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A Conceptual Framework for Digital Libraries for K-12 Mathematics Education: Part 1, Information Organization, Information Literacy, and Integrated Learning

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A CONCEPTUAL FRAMEWORK FOR DIGITAL LIBRARIES FOR K–12 MATHEMATICS EDUCATION: PART 1, INFORMATION ORGANIZATION, INFORMATION LITERACY, AND INTEGRATED LEARNING[1]

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This article is the first of two that present a six-part conceptual framework for the design and evaluation of digital libraries meant to support mathematics education in K–12 settings (see also pt. 2). This first article concentrates on (1) information organization, (2) information literacy, and (3) integrated learning with multimedia materials. The second article reviews (4) adoption of new standards for mathematics education, (5) integration of pertinent changes in educational policy, and (6) ensuring pedagogic and political accountability. Each article concludes with specific recommendations for digital libraries meant to support K–12 mathematics education appropriate to the topics the article discusses. This framework, which may be of some use to researchers and educators in many settings and countries, emphasizes the importance of communication, community building, and learning activities that use different media for the design of digital functionalities and online collections of mathematics learning materials. The major goal of the framework described here is to consider how to bring the larger computationally intensive collections called digital libraries closer to the existing structures and practices of learners and teachers while recognizing the new functionalities and learning opportunities that digital libraries offer.

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Introduction

Many digital library projects focus on information management, collection development, authentication of users, the relative efficiency of specific searching and retrieval algorithms, and the creation of new systems, tools, and functions. Less attention has been paid to the use of digital materials for teaching and learning and how digital collections with powerful functionalities can be planned, designed, and implemented with pedagogic goals in mind [1]. It is a good time to examine digital libraries for mathematics education because (1) there are a growing number of national and international initiatives developing digital tools for mathematics (e.g., [2, 3]), (2) there are a growing number of subject standards developed by classroom teachers and state educational agencies (e.g., [4]), (3) there is increasing momentum to support high-stakes testing in K–12 settings despite what we know about the weaknesses of this approach (e.g., [5–7]), and (4) there is a growing body of research aiming to link subject standards, especially in mathematics and science, and digital tools for K–12 education (e.g., [8, 9]).

Relying on American experiences, this article identifies six elements essential to the design and evaluation of digital libraries intended to support mathematical learning and, in conjunction with the second article, makes a series of related recommendations:

1. The organization of online resources for K–12 mathematics education: digital libraries for educational purposes, especially mathematics education, should include multiple indexing and retrieval schemes, multiple interfaces, and access to synonyms.
2. Information literacy for students and teachers: this literacy includes the ability to generate and use text and multimedia sources (e.g., sound and various image representations) and the ability to demonstrate competence with mathematics vocabularies of all kinds.
3. Integration of online resources and learning activities: key to this integration are information visualization, multiple vocabularies, open inquiry, and the ability to generate learning/research narratives.
4. Sensitivity to and adoption of new standards for mathematics education: digital libraries for K–12 mathematics education must adhere to subject standards developed by professional associations of subject-expert teachers, while still being responsive to local pedagogic and social practices and meanings.
5. Awareness of important policy initiatives by governmental agencies, professional organizations, and private foundations: digital libraries for K–12 math education must be able to evolve as the national,

state, and local policy environments change, for example, respond to the No Child Left Behind Act; integrate new copyright legislation and case law, especially that related to digital material; and mitigate the ill effects of state and federal imposition of high-stakes testing as the presumed best way to demonstrate learning.

6. Ensuring accountability for the quality of online resources, especially their contribution to increasing the success of math education and adherence to educational standards: digital libraries for K–12 mathematics education, as noted above, must reflect the high subject standards developed by professional associations of teachers but also remain grounded in local meanings and practices, including classroom-based assessment; must include communication with parents and other caregivers; must rely on methods for assessment beyond high-stakes testing; must incorporate reflexivity in the classroom for learners and teachers; must emphasize formative evaluation; and must support the pursuit of educational equity.

There are other characteristics important to digital libraries, for example, the integrity of materials, but the six elements above are neglected in many discussions of educational applications of digital libraries, despite their being essential to the design and evaluation of digital libraries for K–12 mathematics education. Figure 1 illustrates some of the relationships among the six elements of our conceptual framework. Informed educational policy should serve as the foundation for educational standards developed by classroom teachers and their professional associations. Teachers can then use digital libraries as one means of achieving those goals, especially through the libraries' use of information organization, information literacy for students and teachers, and integrated learning. Finally, these efforts can contribute to increased accountability for achieving educational goals and increased educational success. The elements help ensure the most significant contributions that digital libraries make to mathematics education: communication, social negotiation of meaning, and actual doing of mathematics rather than the simple retrieval of what others have done.

This six-part conceptual framework is an integrated approach to taking large-scale, often abstract concepts (e.g., the primacy of the user and her local communities of practice) and instantiating them in particular system functions and capabilities. Such a holistic approach is clearly key to closing the significant gap between users' conceptual structures and learning activities, developed over decades and deeply embedded in (local) social relationships, on the one hand, and the structure and functionalities of digital libraries, on the other. The framework's emphasis on digital libraries as communicative technologies is a cornerstone of this argument. Em-

