Students
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JOBS FOR THE FUTURE

DEEPER LEARNING RESEARCH SERIES

THE ROLE OF DIGITAL TECHNOLOGIES IN DEEPER LEARNING

By Chris Dede, Harvard University
December 2014

EDITORS' INTRODUCTION TO THE DEEPER LEARNING RESEARCH SERIES

In 2010, Jobs for the Future—with support from the Nellie Mae Education Foundation—launched the Students at the Center initiative, an effort to identify, synthesize, and share research findings on effective approaches to teaching and learning at the high school level.

The initiative began by commissioning a series of white papers on key topics in secondary schooling, such as student motivation and engagement, cognitive development, classroom assessment, educational technology, and mathematics and literacy instruction.

Together, these reports—collected in the edited volume *Anytime, Anywhere: Student-Centered Learning for Schools and Teachers*, published by Harvard Education Press in 2013—make a compelling case for what we call "student-centered" practices in the nation's high schools. Ours is not a prescriptive agenda; we don't claim that all classrooms must conform to a particular educational model. But we do argue, and the evidence strongly suggests, that most, if not all, students benefit when given ample opportunities to

- Participate in ambitious and rigorous instruction tailored to their individual needs and interests
- Advance to the next level, course, or grade based on demonstrations of their skills and content knowledge
- Learn outside of the school and the typical school day
- Take an active role in defining their own educational pathways

Students at the Center will continue to gather the latest research and synthesize key findings related to student engagement and agency, competency education, and other critical topics. Also, we have developed—and will soon make available at www.studentsatthecenter.org—a wealth of free, high-quality tools and resources designed to help educators implement student-centered practices in their classrooms, schools, and districts.

Further, and thanks to the generous support of The William and Flora Hewlett Foundation, Students at the Center has expanded its portfolio to include an additional and complementary strand of work.

The present paper is the second in our a new set of commissioned reports—the Deeper Learning Research Series—which aim not only to describe best practices in the nation's high schools but also to provoke much-needed debate about those schools' purposes and priorities.

In education circles, it is fast becoming commonplace to argue that in 21st century America, "college and career readiness" (and "civic readiness," some add) must be the goal for each and every student. However, and as David Conley described in the first paper in our series, a large and growing body of empirical research shows that we are only just beginning to understand what "readiness" really means. Students' command of academic skills and content certainly matters, but so too does their ability to communicate effectively, to work well in teams, to solve complex problems, to persist in the face of challenges, and to monitor and direct their own learning—in short, the various kinds of knowledge and skills that have been grouped together under the banner of "deeper learning."

What does all of this mean for the future of secondary education? If "readiness" requires such ambitious and multi-dimensional kinds of teaching and learning, then what will it take to help students become genuinely prepared for college, careers, and civic life?

In the present paper, Chris Dede takes a close look at the role that digital technologies can—and must, he argues—play in the effort to provide all students with meaningful opportunities for deeper learning.

We are delighted to share this second installment in our Deeper Learning Research Series, and we look forward to the conversations that all of these papers will provoke.

To download the papers, introductory essay, executive summaries, and additional resources, please visit the project website: www.studentsatthecenter.org/topics.

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Jobs for the Future works with our partners to design and drive the adoption of education and career pathways leading from college readiness to career advancement for those struggling to succeed in today's economy. We work to achieve the promise of education and economic mobility in America for everyone, ensuring that all low-income, underprepared young people and workers have the skills and credentials needed to succeed in our economy. Our innovative, scalable approaches and models catalyze change in education and workforce delivery systems.

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Students at the Center
JOBS FOR THE FUTURE

Students at the Center—a Jobs for the Future initiative—synthesizes and adapts for practice current research on key components of student-centered approaches to learning that lead to deeper learning outcomes. Our goal is to strengthen the ability of practitioners and policymakers to engage each student in acquiring the skills, knowledge, and expertise needed for success in college, career, and civic life. This Jobs for the Future project is supported generously by funds from the Nellie Mae Education Foundation and The William and Flora Hewlett Foundation.

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Chris has served as a member of the National Academy of Sciences Committee on Foundations of Educational and Psychological Assessment and a member of the 2010 National Educational Technology Plan Technical Working Group. His books include *Scaling Up Success: Lessons Learned from Technology-based Educational Improvement* (Jossey-Bass 2005), *Online Professional Development for Teachers: Emerging Models and Methods* (Harvard Education Press 2006), and *Digital Teaching Platforms* (Teachers College Press 2012).

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INTRODUCTION

The last major transformation of American education occurred a century ago when, as part of its transition from an agricultural to an industrial economy, our nation invented a new model of schooling (Collins & Halverson 2009), one that treats education as a routine, almost mechanical process analogous to the production of material goods on an assembly line. Instead of learning at their own pace and according to their individual needs and interests, students are treated as interchangeable parts: they are sorted by age, grouped into classes of equal size, given identical instruction, tested at fixed intervals, and—provided they meet minimum standards—moved along to the next grade for more of the same.

The deficiencies in this system were widely considered to be tolerable. So long as only the top tier of students—future professionals, managers, and leaders—required a more sophisticated kind of intellectual preparation, a deeper form of learning for the rest was considered unnecessary. If they could follow directions and perform routine work efficiently, they could earn a decent living.

By and large, that educational model is still with us today. Only, rather than moving into stable industrial-era jobs, young people now must compete in a global, knowledge-based, innovation-centered economy (Araya & Peters 2010). Further, if they hope to secure a reasonably comfortable lifestyle, they now must go beyond a high school diploma (Wagner 2008), and they must acquire not just academic knowledge but also character attributes such as intrinsic motivation, persistence, and flexibility (Hilton 2008; Dede 2010; Levin 2012).

As described by the National Research Council in its landmark report, *Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century* (NRC 2012), such cognitive, intrapersonal, and interpersonal capacities are best developed in combination (Table 1 categorizes a broad range of knowledge and skills vital in the 21st century according to these dimensions), and they are best measured not by way of standardized, multiple-choice tests but, rather, via performance assessments that require students to apply their knowledge and skills to real-world contexts.

But if the goal today is to help all students—not just an elite few—to reach and demonstrate mastery of ambitious standards, then how must schools change? In order to make deeper learning possible on a large scale, what kinds of instruction will have to become common practice?

Table 1. A Deeper Learning Agenda: Three Dimensions of College & Career Readiness

Cognitive	Intrapersonal	Interpersonal
Cognitive processes & strategies	Intellectual openness	Teamwork & collaboration
Knowledge	Work ethic & conscientiousness	Leadership
Creativity	Positive core self-evaluation	Communication
Critical thinking	Metacognition	Responsibility
Information literacy	Flexibility	Conflict resolution
Reasoning	Initiative	
Innovation	Appreciation of diversity	

Adapted from Hilton (2008)

In this paper, I argue that what's needed today are teaching strategies very different from the familiar, lecture-based forms of instruction characteristic of industrial-era schooling, with its emphasis on rote memorization, simple comprehension, and the study of a prescribed, one-size-fits-all curriculum. Rather, the balance must shift toward certain kinds of instructional approaches that, while far from new, have rarely been put into practice in more than a small subset of the nation's classrooms and schools. They include, for example, collaborative investigations, extended inquiries, apprenticeships, interdisciplinary projects, and other opportunities for students to discuss and debate complex ideas, to connect academic subjects to their personal interests, and to confront open-ended, real-world problems (*see Table 2 for a fuller list*).

I argue, moreover, that if schools are to provide such forms of instruction effectively and at scale, they will require a new technology infrastructure. This is not to say that individual teachers can't teach for deeper learning without technology. Rather, my argument is that new tools and media can be extremely helpful to many teachers who would otherwise struggle to provide these kinds of instruction.

By analogy, imagine that you wish to visit a friend twenty miles away. You could walk (and some people would prefer to do so), but it would be much easier to use a bicycle, and it would far easier still to use a car.

Table 2. Why Use Technology in Schools?

Technology is a tool, not an end in itself. The goal isn't to create a digital version of business as usual but to empower teachers to make better use of instructional strategies such as:

- Case-based learning, helping students master abstract principles and skills through the analysis of real-world situations
- The sharing of multiple, varied representations of concepts, helping students grasp complex material by showing them alternative forms of the same underlying idea
- Collaborative learning, helping students to understand that their combined efforts are often greater than the sum of their individual knowledge and skills
- Apprenticeships, which give context to schoolwork by introducing students to real-world challenges, responsibilities, colleagues, and mentors
- Opportunities for self-directed learning, which foster academic engagement, self-efficacy, and tenacity by requiring students to define and pursue specific interests
- Interdisciplinary studies, which help students see how differing fields can complement each other, offering a richer perspective on the world than any single discipline can provide
- Personalized learning, which ensures that students receive instruction and supports that are tailored to their needs and responsive to their interests (U.S. Department of Education 2010; Software and Information Industry Association, 2010; Rose & Gravel 2012)
- Connected learning, which encourages students to pursue opportunities to study outside of their classrooms and campuses (Ito et al. 2013)
- The use of diagnostic assessments that are embedded into learning and are formative for further learning and instruction

» If schools are to provide such forms of instruction effectively and at scale, they will require a new technology infrastructure.

In short, teachers don't have to use educational technology; they may prefer to walk. Realistically, however, many, if not most, teachers will be hard-pressed to get from industrial-style instruction to deeper learning without a vehicle. And I see two reasons why this is the case:

Affordability and Scale

First, even if our century-old approach to schooling were able to prepare children to meet the challenges of 2020 and beyond, it will eventually become cost-prohibitive to rely on such a labor-intensive model, one that uses talented human resources ineffectively (Kane & Staiger 2012). In inflation-adjusted dollars, funding for K-12 schools and colleges is in decline; at least 35 states provided less funding per K-12 student for the 2013-14 school year than they did before the recession hit (Leachman & Mai 2014), and 48 states provided less funding for higher education (Mitchell, Palacios, & Leachman 2014). In many states, teachers struggle to make ends meet on "paltry" incomes (Boser & Straus 2014). This shift is not a temporary financial dislocation due to an economic downturn but a permanent sea change that has already affected many other sectors.

Other professions are already transforming to models that use technology to empower typical practitioners to be effective at lower cost. It is critical to note, however, that they are most successful when they use technology to enable new and better types of work processes rather than to automate traditional ones.

