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Preface

This volume began with a request to consider a follow-up to the *Innovations in Science and Mathematics Education: Advanced Designs for Technologies of Learning* book co-edited by Michael Jacobson with Robert Kozma nearly a decade ago. All of the chapters in that volume represented the work of US-based researchers, many of whom had been funded by the US National Science Foundation in the middle to late 1990s. In the intervening years, however, increasingly we see research into the design and use of technology-based learning innovations conducted by international teams of researchers, many of whom are now identified with the emerging field of the *learning sciences*.[1] Consequently, in planning for this new book, it was decided to request chapters from selected contributors to the earlier Jacobson and Kozma volume to illustrate more recent developments and research findings of relatively mature programs of research into innovative technology-enhanced learning environments, as well as to solicit chapters reflecting newer research activities in the field that also include international researchers.

It is important to realize, however, that the societal context in which research such as this is conducted has changed dramatically over the last decade. Whereas in the late 1990s, relatively few schools in countries such as the United States or in Europe (where computer scientists and engineers had developed the Internet and technologies associated with the World Wide Web) even had access to this globally distributed network infrastructure, let alone with significant numbers of computers with high resolution displays and processing capabilities. Today, countries such as South Korea have high speed Internet connectivity to all schools in the nation and nearly all developed countries have national plans for educational advancement that prominently feature discussions of using ICT ("information and communication technologies" that are essentially Internet connect multimedia computers) to help stimulate educational innovations. Further, there is increasing access in businesses, government, and homes to a variety of network-based information resources and Web-based tools, as well as sophisticated digital media such as networked 3D computer games and virtual worlds used daily by millions around the world.

[1]For an excellent collection of papers dealing with theory and research in the learning sciences with background information about the field, the *Cambridge Handbook of the Learning Sciences* edited by Keith Sawyer is highly recommended.

Approaching the second decade of the twenty-first century, it may be safely said that many of the "advanced technologies for learning" of the 1990s are now accessible in various forms by relatively large groups of teachers and students. It is less clear that many of the learner-centered pedagogical innovations such technologies may enable are as widely implemented as unfortunately didactic teaching approaches are still predominately used in the major educational systems around the world. A challenge we now face is not just developing interesting technologies for learning but also more systemically developing the pedagogical and situated contexts in which these learning experiences may occur, hence the major theme of this volume: *designing learning environments of the future*.

We recognize, of course, that one of the few certainties in life in the present century is rapid technological change. Still, we have solicited chapters to provide a representative (but not comprehensive) survey of a wide range of types of learning technologies that are currently being explored by leading research groups around the world, such as virtual worlds and environments, 2D and 3D modeling systems, intelligent pedagogical agents, and collaboration tools for synchronous and asynchronous learner interactions. More important, we believe, are that these various research projects explore important learning challenges, consider theoretical framings for their designs and learning research, and (in most chapters) discuss iterations on their respective designs for innovative learning environments. We hope these considerations of how research findings in these various projects may inform thinking about new designs for learning might serve as models for other researchers, learning designers, teachers, and policy makers who certainly will have to grapple with dynamic changes in the contexts of learning over the next few decades.

The chapter authors are all internationally recognized for their research into innovative approaches for designing and using technologies that support learner-centered pedagogies. This collection will be of interest to researchers and graduate students in the learning and cognitive sciences, educators in the physical and social sciences, as well as to learning technologists and educational software developers, educational policymakers, and curriculum designers. In addition, this volume will be of value to parents and the general public who are interested in the education of their children and of a citizenry in the twenty-first century by providing a glimpse into how learning environments of the present and future might be designed to enhance and motivate learning in a variety of important areas of science and mathematics.

Contents

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Chapter 1
Invention and Innovation in Designing Future Learning Environments

Michael J. Jacobson and Peter Reimann

The best way to predict the future is to design it.

As a central theme of this volume is the *future*, above we suggest a corollary to the famous Alan Kay observation that the best way to predict the future is to invent it, while also acknowledging his seminal technology contributions and his passionate vision for new ways of learning such resources enable. This theme of the future is endlessly fascinating and nearly always – as Kurt Vonnegut observed about life in *Slaughter House Five* – something that happens while making other plans.

