaps are constructed to support both basic research and highly applied efforts to build tools, design software, and develop courses using the products of this research. The research plan is crafted to ensure that supported research will generate a continuous flow of carefully evaluated instructional components, instructional strategies, and tools adaptable to multiple contexts, including university and corporate learning. The tools developed will enable increases in scale that will make these capabilities readily affordable to all. In turn, affordability will permit routine use of new tools in schools, colleges, workplaces, and homes. The research plan embodies the following key characteristics:

- **Focus on pre-competitive R&D.** The product of the research will not be a specific, marketable course or product but rather pre-competitive concepts, technologies, and tools—exemplified in prototype models. Prototypes will be built with an eye to quick translation into practical courses or new immersive, interactive learning environments and interactive tools. While the Roadmap is designed to achieve ambitious long-term goals, it will also be crafted to ensure that supported research will continuously yield results that can be converted into practical products.

- **Focus on real but "stretch" applications**. The new tools envisioned here, stimulated by this Roadmap, will make it possible to measure a richer range of a person's ability —and to do so in a way that is clear to the learner, employer, instructor, and teacher.

- **Focus on post-secondary** (two-year and four-year colleges and universities and industry training functions) and lifelong science, math, engineering and technology education, directly addressing workforce development needs. Our focus here will include teaching specific job-related skills as well as the underlying principles necessary for learning new skills quickly. Corporate America's needs are growing rapidly and solutions are likely to be adopted quickly in these areas of learning. **The insights gained will, however, be useful in all learning—for children, adolescents, and adults.**

**Research Roadmap Components**

A series of five component roadmaps define the overall research plan. Each of the five addresses a critical learning science and technology R&D focus area. The five major research topics, summarized in the table below, were identified at a National Science Foundation-sponsored workshop held in November 2000.

| Component Roadmap | Research Priorities |
|---|---|
| **Instructional Design for New Technology-Enabled Approaches to Learning**<br><br>Understanding how people learn, how experts organize information, and the skills of effective learners | • An integrative framework to enable generalization and integration of research results.<br>• Tools for determining and assessing learner characteristics.<br>• Methods and tools for practice environments.<br>• Understanding how features of games can be used to improve learning. |

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| **Question Generation and Answering Systems for Technology-Enabled Learning Systems**<br><br>How to take advantage of the benefits offered by emerging technologies to facilitate inquiry and get questions answered | • Tools to stimulate learner questions and generate questions that stimulate learning.<br>• Interfaces that make it easier for students to ask questions and to provide guidance on what sorts of questions can be (or should be) asked.<br>• Tools for comprehending and answering learner questions.<br>• Tools for interpreting learner answers.<br>• Tools to advance the discussion with the student and to summon teachers and other experts as needed. |
| **Building Simulations and Exploration Environments for Technology-Enabled Learning Systems**<br><br>How to build complex virtual environments that reflect current understanding of physics, chemistry, biology, mathematics, and other disciplines that permit exploration-based pedagogy | • Interoperability within and across disciplines (geometry, ontology, message passing, etc.).<br>• Certification & management techniques for validating & updating simulations.<br>• Model scalability for use at many levels of resolution and complexity.<br>• Techniques to navigate simulations and visualizations at different levels of detail; feature-based navigation; and scene management.<br>• Adapting simulation and exploration environments to learning environments. |
| **Learner Modeling and Assessment for Technology-Enabled Learning Systems**<br><br>What to measure, when to measure and how to use the information | • Models of content expertise, competency and pedagogy.<br>• Automated modular assessment design, development, delivery and analysis.<br>• Multi-dimensional learner models and measurement methods. |

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| **Integration Tools for Building and Maintaining Advanced Learning Systems**<br><br>Strategies for using learning system tools to build learning systems | • Course building tools for designing scenarios, creating assignments, designing response to information gathered from student observer tools, and programming avatar behaviors.<br>• Shareable Content Objects that can hide the underlying technology and use terms and visualizations familiar to instructional designers.<br>• Tools and services to assist developers in the application of metadata.<br>• Tools to establish an open process for worldwide collaboration on building and maintaining learning environments. |

The following sections offer a general overview of each component roadmap and summarize the research priorities and milestones. The complete roadmaps are available at *www.thelearningfederation.org*.

## Instructional Design for New Technology-Enabled Approaches to Learning

Cognitive science has long recognized that learning environments that provide learners opportunities to apply their knowledge to solve practical problems and invite exploration and play can lead to faster learning, greater retention, and greater motivation. Indeed, apprenticeship experiences and play imitating expert behavior are the most ancient forms of instruction.

Unfortunately, these learning strategies are rarely used today because they are difficult to implement in standard classroom environments. But, expected improvements in technology may significantly reduce the cost and complexity of implementing learning-by-doing environments. The combined forces of high-powered computing, unparalleled bandwidth, and advances in software architecture are poised to make realistic gaming and simulations more feasible and economical. How should these new tools be used, with whom, and for what?

## Research Challenges in Instructional Design

This roadmap identifies research priorities for designing and evaluating simulations and gaming in instructional environments We need to understand the most effective learning strategy for each subject and each learner and use this information to design the learning experience. We need to understand which variables influence learning: motivation, prior experience, interest. We need to understand how best to use discovery-based learning, games, and other exploration-based learning, as well as the most appropriate roles for teachers, coaches, experts, and other supporters of learning.

