Technology Design as Educational Research: Interweaving Imagination, Inquiry, and Impact

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> The reason why we are on a higher imaginative level is not because we have a finer imagination, but because we have better instruments.... The gain is more than mere additions; it is a transformation.
> Alfred North Whitehead, 1963, p. 107.

Designing educational experiences is an imaginative art. As designers, we anticipate and fabricate activities, resources, and conversations that will bring learners' inquiry to fulfillment, enabling their growth toward desirable skills, intuitions, and understandings. As Whitehead suggests, success in this art requires highly developed tools, and the computer, in its protean flexibility, is the most evolved tool of educational imagination.

The tools for our imagination have grown extremely quickly in the past decades. Logo, which is only twenty-five years old, inspired Seymour Papert and his followers to imagine "gears of the mind," powerful tools that allowed learners to make sense of complex phenomena (Papert, 1980). Multimedia enabled Howard Gardner's readers to imagine tools that leverage the "multiple intelligences" for learning, and reduce the influence of formal symbol systems in excluding learners (Gardner, 1993). Powerful visualization, simulation, and animation capabilities led scientists to imagine a new "third path" for learning, that is neither empirical or theoretical, but merges these two through the art of modeling (Horwitz & Barowy, 1994; Snir, Smith & Grosslight, 1993). Miniaturization allowed Alan Kay, Adele

Goldberg, and other educational pioneers to imagine “Dynabooks,” which packaged powerful learning technologies in portable, hand-held devices (Kay & Goldberg, 1977; Goldberg, 1979).

Following close behind these inspired imaginations, a second wave of research has examined the consequences of technology for learning. New methods of teaching and learning have emerged, along with sound evidence of technology’s potential to deepen understanding and improve access to difficult ideas. For example, new methods of teaching physics using microcomputer-based sensors have been developed (Mokris & Tinker, 1987; Thornton, 1987). Large-scale experiments have shown that desktop simulations can enable sixth-graders to understand physics concepts better than their twelfth-grade counterparts (White, 1993). Geometry has been reinvigorated through the use of dynamic graphical construction (Jackiw, 1988-1997). Intelligent tutors have produced a reliable standard deviation gain in students’ learning (Anderson, Corbett, Koedinger, & Pelletier, 1995). Most importantly, we have learned that successful deployment requires simultaneous innovation in software, curricula, pedagogy, teacher training, and assessment (Fisher, Dwyer, & Yocam, 1996).

Today, the strands of imagination and inquiry are continuing forward into exciting new technological platforms. Networking, an old technology with new currency, has many researchers exploring communities of learners unrestricted by geographical boundaries, physical abilities, and other barriers to collaboration (e.g., Riel & Levin, 1990; Ruopp, Gal, Drayton, & Pfister, 1993). Group-oriented software (“groupware”) exploiting this connectivity affords electronically mediated conversations that both facilitate and guide well-structured scientific discourse (Pea, 1993). Another important strand of current research examines the potential of hand-held personal devices to complement computers (Tinker, 1996). At the far extreme of technical accomplishment, cognitive scientists have implemented intelligent tutors that can control the branching path of a learning experience to match an expert model (Wenger, 1987).

In part due to the imagination and inquiries of the researchers cited above and many more unnamed colleagues, educational technology now has widespread legitimacy. In the United States, one finds computers—in labs and classrooms—in almost every school. The organizations that proctor standardized tests permit calculators in ever-growing number. The call for a greater and closer integration of technology and teaching is heard not only from manifestos written on the research fringe, butalso from curriculum committees, textbook authors, and teacher’s organizations.

Despite this sense of flourishing accomplishment, optimism about educational technology is clouded by awareness of the difficulties that lie ahead. Too many of the aforementioned victories have produced glowing research reports but left no trace in classroom practice. Learning technology has a dark history of marginalization in mainstream institutions; technology is dismissed from the classroom as quickly as it arrives. Each wave of “revolutionary” new technology–television, film, and audio workstations—has disappeared quietly into relatively circumscribed niches. In these niches, older technologies surely serve a useful role,although this role is negligible in the overall scale of the institutions involved. By and large, newer technologies and conceptions of the educational mission have not displaced the roles of “chalk and talk” as the predominant tools and practices of teaching. Whether it supports this old pedagogy, or seeks radically novel approaches, computer technology is by no means immune from this marginalization. Indeed, very few high-quality tools have crossed the gap from research prototype into mainstream curricula.

In this chapter, we suggest that technology design as educational research can focus no longer on just imagination and inquiry. Research on technology is like a three-legged stool, and an explicit quest for impact is the third leg required to stabilize research programs. Without this third leg, research totters between boutique studies, which produce much excitement and knowledge about circumstances that defy replication, and large demographic studies, which provide knowledge about the success and failure of today’s educational technology but little direction for tomorrow’s.

We maintain that research has an important role in the future of educational technology because the problems of designing for learning are distinct from the problems of designing for corporate productivity which dominate the mainstream industry (Soloway & Guzdial, 1996). But to be successful, the mission for research must expand to include equal emphasis on imagination, inquiry, and impact. New models of the research projects that include technology design are needed that draw upon the idealistic potential of technology, but engage with the practical problems of educational reform in a rapidly changing society.

We begin by reviewing briefly some of the characteristics that have made past research projects successful. Next we consider why successes in designing learning technology have been mostly localized, with few innovations crossing the threshold to broadscale acceptance. Then we suggest three emerging models for high impact research: open project architecture, principled design experiment consortia, and reusable software kits. We conclude by listing some criteria that span the three models, and may provide guidance for future research projects.

Characteristics of Successful Projects

A wide variety of research methodologies can be applied successfully to design of educational technology. Indeed most of the chapters in this book apply equally well to the technology component of educational research. It is doubtful that the universe of successful projects could result from a monolithic methodological program. Thus, we restrict ourselves to describing broad characteristics that obtain in many successful projects.

