Computers as Mindtools
for Engaging Learners in Critical Thinking

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Introduction

Traditionally, instructional technologies have been used as media for delivering instruction, that is, as conveyors of information and tutors of students. Whn used in this way, information is "stored" in the technology. During the "instructional" process, learners perceive and try to understand the messages stored in the technology as they "interact" it. Interaction is often limited to pressing a key to continue the information presentation or responding to queries posed by the stored program. The technology program judges the learner's response and provides feedback, most often about the "correctness" of the learners response. Technologies that have been developed by instructional designers are often marketed to educators as "validated" and "teacher proof," removing any meaningful control of the learning process by the learners or the teachers. In this paper, we argue that technologies should not support learning by attempting to instruct the learners, but rather should be used as knowledge construction tools that students learn *with*, not *from* . In this way, learners function as designers, and the computers function as Mindtools for interpreting and organizing their personal knowledge.

Mindtools are computer applications that, when used by learners to represent what they know, necessarily engage them in critical thinking about the content they are studying (Jonassen, 1996). Mindtools scaffold different forms of reasoning about conent. That is, they require students to think about what they know in different, meaningful ways. For instance, using databases to organize students' understanding of content organization necessarily engages them in analytical reasoning, where creating an expert system rule base requires them to think about the causal relationships between ideas. Students cannot use Mindtools as learning strategies without thinking deeply about what they are studying.

Using Computers as Mindtools

Many computer applications have been developed explicitly to engage learners in critical thinking. Others can be repurposed as Mindtools. There are several classes of Mindtools, including semantic organization tools, dynamic modeling tools, information interpretation tools, knowledge construction tools, and conversation and collaboration tools (Jonassen, in press). We shall briefly describe and illustrate some of these (space limits prevent illustrations of all Mindtools). For a report of research on Mindtools, see Jonassen and Reeves (1996).

Semantic Organization Tools

Semantic organization tools help learners to analyze and organize what they know or what they are learning. Two of the best known semantic organization tools are databases and semantic networking (concept mapping) tools.

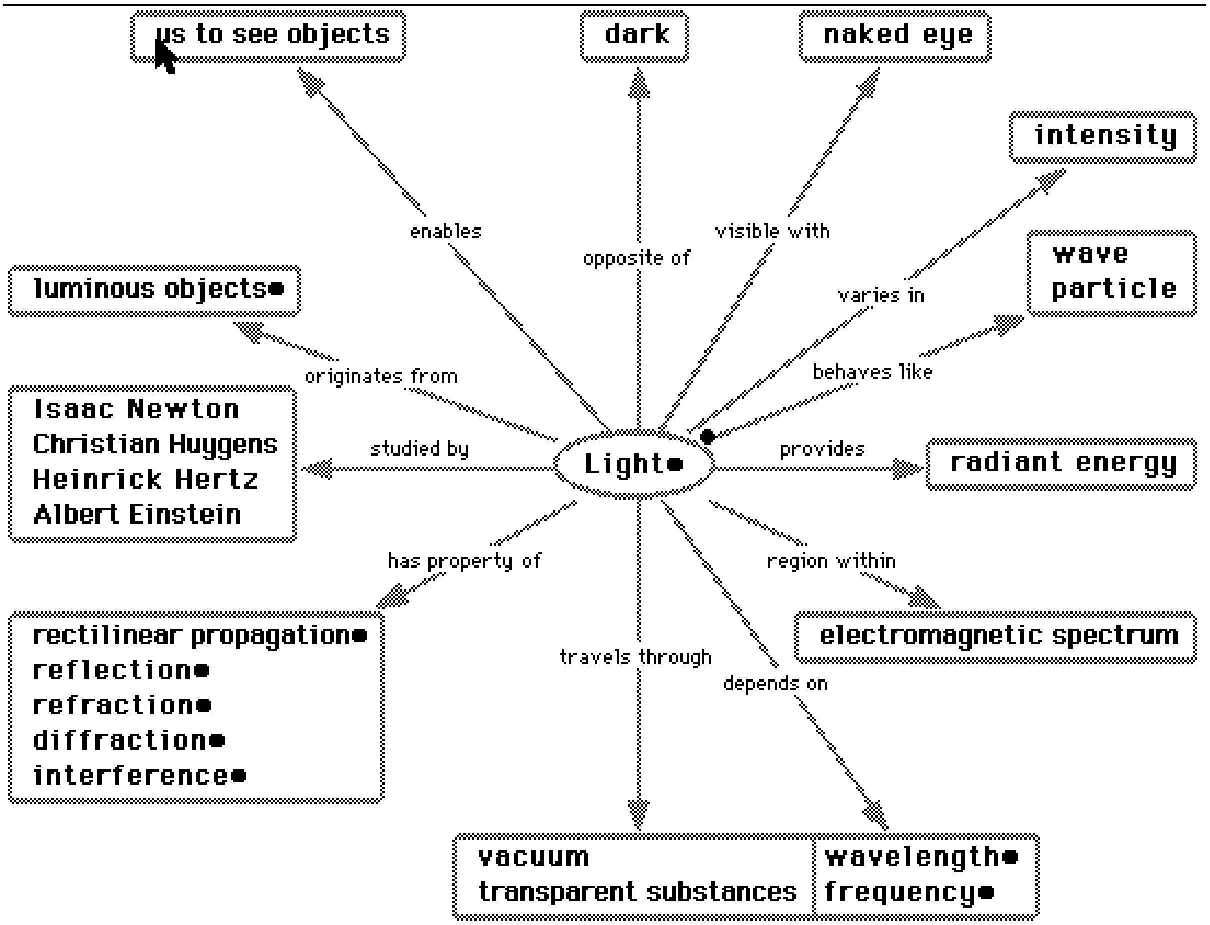
Databases. Database management systems are computerized record keeping systems that were developed originally to replace paper-based filing systems. These electronic filing cabinets allow users to store information in organized databases that facilitates retrieval. Content is broken down into records that are divided into fields which describe the kind of information in different parts of each record.