For example, Hannan and Brooks (2012) documented recent changes in the health professions driven by information technology. As they note, traditional clinical decision making, relying solely on physicians, appears to be unsustainable in terms of cost and productivity. In response, many health care providers have begun to use medical and wellness technologies that enable distributed decision making, in which technology assists other medical staff to make routine decisions, allowing doctors to focus on issues that truly require their expertise.

In the education sector, we tend to downplay serious questions about the division of labor among teachers and other staff, choosing instead to celebrate personal heroism, lauding those atypical educators who sacrifice other parts of their lives in order to help their students. Often, these are wonderful stories of dedication. As a strategy for educational improvement, however, it makes little sense to try to scale up acts of personal heroism to the larger teaching force. Realistically, any sustainable, scalable approach must be practical for good teachers to implement without extraordinary efforts.

As yet, we have not adopted innovative ways of using technology to help education to be more effective and productive at scale, though calls for major shifts in schooling are becoming pervasive. Some have predicted disruptive innovations parallel to those said to be occurring in the business world (Christensen, Johnson, & Horn 2008; Christensen et al. 2011), where the costs of implementing technology infrastructures have been offset by improvements in effectiveness and efficiency. As discussed in detail in the 2010 National Educational Technology Plan, this could prove to be true in education as well, though the short-term costs of investing in new technologies are likely to be relatively high in this country (USDOE 2010), since the U.S. currently ranks low relative to other countries in terms of its level of educational innovation (OECD 2014).

Students' Learning Strengths and Preferences

The second reason why teachers will find it hard to provide deeper learning opportunities without employing technology is that the characteristics of students are changing as their usage of media outside of academic settings shapes their learning strengths and preferences (Dieterle 2009). Across many sectors of the economy, the nature of work has been reshaped by the power of technology to facilitate interactions across distance, as well as to distribute tasks among people and digital tools. And so too has the increasing availability and affordability of powerful mobile devices (e.g., smartphones and tablets) led to parallel shifts in informal learning by people of all ages.

In particular, new media encourage participation, creation, and sharing. Brown and Thomas (2011) emphasize the importance of playful learning, which includes learning in ways that we formally recognize as play (such as games), but also the broader culture of learners sharing information and pushing boundaries. Brown and Thomas distinguish between "learning about," which is the traditional province of school-based learning; "learning to do," which is often represented in formal education through problem-based and project-based pedagogies; and "learning to be" or "becoming," which is currently centered in informal learning, fundamentally about identity formation, and generative for deep engagement as well as the formation of intrapersonal and interpersonal skills.

Jenkins and colleagues have been exploring how people learn through what they describe as "new media literacies," which embody the kinds of intellectual, personal, and social fluencies learners develop as they use technology for learning and doing (Jenkins et al. 2006)—by contrast, the notion that younger people are "digital natives" and older ones "digital immigrants" (Prensky 2001) is a less useful way to conceptualize this, as people's learning preferences and strengths are shaped by their current patterns of media usage, not simply by what happened when they were children. In fact, many adults have new media literacies, and some youth do not.

It is true, however, that a substantial and rising proportion of young people do have technology-based learning strengths and preferences, presenting challenges for their engagement in traditional education (Collins & Halverson 2009). Much research is under way that examines various patterns of participation by youth in these new cultures, relating these to opportunities for connected learning (Ito et al. 2013).

To summarize my argument so far, whether one argues on the basis of alignment to a knowledge-based economy, or the need for greater productivity in the education service sector, or alignment to students' emerging learning strengths and preferences, a transformation to a technology-based, deeper-learning-driven model of 21st-century education is absolutely necessary, and we are now beginning to see new technologies used in ways that promote deeper learning. Again, while it is possible to teach for deeper learning without technology, it is hard to imagine how our schools will scale up such instruction without support from digital tools and media.

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NEW DESIGNS FOR LEARNING: TWO PROVEN STRATEGIES

When considering the role of technology in learning, it is critical to begin with one's educational goals (e.g., to prepare students for 21st-century life, work, and citizenship). Otherwise technology becomes a solution looking for a problem—never a good thing.

To date, however, the digital tools and media that have had the most substantial impact on practice have mainly been used to automate conventional models of teaching, as though the goal were to continue pursuing a narrow set of learning goals related to preparation for an industrial economy. Thus, some learning management systems deliver drill-and-skill instruction, tested through traditional measures, rather than via application to real-world problems. Electronic whiteboards and digitized videos are used primarily to present information. And in one-device-per-student initiatives, laptops, tablets, and cell phones are generally used as delivery platforms for traditional instruction, rather than as means by which to empower students and engage them in deeper learning.

At this point in history, major advances in educational equity and quality are unlikely to come from further improvements in one-size-fits-all presentational instruction, no matter how fancy the gadgets. Thus, it is no surprise that the results of applying technology in education have been generally disappointing so far. Moreover, it's hard to imagine that the nation's educators could make a real shift toward deeper learning without reinventing their teaching tools and platforms to create new types of instructional environments in which students do their work.

In an extensive review of the literature on technology and teaching for the forthcoming *American Educational Research Association Handbook of Research on Teaching* (5th Edition), Barry Fishman and I (Fishman & Dede in press) note the important distinction between using technology to do conventional things better and using technology to do better things (Roschelle et al. 2000). While there may be value in doing some types of conventional instruction better (i.e., more efficiently and effectively), the real value in technology for teaching lies in rethinking the enterprise of schooling in ways that unlock powerful learning opportunities and make better use of the resources present in the 21st-century world. Above all, doing better things means preparing students to be more responsive to the opportunities and challenges of a global, knowledge-based, innovation-centered civilization.

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In our review, Fishman and I consider how and under what conditions technology can be productively employed by teachers to more effectively meet the challenges presented by a rapidly evolving world. We argue that technology as a catalyst is effective only when used to enable learning with richer content, more powerful pedagogy, more valid assessments, and links between in- and out-of-classroom learning. The technologies that we examined in depth were:

- **Collaboration tools**, including Web 2.0 technologies and tools that support knowledge building
- **Online and hybrid educational environments,** which are increasingly being used to broaden access to education, but also have the potential to shift the way we conceive of teaching and learning
- **Tools that support learners as makers and creators,** and which have deep roots in helping students learn to become programmers of computers (and not just users of them)
- **Immersive media** that create virtual worlds to situate learning or augment the real-world with an overlay of computational information
- **Games and simulations** that are designed to enhance student motivation and engagement

We found that all of these technologies can be used in the service of deeper learning. If used strategically and in concert, they can help prepare students for life and work in the 21st century, mirroring in the classroom some powerful methods of learning and doing that pervade the rest of society. Further, they can be used to create a practical, cost-effective division of labor, one that empowers teachers to perform complex instructional tasks. In addition, these media can address the learning strengths and preferences of students growing up in this digital age, including bridging formal instruction and informal learning. And, finally, these technologies can provide powerful mechanisms for teacher learning, by which educators deepen their professional knowledge and skills in ways that mirror the types of learning environments through which they will guide their students.

For reasons of length, it is not practical to delineate all of the ways in which the technologies that Fishman and I describe could be used to pursue deeper learning. However, two approaches stand out as particularly powerful, illustrating how teachers can use a combination of those technologies to create opportunities for students to master a wide range of high-level skills and content.

Both of the approaches described below—the use of **digital teaching platforms** and **immersive authentic simulations**—have been researched in a large number of empirical studies, which have validated their practicality and effectiveness in typical educational settings, and both were selected because the National Educational Technology Plan (USDOE 2010) identified them as particularly promising.

After describing these two technologies in detail, I then go on to discuss some challenges that will have to be overcome in order to implement such approaches successfully, along with a set of recommendations about how to advance the use of technology in deeper learning.

1. Digital Teaching Platforms

Digital teaching platforms (DTPs) are a new kind of classroom learning infrastructure enabled by advances in theory, research, and one-to-one computing initiatives (Dede & Richards 2012). This system is designed to operate in a teacher-led classroom as the major carrier of the curriculum content and to function as the primary instructional environment.

Note that DTPs are not meant to replace teachers or control their work. Attempts since the dawn of computing to build "teacher-in-a-box" instructional systems have produced only simplistic learning environments that have limited effectiveness (with the exception of intelligent tutoring systems limited to a narrow range of subject matter). As Fishman and I (Fishman & Dede, in press) document, the focus in educational technology has appropriately turned from artificial intelligence to amplifying the intelligence of teachers and students.

> » Technology as a catalyst is effective only when used to enable learning with richer content, more powerful pedagogy, more valid assessments, and links between in- and out-of-classroom learning.

A DTP empowers teachers to use four instructional strategies that are atypical in conventional classrooms but which can lead to deeper learning:

- **Case-based learning** helps students master abstract principles and skills through analysis of real-world situations
- **Multiple, varied representations** of concepts provide different ways of explaining complicated things, showing how those depictions are alternative forms of the same underlying ideas
- **Collaborative learning** enables a team to combine its knowledge and skills in making sense of a complex phenomenon
- **Diagnostic assessments** are embedded into learning and are formative for further learning and instruction

These deeper learning capabilities of a DTP function effectively in the give-and-take atmosphere of a classroom. The teacher can shift quickly from large-group demonstrations to small-group activities to individualized practice and assessment. Students move seamlessly from using their devices for these activities to ignoring their computers and participating in dialogues. The teacher is central in guiding student activities through giving assignments, mentoring individuals, and leading discussions. In short, DTPs offer a form of blended or hybrid learning in which the role of providing instruction is shared by teacher and technology, leading to a mix of face-to-face and digitized student experiences.

A full-fledged DTP serves three major functions: First, a DTP is a networked digital portal that includes interactive interfaces for both teachers and students. To use a DTP, each student and the teacher have a laptop, or some equivalent computational device, connected to the network. Teachers use the administrative tools of the DTP to create lessons and assignments for students and to manage and evaluate the work the students do. These capabilities include specific assessment tools, allowing teachers to create tests and other types of measures, assign them to students, and review the results. The teacher tools also provide timely reports on student progress and on their remedial needs, and the tools for students allow them to complete assignments and assessments. More important, these tools allow for both individual and group work: Some students can work independently on individualized assignments, while others work collaboratively on shared assignments.

