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Lifelong Learning — More Than Training

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Abstract

Wisdom is not a product of schooling, but the lifelong attempt to acquire it." — Einstein

Learning can no longer be dichotomized into a place and time to acquire knowledge (school) and a place and time to *apply* knowledge (the workplace). Today's citizens are flooded with more information than they can handle, and tomorrow's workers will need to know far more than any individual can retain.

Lifelong learning is an essential challenge for inventing the future of our societies; it is a necessity rather than a possibility or a luxury to be considered. Lifelong learning is more than adult education and/or training — it is a mindset and a habit for people to acquire. Lifelong learning creates the challenge to understand, explore, and support new essential dimensions of learning such as: (1) self-directed learning, (2) learning on demand, (3) collaborative learning, and (4) organizational learning. These approaches need new media and innovative technologies to be adequately supported.

A theory of lifelong learning must investigate new frameworks to learning required by the profound and accelerating changes in the nature of work and education. These changes include (1) an increasing prevalence of "high-technology" jobs requiring support for learning on demand because coverage of all concepts is impossible; (2) the inevitability of change in the course of a professional lifetime, which necessitates lifelong learning; and (3) the deepening (and disquieting) division between the opportunities offered to the educated and to the uneducated.

This paper explores conceptual frameworks and innovative computational environments to support lifelong learning and it analyzes why training approaches need to be transcended and how this can be done.

1. Introduction

Learning needs to be examined across the lifespan because previous notions of a divided lifetime—education followed by work—are no longer tenable [Gardner, 1991]. Professional activity has become so knowledge-intensive and fluid in content that learning has become an integral and irremovable part of adult work activities. Learning is a new form of labor [Zuboff, 1988], and working is often (and needs to be) a collaborative effort among colleagues and peers. In the emerging knowledge society, an educated person will be someone who is willing to consider learning as a lifelong process. More and more knowledge, especially advanced knowledge, is acquired well past the age of formal schooling, and in many situations through educational processes that do not center on the traditional school [Illich, 1971].

Information overload, the advent of high-functionality systems, and a climate of rapid technological change have created new problems and challenges for education and training. New instructional approaches are needed to circumvent the difficult problems of *coverage* (i.e., trying to teach people everything that they may need to know in the future) and *obsolescence* (i.e., trying to predict what specific knowledge someone will need or not need in the future). Learning should be part of living, a natural consequence of being alive and in touch with the world, and not a process separate from the rest of life [Rogoff & Lave, 1984]. What learners need, therefore, is not only instruction but *access* to the world (in order to connect the knowledge in their head with the knowledge in the world [Norman, 1993]) and a chance to play a meaningful part in it. Education should be a distributed lifelong process by which one learns material as one needs it. School learning and workplace learning need to be integrated.

In training, learning is often restricted to the solution of well-defined problems. Lifelong learning includes training approaches and also transcends them by supporting learning in the context of realistic, open-ended, ill-defined problems. In our environments, learners explore information spaces relevant to a *self-chosen* task at hand; for example: learning on demand provides learner-centered alternatives to teacher-centered tutoring systems, and it augments open-ended, unsupported learning environments by providing advice, assistance, and guidance if needed in breakdown situations.

In this paper I first characterize problems facing workers and learners in the information society. I characterize and differentiate training and lifelong learning approaches. In the remaining part of the paper I focus on lifelong learning by first describing requirements and different approaches to it. Some examples of our work will be used to illustrate innovative systems supporting lifelong learning. I conclude by assessing these approaches and their systems and tools identifying their strengths and weaknesses.

2. Problems in the Information Age

Lack of creativity and innovation. Societies and countries of the future will be successful not "because their people work harder, but because they work smarter". Creativity and innovation are considered essential capabilities for working smarter in knowledge societies [Drucker, 1994]; thus an important challenge is how these capabilities can be learned and practiced. An implicit assumption made is that self-directed and lifelong learning can influence the creativity and innovation potential of individuals, groups, organizations, and countries.

Coping with change. Most people see schooling as a period of their lives that prepares them for work in a profession or for a change of career. This view has not enabled people to cope well with the following situations: (1) most people change careers 3-4 times in their lives even though what they learned in school was designed to prepare them for their first career; (2) the pace of change is so fast that technologies and skills to use them become obsolete within 5-10 years; (3) university graduates are not well prepared for work; (4) companies have trouble institutionalizing what has been learned (e.g., in the form of organizational memories) so that the departure of particular employees does not disable the companies' capabilities; and (5) although employers and workers alike realize that they must learn new things, they often don't feel they have the time to do so.

Information is not a scarce resource. "Dumping" even more decontextualized information on people is not a step forward in a world where most of us already suffer from too much information. Instead, technology should provide ways to "say the 'right' thing at the 'right' time in the 'right' way." Information consumes human attention, so a wealth of information creates a poverty of human attention.

"Ease of use" is not the greatest challenge or the most desirable goal for new technologies. Usable technologies that are not useful for the needs and concerns of people are of no value. Rather than assuming people should and will be able to do everything without a substantial learning effort, we should design computational environments that provide a low threshold for getting started and a high ceiling to allow skilled users to do the things they want to do.

Computers by themselves will not change education. There is no empirical evidence for this assumption based on the last 30 years of using computers to change education (such as computer-assisted instruction, computer-based training, or intelligent tutoring systems). Technology is no "Deus ex machina" taking care of education. Instructionist approaches are not changed by the fact that information is disseminated by an intelligent tutoring system. The content, value, and quality of information and knowledge are not improved just because information is offered in multimedia or over the WWW. Media itself does not turn irrelevant or erroneous information into more relevant information.

The single or most important objective of computational media is not reducing the cost of education. Although we should not ignore any opportunity to use technology to lessen the cost of education, we should not lose sight of an objective that is of equal if not greater importance: increasing the *quality* of education.

The 'super-couch potato' consumers should not be the targets for the educated and informed citizens of the future. The major innovation that many powerful interest groups push with the information superhighway is to have a future in which people show their creativity and engagement by selecting one of at least 500 TV channels with a remote control. The major technical challenge derived from this perspective becomes the design of a "user-friendly" remote control. Rather than serving as the "reproductive organ of a consumer society" [Illich, 1971], educational institutions must fight this trend by cultivating "designers," that is by creating mindsets and habits that help people become empowered and willing to actively contribute to the design of their lives and communities [Fischer, 1998a].

School-to-work transition is insufficiently supported. If the world of working and living (1) relies on collaboration, creativity, definition, and framing of problems; (2) deals with uncertainty, change, and distributed cognition; and (3) augments and empowers humans with powerful technological tools, then the world of schools and universities needs to prepare students to function in this world. Industrial-age models of education and work are inadequate to prepare students to compete in the knowledge-based workplace. A major objective of a lifelong learning approach is to reduce the gap between school and workplace learning.