Databases can be used as tools for analyzing and organizing subject matter (i.e. Mindtools). The database shown in Figure 1 was developed by students studying cells and their functions in a biology course. The database can then be searched and sorted to answer specific questions about the content or to identify interrelationships and inferences from the content, such as "Do different shaped cells have specific functions?" Constructing content databases requires learners to develop a data structure, locate relevant information, insert it in appropriate fields and records, and search and sort the database to answer content queries. A large number of critical thinking skills are required to use and construct knowledge-oriented databases.

cell type	location	function	shape	tissue systems	specialization	related cell
Astocyte	CNS	Supply Nutrients	Radiating	Nervous	Half of Neural Tissue	Neurons, Capillaries
Basal	Stratum Basale	Produce New Cells	Cube, Columnar	Epithelial	Mitotic	Epithelial Cells
Basophils	Blood Plasma	Bind Imm.E	Lobed Nuclei	Connective, Immune	Basic,Possible Mast	Neutrophil, Eosinophil
Cardiac Muscle	Heat	Pump Blood	Branched	Muscle	Intercalated discs	Endomysium
Chondroblast	Cartilage	Produce Matrix	Round	Connective		
Eosinophil	Blood Plasma	Protazoans, Allergy	Two Lobes	Connective, Immune	Acid, Phagocytos (Prote	Basophil, Neutrophil
Ependymal	Line CNS	Form Cerebralspinal Fluid	Cube	Nervous	Cilia	
Erythrocytes	Blood Plasma	Transport O2, Remove CO2	Disc	Connective	Transport	Hemocytoblast, Proeryt
Fibroblast	Connective Tissue	Fiber Production	Flat, Branched	Connective	Mitotic	
Goblet	Columnar Epithelial	Secretion	Columnar	Epithelial	Mucus	Columnar
Keratinocytes	Stratum Basal	Strengthen other Cells	Round	Epithelial		Melanocytes
Melanocytes	Stratum Basale	U.V. Protection	Branched	Epithelial	Produce Melanin	Keratinocytes
Microglia	CNS	Protect	Ovoid	Nervous	Macrophage	Neurons, Astrocytes?
Motor Neuron	CNS(Cell Body)	Impulse Away from CNS	Long, Thin	Nervous	Multipolar,Neuromuscul	Sensory Neuron, Neurog
Neutrophil	Blood Plasma	Inflammation, Bacteria	Lobed Nuclei	Connective, Immune	Phagocytos, Neutral	Basophils, Eosinophil
Oligodendrocyte	CNS	Insulate	Long	Nervous	Produce Myaline Sheath	Neurons
Osteoblast	Bone	Produce Organic Matrix	Spider	Connective	Bone Salts	Osteoclasts
Osteoclast	Bone	Bone Restoration	Ruffled Boarder	Connective	Destroy Bone	Osteoblasts
Pseudostratified	Gland Ducts, Respira	Secretion	Varies	Epithelial	Cilia	Goblet

Figure 1. Content database.

Semantic Networking. Semantic networking tools provide visual screen tools for producing concept maps. Concept mapping is a study strategy that requires learners to draw visual maps of concepts connected to each other via lines (links). These maps are spatial representations of ideas and their interrelationships that are stored in memory, i.e. structural knowledge (Jonassen, Beissner, & Yacci, 1993). Semantic networking programs are computer-based, visualizing tools for developing representations of semantic networks in memory. Programs such as SemNet, Learning Tool, Inspriation, Mind Mapper, and many others, enable learners to interrelate the ideas that they are studying in multidimensional networks of concepts, to label the relationships between those concepts, and to describe the nature of the relationships between all of the ideas in the network, such as that in Figure 2.



The purpose of semantic networks is to represent the structure of knowledge that someone has constructed. So, creating semantic networks requires learners to analyze the structural relationships among the content they are studying. By comparing semantic networks created at different points in time, they can also be used as evaluation tools for assessing changes in thinking by learners. If we agree that is a semantic network is a meaningful representations of memory, then learning from this perspective can be thought of as a reorganization of semantic memory. Producing semantic networks reflect those changes in semantic memory, since the networks describe what learners know. So, semantic networking programs can be use to reflect the process of knowledge construction.