Second, a DTP provides the content of the curriculum and assessments for teaching and learning in *digital* form. This content includes reading material, instructional strategies, exercises, assessments, manipulative activities, special-purpose applications, multimedia materials, and any other digital content and assessments that the teacher wishes to add.

Third, a DTP supports real-time, teacher-directed interaction in the classroom. The system includes special tools for managing classroom activity, monitoring progress on assignments, displaying student work to the entire class through an interactive whiteboard or similar device, managing group discussions, and coordinating large- and small-group activities. In short, the DTP is an assistant for all the types of instructional activities a teacher might wish to implement.

WAYS THAT DTPS SUPPORT DEEPER LEARNING

The three examples of DTPs below were selected for a few reasons. Each was developed with substantial federal investment and studied in practice over an extended period of time. Each has achieved significant uptake by practitioners, attesting to its usefulness and practicality. Further, each is based on a large body of theory and evidence oriented to various principles of deeper learning. For example, WISE (the first example) builds on decades of research into visualization and simulation; ASSISTments (the second example) on decades of research on intelligent tutoring systems; and SimCalc (the third example) on decades of research into the role of learning through collaborative argumentation about mathematical representations.

> The focus in educational technology has appropriately turned from artificial intelligence to amplifying the intelligence of teachers and students.

USING DTPS TO PROMOTE KNOWLEDGE INTEGRATION

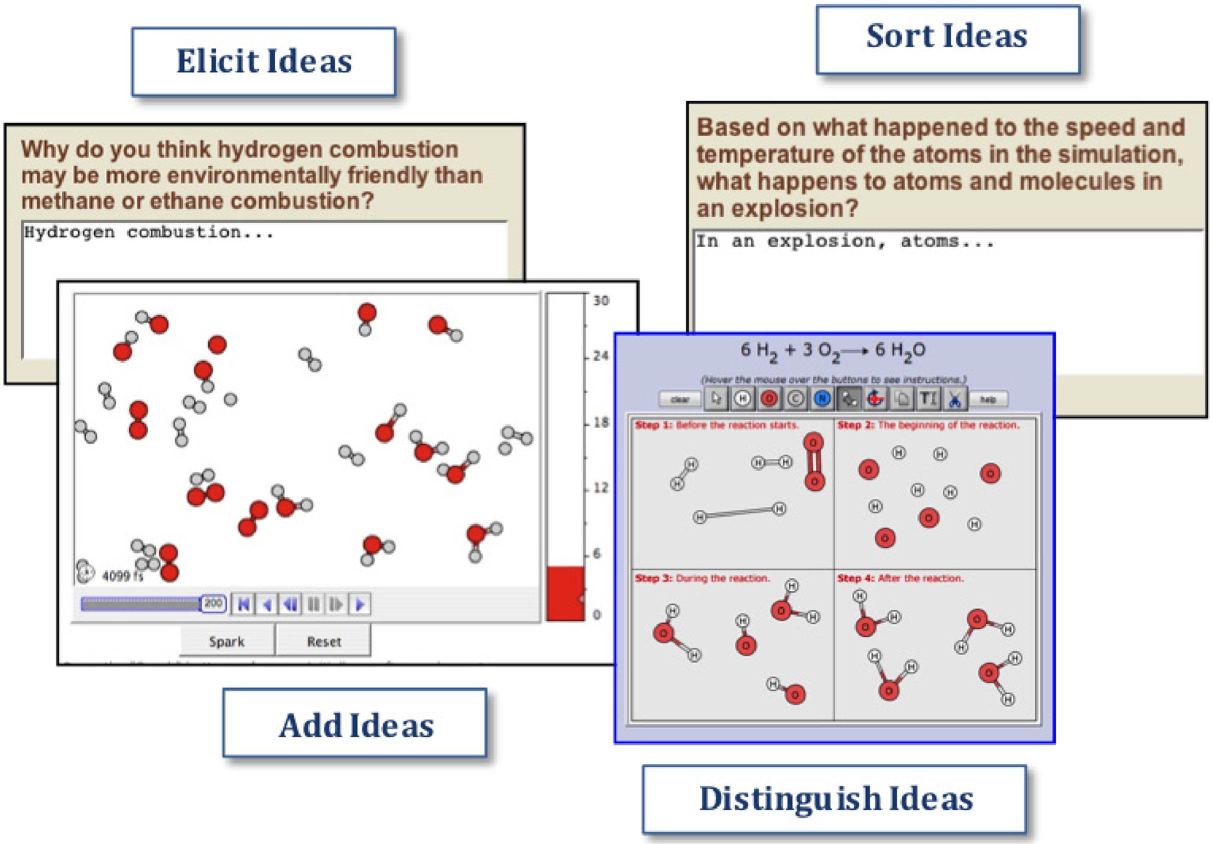
In typical classrooms, teachers spend much of their time presenting material from the front of the room, barraging students with information that tends to have little connection to their existing ideas, and which they ultimately forget. In classrooms that emphasize knowledge integration, by contrast, teachers invite students to share their own emerging ideas and theories, help them to detect gaps in their knowledge, and engage them in using new ideas to address compelling problems (Linn & Hsi 2000).

As Linn (2012) describes, the Web-based Inquiry Science Environment (WISE), which has many characteristics of a DTP (http://wise.berkeley.edu/), supports students' knowledge integration using case-based, collaborative learning in which students interpret multiple representations and are assessed through embedded diagnostics.

WISE is designed to engage students in four specific aspects of knowledge integration: eliciting ideas, adding ideas, distinguishing ideas, and sorting out ideas (Lynn & Eylon 2011). In a classroom using WISE, for example, the teacher might begin by asking students to predict the sequence of events in specific chemical reactions (*see Figure 1*), and then assign them to conduct virtual experiments on those chemicals using the computer to simulate what would happen in the laboratory. (Unlike a real-world laboratory, though, WISE allows students to plug in any number of experimental conditions and variables, giving them the opportunity to try out numerous versions of the experiment and to observe and compare the differing outcomes.)

The teacher might then ask students to reassess their initial predictions in light of this new information, and to discuss and debate their evolving ideas about the given chemical processes (offering them a chance to practice the use of scientific terminology and, perhaps, to come

Figure 1. Knowledge Integration in the WISE Chemical Reactions Unit



Why do you think hydrogen combustion may be more environmentally friendly than methane or ethane combustion?

Hydrogen combustion...

Based on what happened to the speed and temperature of the atoms in the simulation, what happens to atoms and molecules in an explosion?

In an explosion, atoms...

$6\,H_2 + 3\,O_2 \rightarrow 6\,H_2O$

(Hover the mouse over the buttons to see instructions.)

Source: Linn 2012, p. 60

up with personal experiences or examples that show how the science applies to the wider world). Finally, the teachers might assign the students to sort out and clarify their refined ideas by explaining them to a peer, writing a persuasive essay on a relevant topic, or creating a visual representation of the idea, such as a drawing or a concept map that illustrates what they have learned.

Further, WISE includes built-in assessments and rubrics that ask students to link, connect, and distinguish their ideas, and give evidence to support their claims. Thus, after completing a virtual chemistry experiment, students might have to explain why they got the results they did, critique the design of their own experiment, and predict how their ideas would apply to new situations. For example, Linn and Hsi (2000) created an assessment item for WISE that asks students to articulate precisely how the concepts of heat and temperature are distinct. As another illustration, in a global climate unit students are asked to show how the chemical processes at work in an actual greenhouse differ from those predicted to occur in an atmospheric greenhouse effect.

An empirical analysis of over a hundred WISE assessment items developed for grades 6 to 12 found strong evidence of the benefits of their use. The items measure knowledge integration in a psychometrically rigorous manner, and constructed-response items scored with the knowledge integration rubric showed satisfactory reliability across units and years (r >.74; Liu et al. 2008). In addition, a comparison between items that required student-selected and student-generated explanations showed that generating explanations, although significantly more difficult for students, was also more educationally valuable (Linn et al. 2006; Liu et al. 2006).

In short, as exemplified in WISE, DTPs have specific features that strongly support knowledge integration: They provide visual representations that students can use to study new concepts and demonstrate their own ideas, and students can manipulate those representations in order to see how other, contrasting ideas play out. Further, DTPs allow students to store, revise, publish, and share their work via digital galleries, inviting large and small group discussions of their ideas. And, for the teacher, the DTP enables the rapid review of student work using embedded assessments that are truly diagnostic, revealing how much students understand already and what they have yet to learn.