### A framework to enable generalization and integration of research results

Today, an instructional designer can use numerous taxonomies and techniques, many of which are labor intensive. We need to develop and validate techniques for cognitive tasks involving higher-order skills and develop methods for analyzing collective or team tasks. This will enable us to establish a common framework in which researchers can conceptualize their studies and understand how individual studies (i.e., the specific variables and context being tested) fit into the larger picture. Then, research results can be better integrated across factors to identify gaps in understanding.

### Tools for determining and assessing learner characteristics

Each learner brings a unique set of knowledge, skills, preferences, and experiences to a task. We need tools that will enable learning systems to specifically account for those unique characteristics in designing and delivering instruction. Individual learners show variables such as: prior knowledge, prior skill, prior experience, misconceptions, and interests. In addition, a number of other personal attributes have been shown to affect learning: motivation, personal agency/self-efficacy, goal orientation, goal commitment, emotional state, self-regulation, misconceptions, interest, and spatial ability.

### Developing practice environments

Current knowledge of how to create effective simulation-based practice environments is not specific enough to provide robust guidelines for designers. The issue extends beyond the design of simulations, to the question of how to structure such environments so that they strongly support learning. For example, researchers now use modeling techniques to insert realistic human actors into simulations. This can heighten the authenticity of the learning experience by allowing trainees to practice higher-order skills with realistic actors. These computer-generated actors can provide a low-cost alternative to more traditional role-playing strategies by reducing the need for human actors. They can also allow team members to practice effectively, even without live teammates. We need automated tools to streamline the development of simulation-based practice environments, which now are largely manual and typically very costly.

**Determining how features of games can be used to improve learning**

Empirical research is required to better understand what features of games can be used to improve learning outcomes, and to develop guidelines based on that research. Which characteristics of games can be applied to improving learning? The answer to this question seems to be that games increase motivation, but it is not entirely clear why. For example, games typically include competition (either against a human opponent or a computer-generated one); they are often story-based, with strong characters, and such games typically "keep score". The research challenge is to determine which, if any, of these features is essential to learning.

## Research Challenges in Instructional Design

| Research Priorities | R&D Outcomes |
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| **Integrative Framework to Facilitate Generalization and Integration of Research Results** | • Automated tools for classifying and identifying task demands, knowledge types and establishing instructional objectives.<br>• Automated tools for cognitive task analysis that link task demands to knowledge types and learning objectives.<br>• Automated team task analysis capabilities that link task demands with knowledge types and learning objectives.<br>• 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.<br>• Open standards software that can be embedded in third party simulations that diagnose and remediate |

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| | across general, spatial, technological parameters.<br>• Automated processes for adjusting the learning environment in accordance with the learner's initial knowledge and experience.<br>• Empirical results of the relationship between goal orientation and aspects of technology-enabled learning systems across multiple subject domains/ skill classes.<br>• 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%.<br>• 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.<br>• Validated modeling strategies for creating simulated teammates and adversaries that produce achievement equivalent to human actors.<br>• Automated coaching strategies that dynamically adjust according to learner achievement and demonstrate time/cost savings and learning ability.<br>• Tools to guide design of computer-assisted collaboration in learning. |
| **Identify Features of Games that Can Be Used to Improve Learning Learning Systems** | • Document features of challenges crucial for motivation and learning: develop guidelines for implementing challenges across task/domain types and learner characteristics.<br>• Guidelines for developing compelling stories for learning: and mechanisms to assess the appropriateness of a story for learning.<br>• Techniques to increase motivation in games across tasks and learners and demonstrate 50% learning increases. |

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| | • Guidelines for developing games that optimize mastery orientation in games: demonstrate optimization that reflects a 50% increase in mastery orientation.<br>• Techniques to increase motivation in games across tasks and learners and demonstrate 50% learning increases. |

## Question Generation and Answering Systems

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 one research study, a typical student asks .17 questions per hour in a conventional classroom and 27 questions per hour in one-on-one human tutoring. In addition to rarely asking questions, many learners do not know how to ask good questions. Students rarely observe good collaborative dialogue because many classroom environments are set up for teacher monologues more than dialogues.

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. We need computer tools that can: 1) answer students' questions whenever they ask them; 2) formulate answers in a fashion that uses the specific pedagogical theory deemed most appropriate for the learner and subject; 3) deliver quick, correct, relevant, and informative answers; and 4) connect learners to teachers, coaches, and experts, as well as to computer-generated answers. As a longer-term goal, the learning system should have even more sophisticated facilities that diagnose student problems and provide help before the question is asked. We need computer facilities 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.

- Teach learners how to ask good questions, by direct instructions on questioning or by a person or computer that models questioning skills.

## Research Challenges in Question Generation and Answering Systems

The Question Generation and Answering Systems roadmap describes five key research priorities for increasing the frequency and quality of questions, as well as methods for delivering answers to learner questions.

### Tools to stimulate learner questions and generate questions that stimulate learning

We need more systematic research on the characteristics of learning environments that trigger particular categories of questions. The relationship between features of different learning environments and the landscape of questions needs to be documented in order to better understand what characteristics of those environments stimulate genuine, information-seeking questions, rather than questions merely to attract attention, monitor conversation flow, or serve social functions.