The "Gift Wrapping" approach dominates educational reform. Information technologies have been used to mechanize old ways of doing business [Landauer, 1995] — rather than fundamentally rethinking the underlying work processes and promoting new ways to create artifacts and knowledge. In learning, these technologies have been used primarily as add-ons to existing practices [Fischer, 1998c] rather than a catalyst for fundamentally rethinking what education should be about in the next century. Frameworks, such as instructionism, fixed and "balkanized" curricula, memorization, decontextualized rote learning, etc., are not changed by technology itself. We cannot prepare people to live in a twenty-first century world using nineteenth century technology.

Quality employment. The current dislocation problem experienced by workers [Rifkin, 1995] is one example of an increasingly societal trend. Workers in the growing service and information sector will face an accelerating rate of change in the knowledge and skills necessary to stay competitive. Traditional paradigms of education and training will not, in themselves, be sufficient to meet this increasingly important need. Additional infrastructure must be developed that allows people to learn on the job, and knowledgeable experts to communicate and extend their knowledge within and across domains.

3. Training and Lifelong Learning

Lifelong learning is more than training or continuing education. It must support multiple learning opportunities including exploring conceptual understanding as well as narrowing to practical application of knowledge, ranging over different settings such as academic education, informal lifelong learning, and professional and industrial training. Figure 1 summarizes the different emphases of training and lifelong learning along a number of dimensions.

	Emphasis on training	Emphasis on lifelong learning
perceived role of new media	economical , productivity	quality
epistemologies of knowledge	explicate and transfer existing knowledge	understand existing knowledge and create new knowledge
new media	learn about computers	learn with computers
impact of new media	make delivery method more efficient	allow new things to be learnt
teaching	add-on to current teaching methods	change what we teach and how we teach
assessments	number of facts known	articulating knowledge, reflective practitioner
mindset	passive consumer	active designer, co-developer
setting	schools, separate, formal, forced	workplace, families, museums; integrated, informal, discretionary
new knowledge	assigned-to-learn, decontextualized,	need-to-know, on demand, contextualized
learning	rote learning	learning with understanding

Figure 1: Emphasis on Training versus Emphasis on Lifelong Learning

3.1. Training

Learning new skills and acquiring new knowledge cannot be restricted to formal educational settings. Effective learning needs to be integrated into the work process. Current teaching programs train people to use what is effectively a snapshot of an evolving technology. Training is often considered as a variable plugged into an economic model. This short-sighted cycle of training and retraining cannot be broken unless we recognize that learning is a lifelong process that cannot be separated from working [Sachs, 1995].

By *integrating working and learning*, people learn within the context of their work on real-world problems. Learning does not take place in a separate phase and in a separate place, but is integrated into the work process. People construct solutions to their own problems, and the system advises them when they are getting into trouble and provides directly relevant information. The direct usefulness of new knowledge for actual problem situations greatly improves the motivation to learn the new material because the time and effort invested in learning are immediately worthwhile for the task at hand — not merely for some putative long-term gain.

Many conventional frameworks of training (programmed instruction, computer-based training) and working (a best scientific way) are grounded in the behaviorist learning theory of B.F. Skinner and the models of industrial work of F.W. Taylor. Figure 2 contrasts these approaches with the lifelong and self-directed approaches to learning.

Skinner/Taylor		Beyond Skinner and Taylor
there is a "scientific," best way to learn and to work (programmed instruction, computer-assisted instruction, production lines, waterfall models)	--->	real problems are ill-defined and wicked; design is argumentative, characterized by a symmetry of ignorance among stakeholders
separation of thinking, doing, and learning	--->	integration of thinking, doing, and learning
task domains can be completely understood	--->	understanding is partial; coverage is impossible
objective ways to decompose problems into standardizable actions	--->	subjective, situated personal interests; need for iterative explorations
all relevant knowledge can be explicitly articulated	--->	much knowledge is tacit and relies on tacit skills
teacher / manager as oracle	--->	teacher / manager as facilitator or coach
operational environment: mass markets, simple products and processes, slow change, certainty	--->	customer orientation, complex products and processes, rapid and substantial change, uncertainty and conflicts

Figure 2: Transcending Skinner and Taylor

3.2. Lifelong Learning

Lifelong learning needs to promote effective educational opportunities in the many learning settings through which people pass, including home, school, work, and the larger political community.

Professional work cannot simply proceed from a fixed educational background; rather, education must be smoothly incorporated as part of work activities. Similarly, learning takes place not only at all ages and in virtually all professions; increasingly, it takes place among heterogeneous groups of people in families, clubs, and virtual communities. Insights gained from these individual situations need to be developed into broad and effective theories of learning, innovative and intelligent systems, practices, and assessments across many professional genres. A lifelong learning approach permits integration of the best features of school, community, home, and workplace learning.

Figure 3 presents a high-level comparison between school and workplace learning illustrating some of the major differences. In the standard "instructionist" classroom environment, students are generally unable to see the relevance of what they learn because the material presented is disembodied from everyday experience; the material to be learned is formulated externally by teachers and curriculum developers, and problems have an artificially "closed," well-defined nature (i.e., there is one correct answer and one prescribed process for obtaining that answer). These limitations of formal education have led to complaints from corporations that even graduates from the best schools lack the practical design experience needed to perform their jobs.

	Training conceptualized as School Learning	Lifelong Learning conceptualized as Workplace Learning
emphasis	"basic" skills	education embedded in ongoing work activities
potential drawbacks	decontextualized, not situated	important concepts are not encountered
problems	given	constructed
new topics	defined by curricula	arise incidentally from work situations
structure	pedagogic or "logical" structure	work activity
roles	expert-novice model	reciprocal learning
teachers/ trainers	expound subject matter	engage in work practice
mode	instructionism (knowledge absorption)	constructionism (knowledge construction)

Figure 3: A Comparison of Different Conceptualizations of Training and Lifelong Learning

Although there is a growing awareness for the need for more integration of working and learning (e.g., "on-the-job" training programs, performance support systems, simulation environments [Gery, 1997]), many corporate education and training programs have been modeled after schools. Employees attend lectures and seminars where decontextualized knowledge is presented to them by instructors who often know little about the real problems encountered in working life. Conventional studies of workplace learning have concentrated on activities employers have explicitly organized for the purpose of training. This "workplace training," suffers from the same phenomenon of decontextualization as does the school-based environment on which it is modeled. Detterman [Detterman & Sternberg, 1993] (in reviewing earlier summaries of the literature on workplace training by Baldwin and Ford), writes: *"American businesses have a major stake in fostering transfer of training, since they spend up to $100 billion each year to train workers. Yet the estimate is that not more than 10% of training transfers to the job. So business wastes $90 billion each year because of lack of transfer."*

These observations collectively point toward a need for weaving the process of learning into ongoing, self-directed, work-related activities. As a source of examples, informal workplace learning — the "apprenticeship"-style education typical of medical doctors, Ph.D. students, and some crafts people [Lave & Wenger, 1991] — presents features that are interesting for our research goals of supporting learning on demand.