Dynamic Modeling Tools

While semantic organization tools help learners to represent the semantic relationships among ideas, dynamic modeling tools help learners to describe the dynamic relationships among ideas. Dynamic modeling tools include spreadsheets, expert systems, systems modeling tools, and microworlds, among others.

Spreadsheets. Spreadsheets are computerized, numerical record keeping systems that were designed originally to replace paper-based, ledger accounting systems. Essentially, a spreadsheet is a grid or matrix of empty cells with columns identified by letters and rows identified by numbers. Each cell is a placeholder for values, formulas relating values in other cells, or functions that mathematically or logically manipulate values in other cells. Functions are small programmed sequences that may, for instance, match values in cells with other cells, look up a variable in a table of values, or create an index of values to be compared with other cells.

Spreadsheets were originally developed and are most commonly used to support business decision making and accounting operations. They are especially useful for answering "what if" questions, for instance, what if interest rates increased by one percent? Changes made in one cell automatically recalculate all of the affected values in other cells. Spreadsheets are also commonly used for personal accounting and budgeting.

Spreadsheets also may be used as Mindtools for amplifying mental functioning. In the same way that they have qualitatively changed the accounting process, spreadsheets can change the educational process when working with quantitative information. Spreadsheets model the mathematical logic that is implied by calculations. Making the underlying logic obvious to learners should improve their understanding of the interrelationships and procedures. Numerous educators have explored the use of spreadsheets as Mindtools. Spreadsheets have frequently been used in mathematics classes to calculate quantitative relationships in various chemistry and physics classes. They are also useful in social studies instruction and have even supported ecology. Spreadsheets are flexible Mindtools for representing, reflecting on, and calculating quantitative information. Building spreadsheets requires abstract reasoning by the user, they are rule-using tools that require that users become rule-makers. Spreadsheets also support problem solving activities, such decision analysis reasoning requires learners to consider implications of conditions or options, which requires entails higher order reasoning.

Expert Systems. Expert systems have evolved from research in the field of artificial intelligence. An expert system is a computer program that simulates the way human experts solve problems, tha is, an artificial decision maker. They are computer-based tools that are designed to function as intelligent decision supports. For example, expert systems have been developed to help geologists decide where to drill for oil, bankers to evaluate loan application, computer sales technicians how to configure computer systems, and employees to decide among a large number of company benefits alternatives. Problems whose solutions require decision making are good candidates for expert system development.

Most expert systems consist of several components, including the knowledge base, inference engine, and user interface. There are a variety of “shells” or editors for creating expert system knowledge bases, which is the part of the activity that engages the critical thinking. Building the knowledge base requires the learner to articulate causal knowledge.

The development of expert systems results in deeper understanding because they provide an intellectual environment that demands the refinement of domain knowledge, supports problem solving, and monitors the acquisition of knowledge. A good deal of research has focused on developing expert system advisors to help teachers identify and classify learning disabled students.

Systems Modeling Tools. Complex learning requires students to solve complex and ill-structured problems as well as simple problems. Complex learning requires that students develop complex mental representations of the phenomena they are studying. A number of tools for developing these mental representations are emerging. Stella, for instance, is a powerful and flexible tool for building simulations of dynamic systems and processes (systems with interactive and interdependent components). Stella uses a simple set of building block icons to construct a map of a process (see Fig. 4). The Stella model in Fig. 4 was developed by an English teacher in conjunction with his tenth grade students to describing how the boys' loss of hope drives the increasing power of the beast in William Golding's novel, *The Lord of the Flies*. The model of beast power represent the factors that contributed to the strength of the beast in the book, including fear and resistance. Each component can be opened up, so that values for each component may be stated as constants or variables. Variables can be stated as equations containing numerical relationships among any of the variables connected to it. The resulting model can be run, changing the values of faith building, fear, and memory of home experienced by the boys while assessing the effects on their belief about being rescued and the strength of the beast within them. Stella and other dynamic modeling tools, such as Model-It from the Highly Interactive Computing Group at the University of Michigan, probably provides the most complete intellectual activity that students can engage in.