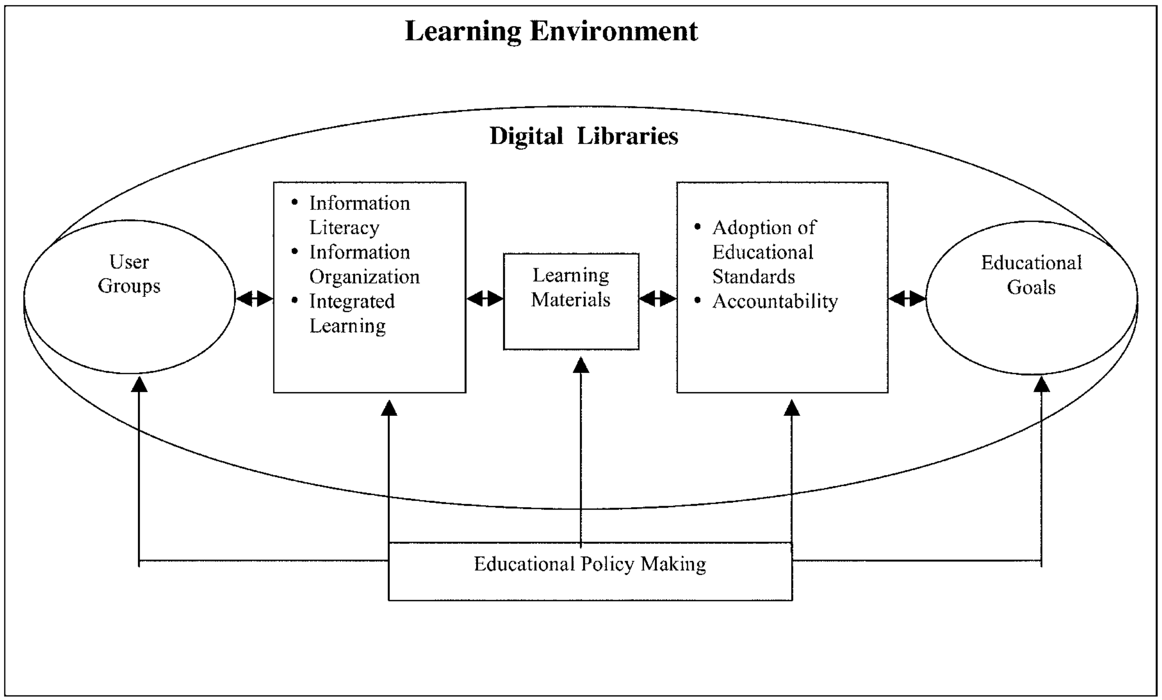

FIG. 1.—The six-part framework

phasizing digital libraries as means for many kinds of communication is essential to ensuring a successful marriage between existing pedagogic assets, for example, the current knowledge structures of learners and teachers and their practices for generating meaning, and the enhanced learning opportunities that well-designed digital libraries make available.

In contrast, the emphasis in the digital libraries literature on the creation of large digital collections and the digitization of existing materials is quite natural given the great challenges such activities present. Decades of research, for example, have clearly shown that the cataloging description of large collections is essential to the delivery of the right materials to the user. Most existing digital libraries, including those built for educational settings, rely much too much on browsing for learners and teachers to identify and find educational materials. Such reliance fails to capitalize on the sophisticated knowledge we have developed about material description and delivery, and it fails to capitalize on learners' and educators' existing pedagogic and social practices. Thus, the proposed conceptual framework builds on national educational standards developed by classroom teachers that help organize learning materials in ways useful to mathematics education in K–12 settings. These standards, to some extent, are driven by national and state policy initiatives and also counterbalance the growing movement to rely on high-stakes, standardized testing. Teachers and educational administrators have many educational goals, and a simple imposition upon them of the expectations carried by digital libraries for the success of K–12 mathematics education is naive and may, in fact, be counterproductive. Instead, we must also understand and explicitly recognize the multiple and sometimes conflicting constituencies who will judge the success of digital libraries in education. The proposed model integrates all of these concerns, and this article will concentrate on the first three elements of the six-part framework: the organization of online resources, information literacy for students and teachers, and the integration of online resources and learning activities.

As noted briefly above, the success of digital libraries in any application is a fruitful union between users' existing knowledge behaviors and understandings, on the one hand, and the sophisticated retrieval, manipulation, display, and integration functionalities that digital technologies offer. Proponents of high-stakes testing, discussed at length in the second of the two articles about the six-part framework, assert that the tests are based on subject standards developed by subject experts. At the same time, however, just as questionnaires provide only shallow understanding of people's behavior and values, so, too, high-stakes tests are poor instruments for measuring students' comprehension and ability to reason, especially as related to mathematics. Thus, our argument will highlight some of the ways that digital libraries can help overcome a naive belief that high-stakes tests are the best way to ensure learning and accountability. Similarly, the argument outlined in this series of two articles affirms that digital technologies, including digital libraries, are not the savior of the American educational system.

That system is based on a long-standing tradition of local control of public education, with the public system administered and monitored by state agencies, local school districts, and community organizations of all types. The primary source of funds for public schools in America is local property taxes, commonly assessed by county and city/town governments. Federal and state funds and large-scale initiatives, such as those related to the mandated integration of digital tools into the curriculum, mandated standards, and high-stakes testing, however, exert significant influence on local school practice and decisions. Successfully navigating this tension, balancing the sometimes contradictory imperatives of local control and local meanings with those of federally mandated change and performance, complicates the design and implementation of digital tools in the classroom. The six-part framework discussed here can help bridge this gap as well.

Libraries and Learning

For quite some time, libraries have been key learning centers in schools. In the analog environment, teachers and librarians arrange books, journal articles, and other learning materials and put them on reserve at the library. Students then come to the library to find and use the reserved materials. These actions reflect and contribute to a structure for knowledge in which teaching and learning activities have been developed for more than a century.

In the digital environment, this existing structure of knowledge has changed, but a new structure has not yet fully evolved. Intellectual and social intermediation in digital libraries exists to a greater or lesser extent depending upon the particular environment in question. Transactional intermediation, including functions such as “e-mail or ask the librarian,” is extremely useful but relatively rare. Consider the following scenario illustrating learning activities typical in the increasingly digital world of higher education in the United States and elsewhere: college students obtain passwords from the university; log into the campus network; use electronic materials such as course reading assignments, reserve books, and multimedia programs; search online databases; participate in class discussion and interact with peers and instructors, whether asynchronously or in real time; and complete class projects. In this scenario, students need to know what they want and how to retrieve the appropriate materials. Explicit consideration of this series of activities, however, is missing in most digital library projects. Research has shown that many students at all levels do not know how to retrieve information in either the physical or digital library. For example, Lori Leibovich [10] reports that many students use search engines to obtain information from the Web randomly and do not consider the reliability and accuracy of the information retrieved.

Users of the digital library, especially in higher education, are expected to be self-motivated, self-sufficient, and self-educated, retrieving materials largely by themselves. These assumptions may fit adult learners or people with sufficient knowledge in a particular domain, but what about schoolchildren?

Information Infrastructure and Learning

How users meet infrastructure is an essential part of the creation and design of digital library projects [11, 12]; infrastructures emerge only when local activities, communities, structures, and practices merge with standardized, global utilities. Christine Borgman [13] points out that the integration, interaction, and interdependence of information-related tasks and activities lead us to think in terms of an information infrastructure. Thus, several layers of an information infrastructure should be explored in the process of designing, implementing, and evaluating large digital collections: global, national, organizational, and personal. These layers must also be examined from technical and social perspectives.