A *theory of lifelong learning* must investigate new approaches to learning required by the profound and accelerating changes in the nature of work and education. These changes include (1) an increasing prevalence of "high-technology" jobs requiring support for learning on demand because coverage of concepts is impossible; (2) the inevitability of change in the course of a professional lifetime, which necessitates lifelong learning; and (3) the deepening (and disquieting) division between the opportunities offered to the educated and to the uneducated.

Lifelong learning is a continuous engagement in acquiring and applying knowledge and skills in the context of self-directed problems and should be grounded in descriptive and prescriptive goals such as:

- learning should take place in the context of authentic, complex problems (because learners will refuse to quietly listen to someone else's answers to someone else's questions);
- learning should be embedded in the pursuit of intrinsically rewarding activities;
- learning-on-demand needs to be supported because change is inevitable, complete coverage is impossible, and obsolescence is unavoidable;

- organizational and collaborative learning must be supported because the individual human mind is limited; and
- skills and processes that support learning as a lifetime habit must be developed.

Learning taking place outside of an (instructionist) classroom can often be characterized as follows: humans are engaged in some activity (some action such as working, collaboratively solving a problem, or playing); they experience a breakdown; and they reflect about the breakdown (i.e., the piece of lacking knowledge, the misunderstanding about the consequences of some of their assumptions, etc.). Schön [Schön, 1983] calls this reflection-in-action. Because self-reflection is difficult, a human coach, a design critic, or a teacher can help the learner to identify the breakdown situation and to provide task-relevant information for reflection. In our own work, we have explored the possibility using computational critics [Fischer et al., 1993] to provide some of this support when humans are not present. Critics make argumentation serve design, that is, they support learners in their own activities.

Engagement and support for self-directed learning is critical when learning becomes an integral part of life — driven by our desire and need to understand something, or to get something done instead of solving a problem given in a classroom setting. A lifelong learning perspective implies that schools and universities need to prepare learners to engage in self-directed learning processes because this is what they will have to do in their professional and private lives outside of the classroom.

It is advantageous for both motivation and the ability to acquire new knowledge that students be able to direct their own learning [Fischer, 1991]. Self-directed learning [Fischer, 1998b] de-emphasizes teaching as a process in which a teacher tells something to a passive learner, but focuses instead on mutual dialogs and joint knowledge construction, which are enhanced by the creation, discussion and evolution of artifacts.

4. Environments in Support of Lifelong Learning

4.1. Requirements

One of the major roles for new media and new technology is not to deliver predigested information to individuals but to provide the opportunity and resources for engaging in meaningful activity, for social debate and discussion, for creating shared understanding among stakeholders, and for framing and solving authentic problems. This global perspective leads to the following requirements for lifelong learning:

- Users set most of the goals, not the system.
- The vocabulary, tools, functions, and practices supported by the system come from the working environment, where they are natural and appropriate.
- The mode of operation emphasizes learning from breakdowns and from fulfilling commitments.
- Tools must appear directly relevant to help with the problem at hand; they must not generate further breakdowns.
- Although learning environments may have some built-in expertise, users will find most expert knowledge by locating other people who have the knowledge.
- Some of the tools must help with cross-domain searching: finding similar problems that have been solved elsewhere and reporting on their solutions.
- The systems should aid users in two kinds of reflection — immediate, to deal with the problem and to organize a solution; and post-mortem, to see if the problem is recurrent and can be avoided by restructuring work processes.
- Systems should feature many interactions among people, because these are the sources of most breakdowns.
- Systems should support not only the individual's solo performance, but work in cooperation with others and while belonging to different groups at the same time: systems should support the improvement of collective knowledge as well as individual knowledge.

Open Systems. The needs of people engaged in lifelong learning will transcend the boundaries of any closed system, making mechanisms such as end-user modifiability and end-user programming a necessity rather than a luxury. One of the biggest challenges facing systems in support of lifelong learning is to allow end-users to become co-developers of systems. Figure 4 differentiates between two stages in the design and use of an artifact. At *design time*, system developers create environments and tools including help systems, guided tours, forms, and so on, and they have to make decisions for users (who may want to be consumers or designers), for situational contexts, and for tasks that they can only anticipate. For print media, a fixed context is decided at design time, whereas for computational media, the behavior of a system at *use time* can take advantage of contextual factors (such as the background knowledge of a user, the specific goals and objectives of a user, the work context) *known only at use time*. The fundamental difference is that computational media have interpretive power — they can analyze and critique the artifacts created by users [Fischer et al., 1993] — and users acting as designers will create artifacts of all kinds. The challenge is to build new innovative systems that allow the users to articulate contextual factors (e.g., in using a specification component [Nakakoji, 1993] and/or infer this information from the environment), which will serve as objects for interpretation.

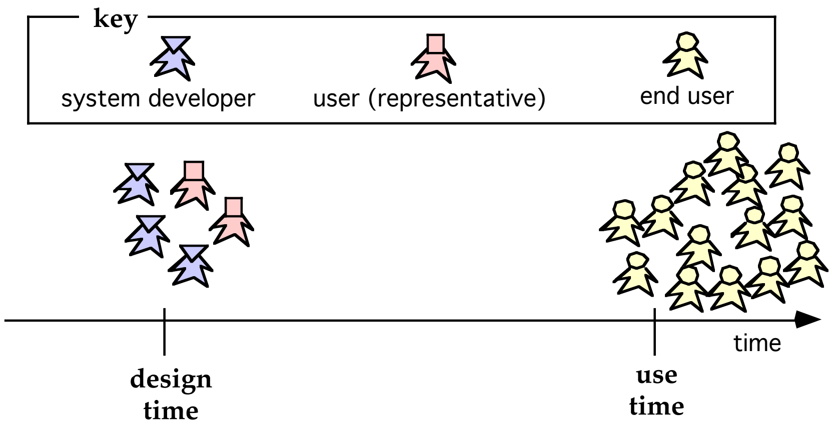

Figure 4: Design and Use Time

Figure 5 characterizes the duality and the distributed nature of knowledge: a specific user can learn (specifically learn in context and on demand) from a computational environment (which contains knowledge and tools contributed by many members of the community of practice), but if this user considers her/himself a designer, she/he will also contribute to the environment (assuming mechanisms are available that allow her/him to do so with a reasonable effort). This perspective illustrates the concepts and need for co-adaptive systems: (1) users learn from the systems; (2) users acting as innovators, co-developers and designers adapt and evolve the systems; and (3) support for organizational learning allows users to share these adaptations with others.