### Interfaces that make it easy for students to ask questions and to provide guidance on what sorts of questions can be (or should be) asked

Cognitive psychologists have identified conditions in which it is appropriate to present information in single or multiple modalities (text, pictures, sound), to present information contiguously in time and space, and to avoid split attention effects. We need to investigate alternative multimedia designs related to computers asking and answering questions. For example, when is it best to deliver information in printed text versus speech, in language versus highlighted pictures, in static illustrations versus animated simulations, or to summon a human instructor or expert?

### Tools for comprehending and answering learner questions

A significant research program is underway in question answering technology, although most is not focused on use for education. The AQUAINT (Advanced Question and Answering for Intelligence) Program managed by the Advanced Research & Development Activity (*http://www.ic-arda.org/InfoExploit/aquaint/*) has developed an ambitious research roadmap in the area and is actively pursuing the broad range of research challenges identified. The work includes developing technologies and methods for understanding and interpreting complex questions, mining enormous databases to create relevant answers to those questions, and formulating and presenting the answers in terms that are clear to the questioner. The project is pursuing difficult technical issues such as managing dialogues where the questions, and the answers, may include pictures, graphs, videos and other media. Learning research will benefit enormously by closer collaboration with such projects but additional research is needed to apply them to learning environments. Learning systems must pay careful attention to the context of the question and try to develop responses that reflect the recommended pedagogy (it may, for example, be best to answer some questions with other questions). And the impact of the question comprehension and answering facilities on learning gains must be closely evaluated.

### Tools for interpreting learner answers

Learners find it easiest to express themselves when they can combine speech, gesture, and facial expressions. Information from all of these input modes must be interpreted, deeply comprehended, and evaluated pedagogically.

### Tools to advance the discussion and to summon teachers and experts as needed

The question-answering system needs to respond to what the student says and also advance the conversation to meet pedagogical goals. The system should be able to recognize when it has reached its limit, and summon teachers or other experts, as needed. These individuals should be able to understand the context of the question and know relevant details about the student so that their responses can be thoughtful, prompt, and relevant.

## Research Challenges in Question Generation & Answering Systems

| Research Priorities | R&D Outcomes |
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| **Tools to Stimulate Learner Questions and Questions that Stimulate Learning** | • Decision aids for identifying the critical components of learning environments that stimulate question asking.<br>• Published models that predict how varying features in a learning environment change quantity and types of questions.<br>• 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.<br>• Spoken language questions in open domains.<br>• Utilities for annotating images for student use in deictic reference.<br>• Automated markup of large text collections in support of question answering.<br>• 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.<br>• Complex answers compiled, merged, and generated from multiple sources, with confidence level.<br>• Dynamically constructed answer justification.<br>• Learning environments selected and tailored automatically to maximize landscape of important questions.<br>• Electronic information within 2 seconds for all question categories; teacher, coach, or relevant expert response within seconds. |

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| **Tools for Interpreting Learner Answers** | • Software utilities and authoring tools for marking up documents in learning repository and natural language processing components.<br>• Tools for tagging and segmenting content to enable automatic matching of content to pedagogical taxonomies and educational objectives that perform as well as humans.<br>• Tools to support integration of pens, eye-trackers, gesture analysis, etc. and to interpret/evaluate visual and action modalities.<br>• 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.<br>• 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.<br>• Systems that summon teachers or experts, as needed.<br>• Systems with audio and video speech recognition and speech synthesis implemented, plus evaluation experiments to assess effectiveness.<br>• Systems that direct the learner to simulation and visual media when needed, interrupt when needed, etc. |

## Learner Modeling and Assessment for Technology-Enabled Learning Systems

Assessment is critical for managing effective education and training. Assessments that provide a rich measure of an individual's or group's knowledge and expertise provide information for teachers, help learners recognize their own level of mastery, and create a rich record than can help future teachers and employers. Continuous assessment provides insights that are key for guiding the direction of instruction and providing optimal feedback, guidance, and learning resources tailored to the specific, immediate needs of individual learners. Ideally, every educational decision-maker, from teacher to human resource director, would have access to real-time valid data just in time to make a decision about an individual, group, or program. Better yet, the system that collects and analyzes the data would itself be smart enough to make the decision, and the system would over time improve its ability to make the best decisions.

## Research Challenges in Learner Modeling and Assessment

This roadmap identifies five R&D priorities that will allow us to 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 will significantly increase the validity, efficiency, utility, effectiveness, and widespread use of learner modeling and technology-enabled assessment.

### Establish models of content expertise, competency, and pedagogy

We need to map and integrate existing content, competency, and pedagogical models into an agreed-upon framework that can standardize and automate task analysis, assessment design, and use. As a first step, we need to specify the skills, knowledge and abilities to be measured. This requires breaking down the content/job/performance domain into its fundamental knowledge and skill components. The more fine-grained the breakout of skill components, the better we can test particular sub-skills, and the more specific the diagnosis of knowledge gaps. This will lead to greater validity and effectiveness of the assessment and learning.

### Automated modular assessment design, development, delivery, and analysis

A modular design for assessment "objects" is needed to simplify development, delivery and analysis. The learning object strategy separates the content of instruction from its presentation/delivery and specifies one or more standard stand-alone units of instruction (the learning objects) and their modular content elements. Assessment "objects" need to be reusable, accessible via search mechanisms, and capable of dynamic assembly like "learning objects" in many current learning systems. Tools are needed to manage object-based strategy for assessment will be more complicated than for learning content. An assessment object-based strategy must specify the reusable components of multiple assessment task types and multiple response types. In addition, it must also include reusable mechanisms for scoring and combining evidence from multiple sources to generate probabilistic inferences about mastery of particular objectives or competencies.