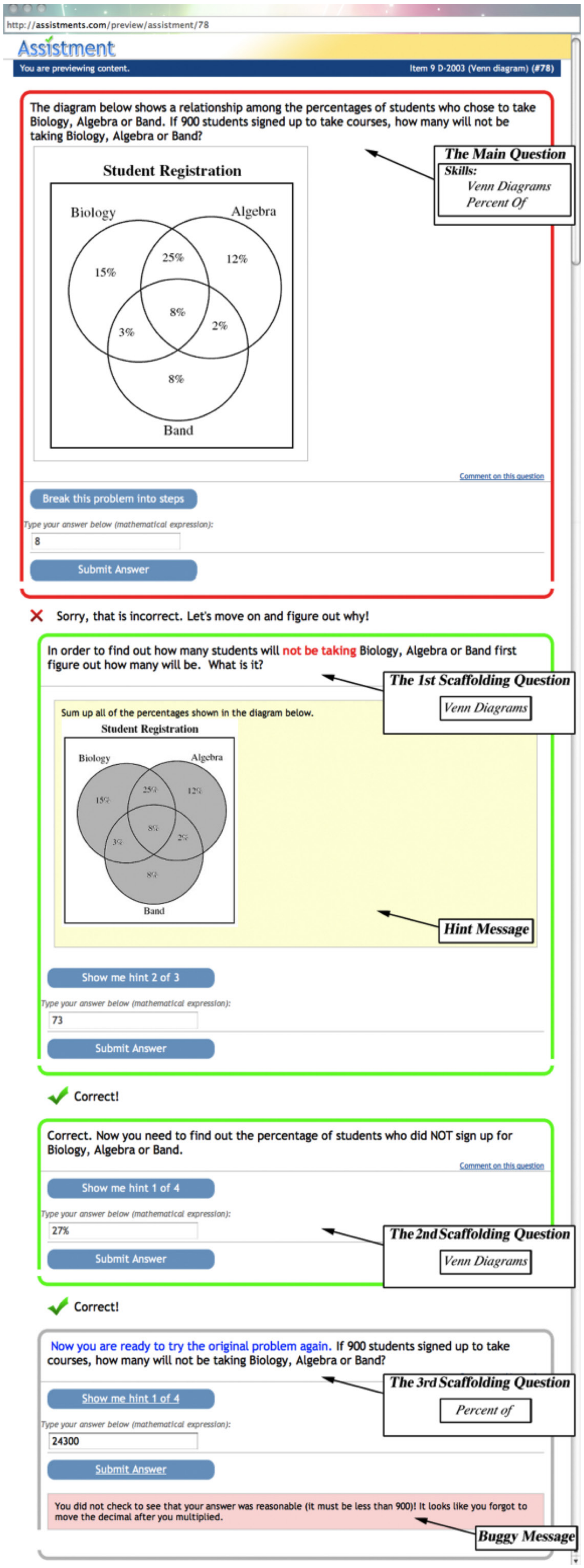
USING DTPS TO PERSONALIZE INSTRUCTION

Digital teaching platforms can also aid teachers in adapting instruction to meet the needs of individual students. For example, the ASSISTments system (http://www.assistments.org) for mathematics learning—which draws from the broader "mastery learning" model first developed in the 1970s—features an online assessment tool designed to spot any gaps in students' background knowledge of a subject so that teachers can decide precisely which skills each student will need to strengthen in order to grasp new and more complicated material.

A major challenge for the mastery learning approach has always been the amount of record keeping it requires. Teachers need to keep track of exactly which skills individual students have mastered, which skills are giving them trouble, and which ones they'll have to learn in order to move on to a new unit. ASSISTments takes care of much of that record keeping while providing a number of additional tools to help teachers individualize instruction (*see Figure 2*). For example, each problem set in ASSISTments is configured to automatically track the amount of practice students get, determining that a student has "mastered" a given skill once she is able to solve a number of problems in row without making any errors. For students who have no trouble with the skill, the assessment is quick, letting them move on to more challenging material. For others, the built-in ASSISTments tutoring may be sufficient to help them reach mastery. Or, since the system provides ongoing reports as to which students are struggling with which skills, teachers can act in a timely fashion to provide other kinds of support.

Given the teacher's hands-on involvement in assigning problems, monitoring individual student progress, and providing guidance as needed, ASSISTments is a much more effective platform for personalized instruction than simpler "learning management systems" that merely keep track of students' progress. To date, two studies—one focusing on fifth-graders, the other on eighth-graders (Mendicino, Razzaq, & Heffernan 2009; Singh et al. 2011)—have shown that ASSISTments led to dramatically increased student knowledge when used for immediate feedback while learners do their homework (when compared to a control condition that represents traditional practice in which students get feedback the next day in class), while additional studies have shown that the program's built-in assessments are valid and useful for teachers and students (Feng, Heffernan, & Koedinger 2009).

Figure 2. ASSISTments Question with Scaffolding, Tutoring, and Buggy Messages


http://assistments.com/preview/assistment/78

You are previewing content.

Item 9 D-2003 (Venn diagram) (#78)

The diagram below shows a relationship among the percentages of students who chose to take Biology, Algebra or Band. If 900 students signed up to take courses, how many will not be taking Biology, Algebra or Band?

Type your answer below (mathematical expression): 8

Sorry, that is incorrect. Let's move on and figure out why!

In order to find out how many students will not be taking Biology, Algebra or Band first figure out how many will be. What is it?

Sum up all of the percentages shown in the diagram below.

Type your answer below (mathematical expression): 73

Correct!

Correct. Now you need to find out the percentage of students who did NOT sign up for Biology, Algebra or Band.

Type your answer below (mathematical expression): 27%

Correct!

Now you are ready to try the original problem again. If 900 students signed up to take courses, how many will not be taking Biology, Algebra or Band?

Type your answer below (mathematical expression): 24300

You did not check to see that your answer was reasonable (it must be less than 900)! It looks like you forgot to move the decimal after you multiplied.

Source: *Computers, teachers, peers: Science learning partners*, page 90

USING DTPS TO PROMOTE COLLABORATIVE LEARNING

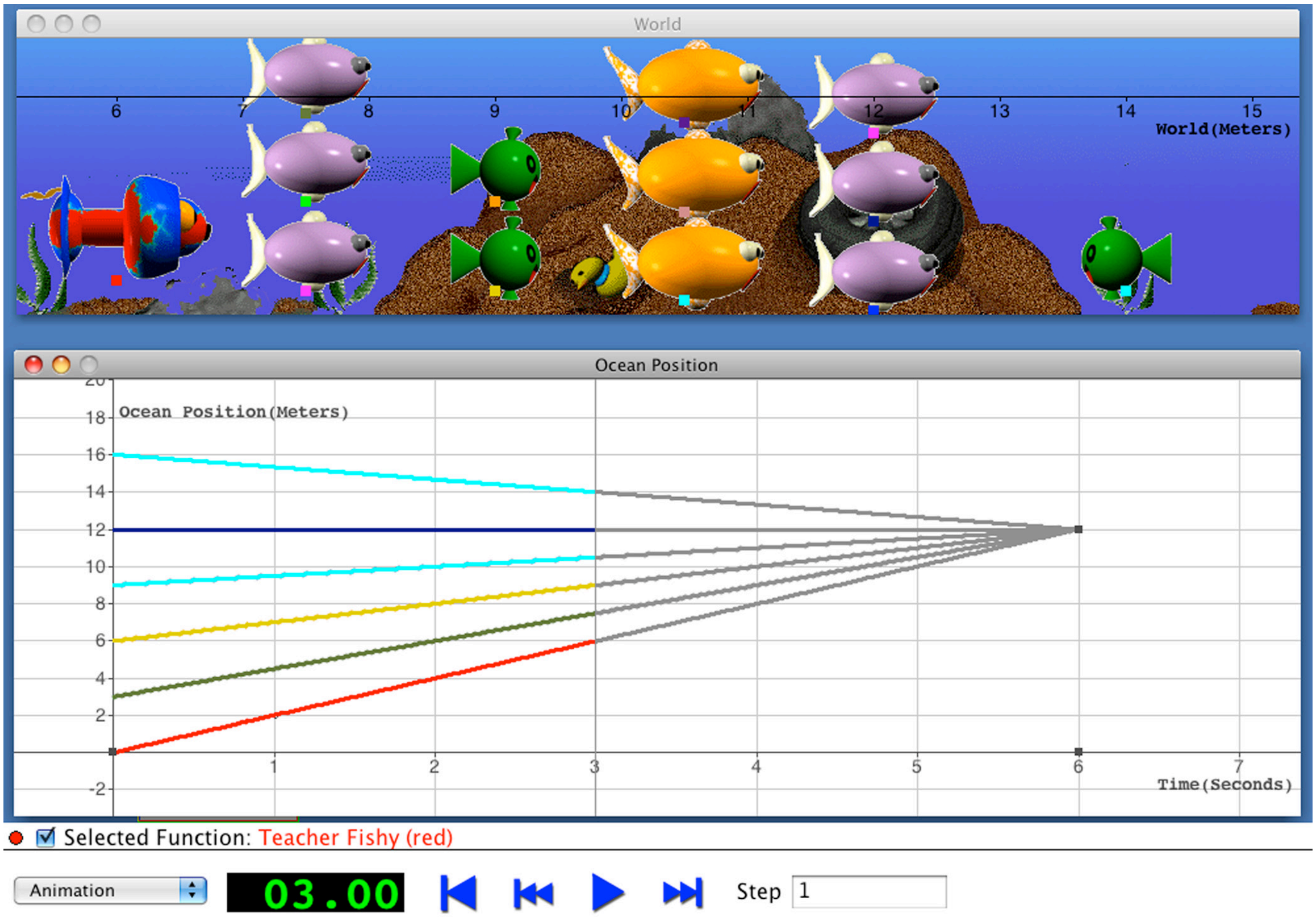
Further, digital teaching platforms have been found to provide powerful support for collaborative learning. For example, Hegedus and Roschelle (2012) describe how SimCalc, a well-known and much-studied mathematics curriculum, is configured to enable highly engaging whole-class discussions.

Since representations of student thinking and work can be rapidly distributed in a networked classroom, teachers have the opportunity to direct everyone's attention to specific participants and their contributions. For example, when using SimCalc's Fishy World (*see Figure 3*), students each "become" a particular fish and learn how the linked graphical representation and symbolic functions relate to their and others' movements. In order to call attention to a particular mathematical concept, the teacher can freeze each student's SimCalc environment, pausing the simulation for a group discussion. Or the teacher can show or hide each student's contribution, in order to have a different kind of discussion. For instance, a graph produced by one student group could be made invisible until the rest of the class has had a chance to talk about what they expect it to show, based upon their own work (Hegedus & Penuel 2008).

In short, much of the pedagogy in SimCalc classrooms involves the teacher facilitating discussions among students about what they learn from the dynamic representations on their computer screens. Substantial research has shown that these mathematical dialogues tend to involve almost everyone in the class, are highly engaging, and lead to deep understandings of the *why* behind mathematical formulas and theorems. And this form of collaborative discussion and debate—stimulated and grounded by the technology—prepares students well for the types of mathematics they will encounter in algebra.

Extensive research studies have been done on SimCalc, documenting its effectiveness and practicality on a variety of dimensions. In particular, the utility of teaching qualitative calculus before algebra has been conclusively established, as has the value of linked multiple representations.[2] As SimCalc illustrates, then, DTPs have many features that facilitate teachers' management of large group argumentation and collaborative dialogue about

Figure 3. SimCalc's Fishy World



Source: *The SimCalc Vision and Contributions: Democratizing Access to Important Mathematics*, page 109

cases that use multiple representations, both of which are important aspects of deeper learning.

THE EVOLUTION OF DTPS

Overall, these examples and findings indicate that there are many benefits to using this complementary suite of media to enable multiple dimensions of deeper learning: case-based instruction, multiple linked representations, embedded diagnostics, and collaborative knowledge building.