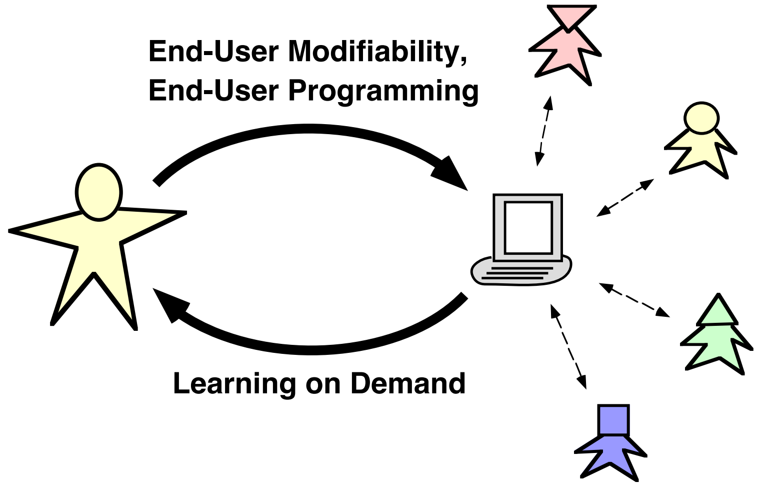

Figure 5: Duality between Learning and Contributing

Collaborative Systems. Even though we face too much information in the abstract, in most specific problem situations we do not have enough knowledge. Learning cannot be restricted to finding knowledge that is "out there". If nobody in a group knows the answer, we have to create new knowledge and new environments that stimulate innovation and creativity by exploiting breakdowns, symmetry of ignorance, experimentation, and external objects serving as objects-to-think-with and objects-to-talk-about. The individual, unaided human mind is limited: there is only so much we can remember and there is only so much we can learn. Talented people require approximately a decade to reach top professional proficiency. This general observation provides the rationale that when a domain reaches a point where the knowledge for skillful professional practice cannot be acquired in a decade, specialization will increase, teamwork will become a necessity, and practitioners will make increasing use of external reference aids (such as printed and computational media). With powerful technologies becoming widely available, people take on more jobs that are more complex or more comprehensive. Therefore, they need help accomplishing unfamiliar tasks that are part of an expanded job. Beyond the need for new and changing domain knowledge, there is also a large demand for new tool knowledge.

4.2. Modes of Learning

Innovative uses of computers in education have focused on two major approaches: intelligent tutoring systems and interactive learning environments [Wenger, 1987]. The strength of *intelligent tutoring systems* [Anderson et al., 1995; Sleeman & Brown, 1982] lies in their ability to teach basic concepts and skills of a problem domain. Tutoring is an adequate mode of learning for getting started learning a new system. One can predesign a sequence of microworlds and lead a user through them [Burton et al., 1984]. But tutoring is of little help in supporting learning on demand when intermediate users are involved in their "own doing". Tutoring is not task-driven because the total set of tasks *cannot* be anticipated. Instead, the system controls the dialogue, and the user has little control over what to do next. Tutoring systems, similar to school education, leave it to the learner to relate training to real-world problem situations.

Interactive learning environments (such as LOGO [Papert, 1980]) avoid the problem of presenting instructional material in a system-controlled order without regard to the learner's situation, but they provide limited support in helping learners detect mistakes or overcome breakdowns [Fischer, 1994b]. Misconceptions may accumulate into chains, in which each later misconception is based on a previous one. Learners get trapped on suboptimal plateaus because they fail to discover the knowledge needed to make better use of their tools and to create better artifacts. Interactive learning environments support autonomous learning; in order to support self-directed learning they need to be augmented with mechanisms that can offer help, support, and reflection for learners who get stuck or who do not know how to proceed.

Figure 6 illustrates the interdependencies between intelligent tutoring systems, interactive learning environments, and domain-oriented design environments [Collins, 1996]. The links in the figure indicate how the different approaches can profit from each other: *domain-oriented design environments* (see below) support learning on demand [Fischer, 1991] and self-directed learning, and they have profited from end-user modifiability (as explored in interactive learning environments [Repenning & Ioannidou, 1997]) and contextualized tutoring (in which tutoring episodes are contextualized to the interests and problem of a learner [Atwood et al., 1991]).

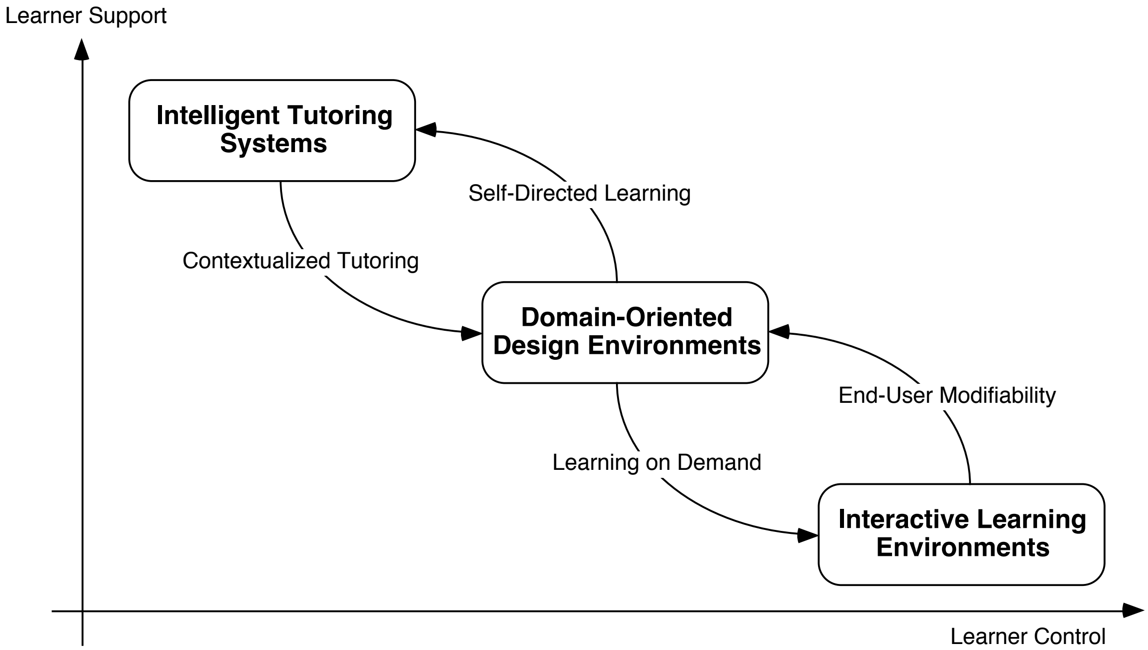

Figure 6: The Relationships Among Intelligent Tutoring Systems, Interactive Learning Environments, and Domain-Oriented Design Environments

4.3. Domain-Oriented Design Environments

For many years we have been trying to find new ways of creating computer-based learning environments, combining the strengths of both approaches while at the same time eliminating some of the weaknesses. Our goal has been to integrate working and learning and to support learning on demand. *Domain-oriented design environments* [Fischer, 1994a] have proven to be powerful and versatile environments for learning that (1) address the limitations of intelligent tutoring systems and interactive learning environments, and (2) provide multiple learning opportunities. Pursuing this line of research, we have emphasized research directions and techniques that augment and complement human intelligence with rich computational environments, including critics, agents, assistants, adaptable and adaptive tools, information access, and information delivery mechanisms [Terveen, 1995].