According to Borgman, information infrastructure can be regarded as public policy, as technical framework, and as technology, people, and "content" [13]. In order to build a successful information infrastructure, then, an information architect must be knowledgeable about all of these components. In the scenario for higher education described above, that general imperative leads to two fundamental questions as we offer such powerful tools and such complex collections to increasingly younger students: How can and should teachers and librarians arrange learning materials in the digital library, and how can schoolchildren find those learning materials? As digital learning and teaching environments emerge and evolve, new teaching and learning models need to be developed when constructing them, for example, the National Science, Mathematics, Engineering, and Technology Education Digital Library (NSDL) at the U.S. National Science Foundation. The NSDL program seeks to create, develop, and sustain a national digital library that can support science, mathematics, engineering, and technology education at all levels [3]. (See also Sutton, Liddy, and Kendall [9] and the NSDL Web site [3].)

More generally, Maria Alberti and Daniele Marini [2] state that computer systems have unparalleled versatility and power for representing concepts and processes, giving students direct access to exploration and manipulation. Such systems are cognitive and metacognitive tools, helping to make abstract ideas both concrete and visible, while "providing an occasion for

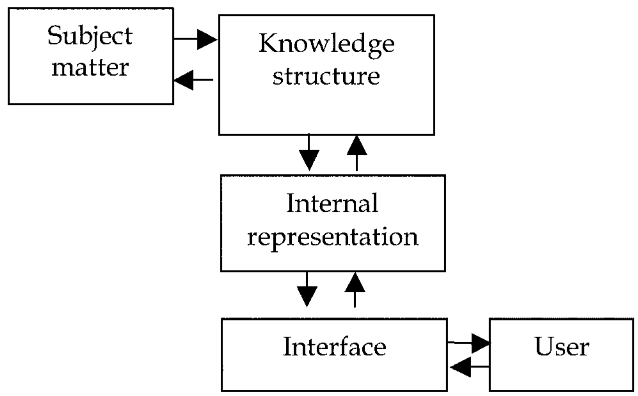

FIG. 2.—Elements of a knowledge-based virtual laboratory. Source: Alberti and Marini [2, p. 111].

turning the thinking process itself into an object of analysis and exploration" (p. 109). Figure 2, a copy of Alberti and Marini's figure (p. 111), presents what they call a knowledge-based virtual laboratory.

This figure and Alberti and Marini's discussion reinforce Andrea di-Sessa's argument that mathematics teachers and system designers should interest students in understanding and operating systems and in the development of such knowledge [14, 15]. Knowledge structure governs such learning activities and those described in the higher education scenario above. In a mutually constitutive way, knowledge structure represents the domain knowledge in different forms and in different modes, while teachers and learners express their ideas and locate learning materials using the knowledge structure.

For example, a teacher has to determine students' previous knowledge related to numbers, calculations, equality, and so on before being able to teach algebra. By doing this assessment, the teacher can identify the students' existing knowledge structures before helping them to develop new knowledge. Then, the teacher needs to connect the new algebraic concepts to students' existing competencies, relying in part on what Lev Vygotsky calls "scaffolding" [16]. When the teacher is teaching algebra, she especially needs to make sure that the students correctly understand the meanings of terms and words used in the classroom and can express themselves using these new concepts and terms. Only then can students reconstruct their knowledge structures as they interpret and make sense of the newly learned mathematical concepts.

This scaffolding process requires a holistic approach that, in turn, provides a framework for constructing digital libraries that can achieve three essential goals:

1. They will guide learning activities with the use of educational multimedia materials, that is, they will support integrated learning.
2. They will help ensure that students and teachers have the required knowledge and digital technology skills, that is, they will help ensure information literacy.
3. They will manage learning materials to match students' and teachers' educational needs, that is, they will be characterized by appropriate kinds of information organization.

The remainder of this article will explore what these characteristics mean and why they are important to the success of digital libraries for K–12 mathematics education.

Information Organization

The organization of online resources for K–12 mathematics education is the foundation of most online mathematics "libraries." The organization of these resources is one of the chief ways that we can increase the utility of such resources for the intended users of the system. A great deal of literature from the field of K–12 mathematics education has been focused on the analysis of mathematics vocabulary (e.g., [17–21]). Why is it important to understand the vocabulary of mathematics? Researchers from different fields have found that one of the fundamental problems in information retrieval is that many users cannot and/or will not describe their information needs using what the system would recognize as appropriate vocabulary [22–26]. Several decades of hard-won experience have taught systems designers and trainers that we cannot simply make users learn what we might term "system language." Instead, the organization of online mathematics resources, particularly indexing and retrieval schemes, clearly must be based on the search behavior, information utilization, and actual work practices of users, building on their existing competencies and interests [14, 27]. In our framework, the definition of information organization is based on this empirically sound assumption.

Civics Online [28] is a good example of such design: it reflects the learning and teaching behavior already in place in K–12 schools in the state of Michigan, uses terminology and information organization that builds on students' and teachers' existing competencies, and helps them to develop new skills. Civics Online is a collaborative, online project involving MATRIX (Michigan State University Center for Humane Arts, Letters, and Social Sciences Online) and H-Net (Humanities and Social Sciences Online), Michigan State University's College of Education, and a cadre of thirteen collaborating K–12 teachers from across the state of Michigan. To achieve its goals, this site provides a rich suite of primary sources of many kinds, a series of (interactive) activities that support the teaching of civics, and a variety of tools for teachers' professional development.

The site team has developed a set of what are called "core democratic values," such as the "rule of law" and "freedom of religion," which function as a kind of controlled vocabulary for the learning and teaching of civics. The user can use these to search for and retrieve multimedia primary sources. This vocabulary is complemented by and integrated with the goals, strategies, and objectives that the state of Michigan has developed in its K–12 curriculum framework for civics. This curricular framework covers all of the major subject areas taught in K–12 schools in the state and is an explicitly hierarchical typology that includes measurable objectives for general goals in civics, such as understanding the purposes of government and the political organization of nations around the world.

The design team of Civics Online plainly recognizes the key function of vocabulary in achieving such goals. With the assistance of its glossary and the core democratic values, students, teachers, and parents can retrieve relevant learning materials from Civics Online and communicate with each other during the learning process, thereby building important civics competencies. Figure 3 displays search functions available in Civics Online, while figure 4 shows the first few terms in the Civics Online glossary. They are arranged alphabetically and are expressed in language appropriate for K–12 students. The authors did a simple search on the term "justice" in the core democratic values dialog box shown in the search page noted earlier. Figure 5 displays a record resulting from that search. The final field in the record provides reference to the pertinent Michigan State standards for curricula in public and private schools in the state.