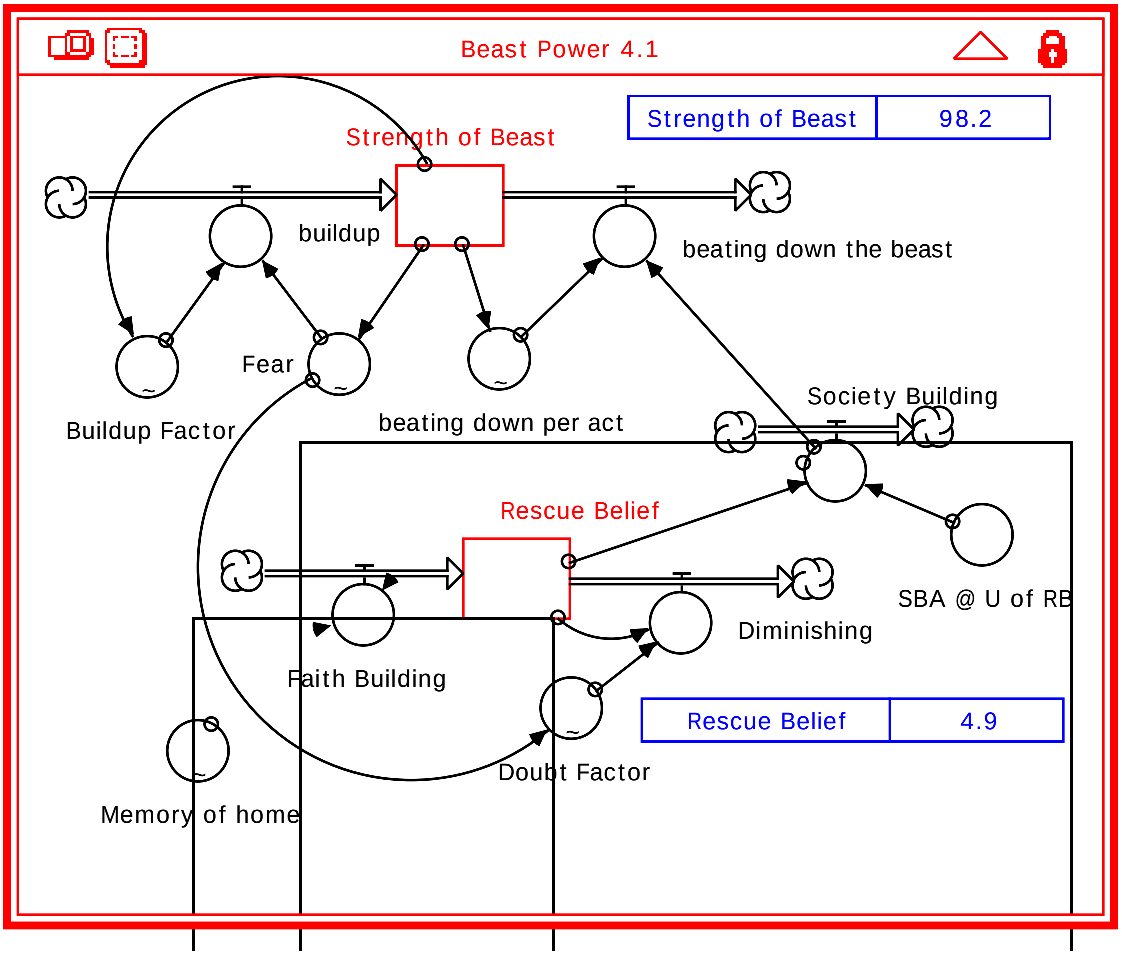


Fig. 4. Conceptual map of the Beast.

Microworlds. Microworlds are exploratory learning environments or discovery spaces in which learners can navigate, manipulate or create objects, and test their effects on one another. Microworlds contain constrained simulations of real-world phenomena that allow learners to control those phenomena. They provide the exploratory functionality (provide learners with the observation and manipulation tools and testing objects) needed to explore phenomena in those parts of the world. Video-based adventure games are microworlds that require players to master each environment before moving onto more complex environments. They are compelling to youngsters, who spend hours transfixed in these adventure worlds. Microworlds are perhaps the ultimate example of active learning environments, because the users can exercise so much control over the environment.

Many microworlds are being produced and made available from educational research projects, especially in math and science. In mathematics, the Geometric Supposer and Algebraic Supposer are standard tools for testing conjectures in geometry and algebra by constructing and manipulating geometric and algebraic objects in order to explore the relationships within and between these objects (Yerulshamy & Schwartz, 1986). The emphasis in those microworlds is the generation and testing of hypotheses. They provide a testbed for testing students' predictions about geometric and algebraic proofs.

The SimCalc project teaches middle and high school students calculus concepts through MathWorlds, which is a microworld consisting of animated worlds and dynamic graphs in which actors move according to graphs. By exploring the movement of the actors in the simulations and seeing the graphs of their activity, students begin to understand important calculus ideas. In the MathWorlds activity illustrated in Fig. 5, students match two