In short, DTPs could help to solve what the National Educational Technology Plan called "a grand challenge for research and development" (USDOE 2010, p. 78):

> Today, we have examples of systems that can recommend learning resources a person might like, learning materials with embedded tutoring functions, software that can provide . . . supports for any technology-based learning materials, and learning management systems that move individuals through sets of learning materials and keep track of their progress and activity. What we do not have is an integrated system that can perform all these functions dynamically while optimizing engagement and learning for all learners. Such an integrated system is essential for implementing the individualized, differentiated, and personalized learning called for in this plan. Specifically, the integrated system should be able to discover appropriate learning resources; configure the resources with forms of representation and expression that are appropriate for the learner's age, language, reading ability, and prior knowledge; and select appropriate paths and scaffolds for moving the learner through the learning resources with the ideal level of challenge and support.

DTPs represent an important step toward achieving that vision, while simultaneously providing a means by which to scale up classroom instruction that aims at deeper learning. Indeed, it is difficult to see how most classroom teachers could (absent extraordinary personal heroism) implement the types of ambitious teaching and learning described above without support from tools and media like a DTP.

What about the interdisciplinary aspects of DTPs as a vehicle for deeper learning? The examples above illustrate how instruction can bridge mathematics, science, and technology. It's not difficult to add engineering to this, enabling integrated, deeper learning in science, technology, engineering, and mathematics (STEM). But is similar technology-based deeper learning feasible for content areas such as the social sciences, reading and language arts, and history?

Recently, Graesser and McNamara (2012) have developed DTP-like curricula in reading/language arts, and—as discussed later—game companies are designing and studying games for teaching history that draw on principles of deeper learning. That said, the extent to which DTP systems can extend their coverage into the arts, social sciences, and humanities is not yet determined, in part because funding for learning technologies has centered on STEM fields. Thus, increased funding for research and development in non-STEM areas is important for enabling technology-based deeper learning across the full spectrum of the curriculum.

Could DTPs eventually be used to enable auto-didactic learning so that the teacher was no longer necessary? For example, could we imagine a massively open online course with a similar architecture that omitted the teacher?

That's not likely. Peer interaction can help to enrich learning in "massive" delivery environments and in settings like Khan Academy, where the teacher's input is limited to broadcast and programmed-interaction mechanisms (Dede 2013). However, the whole concept underlying a DTP is that the teacher's role is essential because digital technology today—and in the foreseeable future—will not have the sophistication needed to deliver the complex types of teaching and assessment that deeper learning requires, particularly in subject areas that do not have a narrow range of "right answers" to problems.

The second type of technology for deeper learning, discussed next, goes beyond a DTP in placing emphasis on the world outside the classroom. Experiences such as internships in 21st-century workplace settings offer potential benefits for student motivation, academic learning, and mastery of skills for the global, knowledge-based, innovation-centered economy (Dede 2012). And some well-known secondary schools that build their learning experiences around real-world internships or apprenticeships (such as High Tech High in San Diego or The Met in Providence) have been shown to be popular and effective (Wagner 2008). However, providing extended, mentored, real-world activities outside classrooms is difficult, particularly to younger students. Moreover, internship/apprenticeship models are hard, if not impossible, to bring to scale, partly because the number of workplace sites willing to accept mentoring responsibilities for students is limited and partly because teachers accustomed to conventional classrooms often struggle to adapt to this form of education. Fortunately, as described below, virtual worlds and augmented realities now offer the opportunity for all students to experience simulated internships without leaving their classrooms.

2. Immersive Authentic Simulations

The concept of immersion has to do with "being there," the subjective sense of having a comprehensive, realistic experience in a place where one is not physically located (Slater 2009, page 3549). For example, a well-crafted movie draws viewers into the world portrayed on the screen such that they feel caught up in that virtual environment. Without actually putting anybody at risk, flight simulators allow pilots to practice flying in dangerous conditions. Likewise, many of today's electronic games insert people into environments that are so richly defined that players tune out their real-world surroundings.

In similar fashion, educational technologies can create powerfully immersive experiences for students via sensory stimuli, the ability to act upon the digital environment, and the use of narrative and symbolism to create credible, engaging situations (Dawley & Dede 2013).

Two types of immersive media underlie a growing number of formal and informal learning experiences (Dede 2009):

- **Multiuser virtual environments (or "virtual worlds")** offer students an engaging "Alice in Wonderland" experience in which their digital avatars in a graphical, virtual context actively participate in experiences with the avatars of other participants and with computerized agents. MUVEs provide rich environments in which participants can interact with digital objects and tools, such as historical photographs or virtual microscopes (Ketelhut et al. 2010).

- **Augmented reality** enables students to interact—via mobile wireless devices—with virtual information, visualizations, and simulations superimposed on real-world physical landscapes. For example, while looking at a tree through a pair of AR glasses, a student might also see text describing its botanical characteristics. While walking through a neighborhood, she might call up a historical photograph showing a 19th-century image of a building layered over its current appearance. Or, for that matter, her mobile device could show her an imaginary object, such as an alien spaceship flying overhead. In short, this type of immersion infuses digital resources throughout the real world, augmenting students' experiences and interactions (Klopfer 2008).

As described earlier, digital teaching platforms offer powerful support for four classroom practices known to lead to deeper learning outcomes: **case-based instruction, the use of multiple representations, collaborative learning, and the use of diagnostic assessments.** By immersing students in authentic simulations, MUVEs and AR promote two additional practices that are associated with deeper learning but are rarely found in conventional schools and classrooms:

- **Apprenticeship-based learning,** which involves working with a mentor who has a specific real-world role and, over time, enables mastery of their knowledge and skills, and
- **Learning for transfer**, which emphasizes that the measure of mastery is application in life rather than simply in the classroom.

MUVEs and AR also can provide rich interdisciplinary and experiential types of learning, which are unusual in traditional education. All these deeper learning capabilities of immersive authentic simulations are designed to function effectively in a classroom and in local settings outside of school.

MUVES (OR "VIRTUAL WORLDS")

Over the past several years, my colleagues and I have designed and studied media for science education that immerse students in virtual ecosystems (EcoMUVE), as well as augmented-reality experiences that guide them through related activities in the real world (EcoMOBILE).

The EcoMUVE middle grades curriculum (http://ecomuve.gse.harvard.edu) teaches scientific concepts about ecosystems while engaging students in scientific inquiry (both collaborative and individual) and helping them learn complex causality. The curriculum consists of two multi-user environments that allow students to explore realistic, three-dimensional pond and forest ecosystems. Each module consists of 10 45-minute lessons and includes a complex scenario in which ecological change is caused by the interplay of multiple factors (Metcalf et al. 2013). Students assume the role of scientists, investigating research questions by exploring the virtual environment and collecting and analyzing data from a variety of sources over time.

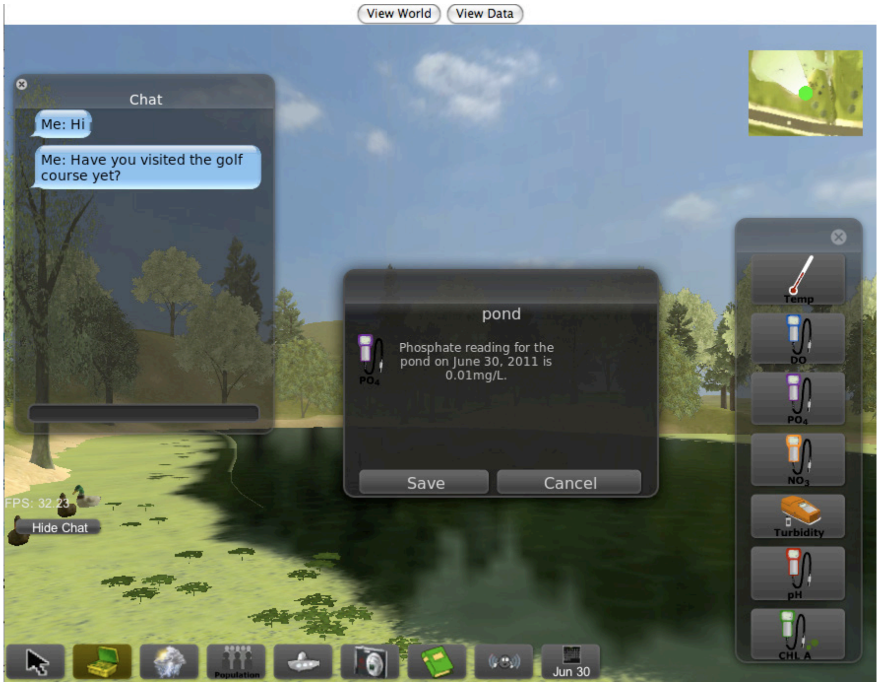
In the pond module, for example, students can explore the pond and the surrounding area, even venturing under the water; see realistic organisms in their natural habitats; and collect water, weather, and population data (*see Figures 4-7*). Students visit the pond over a number of virtual "days" and eventually make the surprising discovery that, on a day in late summer, many fish in the pond have died. Students are then challenged to figure out what happened—they travel backward and forward in time to gather information to solve the mystery and understand the complex causality of the pond ecosystem.

The EcoMUVE curriculum uses a "jigsaw" pedagogy, in which students have access to differing information and experiences; they must combine their knowledge in order to understand what is causing the changes they see. Working in teams of four, students are given roles that embody specific areas of expertise (naturalist, microscopic specialist, water chemist, private investigator) and that influence how they participate and solve problems. Using the differing methods of their roles, students collect data, share it with teammates via tables and graphs that they create within the simulation (Metcalf et al. 2011), and then work collaboratively to analyze the combined data and figure out how a variety of interconnected parts come together to produce the larger ecosystem dynamics. The module culminates with each team creating an evidence-based concept map representing their understanding of the causal relationships at work in the ecosystem, which they present to the class.