In contrast is the Mathematical Sciences Digital Library (MathDL) project at Duke University [29]. MathDL is part of the national digital library supporting science, mathematics, engineering, and technology funded by the National Science Foundation noted above. It is also managed by the Mathematical Association of America and is an online resource intended to support students and teachers of collegiate mathematics. MathDL includes the *Journal of Online Mathematics and Its Applications* (*JOMA*), along with a catalog of commercial products for mathematics and a collection of mathematics learning materials. Figure 6 indicates that MathDL provides only the browse function to identify and navigate through its collections; no indexing mechanisms or search functions are available. This lack of discovery tools is to be expected since the MathDL project is still in an early stage of development. Such a lack, however, also illustrates the usual

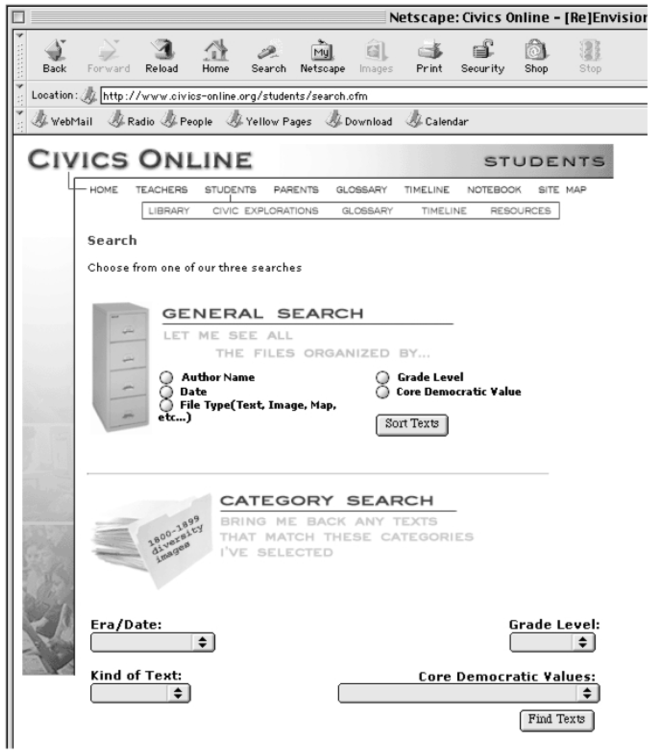

FIG. 3.—Civics Online search interface [28]

FIG. 4.—Civics Online glossary [28]

FIG. 5.—Examples of core democratic values and curriculum standards from Civics Online [28].

state of affairs in digital libraries, including those intended for use in learning environments. What one can do in Civics Online and what one can imagine one can do there are quite different from what the user can imagine about the use of Math DL. Much of the difference springs from Civics Online's robust, well-integrated, and useful vocabulary structure and how that vocabulary structure provides clear organizing principles for the site and useful functionalities to its users.

Unified Medical Language is another example of a vocabulary and indexing scheme based on users' needs [30], as well as of a scheme that helps prepare users to make the most of complex, online corpora. In 1986, the U.S. National Library of Medicine began a long-term project to build the Unified Medical Language System (UMLS), the goal of which is to support "the development of systems that help health professionals and

FIG. 6.—How to browse in the *Journal of Online Mathematics and Its Applications* in MathDL [29].

researchers retrieve and integrate electronic biomedical information from a variety of sources and to make it easy for users to link disparate information systems" (30, intro.).

There are three UMLS knowledge sources: the UMLS Metathesaurus, the SPECIALIST Lexicon, and the UMLS Semantic Network [31]. The Metathesaurus contains information about biomedical terms and concepts from a number of controlled vocabularies and classifications used in a variety of collections, for example, patients' records, administrative health data, bibliographic and full-text databases, and expert systems. The Metathesaurus also "preserves the names, meanings, hierarchical contexts, attributes, and inter-term relationships present in its source vocabularies; adds certain basic information to each concept; and establishes new relationships . . . [among] terms from different source vocabularies." The Lexicon, for its part, has syntactic information for many terms, component words, and English words that are not in the Metathesaurus. The third tool, the Semantic Network, contains information about "the types or categories to which all Metathesaurus concepts have been assigned and the permissible relationships among these types" [31].

Civics Online and Unified Medical Language demonstrate the importance and power of vocabulary-sensitive information organization for digital libraries. The knowledge structure of digital libraries must embrace, reflect, and help define the structure of domain knowledge and also must be integrated into the kinds of learning activities described earlier, for example, the identification of digital learning materials and their utilization. It is wise to recall, with Debra Neuman [32], that words are the keys to concepts and that we cannot expect children to be successful users of digital libraries without the considerable support offered by systems organized clearly and in conjunction with controlled vocabularies. Michael Buckland [33] provides a clear description of the vocabulary complexities and opportunities for vocabulary mismatches that often prevent users from successfully using even the most sophisticated digital library.

Education for Information Literacy

In order to integrate information organization into learning activities and to create corpora of learning materials that use what we know about the primacy of vocabulary in information organization, instructors and learners must be "information literate." Information literacy, despite its contested nature, has become a vital component of the education system [34–37]. Owing to the rapid development of new technologies, the definition of information literacy is still evolving and will continue to be a source of controversy. The Association for Educational Communication and Technology and the American Library Association, nonetheless, outline some useful information literacy standards for students' learning [38]. These standards identify information literacy, the keystone of lifelong learning, as the ability to find and use information. The standards further assert that information-literate learners can harness and use information for a productive and fulfilling life.

"Classic" theorists in information science have promulgated models of the information search and utilization processes, while researchers in education and pedagogy have developed theories of the learning process. These two sets of theories display strong parallels between information searching and learning. Information literacy ties them together [32]. One particularly well-known example is Michael Eisenberg and Robert Berkowitz's Big6 Strategy for information literacy [39]. The Big6 applies an information problem-solving approach, including six components:

Task definition.—defining the information problem and identifying information needed to address it;

Information-seeking strategies.—determining the range of potential sources, evaluating these sources, and prioritizing them to select the best sources;

Location and access.—locating sources, intellectually and physically, and finding information "in" the sources;

Use of information.—engaging the information in a source in a variety of ways, for example, reading, hearing, and viewing, and then "extracting" the most relevant information;

Synthesis.—organizing information from multiple sources and presenting it in an integrated fashion;

Evaluation.—assessing the product(s) for effectiveness and the information problem-solving process itself for efficiency.