Domain-oriented design environments are collections of interrelated tools and information repositories that provide specific support for communicating about and exploring concepts within a domain. Example domains that we have explored include kitchen design, graphical user interface layout, telephone voice messaging systems, local area network design, lunar habitat design, and interactive simulation games using the World Wide Web as a research medium (these efforts are documented in: http://www.cs.colorado.edu/~l3d/Research/). Design environments have the following major components:

- The construction component is the principal medium for modeling a design. It provides a palette of domain-oriented design units, which can be arranged in a work area using direct manipulation. Design units represent primitive elements in the construction of a design, such as sinks and stoves in the domain of kitchen design. Critics can be tied to these domain-oriented design units and to relationships between design units.

- The specification component [Nakakoji, 1993] allows designers to describe abstract characteristics of the design they have in mind. The specifications are expected to be modified and augmented during the design process, rather than to be fully articulated at the beginning. The specification provides the system with an explicit representation of the user's goals. This information can be used to tailor both the critic suggestions put forth and the accompanying explanations to the user's task at hand.
- The argumentative hypermedia component contains design rationale [Moran & Carroll, 1996]. Users can annotate and add argumentation as it emerges during the design process. Argumentation is a valuable component in a critic's explanation; it identifies the pros and cons of following a critic suggestion and helps the user to understand the consequences of following a suggestion.
- The catalog component provides a collection of previously constructed designs. These illustrate examples within the space of possible designs in the domain and support reuse and case-based reasoning [Kolodner, 1993]. Catalog entries are also important components in a critic's explanation. Often a critic does not suggest a course of action but instead points out a deficiency in the current design; catalog entries can then be used as specific examples illustrating sample solutions that address a deficiency noted by a critic.
- Simulation mechanisms [Repenning, 1994]; [Sumner, 1995] support users in their understanding of the behavior of a component or a complete artifact.

Domain-oriented design environments derive their power from the integration of its components. When used in combination, each component augments the values of the others in a synergistic manner.

In contrast to general-purpose environments, specific domain-oriented design systems are instantiated from a generic, domain-independent architecture (using the “seeding, evolutionary growth, reseeding” process model [Fischer et al., 1994]) to support users in a specific domain. They provide specific functionality for manipulating, exploring, and communicating about domain entities. All of these components are not static entities in domain-oriented design environments. As users interact with the environment, they create and compose new artifacts that themselves become part of the system.

4.4. Critiquing

In many lifelong learning situations, human understanding evolves through a process of critiquing existing knowledge and consequently expanding the store of knowledge. Critiquing is a dialog in which the interjection of a reasoned opinion about a product or action triggers further reflection on or changes to the artifact being designed. Our work has focused on applying this successful human critiquing paradigm to human- computer interaction. Computer-based critiquing systems are most effective when they are embedded in domain-oriented design environments. Embedded critics [Fischer et al., 1993] play a number of important roles in such design environments: (1) they increase the designer's understanding of design situations by pointing out problematic situations early in the design process, (2) they support the integration of problem framing and problem solving by providing a linkage between the design specification and the design construction, and (3) they help designers access relevant information in the large information spaces provided by the design environment.

Critiquing is ubiquitous. It is, for example, at the heart of the scientific method. Popper [Popper, 1965] theorized that science advances through a cycle of conjectures and refutations. Scientists formulate hypotheses and put forth these conjectures for scrutiny and refutation by the scientific community. Besides contributing to the growth of knowledge, this critiquing cycle of conjectures and refutations is essential for creating a shared understanding within the scientific community and providing a stable base for future growth in scientific knowledge.

Critics play an important role in making designers aware of breakdown situations [Fischer, 1994b]. Petroski [Petroski, 1985] noted the importance of failure in the growth of engineering knowledge. The activity of critiquing plays an important role in engineering, science, and design in general. It produces many benefits, including the growth of knowledge, error elimination, and the promotion of mutual understanding by all participants. Through the critiquing process, designers gain a better understanding of the design problem by hearing the different points of view of other design participants.

An essential component of domain-oriented design environments consists of computational critiquing systems. They support workers in increasing the quality of an artifact by signaling breakdowns and they exploit breakdown situations as opportunities for learning on demand. Critics are user-centered and support users working on their own activities. They provide information only when it is relevant. They allow users to do what they want and interrupt only when users' plans, actions, or products are considered significantly inferior. They are applicable to tasks in which users have some basic competence because users must be able to generate a plan, action, or product by themselves. They are most useful when no unique best solution exists in a domain and trade-offs have to be carefully balanced. Critics need to be knowledge-based. They must incorporate knowledge about the application domain, support explanation, model individual users, and provide innovative user interfaces.

4.5. The Envisionment and Discovery Collaboratory (EDC)

The Envisionment and Discovery Collaboratory (EDC) [Arias et al., 1999] is a domain-oriented design environment to support lifelong learning by creating shared understanding among various stakeholders, contextualizing information to the task at hand, and creating objects-to-think-with in collaborative design activities. The EDC framework is applicable to different domains, but our initial effort has focused on the domains of urban planning and decision making, specifically in transportation planning and community development. Creating shared understanding requires a culture in which stakeholders see themselves as reflective practitioners rather than all-knowing experts [Schön, 1983]. Collaborative design taking place in such a culture can be characterized by an "asymmetry of knowledge" or a "symmetry of ignorance" [Rittel, 1984]: stakeholders are aware that while they each possess relevant knowledge, none of them has all the relevant knowledge.

Figure 7: The EDC Environment

Figure 7 shows the current realization of the EDC environment. Individuals using the EDC convene around a computationally enhanced table, shown in the center of the figure. This table serves as the Action Space for the EDC. Currently realized as a touch-sensitive surface, the Action Space allows users to manipulate the computational simulation projected on the surface by interacting with the physical objects placed on the table. The table is flanked by a second computer driving another touch-sensitive surface (shown horizontally in Figure 7). This computational whiteboard serves as the EDC's Reflection Space. In the figure, neighbors are filling out a Web-based transportation survey that is associated with the model being constructed. The Reflection and Action spaces are connected by communication between the two computers using the Web as a medium. The entire physical space, through the immersion of people *within* the representations of the problem-solving task, creates an integrated human/computer system grounded in the physical world.

As argued before, much development of technology for learning and design builds on or is constrained by the "single user/single computer" interaction model. The EDC emphasizes the creation of shared interaction, social structures, and cultural embedding for learning within the context of communities of learners. It is being developed as a learning and design support medium where 3-D physical objects interact dynamically with virtual ones over an integrated sensory/display work surface as the computational game board. Based on 10 years of experience in building physical simulation games, we see that powerful collaborative learning and shared decision making can be supported by shared interaction and integration with computational models. Together these form a collaborative environment that builds on both distributed and face-to-face collaborations in classrooms or public sites.