Integrated Attention to Learning, Curriculum, and Technology

Many successful projects draw upon deep wells of understanding of learning. Although it is doubtful that any one theory gives the best account of how technology facilitates learning, it appears to be important that design of technology grows from grounding in a theory. Learning theories of Piaget, Vygotsky, Dewey and cognitive science (highlighted below) have been particularly provocative.

A key element of Piaget's theory was the progression from concrete to abstract thinking (Corsini, 1994). Many designers in the Piagetian tradition have turned this into a design principle by making concrete, manipulable, constructible manifestations of abstract intangible concepts, thus enabling the powerful, sense-making capabilities that learners can apply to concrete objects to guide their development of difficult concepts (Harel & Papert, 1991). For example, Papert developed the "turtle" (originally a hardware device!) in order to provide a concrete manifestation of mathematical procedures that students could build (Papert, 1980).

Vygotskian theory describes a mediational role for artifacts in establishing a context for development (Vygotsky, 1986). Thus, vygotskian-inspired designers emphasize enhancing a collaborative context for discourse by creating tools that mediate conversation. For example, Pea (1994) described how distributed multimedia environments create opportunities for transformative conversations. Likewise, the Cognition and Technology Group at Vanderbilt (1992) has created a set of "macrocontexts" that ground student problem-solving in motivating, resourcerich settings.

Dewey's theory of learning technology stresses the creation of conditions that will support community of inquiry (Dewey, 1938; Hickman, 1990). Dewey has stimulated designers to extend students' ability to engage with situations that they find problematic through an experimental practice (Roschelle, 1996). For example, simulations can allow students to experiment with controlling a steam engine that would be too dangerous to play with in real life (Hollan, Hutchins, McCandless, Rosenstein, & Weitzman, 1986).

Cognitive science is developing the capability to represent aspects of learning as the transformation of symbolic structures (Newell & Simon, 1972). Designers of intelligent tutoring systems use this capability to draw implications from the differences between a student's behavior and the idealized expert behavior (Wenger, 1987). For example, geometry tutors (Anderson, Boyle, & Reiser, 1985) follow a student's progress in completing a proof and remediate when the student falters.

Although grounding in a learning theory appears to be a central element in many successful projects, attention to the deep structure of subject matter is equally important. Indeed, productive projects often have principal investigators whose primary training is in a subject matter field. In a review article entitled "Technology and Mathematics Education," Kaput (1992) identifies aspects of successful technology specific to mathematics. In mathematics, the concept of a "notation system" brings together cognitive, subject matter, and technological perspectives, and Kaput argues that the unique potential of technology in mathematics lies in the prospect of being able to create radically innovative notation systems. For example, computer-based notation systems can create new opportunities for learning because computer-based notation can be dynamic, include interactive constraints, support multiple linked representations, and capture procedures as objects for reflection. Similarly in science education, researchers have understood the subject matter implications of technology in terms of a unifying "modeling" perspective (e.g. Hestenes, 1987; Niedderer, Schecker, & Bethge, 1991). The modeling perspective draws out the specific capabilities of technology to bring together simulation and visualization with strong empirical tools in ways that open up new pedagogical possibilities.

Finally, successful projects cultivate a deep understanding of the affordances of technology. Rather than merely applying technology to a design conceived in terms of learning theory and subject matter, researchers develop a sense of the unique capabilities of technology for education. This sense interpenetrates the conception of subject matter and the understanding of the learning process.

For example, some researchers have drawn upon the capability of computers to propagate constraints automatically. This has led to dynamic geometry environments such as Cabri Géomètre (Laborde, Baulac, & Bellemain, 1988-97) and The Geometer's Sketchpad (Jackiw, 1988-1997). In the dynamic geometry paradigm, the identity of a geometric diagram is determined by its logical description—the compass and straightedge construction steps used to assemble it—rather than by its physical characteristics (location, orientation, and scale). This constraint-based representation enables students to alter the geometric appearance of a construction interactively, by dragging component objects with a mouse while other objects stretch and transform to maintain the logical structure of the total diagram. Students working in such environments find that dragging illuminates the mathematical structure of a construction, revealing the general case (of which any static illustration is merely a single example) as the emergent totality of the endless stream of continuously related example illustrations generated in response to their mouse motion. In addition to this open-ended mode of inquiry and intuition-building, dragging addresses more focused questions or learner issues raised by a particular construction, in that one can manipulate a construction into a single, precise configuration easily—as, for instance, when dragging a general triangle into a configuration in which it becomes a right triangle (or an equilateral triangle or an isosceles triangle). In practice, the dragging paradigm allows students to move fluidly between open-ended and goal-directed modes of inquiry, as special cases, local extrema, and other interesting mathematical phenomena emerge from of a continuous deformation of a geometric construction, drawing attention naturally to the configurations in which the construction reveals them.

Technology Design as Iterative and Transformative

In the broad human computer interaction community, views of software design driven by means-ends analysis are giving way to a more iterative and transformative view. The idea of developing high-quality software by a process that runs sequentially from requirements through delivery (e.g., the waterfall model, Budgen, 1994) is largely discredited now. Psychological theory is less powerful in informing design than grounded empiricism (Landauer, 1991). Rapid prototyping and iterative refinement have taken hold (Schrage, 1996) and the results can be found in popular products like Quicken. Similarly, the view of technology design as automating existing practice has given way to a more encompassing view that “technology changes the task.” (Norman, 1991) Leading designers now argue for a more contextualized view of their role, with more attention to the transformative potential of new software designs (e.g., Winograd, Bennet, & De Young, 1996).