The Big6 approach is widely known in the school library and K–12 communities in the United States, and many schools have implemented the Big6 Strategy to support students' learning and the training of teachers. Further, many private sector companies have implemented this approach for their employees' professional development.

Carol Kuhlthau's well-known model of the information search process (ISP) also has contributed an in-depth understanding of the importance of information search behavior to the development of information literacy [40]. In her model, the first stage of the search process is initiation, in which an individual recognizes her need for information (of course, many information needs are not conscious or explicit). The next step in her model is selection—the individual identifies and selects a general topic to be investigated. The third stage is exploration, wherein the individual attempts to reconstruct her knowledge structure by exploring information on the general topic. In formulation, the fourth and most important stage, the individual focuses on a more specific topic and activities. The next stage is gathering information from the information resources, while the final stage is presentation.

Kuhlthau has expanded her consideration of the ISP to digital libraries. There, she contextualizes her discussion by asking: "What are some of the main considerations for learning in digital libraries? What problems do learners encounter? . . . What are some of the theoretical underpinnings for guiding meaningful learning in digital libraries?" [41, p. 709]. Such a context gives specificity to how digital libraries can undergird new learnings and understandings and how, through coaching, facilitating, and mentoring, teachers and librarians can support learning in digital libraries. In discussing the ISP in digital libraries, Kuhlthau emphasizes the importance of students' development of meaning and formation of personal perspectives on the "information encountered." It is here that information literacy plays a vital role.

Other models of information behavior that give us particular insight into the relationship between information literacy and learning in digital environments include the work of Marcia Bates; Chun-Wei Choo, Brian Detlor, and Dun Turnbull; David Ellis; Gary Marchionini; and Thomas Wilson [42–46]. These models demonstrate how complex our information behavior is and how important material and social circumstances are to the use of digital tools, especially in educational environments. Because learning and teaching that rely on information literacy are so demanding, teachers as well as students face some significant challenges adopting information literacy approaches to education. Among them, of course, is that many teachers are not prepared to use advanced digital technologies in their classrooms. In a study done by the National Center for Education Statistics [47] in the U.S. Department of Education, only one-third of the teachers surveyed felt prepared to use digital technologies. This finding has especially important implications for digital libraries in education because, as a University of California at Irvine study has shown, "teachers who are generally uncomfortable initiating interactive, constructionist engagement with their students are also uncomfortable using computers in teaching" [27, p. 42]. Further, Barry Fishman et al. [48] state that common difficulties for American science teachers are classroom management strategies, the organization of knowledge, and assessment of students' performance. They say that inquiry-oriented teaching demands teachers who have subject knowledge "deeper and broader than in traditional recitation teaching, in order to accommodate students' questions and investigations." Fishman and his colleagues also point out that fostering students' meaning making and creating opportunities for contextualization are an especially demanding, if rewarding, part of teachers' professional development.

Integration of Online Resources and Learning Activities

Information organization and information literacy plainly help to support and define each other. In Civics Online, all materials are organized according to a structured vocabulary, defined by the state of Michigan's education requirements. Instructors and learners can communicate and express their ideas with the structured vocabulary while using online learning materials. The structured vocabulary can help students develop a knowledge structure (a grounded sense of the domain) appropriate to the available learning materials. Similarly, structured vocabulary helps students more fully grasp and create the contextual meanings of these materials on a local level.

Previous studies of language and mathematics have shown that mathematical concepts, for example, the algebraic, geometric, and probabilistic, can help us understand real-world situations [17–21, 49, 50]. Then students, assisted by their teachers and fellow students, must be able to articulate their understanding of these situations and the apposite mathematical concepts in ways appropriate to their local circumstances. There are at least three modes of communication and activities that are demanded in this sort of proactive numeracy:

- Self-generated verbal descriptions of the real-world situation and the appropriate mathematical concepts and relationships;
- Graphical expression, for example, the ability to use software, paper and pencil, and other tools to generate pictures of the situation and the salient relationships among its component parts, in whatever forms are useful;
- An ability to identify and use the right sorts of formulas, definitions, and other generic mathematical tools to describe the situation and address it mathematically.

As we know, a mathematically literate or numerate person is able to accomplish all these tasks and move from one to the other in both familiar and unfamiliar circumstances. These modes are complementary, of course, not identical. Similarly, each mode of expression gives us different insights into the real-world problems we want to understand, while each mode also has limitations.

Chris Hancock [23, p. 240] notes that this sort of numeracy, unleashed by the most successful of digital tools, is "part of the trend away from learning *about* mathematics and science, towards learning to *do* mathematics and science." Thus, digital libraries hoping to support this kind of generative mathematical ability must explicitly integrate concerns with terminology and information organization with the desire to help their users develop an enhanced sensitivity to terminology and a new ability to use such terminology appropriately. In so doing, digital libraries can be very useful in supporting what Kuhlthau [41] identifies as two of the most important activities that students can perform: (1) conversing with each other, their teachers, and others and (2) composing. In math digital libraries, these activities are demonstrations of and spurs to mathematical maturity. Also see Kathleen Schoenberger and Lori Liming [20] and Michal Yerushalmy [51].

G. Marshall [52] is one voice among many that point out that the use of technologies does not automatically ensure achievement of educational goals and that learning goals and outcomes, as well as learners' needs, must be the focus of technology-based instruction. Furthermore, the integration of online learning resources and learning activities must rely on the appropriate use of new standards for education. Information organization and information literacy plainly help to support and define each other. Civics Online, for instance, organizes all materials according to a structured vocabulary, defined by the state of Michigan's education requirements. Instructors and learners can communicate and express their ideas with structured vocabulary while using the online learning materials.

The integration of online resources and learning activities might best be achieved through an organizational transformation of schools. Schools and learning institutions today are already very different from those of previous generations, especially where information technologies (IT) are heavily used and integrated into them. Without falling prey to the extravagant claims of IT's supposed "revolutionary effects," we can recognize that such technologies give rise to new social networks, information behaviors, and organizational forms. For example, in the last five years universities, governmental agencies, and private sector companies have created or expanded their distance education programs, making some totally digital. Many of these programs, however, have either failed or plan to close their doors soon [53]. One of the major reasons for their failure is that many of the distance education programs do a poor job of integrating online resources with learning activities; thus, learners have too often failed to find required learning materials or to identify what they should do in the virtual classroom [54]. Fathom.com, Columbia University's $25 million, for-profit effort in distance education, has recently closed and will fold a more selective set of its online courses into other digital initiatives. Despite working with a number of partners and having access to a large set of distinguished faulty members, Fathom.com could not help users overcome difficulties cited by Ann Kirschner, the company's chief executive: "One of the greatest barriers to online learning was people's unfamiliarity with the process. . . . They know what a book is. They know what a course is. But what exactly is an online course? That they didn't know" [55].