### Multidimensional learner models and measurement methods

In online learning systems, the information in the learner model is usually at a very gross level, representing whatever the system recognizes as “assignable units” or learning objects. We need to add other layers of granularity and dimensionality to the competency data in learner models in online learning systems to more precisely diagnose knowledge gaps and to adapt the instruction continuously.

### Reporting and use of assessment and learner modeling data

Feedback and guidance are essential components of a learning environment. They point out performance errors, correct them, and allow the learner to proceed to mastery. There are many dimensions of feedback and guidance that can be varied: timing, content, amount, specificity, medium, and control. Once we have established rules for feedback decisions, we need software that allows an author to specify rules for triggering particular types of feedback. Authoring software is needed to facilitate entry of feedback segments that can be intelligently, dynamically pieced together, or presented in a variety of media, for example, text, or spoken by a character.

### Web services infrastructure for integration of software applications and services

We need to develop a larger infrastructure to integrate various authoring tools, analysis and reporting services, and decision aids. This would enable a scenario, for example, in which an author would create tasks in one application that could be delivered as part of an online assessment or learning experience. In both cases, the response data would be sent to another service for analysis; the resulting diagnosis could be sent to a reporting service or back to the learning environment to trigger feedback or the next piece of content to be presented. Work in this area will involve close collaboration with standards groups.

## Research Challenges in Learning Modeling and Assessment

| Research Priorities | R&D Outcomes |
|---|---|
| **Establish Models of Content Expertise, Competency, and Pedagogy** | • Map content/competency models and agree on a shared core model and terms.<br>• Map pedagogical models and agree on a meta model and terms.<br>• 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** | • A 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.<br>• Authoring tools to automate creation, storage, and assembly of components.<br>• Tools and mechanisms for scoring and aggregating data from multiple sources.<br>• 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.<br>• Tools to support insertion of monitoring capabilities into multiple learning systems.<br>• Tools to specify analysis and actions based on particular levels of mastery and motivation.<br>• Decision-aids for choosing different types of measurements and level of detail based on context, budget and purpose. |

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| **Tools for Reporting and Use of Assessment and Learner Modeling Data** | • Decision-aids/rules for personalizing feedback, and guidance and personalization of content.<br>• Authoring tools for specifying rules and triggering feedback customized to individual needs.<br>• Authoring tools that enable dynamic assembly of feedback segments and support a variety of feedback media, including text and spoken language.<br>• Real-time generation of reports from multiple databases.<br>• 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.<br>• Prototypes to validate integration of component services (authoring, scoring, analysis, maintenance of learner models; reporting) ready for integration.<br>• Validate integration of component services.<br>• APIs for integration with other e-business services. |

## Building Simulations and Exploration Environments for Technology-Enabled Learning Systems

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, assignments with clear goals, or challenges. If they're well designed, such environments will motivate learners to meet the goal, sustaining their eagerness to build the needed skills. The question is how to use simulations and synthetic environments to improve learning outcomes, while making them easier to build and incorporate into learning environments.

**Research Challenges in Building Simulations and Exploration Environments**

This roadmap identifies four key research topics that collectively should enable simulations and synthetic environments to improve learning outcomes. Building complex virtual environments that permit exploration-based pedagogy requires an unprecedented investment for building an effective community from the numerous groups of people that must contribute to developing these tools.

### Interoperability

Interoperability is the ability of various simulation systems to work with each other in a coherent fashion. Effective combination and reuse of software objects require precise agreement on the coordinate systems and methods for representing complex geometric objects, the system of units employed, and the exact terminology used to describe objects (or ontology). Simulations show motion and interaction and thus require a precise taxonomy of verbs—that is, rates of change and flows of charge, chemicals, and bulk materials. They must also show changes in shape and even basic topology of objects.

### Reuse, updating, and maintenance of simulations

A lightweight management structure can establish and enforce a set of simple rules, oversee final decisions about which objects offered meet the required standards, and maintain an index of components built to the agreed rules. Open source communities provide one such model for building a community of developers capable of providing the advanced simulation tools needed for science and engineering education.

### Navigation of exploration environments

In order to develop orientation skills and situational awareness in a synthetic environment, users need a high level of fidelity to be able to navigate through the virtual space as if it were real. This fidelity requirement poses a number of hardware and software challenges, most of which are far from being solved—including realistic avatars, viewing, sound, movement, touch, and sensory integration.

### Adapting simulation and exploration environments to learning environments

Simulations and virtual environments have to be smoothly integrated into education and training so that they enable, rather than encumber, learning. Future research should explore the nature and degree of support tools necessary for using simulations well in learning environments. In developing thinking skills such as scientific inquiry, simulations and exploration environments may need to be combined with other learner-support mechanisms, such as hints on how to design an experiment.