Fortunately, most educational research have not adopted linear software engineering models in the first place. Given that successful research involves simultaneous innovation in curricula, pedagogy and technology (as we argued above), automating existing practices does not make sense. Indeed many projects begin with the stated objective of transforming practice. Some of the transformations that are usual sought include:

- from rote procedures to active construction
- from character string representations to graphic visualizations
- from concept definitions to mental models

Progressing through iterative phases requires cultivating attention to how students learn from prototypes. Video analysis (see other chapters in this book) has proved to be one useful technique for gathering information for iterative design (Suchman & Trigg, 1991). Some successful projects go farther by engaging with teachers and students in participatory design (Greenberg, 1991). For example, the Mathematics Through Applications project (Greeno et al., in press) developed a mathematics curriculum and software through a process of long term engagement between researchers, teachers, and designers.

Iteration, by itself, is insufficient for coping with the thousands of detailed decisions required in any real technology design. Design guidelines would seem to be helpful but have a rather checkered history. Some, like the Macintosh Human Interface Guidelines (Apple, 1993) have influenced thousands of software products. But, although many research projects have suggested design guidelines for educational software, it is unclear whether any of them are influential. Instead, the best approach appears to be to cultivate good taste, harvest folklore, and adopt conventions. Good taste requires appreciating elegant solutions to common design problems; fortunately available products offer abundant examples of clean, functional designs and complicated, confusing ones (e.g. Norman, 1991). Folklore, often discovered at conferences and informal discussions with other designers, provides a wealth of design guidance not found in a book. For example, a designer of children’s multimedia once explained that young children sometimes cannot perform drag operations (holding the mouse button down while moving it), so they redesigned their product to use only single clicks. Finally, conventions and standards can clarify many design decisions, while lowering the learning curve for newcomers. With standards, there is always an interesting trade-off between convention and innovation. Adopting a coherent design language (Rheinfrank & Evenson, 1996) for a product can shortcut many rounds of iteration.

The Dilemma of Impact

Using technology to advance education will require attention to the interplay between local and systemic factors in design. In a sense, all learning is local: students construct knowledge in response to the problem and resources at hand. Most research projects address local conditions, processes, and resources that enhance learning. Nevertheless if technology design addresses only these local factors, the result is often systemic failure: software that is fragmentary, poorly supported, and easily marginalized. Every research project could observe these characteristics, and yet the overall impact could be marginal. For broad educational improvement, we must begin to address factors which will enable local successes to plug in to larger agendas, scale up to widespread audiences, and evolve to meet new challenges.

Far-reaching impact is elusive for a couple of reasons. First, achieving even local success is hard. The characteristics discussed above, such as the interpenetration of theory, curriculum, and technology is difficult to achieve. Second, the educational community is distributed and diversified. The participants in the educational reform enterprise include professionals with different agendas and vocabularies: teachers, curriculum developers, assessment providers, professional development centers, textbook and software publishers, along with technology designers. In addition, political considerations enter all serious attempts to reform education.

From an enterprise standpoint, the assumption that each technology research project can produce a corresponding impact directly is sharply flawed. Large scale changes, at a minimum, require coordination of reforms across multiple processes, materials, and situations. Moreover, for changes to spread beyond a single site, this coordination must extend to the organizations that hold the power to propagate changes: curriculum groups such as the National Council of Teachers of Mathematics, teacher education and professional development programs, and assessment providers such as the Educational Testing Service. The mutual relationships among these organization are weak, the sense of collaborative endeavor is thin, and exchanges of value are minimal. Achieving impact at the enterprise level from a single research project requires heroic effort.

Despite the difficulties involved, we reject the notion that educational researchers who are designing technology should abandon striving for direct impact and focus on scholarly publication. Education is a practical enterprise, with enormous societal consequences. Due in part to the low profits in educational technology, the marketplace has been slow to provide the scope and scale of quality software that schools require (Office of Technology Assessment, 1988). Importantly, the problems of designing for learning will not be solved by the techniques of designing for usability which are at the heart of most business productivity tools (Guzdial & Soloway, 1996; Norman & Spohrer, 1996). The enterprise needs researchers who focus jointly on learning and technology in order to provide revolutionary inspiration and disciplined inquiries. The question, then, is how to continue to foster creative imagination and thoughtful inquiry while facilitating stronger impact.

In the sections below, we outline three emerging forms of research organization that provide potential answers to this question. Before proceeding, we consider one fairly obvious but fatally flawed answer.

The image of a dysfunctional distributed enterprise with many power centers but no coordination suggests a move toward centralizing control. Indeed some projects have succeeded by instituting centralized control over technology, curriculum, pedagogy, and assessment, under the direction of a single research team. While this approach can work at the scale of a single project, several factors argue against expanding it. First, technology is changing too rapidly and becoming inherently more distributed. It is doubtful that centralized committees could make as wise decisions as a free marketplace of ideas and innovations. Second, a strong tradition of unsolicited research and academic freedom prevails in the educational community. Destroying traditions that have been successful historically in a quest for more impact seems shortsighted. Third, education genuinely needs more radical innovation and reform, not less. Centralized procurement and the propagation of research are unlikely to encourage the requisite risk taking.

Hence the sections below present models of research organization that maintain the tradition of decentralized, unsolicited research and encourage adventuresome innovation. The first model, open project architecture, integrates the efforts of diverse participants in a long term commitment to accumulate research in specific community. The second model, principled design experiment consortia, seeks deep exploration of set of design options by articulating a common experimental methodology. The third model, reusable software kits, stresses the accumulation of independent results in a technical platform that provides for interoperability, integration, and incremental evolution.

Open Project Architecture

As we argued earlier, dramatic success in applying technology in education requires simultaneous innovations in software, curriculum, pedagogy, and assessment. Here we add further that is critical for nonprofit research projects to engage in realistic contexts. This means technological innovations cannot be tested only in special schools, with elite students. Unfortunately, the necessity of creating a realistic context taps much of the power of research team. It is prohibitively expensive to create and manage an entire reform movement solely to study a particular idea. This suggests that research about educational technology must begin to let go of the idea of "controlled conditions" and, instead, embed its innovations directly in reform projects. Shared contexts, managed by a consortium, may provide a more powerful setting for individual investigators taking a special interest in one aspect of the innovation under way. "Technology" research in such a consortium, becomes a special focus on the role of designed artifacts in an integrated teaching and learning effort.