EFFECTIVENESS AND PRACTICALITY

An extensive series of research studies were conducted about the effectiveness and practicality of EcoMUVE across a range of classroom settings, including urban, suburban, and rural schools. Affective measures included students' levels of engagement and self-efficacy in science, while cognitive measures focused on specific concepts in

Figure 4. Students can Collect Water, Weather, and Population Data at the Digital Pond



Me: Hi

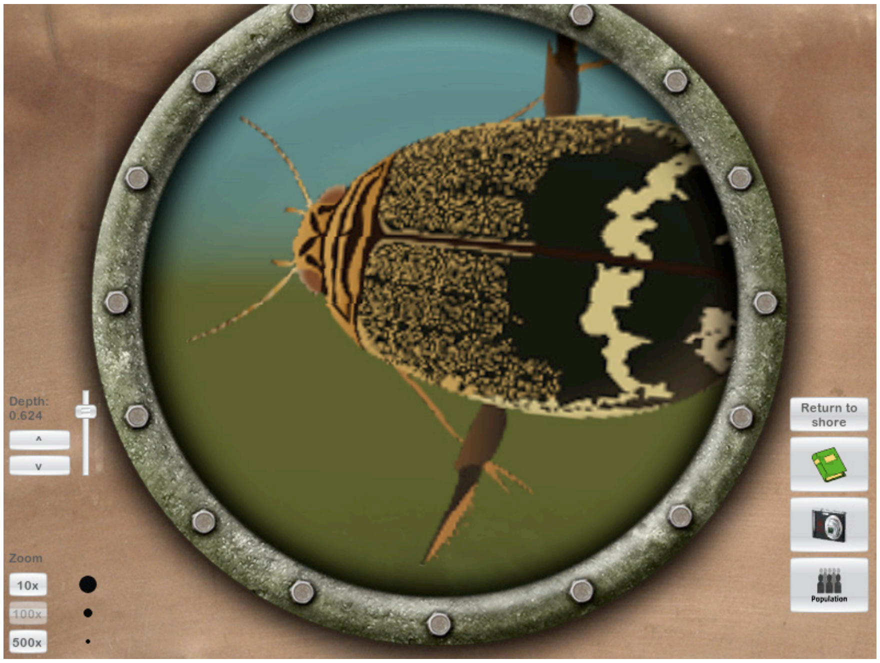
Me: Have you visited the golf course yet?

pond

Phosphate reading for the pond on June 30, 2011 is 0.01mg/L.

Source: *The SimCalc Vision and Contributions: Democratizing Access to Important Mathematics*

Figure 5. The Submarine Tool Allows Students to See and Identify Microscopic Organisms



Source: *The SimCalc Vision and Contributions: Democratizing Access to Important Mathematics*

Figure 6. Talking to Manny and Observing the Bags of Fertilizer

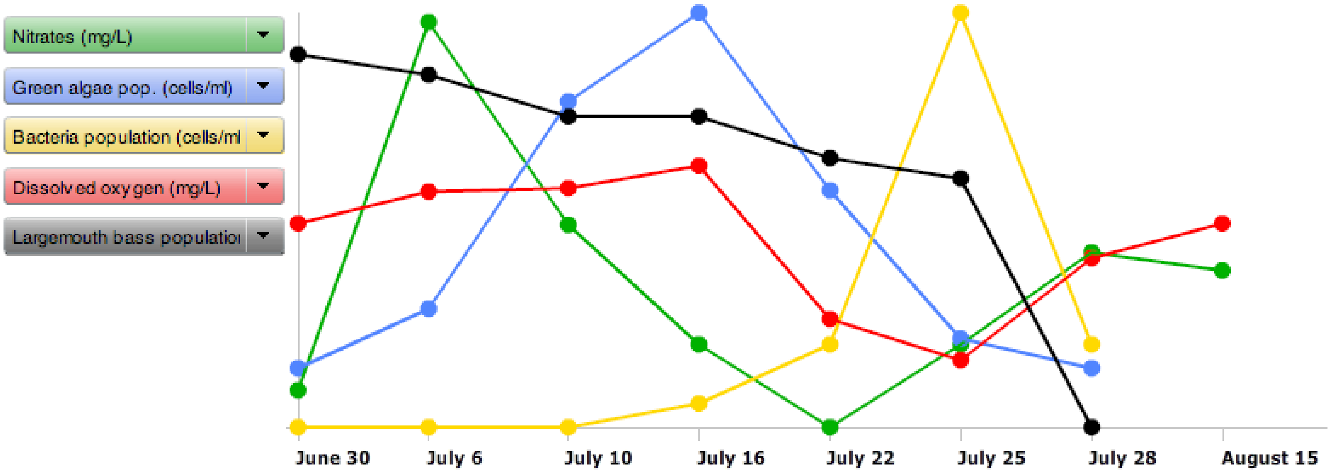
Manny Bract

Hi, I'm Manny. We've been working really hard to get the new housing development ready for the open house. I'm probably going to have to work overtime every day this week to get these lawns in shape! I think this extra fertilizer I picked up should do the trick.

Professional Turf Fertilizer (40 lbs.) Contains nitrogen, phosphorus and potassium – nutrients essential for plant growth. Apply 1 pound for every 1,000 square feet of turf.
Apply only as directed. Avoid applying before it rains to prevent loss of nutrients before they are taken up by plants.

Source: *The SimCalc Vision and Contributions: Democratizing Access to Important Mathematics*

Figure 7. Summarizing and Interpreting Data Gathered Over Time



Source: *The SimCalc Vision and Contributions: Democratizing Access to Important Mathematics*

ecosystems science, the use of collaborative inquiry as a scientific process, and the understanding of complex causalities that are characteristic of ecosystems. Teachers were interviewed about the practicality of using this type of technology in the classroom, and a comparison study measured the outcomes of EcoMUVE in relation to another project-based curriculum that involved lab experiences but not the use of immersive media. Overall, these studies validated the utility and effectiveness of EcoMUVE as an immersive authentic simulation that adds new dimensions to classroom learning and motivation (Metcalf et al. 2013; Chen, Metcalf, & Tutwiler 2014; Grotzer et al. 2013).[3]

Interviews revealed that teachers found the EcoMUVE curriculum to be feasible because of its student-friendliness, customizable lessons, online materials, and appropriate length of study; the only exception was that some teachers noted difficulty with providing one-to-one student access to technology. Overall, they reported that the curriculum is well aligned to standards and supports student engagement and learning of science content, complex causality, and inquiry (Metcalf et al. 2013). Several teachers felt that learning of complex causality was the strongest part of the curriculum; one wrote, "In my experience, students can individually learn the important components of ecosystems, which include photosynthesis, energy conversion, conservation of matter, cycles, populations, food chains, and food webs, but often cannot tie it all together and realize that ecosystems are dynamic and involve the relationships of living things and their environment. EcoMUVE definitely showed complex causality."

The use of immersive authentic simulations appears to hold promise also for non-STEM parts of the curriculum—such as history, language arts, and civics—especially through the playing of high-quality educational games that have been carefully designed to foster learning and transfer (Fishman & Dede in press). [4]

Two recent, large-scale reviews of research on computer-based games describe what is currently known about their capabilities and effectiveness for teaching and learning. In one, Tobias and Fletcher (2011) found that digital educational games that immerse players in virtual worlds and that involve imaginative play, rapid responses, challenges, and competition, are not only highly engaging for most students but can be effective in teaching content and skills that transfer to other schoolwork, training programs, and everyday life (so long as the game and the academic or real-world task involve very similar kinds of thinking processes, and if teachers make those connections explicit).

In contrast, Young and his colleagues (Young et al. 2012) reviewed the available research into the effectiveness of commercially produced educational video games. They found that games that immerse students in virtual worlds have had some positive results for language learning and, to a lesser degree, physical education. Overall, though, they concluded that the evidence to date does not lend much support to the use of such games in classrooms, adding that this may have less to do with the quality of the games themselves than with how they are used: In most schools, game-playing tends to be a brief activity, giving students a low "dosage" of multiplayer interaction, continuity of learning, and extended engagement. It's possible that if teachers gave such games more time, and supervised them more actively, they would have more significant effects on learning.

AUGMENTED REALITIES

Applying academic insights to the real world—and translating real-world experience into academic insights—is an essential feature of deeper learning. Designed to complement EcoMUVE, the EcoMOBILE project (http://ecomobile.gse.harvard.edu) explores the potential of augmented reality—as well as the use of data collection "probeware," such as a digital tool that measures the amount of dissolved oxygen in water—to support learning in environmental science education.

The EcoMOBILE curriculum is a blend of the EcoMUVE learning experiences with the use of digital tools that enhance students' real-world activities, as illustrated by a three-day project that has been field-tested successfully (Kamarainen et al. 2013): During one class period, a group of middle school students participated in an EcoMUVE learning quest, completing a 5-to-10-minute online simulation in which they learned about dissolved oxygen, turbidity, and pH. The following day, the students went on a field trip to a nearby pond to study the relationship between biological and non-biological factors in the ecosystem, practice data collection and interpretation, and learn about the functional roles (producer, consumer, decomposer) of organisms in the life of the pond.

At a number of spots around the pond, students' handheld devices showed them visual representations—overlaid onto the real environment—of the natural processes at work in the real environment, as well as interactive media such as relevant text, images, audio, video, 3-D models, and multiple-choice and open-ended questions. Students also collected water measurements using Texas Instruments NSpire devices (graphing calculators) with Vernier environmental probes (which allow students to measure dissolved oxygen concentration, turbidity (*see Figure 8*), pH, and water temperature).

Both the prior virtual world experience and the augmented reality devices supported students' use of the probes by helping them navigate to a location to collect a sample, providing step-by-step instructions for use of the probes, entering the reading in response to a multiple-choice question, and delivering immediate feedback related to the student-collected measurement (*see Figure 9*).