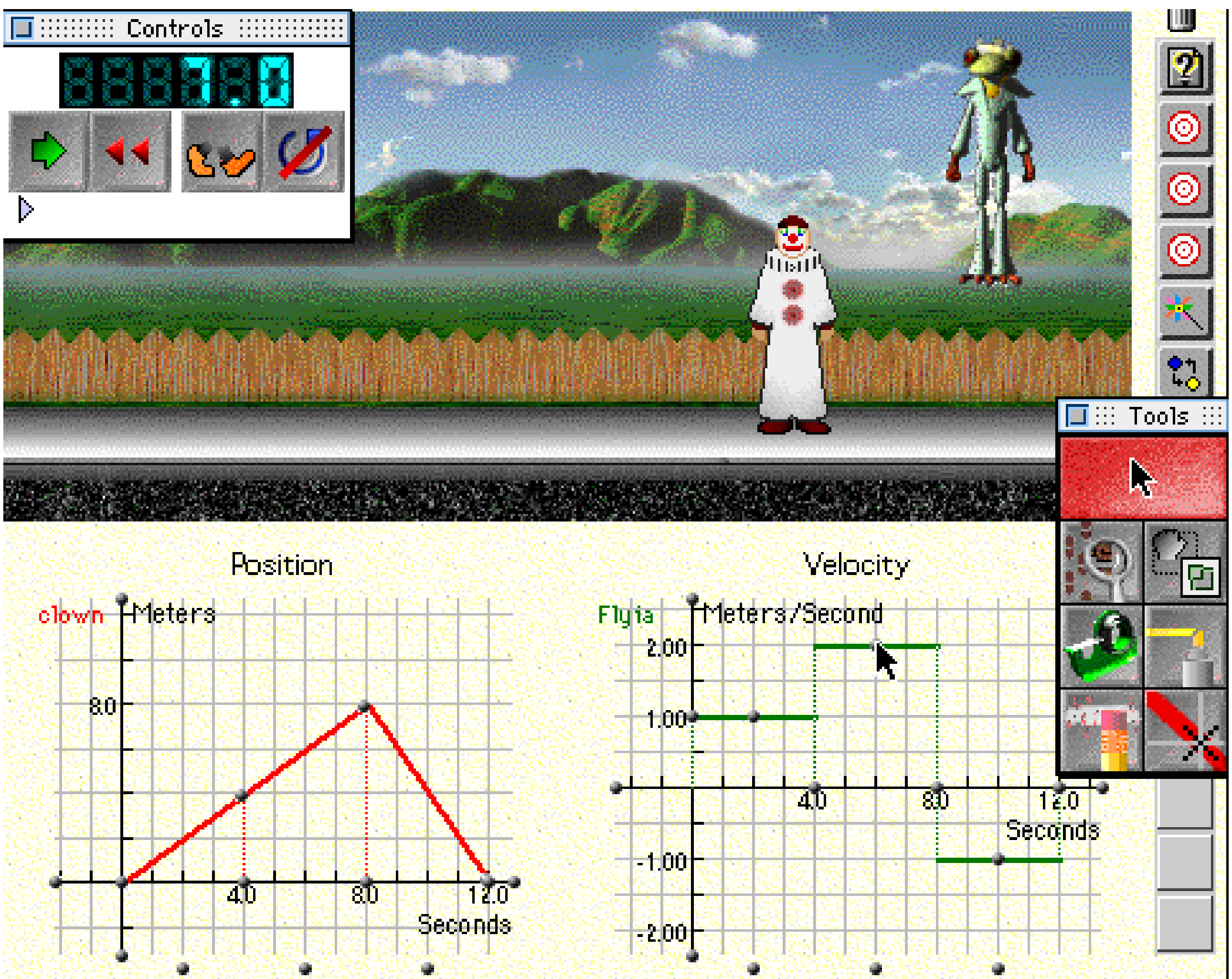


Fig.5. Experiment in Math World..

motions. By matching two motions they learn how velocity and position graphs relate. Students must match the motion of the green and red graphs. To do this, they can change either graph. They iteratively run the simulation to see if you got it right! Students may also use MathWorld's link to enter their own bodily motion. For example, a student can walk across the classroom, and their motions would be entered into MathWorlds through sensing equipment. MathWorld would plot their motion, enabling the students to explore the properties of their own motion.

Information Interpretation Tools

The volume and complexity of information are growing at an astounding rate. Learners need tools that help them to access and process that information. A new class of intelligent information search engines are scanning information resources, like the World Wide Web, and locating relevant resources for learners. Other tools, for helping learners make sense of what they find, are also emerging.

Visualization Tools. We take in more information through our visual modality than any other sensory system, yet we cannot output ideas visually, except in mental images and dreams, which cannot be shared visually except using paint/draw programs. While it is not yet possible to dump our mental images directly from our brains into a computer, a very new and growing class of visualization tools are mediating this process by providing us tools that allow us to reason visually in certain areas. Visualization tools help humans to represent and convey those mental images, usually not in the same form they are generated mentally, but as rough approximations of those mental images.

There are no general-purpose visualization tools. They tend to be specific to the kinds of visuals you wish to generate. An excellent example of a visualization tool is the growing number of tools for visualizing chemical compounds. Understanding chemical bonding is difficult for most people, because the complex atomic interactions are not visible. Static graphics of these bonds found in textbooks may help learners to form mental images, but those mental images are not manipulable and cannot be conveyed to others. Tools such as MacSpartan enables students to view, rotate, and measure molecules using different views (see Fig. 6) and also to modify or construct new molecules. These visualization tools make the abstract real for students, helping them to understand chemical concepts that are difficult to convey in static displays.