On the other hand, consortia have a dangerous side: They can consolidate power in the hands of very few researchers, leading to a research cartel. To differentiate the more benevolent form of consortia, we suggest the idea of "open project architecture." In an open project architecture, a reform context is created by organizing a set of researchers, reformers, and schools around a core, long-term mission. Once a strong context has been established, outside researchers can be invited to participate by performing studies that will advance the mission and the needs of the participants. In order to avoid overtaxing classrooms, outside researchers may need to submit competitive proposals for the studies that they wish to perform. The core group works closely with outside researchers to make sure that integrated results emerge, organized by the research and reform mission.

The Apple Classrooms of Tomorrow (ACOT) project offers a leading example of the power of open project architecture. The ACOT project (Fisher et al., 1996) began with a simple question, "What happens when teachers and students have access to technology whenever they need it?" To answer the question, Apple created classrooms where every teacher and student had a computer, both at school and at home. But ACOT did more than give away technology; it created and managed a context for exploring how technology could change schools. Furthermore, the ACOT team did not mandate a core ideology or program, but, rather, allowed teachers to construct their own future (Walker, 1996). In addition, ACOT classrooms were open to a large collection of researchers, who could establish joint projects with teachers involving technology and curricula. Researchers were available as experts who could help teachers, and to summarize the vast amounts of data that were generated from observations, weekly e-mail reports and journals. This open project architecture allowed an amazing diversity of technologies, pedagogies, and experiments to thrive in ACOT.

In an edited volume (Fisher et al. 1996), ACOT participants reflected on the first decade of this shared context. These reflections exhibit a class of findings that goes well beyond the typical, stand-alone, research project. For example, the researchers were able to rise above the parochial nature of experiments with particular innovations and summarize the large scale, most important factors in successful school reform.

Among these factors, the strongest theme is the need for radical changes in teaching practice in order for technology to make a difference. Indeed it is telling that the reflections in the beginning of the volume begin with the promise of technology, but as the book closes, the authors focus increasingly on the nature of changes in teaching practice. Importantly, ACOT was able to perform longitudinal studies of changes to teaching practice, resulting in a five phase model: entry, adoption, adaptation, appropriation, and invention (Dwyer, Ringstaff, & Sandholtz, 1990). ACOT also produced longitudinal studies of students, showing that as they gradually appropriated computer technology their reports became more dynamic and visual, and their thought processes became more creative and collaborative, and criss-crossed more perspectives (Tierney, 1996). Many of the chapters in the volume provide personal histories of researchers. It is clear from these accounts that not only students and teachers changed, but also the researchers involved with ACOT underwent personal transformations, resulting in deeper understanding of the issues and more intense engagement with classroom-based teaching and learning.

ACOT's open project architecture allowed the project leaders to speak powerfully to national and international audiences about the prospects for and problems of technology and education. The sites that ACOT created became an infrastructure for integrating the work of many innovators and researchers. From the rich, long-term, well-documented experiences at the sites, ACOT was able to address issues that matter to the public and policy makers. For example, ACOT was able to show that ubiquitous computing enables students to be more social, not less (Dwyer, 1996). Additionally, ACOT was able to provide a model of private-public partnerships that engage with the teachers in schools on a long-term basis, and accomplish meaningful change (David, 1996).

An open project architecture is a powerful structure for an educational project because it leverages the costs of setting up complex reform context. In this context, teachers, students and researchers can have the time they need to appropriate technology fully and enter the inventive phase. Moreover, longitudinal, integrative, interdisciplinary research can be performed. This research can accumulate in actual practice, rather than in neglected journals on dusty shelves. By maintaining a long-term commitment to supporting change at particular sites, an open project architecture also supports an interweaving of imagination, rigorous inquiry, and lasting impact.

Principled Design Experiment Consortia

In the early days of educational computing, there were few developers, and, therefore, little need to define the appropriate role for research projects as distinct from commercial endeavors. Today, that situation is changed dramatically; the marketplace for educational software is valued at hundreds of millions of dollars a year and is growing rapidly. Research funding is a fraction of that amount, and is not likely to grow much. At this time, it is increasingly necessary to leverage these few research dollars for the greatest possible impact.

The marketplace in educational technology is quite dynamic and innovating quickly. Particularly in the area of human interface, rapid evolution has occurred independently of the role of university-based research. Now, as the number of educational products available grows, we can anticipate that commercial publishers will have high incentives to make incremental improvements to current applications. Thus, it makes little sense to spend research funds on creating products that exist already. It is particularly important that research projects not automate existing teaching and learning practices; the commercial marketplace is more than adequate to exploit such potential fully.

Indeed, if optimal learning technologies could evolve in an incremental way from products already in the marketplace, there would be little reason to invest in research at all. Therefore, research-based technological innovations often explore novel possibilities that have much higher risks than incremental evolution allows, but also the potential of proportionately higher rewards. diSessa and Abelson's work on Boxer is one example of a principled design experiment with a higher risk and a higher potential reward than related commercial efforts, in this case, commercial versions of Logo (diSessa & Abelson, 1986). Since leaving the laboratory in the early 1970s, various commercial developers have published Logo, along with a string of incremental enhancements. However, diSessa (1985) did not seek merely an incremental improvement to Logo, but rather a reconceptualization according to a set of principles (spatial metaphor, naive realism, and incremental learnability). The implementation of these principles in Boxer moves from the Logo experiment (a child's programming language) to a much richer design space, "reconstructible computational media," in which the technology moves from tool to expressive medium (diSessa & Abelson, 1986). Thus, Boxer explores a design space that is at least a generation removed from incremental variations to Logo; this exploration is riskier than most commercial endeavors could tolerate, but it has potentially greater rewards.