Similarly, while studying the use of the electronic resources in K–12 education, J. L. Branch [56] found that participating junior high school students did not know how to find additional search keywords from assigned topic searches while using CD-ROM encyclopedias. She recommended that the students should have practical education in developing knowledge focused on generating keywords for the use of electronic resources. These findings make explicit the important connections among information literacy, use of digital tools, and the use of (mathematical) language.

According to previous studies of language and mathematics, students are unable to comprehend vocabularies used by their teachers in math class, possibly because mathematics instruction often focuses on computation rather than on the creation and communication of mathematical meanings [17–21, 50]. Without mathematics curricula that explicitly integrate the three elements of numeracy discussed above (verbal descriptions, algorithmic operations, and visual presentation), students lack the knowledge and communication skills to understand and discuss mathematical concepts. In addition, new mathematics education standards and state-mandated tests have had an impact on the language problems in mathematics class. Previous studies of the quality of K–12 mathematics education have indicated the importance of analyzing the language used by teachers and students. Language analysis is not only important to the general improvement of K–12 math education but is especially important to the design of digital libraries for K–12 math education.

During the past decade, we have seen great strides in the design of new learning technologies that support standards-based, constructive, and inquiry-focused learning and teaching practices. Although a substantial body of research demonstrates that these technologies can help students learn when used appropriately, they are “rarely used beyond the small-scale settings in which they are designed” [57, p. 1]. Further, the integration of online learning resources and learning activities relies on the appropriate use of new technologies and media.

Toni Downes and Katina Zammit [34, p. 122] construct a curriculum model for new learning environments (fig. 7). As indicated in their framework, the curriculum model requires both new pedagogical practices and curricular changes. Students’ learning competencies in “the digital age” must be multifaceted. Students must be able to recognize, locate, assimilate, and integrate a rich array of media during the learning process, and students also have to demonstrate their learning outcomes in such media. Such abilities underscore how it is that well-designed digital technologies can help liberate learners, teachers, and others from domination by externally imposed standards, especially high-stakes tests.

Downes and Zammit’s approach identifies several components of education in digitally supported learning environments. The roles of instruc-

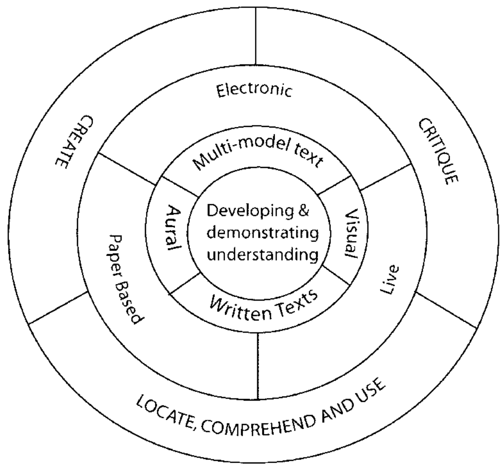

FIG. 7.—A curriculum model for new learning environments. Source: Downes and Zammit [34].

tors and learners are particularly important: instructors must be facilitators, monitors, and consultants, while learners must be engaged by learning materials and must initiate most activities. Active engagement is the core of the learning process, and each individual in the process has to communicate with others consistently, using appropriate rhetorical and technical modes.

1. *Communication modes.*—Both synchronous and asynchronous modes are important for the communication process. These modes provide instructors and learners flexibility to cooperate and work in teams in different phases of the learning process. Communication modes also influence the design of computer-based learning environments. For example, electronic bulletin boards and discussion groups are asynchronous, while chat rooms and live teleconferencing are synchronous. By offering these different communication methods, teachers and course designers provide multiple opportunities to learn, as well as to form and reinforce important social bonds. Some well-known tools commonly used in commercial distance education systems, for instance, WebCT and Blackboard, provide teachers and students with different communication channels such as discussion boards, chat/whiteboards, group e-mail, and file exchange [58, 59].
2. *Communication and information literacy.*—As discussed above in our consideration of information organization, the use of structured mathematical vocabularies, mathematical symbols, and advanced digital functionalities by learners and instructors to communicate

with each other is essential to the learning process [35, 60]. These vocabularies, symbols, and functions help the learner establish a rich knowledge structure, and the learner can use the structure to retrieve internal resources (e.g., lesson plans) and external resources (e.g., related Web sites).

3. *Choice of media.*—Communication modes and media choices are mutually constitutive. For example, an instructor can choose to use a live teleconference (synchronous mode) first to work with learners who can attend the conference. Later on, the instructor can convert a recording of the teleconference to streaming video or another (asynchronous) format for learners who cannot attend. The information resources are similar, but different media are used to serve learners in different circumstances. The MIT OpenCourseWare Pilot is a good example of a project that provides a variety of educational materials that employ different media formats from text, graphics, and videos to different software programs [61].
4. *Design of learning materials.*—Learning activities, learning materials, and learning outcomes are three pillars supporting the learning process. Learning materials are designed to stimulate learning activities, to inspire learners to construct their learning strategies, and to help learners demonstrate their learning outcomes [62]. The instructor can apply different theories such as generative learning, discovery-based learning, situated learning, and cognitive apprenticeship to create learning materials with contextual meanings and to support activities that allow students to create such meanings.
5. *Accessibility and usability.*—The complexity of online environments challenges network administrators, instructors, and learners when the instructor uses a rich array of media online [63]. Difficulties can occur easily. First of all, network administrators and instructors should be aware of learners who may need extra equipment, hardware, and software to participate in learning activities [64]. Second, given the many different file formats for media that exist, instructors must ensure that every learner can receive, view, and manipulate the chosen file formats. Third, special needs should be addressed, such as those faced by learners with physical challenges [65].

Extravagant claims too often surround digital technologies and their supposedly “revolutionizing effects.” Such claims abound not only in the commercial media but, unfortunately, also in educational environments. At the same time, however, it is clear that these same technologies, designed and implemented wisely, can facilitate the kind of active, engaged learning that educational theorists and practitioners demand for their students.

