here are pervasive strategies for school work that may be broadly characterized as knowledge reproduction strategies. They have limited potential for advancing knowledge, and often are not even very effective for purposes of memorization and organization of knowledge. Their most conspicuous failure, however, is in the development of understanding. Knowledge building strategies are, by contrast, focused centrally on the development of understanding. These strategies, however, are comparatively rare among school children [6]. Worse yet, they seem destined to remain so because school discourse effectively excludes them.

Educational computing, unfortunately, tends to support knowledge reproduction strategies rather than knowledge-building ones. While this is obvious regarding much of the courseware on the market, in a more subtle way it is equally true of the software tools that are popularly thought to encourage more active learning. An explanation may be found in the origins of these software tools and in the evolution of the personal computer as a workstation. This evolution has been toward the needs of a business community concerned with storing and retrieving information (hence, the saliency of files and folders), transferring it (hence, cut-and-paste, import-export, and communications software), displaying it (hence, graphing, graphics, desktop publishing, and multimedia presentation software), and making plans and decisions based on it (hence, spreadsheets, accounting, and project-management software). Put it all together, and you have the desktop metaphor. It is not a metaphor for the construction and advancement of understanding. It represents activities that are important in any kind of information processing environment.

We propose that these activities—copying, deleting, storing, retrieving, entering, displaying, and sending—be thought of as first-order knowledge-processing activities. In order to serve the purposes of knowledge-building, however, they must be subordinated to a second-order system of activities that has understanding as its primary purpose. In this article we discuss second-order computing facilities and a system we are developing that aims to foster and support knowledge building in school. The system is computer-supported intentional learning environments (CSILE). It aims to engage students in the same sorts of intellectual and cultural processes that sustain real-world scientists in efforts at knowledge advancement.

Knowledge Reproduction

A common characteristic of many student strategies is that they provide efficient ways of completing school work while avoiding knowledge building. "Copy-delete" is a reading strategy used widely to summarize texts [4, 5]. Students evaluate propositions one-by-one as they encounter them, retaining those judged to be important and "deleting" those judged unimportant. They do not seek to identify the central point of the text. This copy-delete summarization strategy has been adapted for what passes as research in schools—students copying from reference books, skipping unwanted material. It has found new forms in multimedia composing where students copy sound bites, pictures, and movie clips as well as information from reference books, most frequently without referencing sources. "Knowledge telling" is the dominant school strategy for writing [2]. It parallels the copy-delete strategy in its bias for reproducing information. As the name conveys, the strategy is effective for telling what one already knows and thereby avoiding knowledge-transforming activities that occupy expert writers [19].

The copy-delete and knowledge-telling strategies for reading and writing are parallel and might be considered the same strategy applied to different tasks [18]. They bear a striking resemblance to strategies for solving school mathematics [22] and science [7] problems. In these content areas students apply learned algorithms and formulas triggered by superficial cues in the word problems presented to them. Sometimes the answers are nonsensical, but the strategies produce right answers often enough and are so economical that they persist.

The pervasiveness of school strategies that favor low-grade work with available knowledge is born and bred in a discourse model for schooling commonly referred to as the transmission model. Information exists out there; the teacher is the intermediary...
who transmits select bits of it to students. Within the transmission context the dominant discourse activities are presentation and recitation: teachers present information; through recitation and written or oral presentations, students provide teachers with evidence of learning [8]. Verbatim and paraphrased records have clear advantages over interpretation and inferential reasoning because the latter may convey lack of understanding.

Question-asking in schools is not really dialogic. The teacher asks a question and the student is expected to provide an immediate answer. If the answer is acceptable to the teacher, a new question is asked. If not, another student is queried. This is nothing even remotely like the process of progressive refinement of conjectures by which knowledge is constructed in the scientific world [11].

The essence of the transmission model is the belief that learning consists of producing in the mind of the individual student some kind of reproduction of the knowledge that exists out there in the objective or public world. Whether this copy of the truth has been received on authority or constructed through experimentation and discourse may make a difference in terms of efficiency and "ownership," but the intended result is the same. The correct things have been implanted into the mind of the student.