A problem with individual principled design experiments is that each is highly idiosyncratic. This obstructs the synthesis of results across experiments. A methodology is needed to guide the exploration of the space of high-risk/high-reward design options in a more systematic pattern, so that comparisons across experiments can be performed, and so that strong recommendations for future directions can emerge (Collins, 1990).

A promising direction for such a methodology is the formation of a principled design experiment consortia (PDEC). A PDEC is a group of projects that develops:

- a common map of the overall design space, which can organize the different explorations of individual experiments
- a common methodology, to support the comparison and aggregation of results from individual experiments
- a common commitment to achieving impact through the synthesis of the most effective ideas across the individual experiments.

Whereas an open project architecture situates individual research projects in a shared infrastructure (e.g. a set of schools and base technologies), a principled design experiment consortium situates individual research projects in a shared conceptual superstructure. The primary example to date is the National Design Experiments Consortium (NDEC) (Hawkins, 1997). This project created a national conversation among researchers from a range of highly innovative, individual design experiments. Specific goals included working toward a common methodology for design experiments, creating a shared collection of reusable resources, and seeking synthesis of results.

From the work of NDEC members to date, it is obvious that there is no easy methodological solution that will allow grand syntheses across innovative technology projects. The methodologies required in technology design experiments are complex and messy. Collins (1990) suggests teachers as coinvestigators, flexible design revisions, and multiple measures of success or failure. Brown (1991) recognizes the need for a combination of classroom-based and laboratory-based research as well as a mix of qualitative and quantitative methods, and a mix of classical controlled experiments and more transformative explorations. Herman (1993) notes the difficulty of imposing methodological conditions on design experiments, such as the need to design new assessments to match new curricula, the need to investigate process as well as outcome, and the need not only to understand local effects, butalso how to replicate them in different conditions. Herman suggests more focus on communicating the outcome and process goals of design experiments, more emphasis on triangulation and meta-analysis, and increased recognition that cost-effectiveness questions must be conceived broadly. Given these methodological complexities, NDEC did not immediately make progress toward a grand syntheses (Hawkins, 1997) but instead focused on articulating ways of documenting the advances made by design experiments, collecting and sharing resources, and shifting the nature of publications from archival journals to more useful intermediate products.

Although progress in principled design experiment consortia may appear slow, policy-makers in government, schools, and industry need structured syntheses of design options that go beyond incremental improvements. Merely aggregating idiosyncratic projects, each with its own innovations, methodologies, and dissemination plans, is unlikely to achieve a concentrated impact on policy. Through a consortium, a researcher can seek a conceptual superstructure that allows individual design experiments to be conceived as parts of a systematic exploration of a wide range of options. Thus a consortium provides a structure in which individual principled design experiments can be organized to maximize impact.

Reusable Software Kits

Advancement in both research and technology depends on the accumulation and dissemination of knowledge. In technology, growth occurs because prior efforts produce components that encapsulate the complexity of one level of detail, and enable the next generation to tackle a higher level of detail. Transistors allow the design of gate circuitry which allows the design of logic units which allows the design of microprocessors and so forth, all the way up to programming languages. Rarely has educational research on technology evolved along such a vertical trajectory; instead of accumulating knowledge and innovation, each project starts from the same level (a programming language) and builds a stand-alone, monolithic, closed product (an application, a CD-ROM, or a web site).

The classroom impact of a new technology is dependent on an entire complex of dissemination issues that surround and embed the technology itself (as is clear from the ACOT research cited above). Some of these issues derive directly from sweeping questions that must be faced and answered by the researcher, such as: what is the curricular function of the technology? What assessment metric is suitable for evaluating its effect? Other components of the dissemination complex, however, resist centralized or “top-down” solutions. For example, how does the technology interact with the basal text used by particular school district X? What form of training materials will help teachers familiar with previous technology Y? What is the best deployment technique in schools that are experimenting with class scheduling strategy Z? Frequently, answers to these local questions arise only within the communities in which the questions are relevant. Thus, in addition to the opportunity for encoding a vertical accumulation of knowledge in an emerging technology, there is also a horizontally-vast dissemination context to which each new technology must adapt.

The reusable software kit is a research strategy that attempts to maximize the penetration of a technology’s key ideas into the vertical strata of future educational thinking and technology development and to pluralize the dissemination context as broadly as possible. Software Kits pursue these twin goals by offering “open” architectures, thereby making it easy or attractive to integrate, extend, and customize the technology. These open architectures may manifest themselves as code-level building blocks for rearrangement and combination by future technology researchers, or as authoring environments and authoring functionality for use by curricula designers, professional development mentors, classroom teachers, and even students.

While examples of code-level reuse are rare in today's educational technology milieu, we believe that the emerging component software architectures represented by Java, ActiveX, and OpenDoc afford unique opportunities to create software building blocks (see Roschelle & Kaput, 1996). Each of these industry-standard infrastructures allows developers to create modules that can be integrated into larger scale activities, curricula and assessments. (In contrast, tools built to older, "stand-alone application" architectures resist any attempt at integration.) The newer component architecture facilitates vertical integration because useful modules (such as a graph, a table or an equation editor) can be combined into containers (such as a a web browser, a notebook, or an assessment portfolio) to form higher-order products. Furthermore, because component architectures enable such embedding recursively, this pattern of vertical integration can continue again at a higher scale.