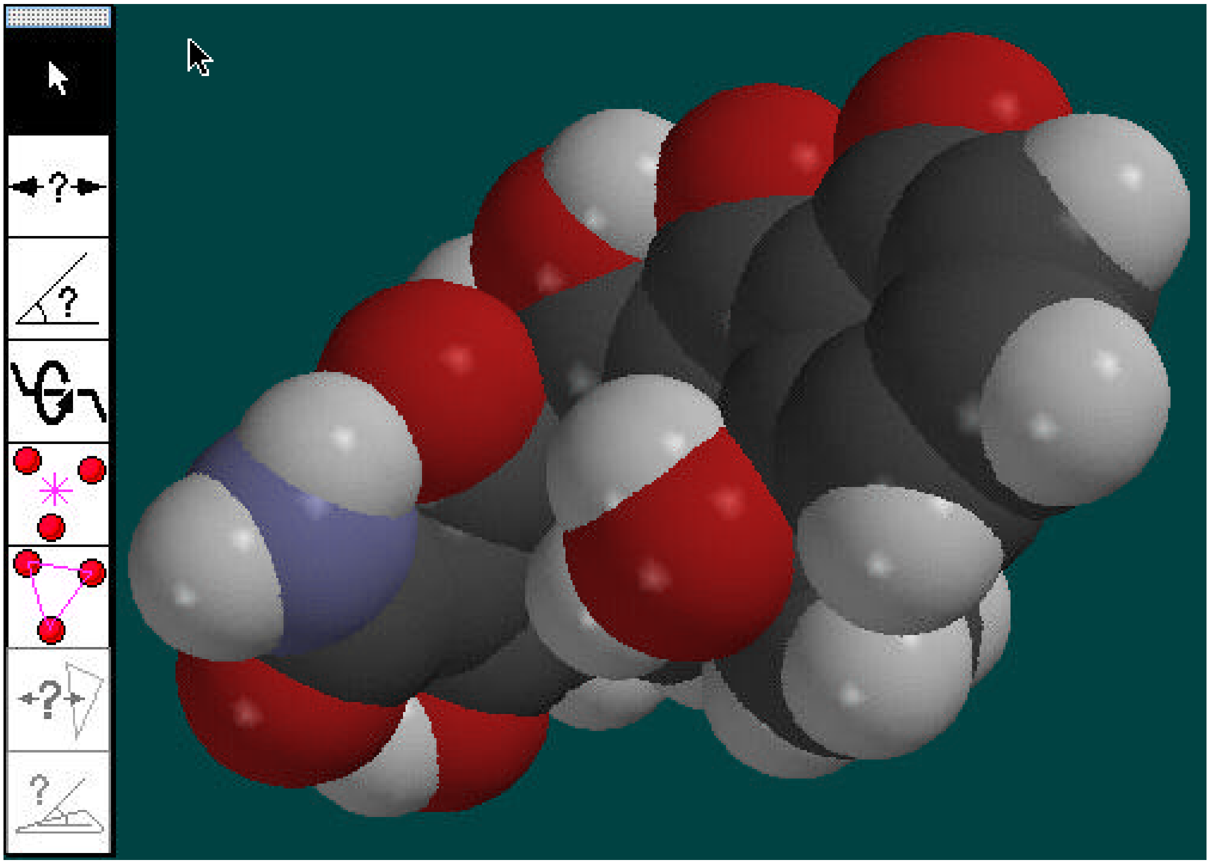


Fig 6. Tool for visualizing chemical compounds.

Knowledge Construction Tools

Papert has used the term "constructionism" to describe the process of knowledge construction resulting from constructing things. When learners function as designers of objects, they learn more about those objects than they would from studying about them.

Hypermedia

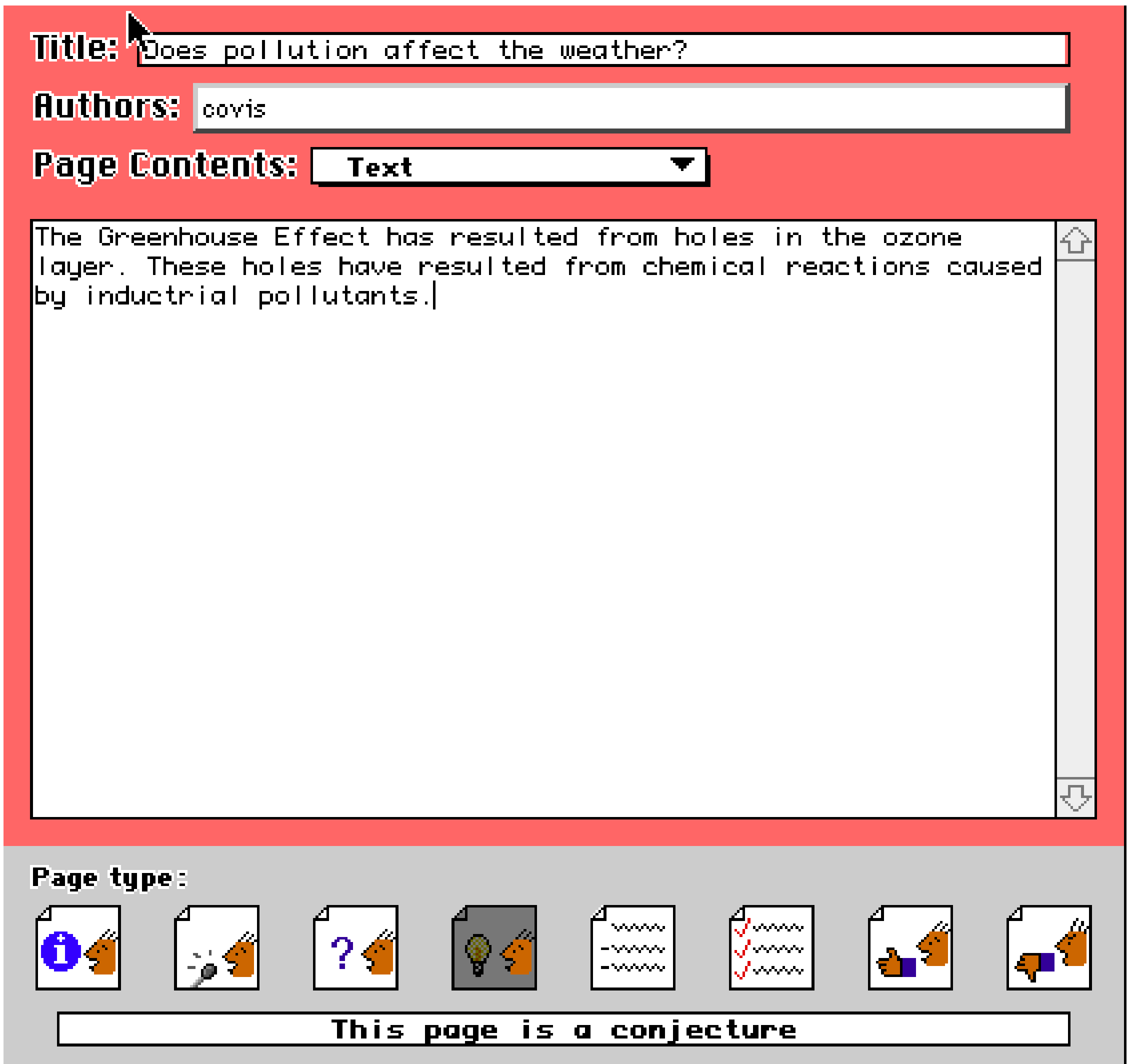
Hypermedia consists of information nodes, which are the basic unit of information storage and may consist of a page of text, a graphic, a sound bite, a video clip, or even an entire document. In many hypermedia systems, nodes can be amended or modified by the user. The user may add to or change the information in a node or create his or her own nodes of information, so that a hypertext can be a dynamic knowledge base that continues to grow, representing new and different points of view. Nodes are made accessible through links that interconnect them. The links in hypermedia transport the user through the information space to the nodes that are selected, enabling the user to navigate through the knowledge base. The node structure and the link structure form a network of ideas in the knowledge base, the interrelated and interconnected group or system of ideas.