## Research Challenges in Simulations and Exploration Environments

| Research Priorities | 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.<br>• Common underlying architecture for maintaining information about the state of the environment related to a particular simulator.<br>• Adoption of unified ontology by communities of simulation developers.<br>• Development of a STEP-like 3D modeling environment that can be used for modeling dynamic interactions and organic shapes. |
| **Reuse, Updating, and Maintenance of Components** | • Established procedures for peer review and validation of results against experiments.<br>• Easy, valid methods for tracking of the provenience of data and methods and identification of authors.<br>• Procedures for bug reports and reliable version control.<br>• Standards for the “metadata” used to identify the data and software.<br>• 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.<br>• Techniques to navigate simulations and visualizations at different levels of detail.<br>• Feature-based navigation and scene management.<br>• Simulations of a full range of instruments that are interoperable with synthetic environments.<br>• Noninvasive and accurate tracking that sense and react to the user and the user's environment.<br>• Avatars that allow merging of motion capture and diagnostic imaging modalities to completely describe human movement.<br>• Complex force feedback (haptics) displays that run on the desktop. |
| **Adapting Simulations and Exploration Environments into Learning Environments** | • Model scalability for use at many levels of resolution and complexity.<br>• Virtual game worlds composed of customizable synthetic environments.<br>• Multi-player, multi-educational resources available anywhere, anytime through any internet-connectable interface.<br>• Predictive computer-based modeling and simulation that can substitute for many aspects of physical testing and experimentation. |

# Integration Tools for Building and Maintaining Advanced Learning Systems

As we have built specifications and standards to support web-based system-directed learning systems, the means for creating interoperable and robust instructional content have emerged. But current specifications have defined a technically complex infrastructure that is unfriendly to instructional designers. This roadmap identifies the development and integration tools to bridge the gap between the complexity of web-based learning systems and the instructional design community.

## Research Challenges in Integration Tools

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.

Tools that are intuitive, non-technical to the user, and robust will require research, experimentation, and time to develop. If the underlying infrastructure continues to change very rapidly, tools evolution will continue to be modest. Stabilization of underlying infrastructure standards will be key to developing next-generation learning tools, even though (some argue) locking into technical standards too early may stifle innovation. While standards can be confining, few could argue the success of the Internet and the World Wide Web, which exist precisely because of open standards. Broad public access to learning content requires an infrastructure that interoperates. We need a common infrastructure in order to produce deliverable advanced capabilities.

Another challenge is striking the balance between ease of use and robustness. It may continue true that the most effective learning environments are the most difficult and expensive to develop, and therefore of limited use. It may also turn out that search based "just in time" instructional material that is very simple to construct, store, find, and deliver becomes the mainstay of distributed learning.

The research identified in this roadmap will address both possibilities. The roadmap requires that we examine existing and emerging interchange protocols, formats and services that relate to the entire process of content development through to deployment.

Interfaces to other services such as authentication, learner profiles, and assessment, need to be identified and rationalized. We need experiments that demonstrate the interoperation of different levels of development.

### Course building tools

Little work has been done from the perspective of instructional design, to understand the flow and interchange requirements. As a result, today courses of instruction must be essentially hand-crafted and then packaged and exported to larger delivery systems. The cycle of build-test-modify-repeat is cumbersome, complex, costly and off-putting to developers. It stifles innovation in content that might otherwise occur. Tools are required at a variety of abstraction levels yet must seamlessly exchange information, structure, logic, content, and rules during the development process. A defined environment is needed that allows content to be developed and tested with few intermediate steps.

### Shareable content objects to simplify use

Content development is the deliberate process of creating and organizing a variety of digital assets such as text, graphics, pictures, illustrations, etc., into a form that can be electronically delivered to a learner. Content objects vary in size and complexity, but often address a single idea, subject, or learning objective. Over the years, content-writing tools have been created by software engineers who are familiar with the underlying interactive media capabilities of computers. Understandably, many of these engineers know little about instructional design strategies, terminology, or models. As a result, their tools tend be complex and "techie." If tools can be made that are simple and easy to use by non-technical authors, more people who understand learning and instruction can contribute to a growing body of sharable content objects. Development costs will reduce, and quality will increase as communities of practice develop.

### Tools and services to assist developers in the application of metadata

Standards for learning object metadata now exist, but few tools or practices have been developed. Current metadata standards do not address how and when metadata should be applied or used. Most tools are cumbersome and time-consuming, and few search engines use learning object metadata effectively. Tools and services are required to assist developers in applying metadata at all levels of content development. These tools need to be customized to meet the needs of various communities of practice. A special area of required research would develop tools and/or agents that can perform intelligent searches of metadata during authoring, and eventually in real time, for “on the fly” content aggregation.

**Tools for collaborative building and maintenance of learning environments**
Technology based learning design communities have recently embraced the idea that instructional content can and should be developed as potentially reusable and interoperable objects. These objects then need to be organized into contextually relevant groups for delivery to the learner. Tools that can import content objects and provide scaffolding for related activities such as assessment, instruction, or problem solving have been developed only recently, and are still in a relatively primitive state in part because the underlying technology standards for content objects are fairly new, and because the process of creating instruction through the aggregation of content objects is somewhat new to instructional designers. A new class of tools is needed that can ease the search and importing of content objects, determine delivery ordering and scaffolding, and permit the application of sequencing rules that are part of a particular instructional strategy.