Component architectures also make horizontal diversity possible because local schools, teachers or students can replace standard components with other components that suit their specific needs. Indeed, software kit research designs often include authoring tools that allow core innovations to be expressed in educational contexts that are designed by users (beyond or in addition to those contexts generated explicitly by the developers). From a functional perspective, authoring features range from simple provisions that permit users to record their comments, thoughts, and ideas while interacting with the technology, to the ability to develop complete supplemental curricular activities in the form of interactive notebooks (e.g. Mathematica, MathCad), multimedia presentations (e.g. Sketchpad, Jackiw, 1988-97) or custom-configured simulation environments (e.g. MathWorlds, Roschelle, Kaput, & DeLaura, 1996). From the standpoint of impact, these tools encourage users to rework raw technology concepts into the forms that are most appropriate for their particular uses and to distribute and expand the network of interest groups who incorporate technology into the classroom.

Several products in the history of educational technology suggest the powerful benefits of supporting authoring and composition through open standards and reusable modular components (see Roschelle, Kaput, Stroup & Kahn, in press, for full discussion). Most impressively, the worldwide web has energized an enormous audience of potential educational authors by providing open standards for delivering, displaying, and linking multimedia documents. At its best, component architecture can engage both grassroots authors and major publishers to accomplish the horizontal and vertical dimensions of integration. Component architectures (such as Java, ActiveX, and OpenDoc) are overcoming the limitations of the worldwide web to static text and images and allowing fully interactive environments to be embedded in curricular documents. This trend should encourage a broad move towards reusable software kits among educational developers, authors, and publishers.

Reusable software kits can be a powerful strategy because they extend the progressive, cumulative, and communitarian properties of scientific practice to the development of technology. Science improves knowledge rapidly because it permits distributed inquiry in which results accumulate and are subject to the standards of a self-critical community. Component software architectures replace the monolithic, stand-alone, closed systems of past designs for educational technologies, with the potential for modular, interoperable, open systems. Eventually, these systems could allow a more progressive, cumulative, self-critical community of practicioners in educational technology.

A community of practice based around reusable software kits could have three desirable characteristics. First, the community could engage in rapid prototyping and experimental comparison. Researchers, activity designers, teachers, and students would be able to design new, technology-rich settings and curricula by combining preexisting modules. Because modules can be exchanged easily, experimental comparisons become feasible. Second, the community could aim for scalable integration of the best innovations. The products of multiple research projects could be integrated into a suite of tools that scale to support the full needs of a classroom, a school, or a school district. Finally, reusable software kits could enable incremental evolution. An innovator could focus on improving one particular tool in a reusable kit, without needing to rewrite all of the auxiliary and complementary components in the suite. Focused innovation could lead to faster progress. Moreover, component strategy would allow an improvement in a single tool to be substituted into an overall activity, a curriculum, or an assessment without affecting the other pieces. Thus, insetad of needing to rewrite all the software to accommodate each innovation, a suite of powerful tools could assimilated improved components incrementally.

Conclusion

We have argued that the design of technology as educational research is maturing in phases. A first phase focused on radical imagination and the transformative opportunities that new technology brings. A second phase stressed rigorous inquiry and the need to understand how, what, and why children learn with technological resources. Increasing maturation and large-scale investment are leading to a third phase where the quest for impact will take its place alongside imagination and inquiry. Research will continue to be a strong element in the design and use of educational technology as long as researchers manage to maintain a balance among these three phases—imagination, inquiry, and impact—which now might be understood better as three aspects of the overall problem.

The history of learning technologies will support no easy generalizations about necessary or sufficient methodological principles for successful research-based innovation. At the level of general guidelines, however, it appears that research projects seek a deep interpenetration of learning theory, subject matter, and technological affordances. Learning theories may draw upon Dewey, Piaget, Vygotsky, cognitive science or alternative frameworks. The consideration of subject matter often leads to a large organizing idea, like "notation systems" or "modeling" which creates a disciplinary viewpoint on the potential power of new media. Finally, careful attention to the affordances of technology, such as the possibility of creating manipulable constraint systems, frequently catalyzes new insights into subject matter and the nature of learning.

In terms of design practices, we noted that the normative mode of design in educational technology is iterative and transformative. Yet, the vast number of design decisions in any realistic technology project cannot be made through iterative experimentation alone. Hence, designers cultivate good taste, harvest folklore, and utilize appropriate conventions. Again, no single design methodology integrates the balance of factors that a successful team must bring to bear in creating a worthy new technology. Technology design as educational research remains a skilled art that aspires to greater rigor and replicability.

We argued further that the quest for impact requires aggregating, integrating, and synthesizing design experiments above the level of the individual project. At this point, there is little possibility for an individual project to have a simple correlation to a large-scale change in educational practice.We suggested three strategies for achieving larger scale impacts. The open project architecture strategy manages a common school-based infrastructure that can serve as a site for integrating many research studies. A natural compliment to this strategy is the principled design experiment consortia which create a common conceptual superstructure. This superstructure enables individual experiments to be seen as exploring interesting points in an overall design space, and the push toward a common methodology allows extrapolation across points in the design space. The reusable software kit strategy seeks to create a chance for vertical integration and horizontal diversification of the ideas of software developers, authors, teacher-educators, teachers and students.

All three strategies contain some common elements. Taken together, these common elements might indicate the overall direction in which a methodology for educational technology is evolving. First, each of the three strategies deliberately creates a mechanism for accumulating contributions, integrating partial solutions, and supporting widespread dissemination. In the open project architecture strategy, the mechanism is a common school-based infrastructure; in the principled design experiment consortia strategy, the mechanism is common conceptual superstructure; and in the reusable software kit strategy the mechanism is a common technological architecture. Research methodologies probably will emerge that draw upon all three of these possible means for accumulating work, and that achieve both vertical and horizontal integration. Second, each of the three strategies involves closer partnerships (and indeed leads to communities) that cross the traditional barriers among researchers, commercial publishers, and teachers. This list of participants might easily grow to include parents, students, and policy-makers. We can expect that research methodologies for technological innovations will continue to respect the value that each participant brings and to seek opportunities for mutually valuable contributions. Third and finally, we note that each strategy presumes a growing legion of sophisticated participants who can balance the creativity and rigor needed to succeed. At present, there are too few places where a student can learn the wide variety of research and innovation skills that any of the strategies requires. We close by urging educational technologists to focus some of their energies expanding their own community of practice and increasing the opportunities for diverse participants to enter the practice and thrive.