Recommendations

Communication is the essence of the six-part framework for K–12 mathematics education using digital libraries described here: information organization, information literacy, digital libraries as tools for integrated learning, new standards for education, educational policy making, and political accountability. The discussion in this article has explored the constitutive importance of vocabulary development, the user perspective, the doing of mathematics rather than only reading about it, the value of reflection and self-evaluation, the need for multiple (multimedia) modes of creation and exploration, and the primacy of community and communication in learning. The second article more explicitly explores educational policy, educational equity, subject-specific standards, and pedagogic and political accountability. The authors believe that this framework is key to the success of digital libraries in K–12 mathematics education: it provides a means to translate a dedication to users' success to specific ways to support K–12 mathematics education (see the recommendations below), and it underscores how the design and implementation of digital tools is never without social, political, and highly localized contexts. Using this kind of framework, designers and users of digital libraries for mathematics education can create the kinds of communities that are the wellspring of learning and the products of learning.

With this framework as a foundation, especially this article's discussion of information organization, information literacy, and digital libraries as tools for integrated learning, we offer the following recommendations for designing and evaluating digital libraries in K–12 math education in the United States. These recommendations reflect the importance of communication, reasoning, reflection, collaboration, and representation to the success of digital libraries in educational environments. Table 1 summarizes these recommendations.

Different indexing mechanisms.—These should be available to index the rich array of multimedia materials that digital libraries can make available and create. These alternative ways to classify materials should be linked to subject standards (as in Civics Online, described above) as well as more generally based on an end-user perspective that allows students and instructors to match their mathematics knowledge structures and terminologies with the indexing mechanisms available in digital libraries for math education. See Buckland [33] on the essential role that vocabulary plays in digital libraries and the serious obstacles difficulties with vocabularies present to the success of digital libraries. He also ties his discussion of vocabularies to important questions of identity and social categories.

Access to synonyms.—Students and teachers must have access to synonyms, including those developed in educational standards, in order to help

TABLE 1
RECOMMENDATIONS FOR THE DESIGN OF DIGITAL LIBRARIES

Characteristics of Successful Digital Libraries for K–12 Math Education
Different indexing mechanisms, some aligned with educational standards
Access to synonyms, some also linked to educational standards
Range of resources with regard to difficulty and learning capability, also calibrated with educational standards
Multiple retrieval mechanisms and interfaces
Text as well as multimedia sources
Ability to create and manipulate objects online
Information visualization functions
Ability to reflect on learning and create narratives
Support of exploratory learning and open inquiry

match their conceptual structures and vocabularies to those of digital libraries. This imperative is especially strong for research across multiple resources. Raya Fidel and colleagues [66] also recommend the availability of an encyclopedia and help with spelling, while Schoenberger and Liming [20] demonstrate the value of glossaries of mathematical terms made by students. Such glossaries (1) are indispensable tools in students' development of abilities to use mathematical terms and concepts correctly and (2) are tools for demonstrating those abilities.

Range of resources.—Digital libraries for learning all topics, including mathematics, must also include a range of resources with regard to conceptual complexity, especially "basic information" related to curricular needs, for example, textbooks and young adult trade books [32]. These levels of complexity should also be linked to educational standards.

Text resources.—There must be text as well as multimedia resources available since many students cannot take notes or otherwise recall information from multimedia sources [32].

Multiple retrieval means.—There must also be multiple retrieval mechanisms and interfaces in math education digital libraries. Different indexing mechanisms can facilitate different retrieval protocols as described by a wide range of researchers [10, 41–44, 46]. Tamara Sumner and associates [1], in studying thirty-eight K–12 and college science teachers, also found that good digital libraries of scientific materials demand the integrated and high-quality use of graphics, well-organized materials, language appropriate to the intended audience(s), and alternative "content" descriptors—also see Ian Witten and David Bainbridge [67].

Creation of online objects.—Digital libraries for math education must allow students and instructors to create and manipulate objects online by using digital tools to do mathematics and not just learn about doing mathematics. These functionalities should apply to material created by students, as well as to material retrieved by students.

Information visualization.—Students and instructors should be able to use techniques of information visualization to present and communicate their ideas, to create, not simply retrieve, mathematical material. Many students need such hands-on experience to support their learning activities. Using multimedia creation capabilities and multimedia materials available from digital libraries enriches these learning activities and provides multiple opportunities and modalities for such expression. Figure 8 illustrates how Neptune's functionalities can show learners immediately and in clear graphical form what happens when they manipulate values of two related variables on a Cartesian plane [68].

Necessity of reflection on learning.—Students must be able to use digital libraries to reflect on their learning and create narratives, for example, research journals to support and encourage enhanced understanding of material, especially as that material grows in complexity and cross references [41]. Yerushalmy [51] shows how students of algebra can successfully use digital environments to create narratives that use sophisticated verbal and iconic elements. These narratives are rich combinations of natural language, iconic notations, and complex mathematical ideas, melding qualitative and quantitative modes of analysis.

Tools for exploratory learning.—There must be tools, functionalities, and a classroom culture that support exploratory learning and open inquiry [50, 57, 69]. This kind of culture especially maximizes children's willingness to experiment and, thus, increases their expectations of themselves and their classmates as mathematicians. Describing one such environment where students did programming among other tasks, diSessa [15, pp. 355–56] notes that "the library became a social networking device in which students saw what others were capable of, and from which they 'stole' ideas and code for their own use."

Conclusion

This article outlines a framework for the creation and evaluation of digital libraries for mathematics education in K–12 settings. This conceptual approach emphasizes the importance of the organization of learning materials, information literacy education, and integrated learning. The organization of learning materials, in particular, must be based on the analysis of mathematics vocabulary and users' search behavior, information utilization, and actual work practices to facilitate the use of learning materials.