## Research Challenges in Integration Tools

| Research Priorities | R&D Outcomes |
|---|---|
| **Course Building Tools** | • Extensible model for how tools and services might interconnect and self-discover.<br>• Enabling Formats and Standards. |
| **Shareable Content Objects to Simplify Use** | • Content creation tools designed for instructional designers that hide technical implementation.<br>• Tools that seamlessly integrate varied content types for non-technical authors.<br>• Seamless search and access to digital assets.<br>• Tools that support merging content formats including: static, interactive, stream-based, and active; and examine the authoring, integration and deployment issues.<br>• Integration tools for combining disparate media types. |
| **Tools and Services to** | • Implementation guidelines for developers in different domains. |

| | |
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| **Assist in Application of Metadata** | • Tools to map semi-automatically across domains and determine impact on content developers.<br>• Tools to automate the application of metadata to all levels of content, perhaps through intelligent analysis by agents.<br>• 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.<br>• Rules-based sequencing approaches capabilities for non-technical designers.<br>• 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.).<br>• Search strategies to enable "real time" assembly of content based on learner profiles, mastery, subject, etc. |

# Creating an Effective Management Structure to Implement the R&D Roadmap

The R&D Roadmap identifies critical, long-term technical issues that need to be addressed if we are to realize the potential for technology to transform the way we learn. This potential cannot be fully exploited without significant, sustained basic and applied research in learning science and technology.

Current R&D funding levels are grossly inadequate. R&D efforts are fragmented and often discontinuous. There is no established community of researchers, industrial participants, educators, and educational institutions from which to mobilize teams that span technology and learning to develop, evaluate, and distribute tools. Large-scale, sustained efforts are required. We must involve multiple disciplines in both academia and industry including education, psychology, cognitive science, communication, human-computer interaction, software engineering and design, information science, computational linguistics, statistics, social scientists, and subject-matter experts.

This management plan describes the critical characteristics of a management structure that can execute the technical research plan this Roadmap proposes. The scale and scope of the research identified in this Roadmap is unprecedented in education. It will require a new partnership melding the talents and resources of government, industry, and private foundations.

This new partnership will not replace current learning science and technology R&D programs. Indeed, existing programs have contributed significantly to producing the research results that provide solid evidence that progress is possible. But a new R&D program is essential to enable large-scale, focused, sustained efforts that are not supported by existing programs. A new research management approach is essential to build the needed research teams, focus the research, and guide research by identifying where intellectual effort is most likely to bear fruit. This management approach should complement the current learning science and technology R&D programs to ensure that more applied research and larger-scale demonstration projects are supported. These efforts are critical to create a range of interoperable, well-performing and extensible software tools that can lower the cost of entry for educational materials and systems. This will enable economies of scale and scope and make possible widespread, routine use of advanced learning systems.

## Management Structure Requirements

It is essential that the research be well managed. An effective management structure can: ensure critical research challenges are addressed; maintain proper balance across research priorities; form research teams; ensure proper linkage of program components; track progress towards goals; and ensure dissemination of results. An effective management structure should:

- Support a broad portfolio of research ranging from basic research to demonstrated tools and systems.
- Provide mechanisms for combining government and corporate research funds.
- Produce continuous feedback from institutions attempting to use the developed tools in practical environments.
- Help create interdisciplinary R&D teams.
- Facilitate close collaboration among business, academic, and government research, development, and demonstration teams.
- Fund and manage projects that involve significant numbers of people working together for multiple years.
- Assess progress, and when necessary eliminate failing projects and approaches.
- Permit contractual flexibility allowing fast response, and timely use of talent wherever it is found (e.g. university, corporate, and non-governmental organizations).
- Support international collaboration where appropriate.
- Disseminate research that private firms can convert into practical products.
- Attract and foster creative research managers respected by the research community. Know, and take advantage of, the results of other information technology R&D efforts and ensure LS&T requirements are articulated to the broader IT community.

# Current Management Models

Federal R&D funding is allocated using many mechanisms under diverse authorities. Each approach stems from specific agency needs and the historical era when programs began. Research funding mechanisms include:

- Direct federal management of research (e.g. the NASA manned space program or the National Institute of Standards and Technology).

- Government Owned and Government Operated (GOGOs) and Government Owned and Corporate Operated (GOCOs) laboratories such as the Department of Energy's national Laboratories, Federally Funded Research and Development Centers (FFRDCs) such as MITRE and the Institute for Defense Analysis, and other laboratories. Altogether there are more than 700 such facilities employing more than 100,000 scientists.[2] The organizations typically conduct most of their work in their own facilities, but can also manage external contract with university or corporate research organizations, or arrange for Cooperative R&D Agreements (CRADA) in which government and private research organizations agree to collaborate without direct transfer of funds.

- Competitively funded, investigator-initiated, peer-reviewed grants to universities, businesses, and consortia funded through organizations such as NSF, and much of NIH. These programs can also fund multi-year, multi-participant research partnerships such as the Semiconductor Research Corporation, the NSF Research Centers, and the planned NSF Science of Learning Centers.[3]

- DARPA's traditional approach of giving an ambitious research challenge and significant resources to a single program manager with great flexibility about how to manage the research. (In recent years DARPA has focused much more heavily on delivering practical products that can yield measurable military significance within 3 years.)

- Directed set-asides for small businesses through the Small Business Innovation Research (SBIR) program.