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References

Anderson, J., Boyle, F., & Reiser, B. (1985). Intelligent tutoring systems. *Science*, *223*, 456-462.

Anderson, J. R., Corbett, A. T., Koedinger, K., & Pelletier, R. (1995). Cognitive tutors: Lessons learned. *Journal of the Learning Sciences*, *4*, 167-207.

Apple Computer, Inc. (1993). *Macintosh human interface guidelines.* Reading, MA: Addison-Wesley.

Brown, A. (1991). Design experiments. Theoretical and methodological challenges in evaluating complex interventions in classroom settings. *Journal of the Learning Sciences.*

Budgen, D. (1994). *Software design.* Reading, MA: Addison-Wesley.

Cognition and Technology Group at Vanderbilt. (1992). The Jasper experiment: An exploration of issues in learning and instructional design. *Educational Technology Research and Development, 40(1),* 65-80.

Collins, A. (1990). *Towards a design science of education* (Technical Report No. 1). New York: Center for Children and Technology, Educational Development Center.

Corsini, R. J. (1994). *Encyclopedia of psychology* (2nd ed., pp. 86-89)., New York: Wiley.

David, J. L. (1996). Developing and spreading accomplished teaching: Policy lessons from a unique partnership. In C. Fisher, D. C. Dwyer, & K. Yocam (Eds.), *Education & technology: Reflections on computing in classrooms.* pp. 237-250. San Francisco: Jossey-Bass.

Dewey, J. (1938). *Experience and education.* New York: Macmillan.

diSessa, A.A. (1985). A principled design for an integrated computational environment. Human-computer interaction, 1, 1-47.

diSessa, A.A. & Abelson, H. (1986). Boxer: A reconstructible computational medium. Communications of the ACM, 29(9), 859-868.

Dwyer, D. C. (1996). The imperative to change our schools. In C. Fisher, D. C. Dwyer, & K. Yocam (Eds.), *Education & technology: Reflections on computing in classrooms.* pp. 15-33. San Francisco: Jossey-Bass.

Dwyer, D. C., Ringstaff, C., & Sandholtz, J. (1990). *The evolution of teachers' instructional beliefs and practices in high-access-to-technology classrooms.* Paper presented at the annual meeting of the American Educational Research Association, Boston, MA.

Fisher, C., Dwyer, D. C., & Yocam, K., Eds. (1996). *Education & technology: Reflections on computing in classrooms.* San Francisco: Jossey-Bass.

Gardner, H. (1993). *Multiple intelligences: The theory in practice.* New York: Basic Books.

Goldberg, A. (1979). Educational uses of a dynabook. *Computers & Education, 3*, 247-266.

Greenberg, S. (Ed.) , (1991). Computer supported cooperative work and groupware. London: Academic Press.

Greeno, J. G., McDermott, R., Engle, R.A, Knudsen, J., Cole, K. Lauman, B., Goldman, S. & Linde, C. (in press). *Research, reform, and aims in education: Modes of action in search of each other.*

Harel, I. & Papert, S. (Eds.), (1991). *Constructionism*. Norwood, NJ: Ablex.

Hawkins, J. (1997). *The National Design Experiments Consortium: Final report.* New York: Center for Children and Technology, Educational Development Center.

Herman, J. L. (1993). *Finding the reality behind the promise: Assessing the effects of technology in school reform*. Paper presented at the annual meeting of the American Educational Research Association, Atlanta, GA.

Hestenes, D. (1987) A modelling theory of physics instruction. *American Journal of Physics, 53,* 1056-1065.

Hickman, L.A. (1990). John Dewey's pragmatic technology. Indianapolis, IN: Indiana University Press.

Hollan, Hutchins, McCandless, Rosenstein, and Weitzman. (1986). Graphical interfaces for simulation. In Rouse (Ed.) *Advances in man-machine* *systems* (Vol. 3), Greenwich, CT: Jai Press.

Horwitz, P., & Barowy, W. (1994). Designing and using open-ended software to promote conceptual change. *Journal of Science Education and Technology, 3*, 161-185.

Jackiw, N. (1988-97). *The Geometer's Sketchpad* (Software; various versions). Berkeley, CA: Key Curriculum Press.

Kaput, J. (1992). Technology and mathematics education. In D. Grouws (Ed.), *A handbook of research on mathematics teaching and learning.* New York: Macmillan. (pp. 515-556).

Kay, A. and Goldberg, A. (1977). Personal dynamic media. *IEEE Computer,* 10(3), 31-41.

Laborde, J-M., Baulac,Y., & Bellemain, F. (1988-97). *Cabri Géomètre* (Software, various versions). Grenoble, France: IMAG-CNRS, Universite Joseph Fourier.

Landauer, T.K. (1991). Let's get real: A position paper on the role of cognitive psychology in humanly useful and usable systems. In J. M. Carrol, (Ed.), *Designing interaction.* Cambridge: Cambridge University Press. (pp. 60-73).

Mokris, J. R. & Tinker, R. F. (1987). The impact of microcomputer-based labs on children's ability to interpret graphs. *Journal of Research in Science Teaching, 24(4),* 369-383.

Niedderer, H., Schecker, H., & Bethge, T. (1991). The role of computer aided modelling in learning physics. *Computer Aided Learning.*

Newell, A. & Simon, H. A. (1972). *Human problem solving.* Englewood Cliffs, NJ: Prentice-Hall.

Norman, D. A. (1991). *The psychology of everyday things.* New York: Basic Books.

Norman, D. A. & Spohrer, J. C. (1996). Learner-centered education. *Communications of the ACM, 39(4),* 24-27.