While hypermedia systems have traditionally been used as information retrieval systems which learners browse, learners may create their own hypermedia knowledge bases that reflect their own understanding of ideas. Students are likely to learn more by constructing instructional materials than by studying them. Designing multimedia presentations is a complex process that engages many skills in learners, and it can be applied to virtually any content domain. Carver, Lehrer, Connell, & Ericksen (1992) list some of the major thinking skills that learners need to use as designers, including project management skills, research skills, organization and representation skills, presentation skills, and reflection skills.

Conversation Tools

Newer theories of learning are emphasizing the social as well as the constructivist nature of the learning process. In real world settings, we often learn by socially negotiating meaning, not by being taught. A variety of synchronous and asynchronous computer-supported environments are available for supporting this social negotiation process. Online telecommunications include live conversations, such as Chats, MOOs, and MUDs and videoconferencing, and asynchronous discussions, including electronic mail, Listservs, bulletin boards, and computer conferences. These many forms of telecommunications can be used for supporting interpersonal exchanges among students, collecting information, and solving problems in groups of students (Jonassen, Peck, & Wilson, 1998).Interpersonal exchanges may include keypals, global classrooms, electronic appearances, electronic mentoring, and impersonations (Harris, 1995). Examples of information collections include information exchanges, database creation, electronic publishing, electronic field trips, and pooled data analysis. Problem-solving projects include information searches, parallel problem solving, electronic process writing, serial creations, simulations, and social action projects.

Online communication presumes that students can communicate, that is, that they can meaningfully participate in conversations. In order to do that, they need to be able to interpret messages, consider appropriate responses, and construct coherent replies. Many students are not able to engage in cogent and coherent discourse. Why? Because, most students have rarely been asked to contribute their opinions about topics. They have been too busy memorizing what the teachers tell them. So, it may be necessary to support students’ attempts to converse. A number of online communication environments have been designed to support students' discourse skills, such as the Collaboratory Notebook (O'Neill & Gomez, 1994). The Collaboratory Notebook is a collaborative hypermedia composition system designed to support within- and cross-school science projects. What is unique about the Collaboratory is that it focuses on project investigations rather than curricular content. During a project, the teacher or any student can pose a question or a conjecture (Fig. 6), which can be addressed by participants from around the country. The Collaboratory provides a scaffolding structure for conversations by requiring specific kinds of responses to messages. For instance, in order to support the conjecture in Fig. 6, learners can only "provide evidence" or "develop a plan" to support that conjecture. This form of scaffolded conversation results in more coherent and cogent conversations.



Collaborative conversations are becoming an increasingly popular way to support socially co-constructed learning. Many more sophisticated computer-supported conferencing environments are becoming available to support learner conversations.

Rationales for Using Technology as Mindtools

Why do Mindtools work, that is, why do they engage learners in critical, higher-order thinking about content?