## Research Management Needs

The research management needs identified in the Learning Federation research plan are in many ways analogous to the modern requirements of military research and development. The Department of Defense (DoD) has recognized that its research is often most effective when it's directed in ways that help private firms develop innovative new products that will ultimately be purchased by the DoD. A generation ago, this process proceeded under the premise that DoD would (a) be the first customer and (b) be able to purchase enough of the product to justify the private firm's production. In the past decade, this assumption can no longer be made since state-of-the-art products from DoD research often find their way into commercial products. Examples include the development of new materials and computer chips used in video games before they are used for defense purposes. Large as they are, DoD markets for new technologies are simply not big enough to justify initial production and marketing investments. As a result, DoD research has shifted dramatically to support rapid technical advances in areas where rapid commercial innovation will yield products directly relevant to DoD needs.

The research management strategy for executing the Roadmap should draw on the best features of DoD, particularly DARPA, and NSF R&D programs, and should incorporate the following features:

- R&D managed in accordance with a clearly defined roadmap that identifies goals and priorities for achieving them and that is regularly updated after consulting with experts in business, universities, and government.
- A strong team of program managers with a very small staff, each assigned a major component of the roadmap.
- Flexibility in research management (e.g. "other transactions authority") allowing fast response to new opportunities and an ability to draw on expertise wherever iit may be found.
- Flexibility to establish new research centers, including corporate and university partnerships, that can focus efforts on a task for at least three to five years.
- The ability to establish a captive research center (analogous to work conducted on the NIH campus) if, and only if, the oversight board is convinced that such a capability is needed.

It will not be easy to devise a system capable of meeting these goals in ways that meet the needs of business and government investors alike. But it is necessary, given the enormous public skepticism about the utility of more investment in learning research. In the federal government, the creative, high-risk management style of the DARPA probably most closely resembles the style of operation needed to successfully manage the research identified in the Roadmap.

## Models for Public Support

First, can these programs be managed best as an extension of an existing agency or should a new organization be formed? As in the case of federal research management, there are many models for public support to choose among. None of the major agencies appears well suited to the task of managing the work described earlier. Research organizations such as NSF are not organized for such operational missions, although NSF does have a small program that funds IMAX movies, science museum projects, and other nontraditional educational materials, and NSF has supported on a limited basis development of instructional technology. The Department of Education started several software development programs during the 1990s, but almost all have been eliminated and replaced with block grants to states.

If a new organization is contemplated, there are many options to consider. The federal government has approximately 100 "independent agencies" including the Corporation for Public Broadcasting, the National Foundation on the Arts and the Humanities, the Smithsonian Institution, and the National Commission on Libraries and Information Science.

The proposed **Digital Opportunity Investment Trust (DO IT)** offers by far the most promising, thoughtful model for managing the research identified in the Roadmap. The management structure should provide ultimate accountability to the Congress, but also ensure that the management enjoys the stability and independence from political interference needed to ensure the highest-quality product. The NSF provides a widely acceptable model for meeting this goal. Its Director is appointed to a six-year term and reports to a strong, independent board. This model was also used in the newly authorized Office of Innovation and Improvement in the US Department of Education. DO IT's proposed structure and governance reflect these criteria.

## Recommended Funding

Current funding comes from several different agencies and is often fragmented and discontinuous. Most of the current research in post-secondary education and training is funded on such a small scale that real innovations cannot be developed or tested. Market realities have forced firms producing learning products to concentrate on near-term product development. They have been unable to undertake the basic research and development necessary to explore bold new approaches.

A number of recent studies have examined the opportunities presented by new learning technologies and concluded that additional funding is needed, and that a new way to manage the efforts are needed to capture the opportunity. These include:

- President's Committee of Advisors on Science and Technology (PCAST), *Report to the President on Educational Technology* (1997).

- The Web-based Commission, *The Power of the Internet for Learning* (2001).

- Dept. of Education, *eLearning: Putting a World-Class Education at the Fingertips of All Children* (2000).

- President's Information Technology Advisory Committee, *Using Information Technology to Transform the Way We Learn* (2001).

- CEO Forum, *Key Building Blocks for Student Achievement in the 21st Century (2003).*

The President's Committee of Advisors on Science and Technology (PCAST) argued for more federally funded research and recommended that "after a brief transitional period involving substantial yearly increases, a steady-state allocation of no less than 0.5 percent of our nation's aggregate K-12 educational spending (or approximately $1.5 billion per year at present expenditure levels) be made." The PCAST noted "In 1995 the U.S. spent about $70 billion on prescription and nonprescription medications, and invested about 23% of this amount on drug development and testing. By way of contrast, our nation spent about $300 billion on public K-12 education in 1995, but invested less than 0.1% of that amount to determine what educational techniques actually work, and to find ways to improve them."[4]

The President's Information Technology Advisory Panel (PITAC), in its February 2001 report to President Bush, re-iterated the PCAST's recommendation and called for partnerships with industry and private foundations to co-fund an aggressive information technology R&D initiative. The PITAC urged for a “meaningful investment increase, capable of generating the quantum leap forward that is needed, and our realistic assessment of the Nation’s ability to appropriately identify, qualify, staff, and manage the research projects.” The PITAC recommended that federal investments ramp up rapidly to $400 million per year with an expectation of equal funding from other sources, for a total of $800 million. The Committee recommended partnerships to manage effectively and efficiently as much as $200 million per year including matching funds.[5]

We recommend an R&D funding level within DO IT of $225 million. This amount represents funding for new or expanded activities that reflect the urgency, breadth, collaboration, and scale of needed research. The amount available for research would be less than the $1.5 billion recommended by PCAST and less than the $800 million recommended by PITAC. But it would take a major step forward in the research investment urgently needed to apply learning science and technology effectively to education, training, and lifelong learning for the 21st century.