Crucial processes relevant for lifelong learning and supported by the EDC are:

- dealing with a set of possible worlds effectively (i.e., exploring design alternatives) to account for the design is an argumentative process, where we do not prove a point but we create an environment for a design dialog [Simon, 1996];
- using the symmetry of ignorance (i.e., that all involved stakeholders can contribute actively) as a source of power for mutual learning by providing all stakeholders with means to express their ideas and their concerns [Rittel, 1984];
- incorporating an emerging design in a set of external memory structures, and recording the design process and the design rationale [Fischer et al., 1996];
- creating low-cost modifiable models, which help us to create shared understanding, have a conversation with the materials [Schön, 1983], and replace anticipation (of the consequences of our assumptions) by analysis;
- using the domain-orientation to bring tasks to the forefront and supporting human problem-domain communication [Fischer & Lemke, 1988];
- increasing the "back-talk" of the artifacts with critics [Fischer et al., 1993];
- using simulations to engage in "what-if" games [Repenning, 1994].

The EDC is a contribution to create a new generation of *collaborative* domain-oriented design environments. It shifts the emphasis away from the computer screen as the focal point and creates an immersive environment in which stakeholders can incrementally create a shared understanding through collaborative design. It is an environment that is not restricted to the delivery of predigested information to individuals, but it provides opportunities and resources for design activities embedded in social debates and discussions in which all stakeholders can actively contribute rather than assume passive consumer roles [Fischer, 1998a].

The EDC will prepare the next generation of knowledge workers for lifelong learning and innovation in a world where the traditional bounderies between formal educational institutions and the world at large will dissolve. By reaching out, there is a natural exchange with industries and communities of ideas, skills, and technology. In this reciprocal relationship, graduates of our programs migrate to various places of work to continue their learning. Workers and community members benefit from learning how to participate in and shape the future of their workplaces and their communities through informed collaboration.

4.6. Working Shops — An Environment for Teachers to Engage in Lifelong Learning

Teachers are the ultimate change agents [Guzdial & Weingarten, 1995] (see also: <http://www.cc.gatech.edu/gvu/edtech/nsfws/>). Creating new paradigms for learning requires teachers who understand and are committed to the improvements envisioned. Teachers—more than other members of our society — need to be lifelong learners. We have developed a new concept entitled *Working Shops* , which views teachers as lifelong learners who learn about new aspects of learning, teaching, and innovative use of technology in the context of their work, exploiting specifically possibilities that they can learn most readily from each other.

In the context of our collaboration with schools in the Boulder Valley School District, we have studied not only the application of technology to learning, but the organizational aspects of learning as well. Widespread experience in educational reform demonstrates that how people learn and the context of learning are as important as what they learn. Creating an environment to support teachers as lifelong learners requires an examination of how teachers as professional practitioners can make effective use of the rich individual and collective experiences, outside resources, new information, and the environment itself to support and enhance student learning.

Working Shops involve a regular, continuous meeting of colleagues who, sharing diverse experiences and ideas, learn together in the process of doing meaningful work. Working Shops provide an indistinguishable mix of acquiring and applying knowledge, focused around the creation of concrete products that are valued by those in the shop and, ultimately, the larger community. Working Shops were conceived in response to the isolated workshop and daily work experiences. Drawing on learning models outside of education (e.g., apprenticeships, artists' studios, and scientific laboratories), Working Shops reshape professional development by emphasizing a process of continual, contextual doing and producing, and by creating a community of practice thereby creating a more effective and sustainable process of professional development.

The Working Shops strategy is grounded in the recognition that real and substantial learning requires *time* (during the working day) and *context* (connected to actual, ongoing work). The basic design of the Working Shops process is deceptively simple: Teachers work in teams, meeting once a month during the school day to work on innovative projects and curricula of common interest, learning how to use new technologies or practices in the context of designing and implementing the projects and curricula. Through their collaborative efforts the teams simultaneously develop new pedagogical strategies and tools, acquire new skills and knowledge, and enhance their sense of professional value and collegiality.

Working Shops were envisioned, created and put into practice to complement and transcend training approaches toward professional development for educators that rely almost exclusively on de-contextualized, individualized, instructionist strategies [Watkins & Marsick, 1993]. Teachers are expected to learn on their own time, away from the work context in which the new knowledge needs to be applied. The primary professional development modality is the workshop — a class or a series of three or four classes, that lasts for a few hours. Single-shot "professional development workshops" are far from sufficient to help teachers develop and sustain new approaches to instruction. Teachers and researchers must become "communities of learners" that constantly search for new ways to improve.

5. Assessment

5.1. Lifelong Learning — More Than Training

Learning is more than being taught [Illich, 1971]. Teaching is often fit "into a mold in which a single, presumably omniscient teacher explicitly tells or shows presumably unknowing learners something they presumably know nothing about" [Bruner, 1996]. A critical challenge is a reformulation and reconceptualization of this impoverished and misleading conception. Although this model may be more realistic for the early grades in schools, it is obviously inadequate for learning processes as they occur in lifelong learning, where knowledge is distributed among many stakeholders and "the answer" does not exist or is not known. Group discussions, conversations around dinner tables, and classrooms have the potential to be opportunities in which knowledge is created and constructed by communities of mutual learners.

Historically, the role of a teacher or a learner was associated with a person. In today's world, being a teacher or being a learner is associated only with a specific context. "Official" teachers should feel comfortable to become learners in many situations. Mutual competency and symmetry of ignorance, supported by objects-to-think-with (externalization of ideas, concepts, and goals), leads to settings and opportunities for learning by all participants. This is most obvious in the context of design activities, as illustrated above with the discussion of the

Envisionment and Discovery Collaboratory. Design is collaborative in nature, the relevant knowledge to engage in a design task is distributed among stakeholders, and communication breakdowns occur because the stakeholders belong to different work cultures, which use different norms, symbols, and representations. Knowledge is not transferred or delivered in such situations, but it is jointly constructed.

Observations of learners in our environments in the past indicated that they took advantage of multiple learning opportunities. However, we intend to carefully investigate possible limitations of our approach, for example, the strengths and weaknesses of learning on demand. Limitations may include: (1) the acquisition of certain essential skills should not be deferred until they are needed because the time to learn them may be not available or the environment may be too dangerous for safe learning processes; (2) learning on demand is task driven and therefore may be limited to exposing users to isolated pieces of knowledge while providing only limited support for learning essential principles; (3) users may encounter difficulties in decontextualizing knowledge so that it can be used in new settings; and (4) whereas learning on demand may be well suited for evolutionary extensions of a knowledge base, it may not support substantial restructuring, because the additional features learned occur only in the neighborhood of what learners already know.