Learners as Designers

The people who learn the most from designing instructional materials are the designers, not the learners for whom the materials are intended. The process of articulating what we know in order to construct a knowledge base forces learners to reflect on what they are studying in new and meaningful ways. The common homily, "the quickest way to learn about something is to have to teach it,"explains the effectiveness of Mindtools, because learners are teaching the computer. It is important to emphasize that Mindtools are not intended necessarily to make learning easier. Learners do not use Mindtools naturally and effortlessly. Rather, Mindtools often require learners to think harder about the subject matter domain being studied while generating thoughts that would be impossible without the tool. While they are thinking harder, learners are also thinking more meaningfully as they construct their own realities by designing their own knowledge bases.

Knowledge Construction, Not Reproduction

Mindtools represent a constructivist use of technology. Constructivism is concerned with the process of how we *construct* knowledge. When students develop databases, for instance, they are constructing their own conceptualization of the organization of a content domain. How we construct knowledge depends upon we already know, which depends on the kinds of experiences that we have had, how we have organized those experiences into knowledge structures, and what we believe about what we know. So, the meaning that each of us makes for an experience resides in the mind of each knower. This does not mean that we can comprehend *only* our own interpretation of reality. Rather, learners are able to comprehend a variety of interpretations and to use each in constructing personal knowledge.

Constructivist approaches to learning strive to create environments where learners actively participate in the environment in ways that are intended to help them construct their own knowledge, rather than having the teacher interpret the world and insure that students understand the world as they have told them. In constructivist environments, like Mindtools, learners are actively engaged in interpreting the external world and reflecting on their interpretations. This is not "active" in the sense that learners actively listen and then mirror the *one* correct view of reality, but rather "active" in the sense that learners must participate and interact with the surrounding environment in order to create their own view of the subject. Mindtools function as formalisms for guiding learners in the organization and representation of what they know.

Learning *with* Technology

The primary distinction between computers as tutors and computers as Mindtools is best expressed by Salomon, Perkins, and Globerson (1991) as the effects *of* technology versus the effects *with* computer technology. Learning *with* computers refers to the learner entering an intellectual partnership with the computer. Learning *with* Mindtools depends "on the mindful engagement of learners in the tasks afforded by these tools and that there is the possibility of qualitatively upgrading the performance of the joint system of learner plus technology." In other words, when students work with computer technologies, instead of being controlled by them, they enhance the capabilities of the computer, and the computer enhances their thinking and learning. The result of an intellectual partnership with the computer is that the whole of learning becomes greater than the sum of its parts. Electronics specialists use their tools to solve problems. The tools do not control the specialist. Neither should computers control learning. Rather, computers should be used as tools that help learners to build knowledge.

(Un)intelligent Tools

Educational communications too often try to do the thinking for learners, to act like tutors and guide the learning. These systems possess some degree of "intelligence" that they use to make instructional decisions about how much and what kind of instruction learners need. Derry and LaJoie (1993) argue that "the appropriate role for a computer system is not that of a teacher/expert, but rather, that of a mind-extension "cognitive tool" (p. 5). Mindtools are *un*intelligent tools, relying on the learner to provide the intelligence, not the computer. This means that planning, decision-making, and self-regulation of learning are the responsibility of the learner, not the computer. However, computer systems can serve as powerful catalysts for facilitating these skills assuming they are used in ways that promote reflection, discussion, and problem solving.

Distributing Cognitive Processing

Computer tools, unlike most tools, can function as intellectual partners which share the cognitive burden of carrying out tasks (Salomon, 1993). When learners use computers as partners, they off-load some of the unproductive memorizing tasks to the computer, allowing the learner to think more productively. Our goal as technology-using educators, should be to allocate to the learners the cognitive responsibility for the processing they do best while requiring the technology to do the processing that it does best. Rather than using the limited capabilities of the computer to present information and judge learner input (neither of which computers do well) while asking learners to memorize information and later recall it (which computers do with far greater speed and accuracy than humans), we should assign cognitive responsibility to the part of the learning system that does it the best. Learners should be responsible for recognizing and judging patterns of information and then organizing it, while the computer system should perform calculations, store, and retrieve information. When used as Mindtools, we are engaging learners in the kinds or processing that they do best.

Cost and Effort Beneficial

Mindtools are personal knowledge construction tools that can be applied to any subject matter domain. For the most part, Mindtools software is readily available and affordable. Many computers come bundled with the software described in this paper. Most other applications are in the public domain or available for less than $100. Mindtools are also reasonably easy to learn. The level of skill needed to use Mindtools often requires limited study. Most can be mastered within a couple of hours. Because they can be used to construct knowledge in nearly any course, the cost and learning effort are even more reasonable.

Summary

Computers can most effectively support meaningful learning and knowledge construction in higher education as cognitive amplification tools for reflecting on what students have learned and what they know. Rather than using the power of computer technologies to disseminate information, they should be used in all subject domains as tools for engaging learners in reflective, critical thinking about the ideas they are studying. Using computers as Mindtools by employing software applications as knowledge representation formalisms will facilitate meaning making more readily and more completely than the computer-based instruction now available. This paper has introduced the concept of Mindtools and provided brief descriptions and some examples. More information and examples are available on the World Wide Web (http://www.ed.psu.edu/~mindtools/).

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