Office of Technology Assessment. (1988). *Power on! New tools for teaching and learning.* Washington DC: US Government Printing Office.

Papert, S. (1980). *Mindstorms.* New York: Basic Books.

Pea, R. D. (1994). Seeing what we build together: Distributed multimedia learning environments for transformative communications. *Journal of the Learning Sciences, 3(3),* 283-298.

Pea, R. D. (1993). Distributed multimedia learning environments: The Collaborative Visualization Project. *Communications of the ACM, 36(5),* 60-63.

Rheinfrank, J. & Evenson, S. (1996). Design Languages. In T. Winograd, (Ed.), *Bringing Design to Software.* (pp 63-80). New York: Addison Wesley.

Riel, M., & Levin, J. (1990). Building electronic communities: Successes and failures in computer networking. *Instructional Science, 19,* 145-169.

Roschelle, J. (1996). Designing for cognitive communication: epistemic fidelity or mediating collaborating inquiry. In D. L. Day & D. K. Kovacs (Eds). *Computers, communication & mental models.* (pp.13-25). London: Taylor & Francis.

Roschelle, J., & Kaput, J. (in press). Scalable integration of educational software: Exploring the promise of component architectures. *Journal of Interactive Media in Education.*

Roschelle, J., & Kaput, J. (1996). Educational software architecture and systemic impact: The promise of component software. Journal of Educational Computing Research, 14(3), 217-228.

Roschelle, J., Kaput, J, & DeLaura, R. (1996). Scriptable applications: Implementing open architectures in learning technology. In P. Carlson & F. Makedon (Eds.), *Proceedings of Ed-Media 96--World Conference on Educational Multimedia and Hypermedia.* (pp. 599-604). Charlottesville, VA: American Association of Computers in Education.

Ruopp, R., Gal, S., Drayton, B., & Pfister, M. (Eds.). (1993). *LabNet: Towards a community of practice.* New York: Lawrence Erlbaum.

Schrage, M. (1996). The culture(s) of prototyping. *Design Management Journal, 4(1),* 55-65.

Snir, J., Smith, C., & Grosslight, L. (1993). Conceptual-enhanced simulations:

A computer tool for science teaching. *Journal of Science Education and Technology, 2(2)*, 373-388.

Soloway, E., & Guzdial, M. (1996). Designing for learners. In M. Guzdial & F. W. Weingarten (Eds.), *Setting a computer science research agenda for educational technology*. (pp. 10-22). Washington, DC: Computing Research Association.

Suchman, L. & Trigg, R. (1991). Understanding practice: Video as a medium for reflection and design. In J. Greenbaum & M. Kyng (Eds.), *Designing by doing: A tool box approach to collaborative system design*. Hillsdale, NJ: Lawrence Erlbaum.

Tierney, R. J. (1996). Redefining computer appropriation: A five-year study of ACOT students. In C. Fisher, D. C. Dwyer, & K. Yocam (Eds.), *Education & technology: Reflections on computing in classrooms*(pp. 169-183). San Francisco: Jossey-Bass.

Tinker, R. (1996). *The whole world in their hands* [on-line]. Washington, DC: US Department of Education. Available: http://www.ed.gov/Technology/Futures/tinker.html)

Thornton, R. K. (1987). Tools for scientific thinking: Microcomputer-based laboratory for physics teaching. *Physics Education, 22*, 230-238.

Vygotsky, L. (1986). *Thought and language.* Cambridge, MA: MIT Press.

Walker, D. F. (1996). Towards an ACOT of Tomorrow. In C. Fisher, D. C. Dwyer, & K. Yocam (Eds.), *Education & technology: Reflections on computing in classrooms.* (pp. 91-106). San Francisco: Jossey-Bass.

Wenger, E. (1987). *Artificial intelligence and tutoring systems.* Los Altos, CA: Morgan Kaufmann.

Winograd, T., Bennet, J., & De Young, L. (Eds.). (1996). *Bringing design to software.* Reading, MA: Addison-Wesley.

White, B. Y. (1993). ThinkerTools: Causal models, conceptual change, and science education. *Cognition and Instruction, 10(1)*, 1-100.

Whitehead, A. N. (1963). *Science and the modern world.* New York: New American Library.

Technology design as educational research: Interweaving imagination, inquiry & impact. In A. Kelly & R. Lesh (Eds.), Research design in mathematics & science education (pp. 777â€“797). Mahwah, NJ: Lawrence Erlbaum Associates. Google Scholar.Â The role of scaling up research in designing for and evaluating robustness. Educational Studies in Mathematics, 68(2), 149â€“170. Article. Technology Design as Educational Research: Interweaving Imagination, Inquiry, and Impact. Jeremy Roschelle SRI International. Nicholas Jackiw Key Curriculum Press. to appear as: Roschelle, J. & Jackiw, N. (in press).Â Designing educational experiences is an imaginative art. As designers, we anticipate and fabricate activities, resources, and conversations that will bring learnersâ€™ inquiry to fulfillment, enabling their growth toward desirable skills, intuitions, and understandings. As Whitehead suggests, success in this art requires highly developed tools, and the computer, in its protean flexibility, is the most evolved tool of educational imagination. The tools for our imagination have grown extremely quickly in the past decades. DOI link for Handbook of Research Design in Mathematics and Science Education. Handbook of Research Design in Mathematics and Science Education book. Edited By Anthony Edward Kelly, Richard A. Lesh.Â Technology Design as Educational Research: Interweaving Imagination, Inquiry, and Impact. You currently do not have permission to access this title. Please click 'Get Access' to see if you or your institution has access to this content. Get Access.Â fabricate activities, resources, and conversations that will bring learners' inquiry to fulfillment, enabling their growth toward desirable skills, intuitions, and understandings. As Whitehead. suggested, success in this art requires highly developed tools, and the computer, in its protean.