For a discussion of the epistemological issues raised by this conventional approach see [3]. Most significant here is that this transmission view of learning creates a climate in which copy-delete, knowledge-telling, and related math and science strategies are perfectly reasonable strategies for students to employ. These are strategies that make direct links between the knowledge out there and knowledge in the mind, minimizing possibilities of distortion.

Software

If we think of classroom discourse in terms of transmission models, then the object is to get the best of existing information to students. This general bias is reflected in the following uses of technology and interface design:

(a) Computer-assisted, individualized instruction and tutoring systems. These systems are characterized by provisions for identifying and tailoring instruction to the knowledge needs of the individual learner. Whether this is done in a flexible and subtle way or in a heavy-handed test-and-teach way, it casts the student into the role of recipient of knowledge rather than active constructor of it. For in active knowledge building, it is essential to be able to identify your own knowledge needs—to recognize what is unclear, puzzling, doubtful, incoherent, and so on. As we have argued elsewhere [21], the trick is to turn intelligence over to the user, not to hide it in the computer. This is not to deny an important role for intelligent tutoring—especially when it comes to learning specific skills—just to argue that such systems must be placed in a support rather than primary role.

(b) Business/Presentational Software. Facilities for assembling and presenting material are valuable, yet bring with them cognitive risks. Users often spend more time on visual appeal than on substance. Cut-and-paste and transfer of information between applications encourage shallow processing of content and collages—items linked together because of superficial topical resemblance.

(c) Email and Bulletin Boards. To understand limitations of email and bulletin boards for knowledge building, it is important to understand contrasting knowledge-building technologies, and we will elaborate on these. At this point we state a central feature: The flow of information must allow for progressive work on a problem, with ideas remaining active over extended periods of time and revisited in new and unexpected contexts.

Knowledge Building

From a constructivist standpoint, conceiving a new idea and learning are fundamentally the same process, as indicated in the following remark by Karl Popper:

. . . What I suggest is that we can grasp a theory only by trying to reinvent it or to reconstruct it, and by trying out, with the help of our imagination, all the consequences of the theory which seem to us to be interesting and important. . . . One could say that the process of understanding and the process of the actual production or discovery of . . . [theories, etc.] are very much alike. Both are making and matching processes. [17]

In a footnote, Popper explained, "The matching aspect is that it has to fit into a framework . . . ".

A 5th-grade girl in one of our CSILE classrooms expressed essentially the same idea, in response to being asked how she would know when she had learned something:

I think that I can tell if I've learned something when I'm able to form substantial theories that seem to fit in with the information that I've already got; so it's not necessarily that I have everything, that I have all the information, but that I'm able to piece things in that make sense and then to form theories on the questions that would all fit together.

The concept of learning represented in these quotations is radically different from knowledge reproduction. It is, clearly, a constructivist view, but it goes well beyond simplistic notions of learning by discovery. In this view, learning—like scientific discovery and theorizing—is a process of working toward more complete and coherent understanding.

The kind of discourse that supports such learning is not discourse in which students display or reproduce what they have learned. It is the kind of discourse that advances knowledge in the sciences and disciplines. It is the discourse of "conjectures and refutations," as Popper [16] called it. It is progressive in the sense that Lakatos [11] spoke of progressive research programs: The discourse advances by trying to deal with puzzling facts in ways that lead to more powerful explanations. In the sciences and learned disciplines this discourse is carried on through many media—journals, conferences, correspondence, debates, with discourses often extending over years.

If we are to support such knowledge-building discourse within the frameworks of education we need to establish the construction of knowledge as a social activity, with new
Ideas and information brought into the discourses of a community that shares goals for knowledge advancement and recognizes contributions. To accomplish this we need to develop technology that can help condense the discourse, sustain it through interruptions and across distances, and give it continuity over time. All of this is made difficult by the existing forms of schooling, geared to knowledge transmission, which reduce discourse to brief, topic-centered episodes, with none of the sustained effort toward coherence and completeness of explanation that are required for progressive building of knowledge.