A variety of modes of research should be supported: single investigator, multi-investigator grants, as well as small and large centers. Large-scale, sustained efforts, that may last five or more years are required. Research efforts should involve multiple disciplines and draw on expertise from academia, industry, and government laboratories. Efforts that cost several million dollars per year should not be unusual. Projects should focus on non-incremental, high-risk, high-potential projects spanning theory, experiment, and application. The research should not undertake generic information technology R&D such as Internet security or higher-resolution displays, but should leverage and inform these investments.

Conventional, peer-reviewed university research in learning should clearly continue, but a new approach is urgently needed to capture the opportunity. Given the demonstrated difficulty of funding a diffuse research program in learning, the new management approach should err in the direction of a focus on building workable tools—a process that can lead to a highly practical (and often very basic) research agenda.

## Evaluating Progress

The ultimate goal of the R&D described here is improved learning outcomes. Objective goals include faster learning speed and greater retention, without unacceptable increases in costs, and lowering the standard deviation of outcomes. Each component roadmap defines a chronology of R&D, with milestones for years Three, Five, and Ten, and recommended measures for evaluating progress. On a broader scale, proposed metrics include:

- Recognized learning improvements.
    - Increase learning speed by 30 – 50%
    - Heighten transferability of training to practical experience by 30%-50%
    - Improve retention of knowledge and skills
    - Raise performance equivalent to an improvement of 1-1.5 letter grades
- Retention of diverse populations at all levels of education and training and in all disciplines.
- High level of technology-enabled tools in use among teachers and specialists.
- Greater ease for teachers and specialists in building new instructional systems in a variety of subjects that support the full range of students.
- Certification and accreditation of the learning systems to science, technology, engineering, mathematics, humanities, and other learning needs (basic mathematics and sciences as well as other disciplines; training for specific competencies in certification skills).
- Cost-effectiveness.

# Conclusion

Throughout a person's life, corporate and personal success depends as never before on the quality of education that's available. The basic skills the modern workplace requires have risen dramatically for workers of all ages. To excel, employees must be able to think and read critically, express themselves clearly and persuasively, and solve complex problems. Explosive growth in information and knowledge makes it impossible for education and training programs to fully explore even a single topic. To assimilate this explosion of information, all our citizens need new intellectual tools and learning strategies to think productively about science and technology, mathematics, history, social phenomena, and the arts. Providing these intellectual tools and learning strategies will require re-thinking how we teach and learn. We must make learning more productive and more engaging, and we need strategies to vastly increase access to high quality education and training to ensure that all citizens can participate. The only affordable way to accomplish this is to exploit emerging technologies to implement the recommendations of cognitive scientists to guide and enhance learning. The Roadmap in this report suggests a practical way to accomplish this transformation of learning.

We have a great deal of work to do, but the opportunity to make making learning more productive and more engaging for all people is simply too important for us to ignore. In a world economy that demands and rewards the best-educated citizenry, the United States needs to keep pace. It is difficult to imagine any innovation since the land-grant college legislation of the l9th century that could more positively affect our nation's long-term prosperity. We urge the Congress to seize this practical opportunity , offered by the establishment of the Digital Opportunity Investment Trust, to ensure that the benefits of a technologically sophisticated society are broadly shared.

# End Notes

[1] Benjamin S. Bloom, "The 2 Sigma Problem: The Search For Methods of Group Instruction as Effective as One-to-One Tutoring," *Educational Researcher* vol 13: no. 6, June-July 1984

[2] C. Dan Brand, Chair, Federal Laboratory Consortium (FLC), "Leveraging our Federal Research and Development (R&D) Investment Through Technology

Transfer," *Testimony before Committee on Commerce, Science and Transportation, Subcommittee on Science, Technology and Space*, U.S. Senate, April 15, 1999

[3] For a recent review of research partnerships see Charles W. Wessner, Editor, *Government-Industry Partnerships for the Development of New Technology*, National Research Council, 2003

[4] *Report to the President on the Use of Technology to Strengthen K-12 Education in the United States*, President's Committee of Advisors, on Science and Technology, Panel on Educational Technology, March 1997

[5] President's Information Technology Advisory Committee, "Using Information Technology to Transform the Way We Learn," *Report to President G.W. Bush*, February 2001

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Lisa Ferro, MITRE
Warren Greiff, MITRE
Art Graesser, University of Memphis
Max Louwerse, University of Memphis

**Learner Modeling and Assessment Workshop Co-Chairs:**

Eva Baker, UCLA
Randy Bennett, Educational Testing Service
Ralph Chatham, DARPA
Randy Hinrichs, Microsoft

**Instructional Design Workshop Co-Chairs:**

John Bransford, Vanderbilt University Peg Maddox, CISCO

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Gerry Higgins, SimQuest, LLC Andries van Dam, Brown University

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***The Learning Federation***
Federation of American Scientists
1717 K St. NW Suite 209
Washington, DC 20036
T (202) 454-4685
F (202) 675-1010
www.thelearningfederation.org
khowell@fas.org.