Successful information literacy education, whatever its character [36,

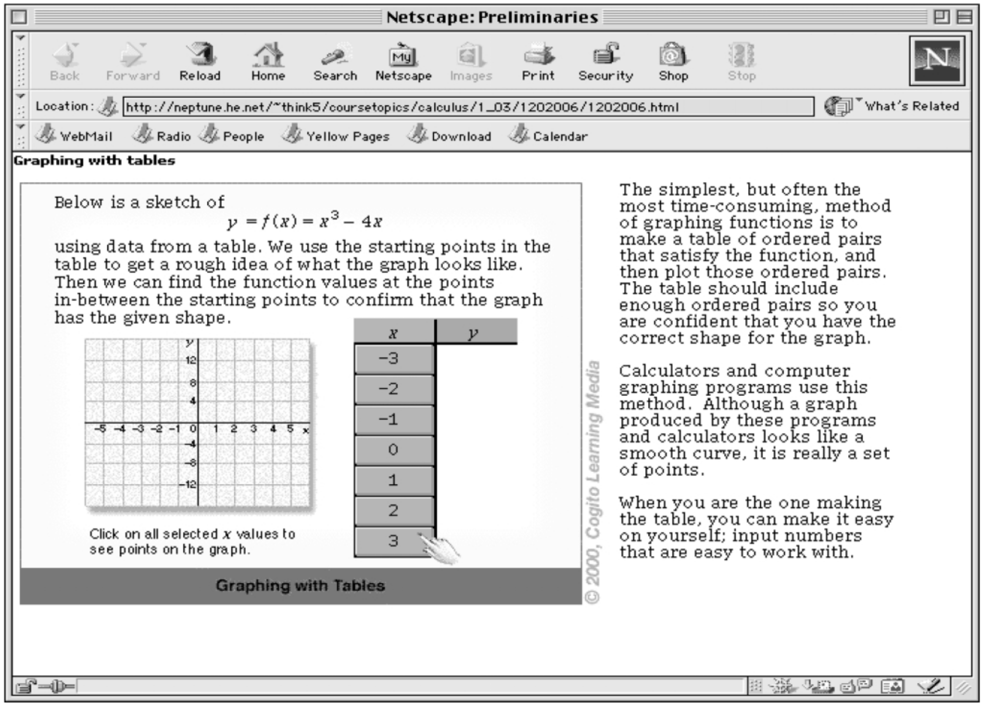

FIG. 8.—How to graph two variables. Source: Neptune [68]

70], integrates information organization into learning activities and uses information organization to create corpora of learning materials that use what teachers and students know about the primacy of vocabulary in information organization. Therefore, information literacy must be part of pre- and in-service teacher education to enhance the quality of teacher preparation. Information literate teachers can promote integrated learning that enables students to become more active learners, to know how to identify and find learning materials, to construct meaning from them, to communicate meaning effectively, and to extend their own knowledge structures. Such integrated learning allows teachers and students to enhance educational achievement and achieve important educational goals. Even though our ability to map knowledge domains varies widely, these goals are much the same whether the knowledge domain is poetry, thermodynamics, or geometry.

Information organization, literacy, and integrated learning, the first three parts of our six-part, holistic framework for integrating digital libraries into K–12 mathematics education, are essential to overcoming the gap that exists and will continue to exist between users' conceptual structures and learning activities, on the one hand, and the structure of digital libraries, on the other. Further, these elements must be combined with the other three that make up the six-part framework: adopting appropriate standards for math education, sensitivity to educational policy making, and accountability to parents, the public, and other important constituencies, including political leaders. We will discuss these final three elements in the second article exploring this framework.

The design of digital libraries for K–12 education must take an integrated approach. Without such a holistic perspective, digital collections for K–12 math education are not likely to effect the positive changes that even the most realistic expectations involve. We have to develop and implement not only digital tools but also appropriate models to construct digital libraries. Otherwise, it is unlikely that we can manage the collections of digital libraries in K–12 math education based on learning goals and activities. These libraries must provide rich opportunities for students and instructors to access, evaluate, and use the collections. It is only then that students can engage with the collections in creating new objects and meanings in the process of learning mathematics, and it is these objects and meanings that constitute learning.

As mathematicians and mathematics instructors consistently assert, communication is key to the learning of mathematics. Communication is not limited to hearing or reading what others say about mathematics; rather, communicating with others is how we try out mathematical ideas and become part of the community of mathematics "speakers." Further, decades of educational and cultural research have clearly shown that meaning is a result of a community's constant negotiation and renegotiation. We know that "through communication, ideas become objects of reflection, refinement, discussion, and amendment" [4]. Meaning and learning are not simply individual accomplishments—rather, they are important means to achieve community, to create identity in community, and to demonstrate one's participation in community [71].

Among the ways that digital libraries can contribute to mathematics education is making the tacit knowledge of students explicit. Thomas Rowan and Barbara Bourne [50], citing the reports and standards of the National Council of Teachers of Mathematics (NCTM), and others consistently emphasize that students come to school with impressive learning tools: a wide variety of experiences, fluency in languages and numeracy appropriate to a number of situations, and immense curiosity (also see Barton and Hamilton [72, pp. 176–82] on home numeracy practices). Successful teachers of all kinds are able to tap this potential and direct it through creative and expressive learning.

Communication is clearly a key component of that kind of teaching. In particular, as the NCTM [4] itself reminds us, "As students generate and examine numbers or objects on the . . . computer screen, they have a common (and often easily modifiable) referent for their discussion of mathematical ideas." It is in the creation and re-creation of ideas in community that digital libraries offer the best and most promise for mathematics education—not simply storage and retrieval of others' work, no matter how encyclopedic. Further, diSessa notes that successful digital environments for mathematics allow learners to create and modify the "dynamic and interactive characteristics of the medium," not just use them [15, p. 338].

Digital libraries have the potential, when used by good teachers, to help lead America away from its virtual addiction to high-stakes standardized testing. Among the chief ill effects of such tests for mathematics is their tendency to focus almost exclusively on "procedural and computational components of mathematics," that is, calculation and rote learning, at the expense of analytic thought and deeper understanding [73, p. 139]. This failure is especially problematic in that it ignores the kinds of standards and benchmarks developed by local teachers and by professional associations of highly experienced classroom mathematics teachers who are best positioned to define what children need in order to learn to do mathematics rather than just learn about mathematics. Rowan and Bourne emphasize how it is that computers and calculators can help students become mathematicians rather than rote learners: these technologies "provide a means for students to investigate patterns and algorithms in ways that motivate and encourage deeper thinking than might otherwise occur" [50, p. 16].

The communicative power of computers and digital libraries is what offers the best hope for enhancing mathematics education, not simply comprehensive collections and complex retrieval algorithms. As J. C. R. Licklider [74] and Douglas Englebart [75] taught us decades ago, the power of digital tools lies in how they connect us to each other and thereby help us create new meanings and new knowledge together. Recent research—for example, the study of computer-supported cooperative work and the "community turn"—has only underscored how right they were [76, 77].

The authors hope that our exploration of the complex context in which such digital initiatives exist offers a conceptual framework for designing and evaluating digital libraries in K–12 math education that other researchers may find useful. Realizing the significant promise of digital libraries in all contexts depends as much upon our ability to develop and implement such frameworks as it does upon our ability to develop digital tools themselves.

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