Fundamental requirements beyond a supportive discourse community include means for representing current understandings and for bringing new information, suggestions, and criticisms to bear. Ideas need to be preserved and accessible to users of diverse talent and perspective in order to bias development toward increasingly sophisticated and multicultural perspectives. Progressive discourse does not mean simply that participants reach consensus or a decision. It means that participants, even if they hold differing views, all feel that some advance has been made, in their own understanding.

In addition to such global characteristics we have identified the following features that enhance knowledge building:

1. **Balance between public and private, and individual and group knowledge processes.** Participants need simultaneous access to the work of others to provide comparative models and opportunities to appropriate ideas more advanced than they might think of on their own. While access and interchange are important, so is time for reflection and refinement. Some participants shy away from public display. Facilities must allow users to enter notes anonymously and to move ideas between public or private spaces depending on need and response.

2. **Contribution and notification.** The challenge is to keep ideas from being trapped in file folders or topical groupings—or in individual file structures—and thus not available for upgrading and public debate. Commenting, labeling, and linking facilities, along with attendant notification systems must serve to link users and ideas in profitable ways.

3. **Source referencing.** Automatic source referencing preserves the centrality of the author's idea while crediting contributors and providing historical accounts of knowledge building. Designed properly, such facilities should upgrade copy-delete to a reference-and-contribute strategy.

4. **Storage and retrieval for situating ideas in a communal context.** Ideas are placed in the context of entries by others, with indexes that provide overlap and increase chances that notes written by authors working in different contexts on different aspects of a problem will be joined. This is not to deny the importance of unique identifiers, but to highlight the design challenge of situating ideas in broader contexts.

5. **Multiple points of entry for users of different ages and levels of sophistication.** Multirepresentational note forms (text, graphics, sound, mathematical) must be equally accessible, and entry on the basis of simple drawings, two-word texts, or other simple efforts must be possible for the youngest and most naive users. At the same time, sophisticated users must find the environment challenging without being weighed down by irrelevant material.

6. **Coherence-producing mechanisms for dealing with information overload.** In knowledge-building environments ideas are multiply tagged, linked, referenced, subordinated, superordinated, and so forth as they prove useful for knowledge activity. Ideas that foster no such activity are evident, as well. Combined database activity and notification facilities can be used to inform authors of ideas fading for lack of attention. Ideas can then be reinstated, returned to personal space, or deleted. In this way ideas of limited value are removed from the main corpus at the same time that productive activity is encouraged.

7. **Linked resources providing access to the world's most advanced knowledge resources.** Parallel local- and wide-area architectures with links to home, science centers, museums, art galleries, and so forth, are needed so sature student discourses within a greatly expanded discourse community. Further, links to all manner of knowledge resources—CD-ROM encyclopedias, microworlds, intelligent tutors, and so forth—are needed so that (a) best resources are available to support and expand dialogues in the central workspace and (b) dialogues in the central workspace enhance the educational value of linked resources.

**Current-day CSILE**

Although our goal is to embody all the preceding features in one coherent CSILE system, they are only partially implemented in the current version. We present a description of current-day CSILE, detailing installations and findings based on six years of use in public schools:

1. **Description.** In line with the objective of engaging students in conjecture, theory building, and analysis, and providing them with larger and more varied audiences for reflective engagement with ideas, CSILE has a communal database through which student-generated notes are, by default option, accessible to others. Such generalized access means that commenting on one another's knowledge-building efforts can become a natural and important activity. The comment presented in 1) in the box gives some sense of the support and challenges to progressive inquiry students provide for one another.

The database consists of text and graphical notes, all produced by the students and accessible through database search procedures. Anyone can add a comment to a note or attach a graphic note subordinate to another graphic note, but only authors can edit or delete notes. Graphical notes can also be used to create organizing frameworks for notes. Authors are notified when a comment has been made on one of their notes.

Specialized discourse environments [10] have provided the most
successful students model to date for engaging students in discourses centered on their theories. The note shown in 2) in the box is a typical sample of a coauthored note, in this case written by a pair of students working on the problem “How does gravity work?” Note that students’ theories are central and these young students are actively engaged in refining their ideas through uncovering and resolving gaps in their understanding.

We envision increasingly flexible discourse tools to support more varied and age-appropriate discourses.