Tearing down institutional boundaries. Current educational practices create boundaries that make it very difficult to continue to evolve workers' skills. For example, we educate workers for jobs in U.S. industries in school settings that have no contact with those industries. Those providing the instruction are often ignorant of the skills that the industries need. Once the workers are placed in industry, however, the problem is still not resolved because industry itself typically takes the standard education model and separates education from practice. In most cases, industry trainers are no better informed about the skills that are needed than are public school teachers. In industry, it is common to find instructors "teaching" students to do a job that the instructor has never performed, or teaching abstract concepts because allowing students contact with the real environment is too dangerous to try in the classroom. In summary: "current practices, both in public and industry-based education, increase the gap between working and learning." Our approach is to close the learning-practice gap by forming alliances between formal education institutions and industry.

Informal workplace learning (as it often occurs naturally in apprenticeship relationships, such as internships of medical doctors, Ph.D. studies, etc.) has features that make it interesting to serve as a model for lifelong learning:

- it requires the integration of problem framing and problem solving (problems are not given);
- workers/learners are confronted with more demanding aspects of the work accidentally, that is, only when a problem (a breakdown) arises in the context of their work;
- the world is used as a resource (as opposed to closed-book exams in schools); and
- communication plays a critical role (discussing issues with co-workers, clients, customers, etc.).

Zuboff ([Zuboff, 1988], p. 395) characterizes well how learning increasingly is being integrated into everyday work activities: *"The informated organization is a learning institution, and one of its principal purposes is the expansion of knowledge — not knowledge for its own sake (as in academic pursuit), but knowledge that comes to reside at the core of what it means to be productive. Learning is no longer a separate activity that occurs either before one enters the workplace or in remote classroom settings. Nor is it an activity reserved for a managerial group. The behaviors that define learning and the behaviors that define being productive are one and the same. Learning is not something that requires time out from being engaged in productive activity; learning is the heart of productive activity. To put it simply, learning is the new form of labor."*

5.2. Beyond Gift-Wrapping: Innovative Media and Technologies Supporting Lifelong Learning

Moving beyond the "gift-wrapping approach" [Fischer, 1998c] implies that we explore the fundamentally new possibilities and limitations of computational media on how we think, create, work, learn, and collaborate. It simply isn't good enough to spend money on new technologies and then to use it in old ways. New tools will not just help people do cognitive jobs more easily but in the same way they used to, but they will also lead to fundamental alterations in the way problems are solved. Lifelong learning requires that we change mindsets, for example, seeing and understanding breakdowns and symmetry of ignorance as opportunities rather than as things to be avoided. and that teachers understand their roles not only as truth-tellers and oracles, but as coaches, facilitators, mentors, and learners.

Printed media and the widespread human ability to read and write are foundations on which our current societies are built. An important question to be asked is: "Will computational media cause a change of a similar magnitude compared to our society moving from an oral to a literary society?" Socrates and Plato were arguing about the trade-offs associated with this change or when Gutenberg's printing press eliminated the scribes and gave everyone the opportunity to become literate. The fact that societies have often overestimated change in the short run and underestimated it in the long run suggests that we should make every effort to understand the long-term societal impacts of computational media and to identify their unique properties, in which are absent in principle in printed media.

Printed media do not have interpretive power — they can convey information to us, but they cannot analyze (as critiquing systems do) or simulate the work products created by us and thereby increase the "back-talk" of an artifact by presenting a reasoned opinion about it. Computational media can make information relevant to the task at hand, thereby reducing the information overload problem or the need for decontextualized learning. This principle can be illustrated by the current generation of help systems: while Microsoft Word's "Tip of the Day" provides us with a piece of decontextualized information, few help systems provide us with information (explicitly asked for or volunteered) relevant to a breakdown situation in our activity.

The current generation of computational environments fall short in many ways to support humans in their activities (because they are used in a "gift-wrapping" mode). People are forced to focus on the computer rather than on their tasks. Environments are needed that support "human problem-domain interaction" rather than just "human-computer interaction" [Fischer, 1993]; they need to be "ready-to-hand" meaning that for members of a community, they disappear as a separable object of observation and become an integral part of their practice.

Lifelong learning needs to be supported by new media and new technologies, because some of the essential support mechanisms will not be available as paper and pencil technologies; for example, pencil and paper based information repositories will not be able (1) to provide pieces of information relevant to the task at hand, (2) to maintain consistency between different representations automatically or semi-automatically, (3) to generate different external views dynamically from one complex internal structure, (4) to create links between the static description and the dynamic behavior, and (5) to link action and reflection spaces. We must create innovative new media and technologies (such as simulations, visualizations, critiquing, etc.) to let people "experience" knowledge in new ways.

6. Conclusions

Training and lifelong learning are essential problems for our current and future information societies. Unfortunately (as is probably the case with all important questions and challenges) there are no simple answers and no simple facts that would allow enumerating briefly failures and successes. To acknowledge the complexity of these issues implies that we rethink, reinvent and redesign the way how we think, work, learn, and collaborate in the future. A lifelong learning perspective is more than training and continuing education: it forces us to rethink and reinvent our schools and universities [Brown & Duguid, 1995; Noam, 1995].

We have to understand the co-evolutionary processes between fundamental human activities and their relationships and interdependencies with new media. We need progress and a deeper understanding of new theories, innovative systems, practices, and assessment. We have to create new intellectual spaces, new physical spaces, new organizational forms, and new reward structures to make lifelong learning an important part of human life. We need individuals, groups, and organizations to personally engage in and experience these new forms — risk takers who use their creativity and imagination to explore alternative ways of learning.

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7. References

Anderson, J. R., Corbett, A. T., Koedinger, K. R., & Pelletier, R. (1995) "Cognitive Tutors: Lessons Learned," *The Journal of the Learning Sciences*, 4(2), pp. 167-207.

Arias, E., Eden, H., Fischer, G., & Scharff, E. (1999) *Creating Shared Understanding through Collaborative Design with the Envisionment and Discovery Collaboratory,* At http://www.cs.colorado.edu/~gerhard/pub.html.

Atwood, M. E., Burns, B., Gray, W. D., Morch, A. I., Radlinski, E. R., & Turner, A. (1991) "The Grace Integrated Learning Environment—A Progress Report," In *Proceedings of the Fourth International Conference on Industrial & Engineering Applications of Artificial Intelligence & Expert Systems (IEA/AIE 91)*, ACM, pp. 741-745.

Brown, J. & Duguid, P. (1995) *Universities in the Digital Age,* at http://www.parc.xerox.com/ops/members/brown/papers/university.html.

Bruner, J. (1996) *The Culture of Education*, Harvard University Press, Cambridge, MA.

Burton, R. R., Brown, J. S., & Fischer, G. (1984) "Analysis of Skiing as a Success Model of Instruction: Manipulating the Learning Environment to Enhance Skill Acquisition," In B. Rogoff & J. Lave (eds.), *Everyday Cognition: Its Development in Social Context*, Harvard University Press, Cambridge, MA - London, pp. 139-150.