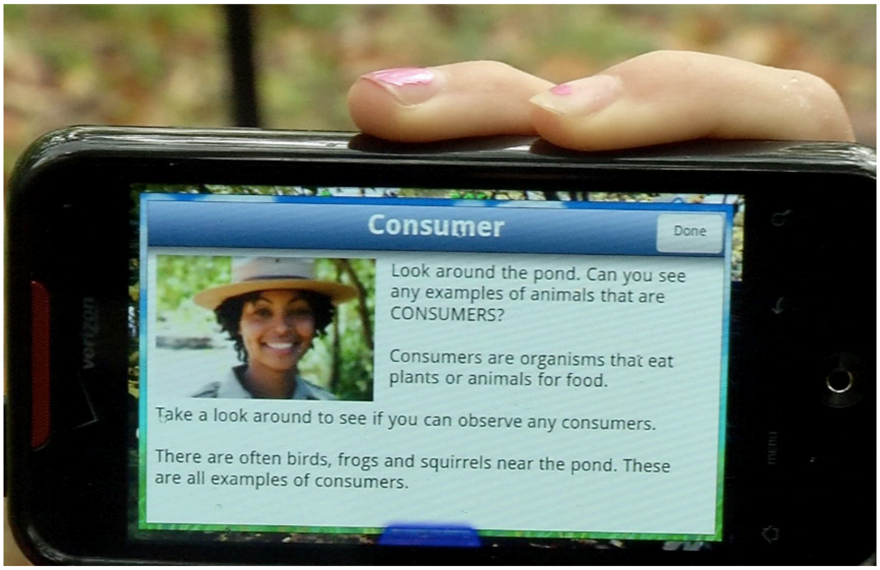
Back in the classroom, students compiled all of the measurements of temperature, dissolved oxygen, pH, and turbidity that had been taken during the field trip. They looked at the range, mean, and variations in the measurements and discussed the implications for whether the pond was healthy for fish and other organisms. They talked about potential reasons why variation may have occurred, how these measurements may have been affected by environmental conditions, and how to explain outliers in the data.

THE EFFECTIVENESS AND PRACTICALITY OF AUGMENTED REALITIES

A rigorous evaluation showed that participating students were highly engaged with the EcoMOBILE technology and

Figure 8. Collecting Water Quality Data on Turbidity Using Digital Probes

Figure 9. Handheld Device Delivering Information about Students' Research Assignment



Consumer

Look around the pond. Can you see any examples of animals that are CONSUMERS?

Consumers are organisms that eat plants or animals for food.

Take a look around to see if you can observe any consumers.

There are often birds, frogs and squirrels near the pond. These are all examples of consumers.

with science learning more broadly (Kamarainen et al. 2013). Student learning gains on the content survey were significant both from a statistical perspective and from the viewpoint of the teachers, who compared these gains to memories of prior field trips without technological support, which limited their pedagogical options. The results of the students' surveys and teacher feedback suggest that there are multiple benefits to using this suite of technologies for teaching and for deeper learning that parallel the benefits already discussed for EcoMUVE (Kamarainen et al. 2013). What EcoMOBILE added is the complexity of the real world (e.g., data values vary depending on the location at which the measurement is conducted and how many samples are gathered).

Teachers reported that the combined technologies promoted student interaction with the ecosystem and with classmates, and that field trip dynamics were student-centered rather than teacher-directed, giving students expanded opportunities to engage in activities that resemble scientific practice. Teachers indicated that allowing the students a window into the unseen parts of the environment also helped them to identify with scientific practices and motivated them in a new way. These results suggest that combining augmented reality with virtual worlds holds great potential for helping students to integrate the teaching and learning of science, mathematics, and technology, and to transfer what they learn in the classroom to real-world situations.

THE EVOLUTION OF IMMERSIVE AUTHENTIC SIMULATIONS

Overall, the evidence suggests that these sorts of immersive media can be used in a number of ways to promote deeper learning, such as by facilitating case-based instruction, collaborative activities, simulated apprenticeships, and the development of scientific inquiry skills, including the collection and analysis of data to provide warrants for specific claims. Simulations allow students to learn skills under controlled conditions that may be difficult to replicate in the real world (Dawley & Dede 2013) but which convey some degree of authenticity, allowing what is learned in one setting to transfer to the other. And augmented realities *embed* learning in the real world, giving students a deeper understanding of the immediate environment (Dunleavy & Dede 2013). On their own, each of these approaches has important benefits for students, and blending them together presents even greater opportunities for deeper learning.

Further, researchers have only just begun to explore the ways in which immersive media might contribute to high-quality educational assessment. While participating in EcoMUVE or another simulation, for example, students generate enormous amounts of information about their motivation and engagement, efforts to collaborate with their peers, problem-solving strategies, persistence, understanding of core content, and—to the extent that the simulation requires them to assess their own work, explain the strategies they pursued, and reflect on the simulation—evidence of their metacognitive development. However, in order to make good use of this information, zeroing in on what students do and do not know as a result of participating in open-ended learning activities, educators will need new types of assessment tools and analytic methods.

Such work is still in its early stages, but a number of approaches already seem promising, suggesting how unobtrusive, real-time diagnostic assessments might be woven into an immersive simulation (Dede 2012):

- **Capturing exploratory paths.** An important predictor of a student's understandings about scientific inquiry is the set of paths that she takes when exploring a virtual world, allowing her to determine the contextual situation, identify anomalies, and collect data related to a hypothesis for the causes of an anomaly.
- **Analyzing the use of guidance systems.** Data on students' use of the "Help" or "Hints" feature woven into a simulation—such as when they first chose to ask for guidance, which messages they viewed, where they were in the simulation when they did so, and what actions they took subsequently—can be used as diagnostic information, providing useful insights into what topics and skills cause them to struggle.
- **Interacting with animated pedagogical agents.** APAs are "lifelike autonomous characters [that] cohabit learning environments with students to create rich, face-to-face learning interactions" (Johnson, Rickel, & Lester 2000, p. 47)—i.e., they're people in the virtual world, and one can ask them questions about the environment. Typically, over time, students learn how to ask questions that lead APAs to give them new information that helps them complete the tasks they've been assigned within the simulation. And in the process, these interactions

create a record of students' approaches to gathering knowledge and collecting evidence. (Additionally, APAs can be programmed to elicit other kinds of diagnostic information, such as by asking the student to summarize what he has learned so far.)

- **Documenting progress and transfer in similar settings.** Once students have completed a simulation, teachers can introduce them to a similar but not identical one in order to assess how well they can apply what they've learned from the first activity to the second. Further, by calling attention to the ways in which their knowledge transfers from one environment to the other, teachers can help students synthesize what they've learned, seeing how specific lessons can lead to broader understandings.
- **Attaining "powers" through accomplishments.** Like leveling up in games, students can attain new powers through reaching a threshold of experiences and accomplishments. These new capabilities document team achievements, promote engagement, facilitate learning, and offer additional opportunities for interwoven assessment.

Consistent with the principles of deeper learning, all of these types of assessment are based not on proxies (e.g., test items, essays) for real-world performance, but instead on authentic actions in rich simulated contexts.

The assessment strategy overarching these design approaches is similar to what a workplace mentor would use in measuring an intern's motivation and learning. For a middle-grades student in a research team internship, part of the goal would be to reach some threshold of scientific understanding and performance, but beyond that threshold the apprenticeship's primary objectives would focus on intrinsic motivation, self-efficacy, and love of learning (Tai et al. 2006), outcomes that can be difficult to measure. Immersive authentic simulations are analogous to such an internship; while they teach basic concepts and formulaic skills, they also offer a powerful method of scaffolding intellectual, emotional, and social capacity and commitment for future involvement (Dieterle 2009), as well as for assessing students' progress toward these outcomes.

In short, the development of more sophisticated assessments is essential for the evolution of deeper learning, and technology offers a powerful vehicle by which to accomplish this.

That said, virtual worlds are based on models that simplify the real world and introduce misconceptions unless they are coupled with real-world experiences that reveal complexities that the simulation suppresses. Augmented realities can help with this, but it may be difficult to augment every context of academic interest. Internships and apprenticeships in organizations provide types of experiences no technology can duplicate (e.g., face-to-face contact with mentors working in those settings). As discussed earlier in this paper, to attain the full benefits of deeper learning, it is critical to use technology to extend and empower good teaching and learning, not to replace them.

CHALLENGES AND RECOMMENDATIONS

For those local, state, and federal policymakers who do see the great potential in technology-enhanced teaching and learning, I conclude by recommending three main priorities for the coming years:

STAY FOCUSED ON REDUCING ACHIEVEMENT GAPS

The technology-enhanced innovations discussed in this paper are meant not just to strengthen teaching and learning overall but, especially, to help reduce the achievement gaps that divide the nation's students. To many of the designers of such digital tools, the most important goal is to ensure that all children—no matter their zip code—are provided with powerful educational resources that can be customized to meet their needs.

No doubt, "digital divides" will persist into the foreseeable future, with affluent children continuing to be the first to acquire the latest, most exotic technologies. Increasingly, however, even children living in impoverished communities have access to powerful mobile devices that enable them and their teachers to take full advantage of all the deeper learning opportunities that this paper describes.

This commitment to equitable access is basic to the concept of Universal Design for Learning, which has come to enjoy widespread support in the field of educational technology. In brief, UDL is a set of shared principles emphasizing the creation of digital tools that can be customized to serve a diverse range of users. Specifically, UDL calls upon its adherents to:

- **Provide multiple and flexible methods of presenting information.** Examples include digital books, specialized software and websites, text-to-speech applications, and screen readers
- **Provide multiple and flexible means of expression,** with options for students to demonstrate what they have learned. Examples include online concept mapping and speech-to-text programs
- **Provide multiple and flexible means of engagement,** in order to tap into diverse learners' interests, challenge them appropriately, and motivate them to learn. Examples include choices among different scenarios or content for learning the same competency, and opportunities for increased collaboration or scaffolding (USDOE 2010, p. 19)

Increasingly, research into teaching and learning lends support to UDL's core premises, including the recognition that *anybody* can appear gifted in some contexts and disabled in others, depending on the particular skills to be learned and the instructional methods and media to which they have access. Some students labeled as dyslexic, for example, struggle when confronted with words on paper but read with little difficulty when given electronic supports. And other students might be considered strong readers until asked to read a text in Braille.

> » Technology is just a tool, one that can empower people to change the ways in which education is structured and delivered.

In other words, learning is best characterized by continua, not dichotomies: All of us are a mixture of gifted and disabled, depending on our individual strengths and weaknesses, and all of us can benefit from appropriate methods and media. This is not to imply that everybody faces an equal level of challenge—some people struggle with profound physical, cognitive, emotional, or financial difficulties—but it is to insist that while learners may need support in differing degrees, they are not different in *kind*. Given effective, customized tools such as DTPs and immersive authentic simulations, all of us can learn deeply.