2. Installations. CSILE is currently available in elementary, secondary, and postgraduate sites. There are nine sites in all, ranging from Baffin Island, NWT (approximately 80% Inuit population) to Oakland, California (inner-city, predominantly Hispanic and Southeast Asian). The base site in Toronto (close to our development lab and the site where new versions are first tested) is an ethnically mixed, predominantly middle class elementary site with CSILE in use daily in grades 1–6. A CSILE-based local area network (LAN) was first installed at this site six years ago linking two 5th- and 6th-grade classrooms. The 1st through 4th grade installations have now been in operation for three years, though this year is the first installation with Macintosh equipment, allowing all grades to be joined by a common LAN.

The standard CSILE installation has eight networked computers per classroom, connected to a file server, which maintains the communal database. CSILE is implemented with a client/server architecture optimized for real-time sharing of information.

1. Comment by 5th- to 6th-grade CSILE student

I have found your note on the circulatory system very interesting. I never knew that much before. I need to understand ... Does the speed at which we take breaths have any connection with the rate at which the blood gets pumped through our body? If so, what difference will the effect of breathing very fast have on us?

You can tell me in person.

Jessica

2. Group note produced in CSILE by 5th- to 6th-grade students

Problem: How does gravity work?

My theory: I think that gravity is really important. Without gravity we’d all fly off the face of the earth and be living in space. Gravity is also the thing that keeps the earth orbiting the sun. (Lisa)

My theory: I think gravity is generated by the earth's core. The closer you get to the earth's core, the more gravity there is. This is why there is no gravity in space. The earth's core acts like a giant magnet, pulling everything downward. (Carol)

I need to understand: Do other planets have gravity? (Carol)

New information: I read somewhere that other planets have gravity, but the amount of gravity is different depending on how big the planet is. (Lisa)

My theory: My theory is that bigger planets have bigger cores, and therefore have more gravity. (Carol)

New information: I read that scientists think gravity is caused by a particle called the graviton. To understand this, you need to know that everything is made of particles. There are two types of particles, matter particles, which have a half spin, and force particles, which have a full spin. Matter particles give off force particles like gravitons. Therefore, anything that has mass has gravity. (Lisa)

My theory: The more mass an object has, the more gravity it has, because mass causes gravity. Therefore, everything has gravity, even people.

The portable database server is written in C, with Unix (C, XWindows, TCP/IP) and object-oriented Macintosh (C++, MacApp, TCP/IP and AppleTalk) clients.

3. Findings. Results available to date suggest the model is powerful. CSILE students consistently show significant advantages over control-group students on:

- Standardized achievement tests of reading and language
- Portfolio selections and learning commentaries in the areas of writing, mathematics, and science
- Comprehension of difficult text and transfer of learning to novel problems
- Graphical literacy
- Depth of explanations in students' written reports
- Beliefs about learning consistent with a progressive view of knowledge advancement

Additionally, CSILE-based interactions enhance face-to-face learning by sustained problem solving over lengthier periods of time and with higher-level goals [13].

In summary, CSILE students consistently outperform control students (for more detailed accounts see [9, 12, 13, 14, 20]). Results also demonstrate that for most measures, each additional year students spend working with CSILE yields an additional advantage in results, and there is equal engagement by students at low and high ends of the ability spectrum, and by females and males.

Conclusion

The goal of computer-based knowledge-building environments in education is to fundamentally alter educational discourse so that knowledge reproduction processes give way to knowledge-building processes. In line with this we argue that current-day special-purpose software, along with email, bulletin boards, presentation software, and the like, must be subsumed by more powerful second-order, or what we refer to as knowledge-building environments for progressive discourse. CSILE is designed to encourage group processes and progressive discourse via its communal database. As authors of
public-access material, students come to see themselves as contributors to knowledge, not passive recipients. Their ideas are objects of inquiry, to be refined through interaction with others. Teachers do not direct discourses but engage in them, leading by virtue of being more expert learners. The best of the teacher's understanding is available to students, but does not circumscribe what is to be learned or investigated. As suggested by data presented earlier, such environments can lead to substantial educational achievements for students.

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