Collins, A. (1996) "Design Issues for Learning Environments," In S. Vosniadou, E. D. Corte, R. Glazer, & H. Mandl (eds.), *International Perspectives on the Design of Technology-Supported Learning Environments*, Lawrence Erlbaum Associates., Mahwah, New Jersey, pp. 347-361.

Detterman, D. K., Sternberg, R. J. (1993) *Transfer on Trial: Intelligence, Cognition, and Instruction*, Ablex Publishing Corporation, Norwood, NJ.

Drucker, P. F. (1994) "The Age of Social Transformation," *The Atlantic Monthly*(November), pp. 53-80.

Fischer, G. (1991) "Supporting Learning on Demand with Design Environments," *International Conference on the Learning Sciences*, pp. 165-172.

Fischer, G. (1993) "Beyond Human Computer Interaction: Designing Useful and Usable Computational Environments," In *People and Computers VIII: Proceedings of the HCI'93 Conference (Loughborough, England)*, Cambridge University Press, Cambridge, UK, pp. 17-31.

Fischer, G. (1994a) "Domain-Oriented Design Environments," *Automated Software Engineering*, 1(2), pp. 177-203.

Fischer, G. (1994b) "Turning Breakdowns into Opportunities for Creativity," *Knowledge-Based Systems, Special Issue on Creativity and Cognition*, 7(4), pp. 221-232.

Fischer, G. (1998a) "Beyond 'Couch Potatoes': From Consumers to Designers," *3rd Asia Pacific Computer Human Interaction Conference*, pp. 2-9.

Fischer, G. (1998b) *Conceptual Frameworks and Innovative Computational Environments in Support of Self-Directed and Lifelong Learning,* At http://www.cs.colorado.edu/~gerhard/reports/bmbf1998.pdf.

Fischer, G. (1998c) "Making Learning a Part of Life-Beyond the 'Gift-Wrapping' Approach of Technology," In P. Alheit & E. Kammler (eds.), *Lifelong Learning and Its Impact on Social and Regional Development*, Donat Verlag, Bremen, pp. 435-462.

Fischer, G. & Lemke, A. C. (1988) "Construction Kits and Design Environments: Steps Toward Human Problem-Domain Communication," *Human-Computer Interaction,* 3(3), pp. 179-222.

Fischer, G., Lemke, A. C., McCall, R., & Morch, A. (1996) "Making Argumentation Serve Design." In T. Moran & J. Carrol (Eds.), *Design Rationale: Concepts, Techniques, and Use,* Lawrence Erlbaum and Associates, Mahwah, NJ, pp. 267-293.

Fischer, G., McCall, R., Ostwald, J., Reeves, B., & Shipman, F. (1994) "Seeding, Evolutionary Growth and Reseeding: Supporting Incremental Development of Design Environments," *Human Factors in Computing Systems (CHI'94)*, pp. 292-298.

Fischer, G., Nakakoji, K., Ostwald, J., Stahl, G., & Sumner, T. (1993) "Embedding Critics in Design Environments," *The Knowledge Engineering Review Journal*, 8(4), pp. 285-307.

Gardner, H. (1991) *The Unschooled Mind*, Basic Books, Inc, New York.

Gery, G. (1997) "Granting Three Wishes through Performance-Centered Design," *Communications of the ACM*, 40(7), pp. 54-59.

Guzdial, M., Weingarten, F. W. (1995) *Setting a Computer Science Research Agenda for Educational Technology*, (CRA Report No. 1995). National Science Foundation.

Illich, I. (1971) *Deschooling Society*, Harper and Row, New York.

Kolodner, J. L. (1993) *Case-Based Reasoning*, Morgan Kaufmann Publishers, Inc., San Mateo, CA.

Landauer, T. K. (1995) *The Trouble with Computers*, MIT Press, Cambridge, MA.

Lave, J., Wenger, E. (1991) *Situated Learning*, Cambridge University Press, Cambridge, UK.

Moran, T. P., Carroll, J. M. (1996) *Design Rationale: Concepts, Techniques, and Use*, Lawrence Erlbaum Associates, Inc., Hillsdale, NJ.

Nakakoji, K. (1993) *Increasing Shared Understanding of a Design Task Between Designers and Design Environments: The Role of a Specification Component*, Ph.D., University of Colorado at Boulder.

Noam, E. M. (1995) "Electronics and the Dim Future of the University," *Science,* 270(5234), pp. 247-249. Available at: http://www.asis.org/annual-96/noam.html

Norman, D. A. (1993) *Things That Make Us Smart*, Addison-Wesley Publishing Company, Reading, MA.

Papert, S. (1980) *Mindstorms: Children, Computers and Powerful Ideas*, Basic Books, New York.

Petroski, H. (1985) *To Engineer Is Human: The Role of Failure in Successful Design*, St. Martin's Press, New York.

Popper, K. R. (1965) *Conjectures and Refutations*, Harper & Row, New York, Hagerstown, San Francisco, London.

Repenning, A. (1994) "Programming Substrates to Create Interactive Learning Environments," *Journal of Interactive Learning Environments, Special Issue on End-User Environments*, 4(1), pp. 45-74.

Repenning, A., Ioannidou, A. (1997) "Behavior Processors: Layers between End-Users and Java Virtual Machines," *Proceedings of the 1997 IEEE Symposium of Visual Languages*, pp. 402-409.

Rifkin, J. (1995) *The End of Work*, G. P. Putnam's Sons, New York, NY.

Rittel, H. (1984) "Second-Generation Design Methods." In N. Cross (Ed.) *Developments in Design Methodology,* John Wiley & Sons, New York, pp. 317-327.

Rogoff, B., Lave, J. (1984) *Everyday Cognition*, Harvard University Press, Cambridge, MA.

Sachs, P. (1995) "Transforming Work: Collaboration, Learning, and Design," *Communications of the ACM*, 38(9), pp. 36-44.

Schön, D. A. (1983) *The Reflective Practitioner: How Professionals Think in Action*, Basic Books, New York.

Simon, H. A. (1996) *The Sciences of the Artificial,* (Third ed.), The MIT Press, Cambridge, MA.

Sleeman, D. H., Brown, J. S. (1982) *Intelligent Tutoring Systems*, Academic Press, London - New York.

Sumner, T. (1995) *Designers and Their Tools: Computer Support for Domain Construction*, Ph.D., Department of Computer Science, University of Colorado at Boulder.

Terveen, L. G. (1995) "An Overview of Human-Computer Collaboration," In *Knowledge-Based Systems Journal*, Butterworth-Heinemann Ltd, Oxford, England, pp. 67-81.

Watkins, K. E., Marsick, V. J. (1993) *Sculpting the Learning Organization -- Lessons in the Art and Science of Systemic Change*, Jossey-Bass, Inc, San Francisco.

Wenger, E. (1987) *Artificial Intelligence and Tutoring Systems*, Morgan Kaufmann Publishers, Los Altos, CA.

Zuboff, S. (1988) *In the Age of the Smart Machine*, Basic Books, Inc., New York.