Much more research and development will be required before we can say precisely which sorts of digital tools, used in what ways, will help us to close the nation's persistent achievement gaps. But we do know that these instructional strategies are promising. And they are certainly more likely to succeed than continued attempts to provide one-size-fits-all instruction.

BUILD PROFESSIONAL CAPACITY TO USE DIGITAL TOOLS EFFECTIVELY

Ultimately, the effectiveness of any technology-enhanced resource will depend on the capacities of the educators involved. As described earlier, the technology itself is not the innovation. Rather, the technology is just a tool, one that can empower people to change the ways in which education is structured and delivered.

However, that requires a kind of professional development that can be extremely challenging to provide. In order to take advantage of programs like SimCalc and EcoMUVE, educators must not only learn new content and skills but, at the same time, "unlearn" many common beliefs and assumptions about the nature of teaching, learning, and schooling. For those teachers who cannot relinquish the lectern, and who feel uncomfortable letting students make and discuss their own scientific predictions, or participate in unscripted simulations, or design their own virtual experiments, such digital tools will be problematic. In short, learning to use programs like SimCalc and EcoMUVE may require not just intellectual and technical support but also efforts to rethink one's basic ideas about teaching, a process that can be emotionally difficult.

Unfortunately, at present, most teacher professional development programs are not of high quality, offering "fragmented, intellectually superficial" seminars (Borko 2004, p. 3), which are unable to provide ongoing daily guidance for teachers as they attempt to implement novel curricula or pedagogies, often in environments made hostile by reluctant peers or administrators who see those innovations as undercutting the existing school culture.

Current debates about and innovations in teacher development mostly lie outside the scope of this paper. However, it is worth noting that technology-enhanced tools are becoming available in this field, too, in the form of online and blended (i.e., combining online and face-to-face) programs, which are tailored to teachers' busy schedules, draw upon resources that aren't available locally, provide "just-in-time" support (via the Internet, whenever teachers need guidance from a coach or mentor), and offer chances for teachers to connect with each other over time, building the sorts of professional learning communities that often help individual teachers to reconsider their core beliefs about education (Frumin & Dede forthcoming; Dede 2006).

Finally, many of my colleagues and I would argue that if we want educators to learn how to use programs such as SimCalc and EcoMUVE effectively, then we should give them professional development opportunities that also make use of digital teaching platforms and immersive authentic simulations, demonstrating the opportunities that we hope they will provide to their students. For example, teachers' online communities can sponsor collaborative research and writing projects, or they might allow for the modeling of apprenticeships, by having master teachers share their experiences using technology.

INVEST IN RESEARCH AND DEVELOPMENT

To date, researchers have found that digital technologies—particularly digital teaching platforms and immersive authentic simulations—have great potential to promote deeper learning across the curriculum. However, much work remains to be done before those technologies will be truly practical, affordable, and scalable. And that will require much greater and more targeted support for research and development than the piecemeal funding that exists today, offered mainly through a handful of relatively small federal programs.

At present, the most glaring need is for studies that aim to produce "usable knowledge" about technology-enhanced instruction, motivated not merely by intellectual curiosity but out of a desire to address persistent problems in practice and policy (Stokes 1997). Not to disparage basic research or theoretical work, but in my opinion, greater investments in applied research are warranted. The most important priorities today are to build high-quality teaching tools that promote deeper learning and to help education stakeholders grasp the value of such tools, identify good ones, and invest in them wisely.

Second, I would argue that the process of creating and sharing such usable knowledge is best accomplished by a community of researchers, practitioners, and policymakers, and not by scholars working in isolation (Penuel et al. 2011). Creative "outlier" ideas can be valuable, but if the goal is to develop and invest in teaching tools that promote deeper learning, then what is required is a multidimensional perspective, touching on the whole range of academic, interpersonal, and intrapersonal capacities that have been shown to matter to young people's long-term success. That sort of work begs for a group effort, combining various research methods and integrating knowledge from several fields—from cognitive psychology to teacher development to curriculum studies to educational technology (Dede 2011).

Third, rather than assuming that an educational technology "is effective" in some universal manner (Means 2006), research and development should focus on what works for *whom*, *when*, and in *what contexts*. Numerous studies document that no single pedagogy is optimal for all subject matter and every student (Lampert 2001; Shulman 1986). The best way to invest in new technologies for deeper learning is to begin by acknowledging that context matters, and that the tools must be flexible enough to serve the given school, its teachers and students, its curriculum, and its culture. In short, such tools should be designed with local adaptations in mind. Education reformers often assume that innovations cannot be brought to scale unless they can be replicated precisely and implemented with fidelity. However, as I have found in my own research, the successful implementation, use, and spread of virtual teaching tools often depends on the process of evolution that they undergo at the local level (Clarke & Dede 2009).

At this point in history, the primary barriers in transforming to a deeper learning educational system are not conceptual, technical, or economic, but instead psychological, political, and cultural. Some people oppose any form of educational change that is not fully understood, arguing that traditional schooling was effective for them and that innovators should not "experiment on children." But the most dangerous experiment we can perform is to keep our current systems of schooling in place. Over time, the disconnect between what our society needs and what industrial-age educational models can provide is widening; cohort after cohort of students has needlessly high rates of failure, creating terrible consequences for those learners and our nation.

With investment, we can have all the means necessary to implement deeper learning models of education that prepare all students for a future very different from the immediate past. Whether we have the stakeholder commitment and societal will to actualize such a vision remains to be seen.

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ENDNOTES

[1] See: www.kaputcenter.umassd.edu/products/curriculum_new

[2] The best summary of these findings is Hegedus and Roschelle (2013).

[3] The development process for the EcoMUVE modules was coupled with classroom testing that in turn informed software and materials development. This process resulted in a series of evidence-based findings. EcoMUVE impacted students' learning of science content on an ecosystems inventory (Cronbach's alpha=0.75) with a mean gain of 0.71 (an effect size of 0.11) with a significant pre- to post-test difference ($t(287) = 1.92$, $p < .05$). The fidelity of implementation (technology performance, time on task, etc.) was important to achieving the gains. The full analysis is published in Metcalf et al. (2013). EcoMUVE also resulted in gains on an assessment of attitudes toward science (Cronbach's alpha=0.69). Seventh and eighth graders gained a mean of 2.53 points (an effect size of 0.52) ($t(287)=8.77$, $p <.0001$) on science-related attitudes as reported in Metcalf et al. 2013. Again, fidelity of implementation was important to achieving the gains. A second study used pre- and post-measures (40 Likert scale questions) as well as "checkpoint" surveys at the beginning, middle, and end of the curriculum to assess whether student engagement might attenuate (possibly due to novelty effects) or increase during the student-led, collaborative inquiry experiences. This study, reported in Chen, Metcalf, and Tutwiler (2014) found that sixth graders reported greater self-efficacy in inquiring scientifically and more sophisticated views about the role of authorities in justifying scientific claims on the post-test. Throughout the experience, student interest in EcoMUVE decreased somewhat but stayed high. Student responses shifted from a focus on the opportunity to interact in a virtual computer environment to an increasing appreciation of the pedagogical aspects of the student-centered, inquiry-based activities.

Shifts were also found in students' complex causal reasoning about non-obvious causes; distant drivers of ecosystems dynamics and the system parameters; and processes, steady states, and change over time with the details of the analysis published in Grotzer et al. (2013). Seventh and eighth graders pretest responses fit those expected based upon the extant research. They detected significantly more spatially local as opposed to distant causes and used event-based explanation rather than focusing on processes and steady states. In response to EcoMUVE, they showed significant shifts with fewer spatially local explanations (mean difference = .69 ($t(77) = 3.22$, $p < .0018$), fewer obvious causes (mean difference = 0.91 ($t(77) = 7.50$, $p < .0001$), fewer event-based explanations (mean difference = .83 ($t(75) = 3.75$, $p < .0003$), and significant increases in understanding the importance of effects over distance in analyzing ecosystem problems (McNemar test, $X^2(1,69) = 14.73$, $p <.0001$). Post-test responses focused more on processes, change over time, and domino-like narratives connecting causal mechanisms to the processes in the pond as well as spatially distant causes.

A quasi-experimental comparison study to a non-MUVE-based curriculum (designed to explicitly teach complex causality based on the Causal Patterns in Science Ecosystems Module developed by Grotzer and colleagues (2011, 2002) revealed differential gains for each group. Both groups demonstrated gains in attitude and content knowledge and mentioned fewer spatially local causes and increased spatially distant causes as well as increased non-obvious causes on the post-test than pre-test. EcoMUVE students also mentioned fewer obvious causes pre- to post-test. On the post-test, EcoMUVE students mentioned post-test obvious causes significantly less ($\beta= -0.2892$, $t(4)=-4.17$, $p <.05$) and spatially local causes more frequently ($\beta= 2.902$, $t(4)=-4.44$, $p <.05$) than the comparison group. Comparison students mentioned more distant causes ($\beta= 0.551413$, $t(4)=-4.93$, $p <.05$) than EcoMUVE students. Students' thinking about complex causal patterns shifted with use of EcoMUVE in meaningful ways similar to a curricular intervention focused specifically on complex causality. This suggests the value of explicit reflection upon the causal reasoning assumptions in which students engage; greater support for causal explanation in contrast to observation of correlational patterns might strengthen the impact of EcoMUVE.

[4] A prominent example is the work of Muzzy Lane (http://muzzylane.com), which is developing immersive simulations in a variety of curricular areas, including language learning, social sciences, and history.

[5] The content-related post-survey corroborated teacher beliefs that students' understanding of the water quality variables increased, and a self-report affective survey indicated an increase in students' understanding of scientific practices and causes of ecological change, as well as higher self-efficacy related to using tables and graphs (Kamarainen et al. 2013). A cumulative measure asking students to provide examples of food web, habitat, and biotic-abiotic relationships showed gains. On the post-survey, 63 percent of students cited authentic examples of ecological relationships connected to their local environment compared to 33 percent on the pre-survey in their open-ended responses.

[6] A research agenda for improving teacher professional development via technology is described at length in Dede et al. 2009.

[7] The National Educational Technology Plan provides an extended discussion of this type of professional learning in its section on teaching (USDOE 2010), as well as in its follow-on research on connected educators (http://connectededucators.org/).

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