A second theme – *design* – is one in "vogue" in the field of the learning sciences as there is design-based research, learner-centered design, learning by design, and so on. "Design" has connotations of someone creating an artifact that is generally new or innovative, which suggests a question: What is the relationship of design to innovation? John Seely Brown (1997), for example, wrote that in corporate research at Xerox Palo Alto Research Center (PARC), a view emerged that *innovations are inventions implemented*. A distinction is thus made between "inventions," that is, novel and initially unique artifacts and practices, and "innovations" that become more widely disseminated or appropriated by commercial environments – which, by extension, we suggest may also include communities of practice or social environments more generally. However, inventions are not "pushed" fully formed into an environment, as was Athena from the head of Zeus with armor, shield, and spear in hand. Rather, they are introduced into an environment and often foster changes in it that lead to iterative changes and developments of the original invention itself and the environment. Put another way, the transformation of inventions to innovations reflects *coevolutionary* processes of iterative changes of artifacts, practices, and the environment. J. S. Brown also notes that in the corporate world, it was often the case that considerably more resources were required for efforts involving innovations versus those necessary to create inventions initially.

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By extension, we suggest that considerations of future learning environments may distinguish between the *design of "inventions"* (i.e., designing new pedagogies) and new types of learning environments, and the *design of "innovations"* (i.e., designing *implementations* of pedagogical and learning environment inventions). From this perspective, learning and technology research may focus on pedagogies and learning environments from the *invention* or the *innovation* perspective, or as a coevolutionary (and thus inherently longer term) trajectory from invention to innovation. For example, the history of the *SimCalc* Project exemplifies this last scenario. The initial design goals for *SimCalc* from the middle 1990s may be viewed as an advanced learning technology-based *invention* to help students learn core ideas about the mathematics of change and variation (i.e., calculus; see Roschelle, Kaput, & Stroup (2000)), whereas the research reported in this volume details research into *SimCalc* as it has been iteratively evolved and designed as an *innovation* being more widely utilized to help students understand challenging conceptual dimensions of algebra (see Roschelle, Knudsen, & Hegedus, this volume).

Whereas the notion of a learning environment has frequently been used to depict technical aspects, such as specific learning software, it has become accepted over the last decade that there is much more to the "environment" than the technology employed. The chapters in this book clearly incorporate this more holistic view that includes – in addition to the technology – tasks, assessment forms, and social (including organizational) aspects of educational settings such as classrooms. This widening of scope has resulted partly from research that has identified teaching practices and school leadership as two critical factors affecting the breadth and depth of uptake of learning technologies in schools, once issues of access to technology and teachers' basic technology skills have been addressed (Kozma, 2003; Law, Pelgrum, & Plomp, 2008). Teaching and leadership practices are, in turn, strongly affected by assessment regimens and accountability systems, and their objectives and rationales as expressed in educational policies.

Since the earlier volume was published (Jacobson & Kozma, 2000), a variety of learning technologies – often referred to as *information and communication technologies* (ICT) – have become ubiquitous in many educational sectors, at least in economically developed countries. As Kaput argued for in mathematics education, technology has become "infrastructural" (Kaput & Hegedus, 2007). In many classrooms, more or less advanced learning technologies are increasingly essential to the accomplishment of teaching and learning. However, as is the case for any infrastructure (such as roads or electricity), positive effects are neither immediate nor guaranteed; results depend on how the infrastructure is used. In the classroom, the key infrastructure users are the teachers because they not only use learning technologies themselves, but also they orchestrate the use for *other* users, the students. With respect to the technologies and pedagogical concepts included in this book, they all are infrastructural in the sense that they do not address a specific curricular area or focus on teaching a small set of skills, but they all create a space of possible designs. Some of them do so with a focus on representational designs, others are primarily concerned with designs for participation and ways of learning.

As we approach the second decade of the twenty-first century, many of the "advanced technologies for learning inventions" that were a focus of research in the 1990s – such as artificial intelligence, virtual reality, globally distributed hypermedia, network mediated communication, and so on – have now safely achieved the status of "invention." Thus a major challenge we now face is to engage in the even more challenging research concerned with the coevolution of *innovations* of learning environments and infrastructures and how these might enhance or even transfer learning in significant ways.

We make no pretenses for "predicting" how future environments for learning might look or be used. Rather, we have selected chapters for this volume that are representative of international learning sciences oriented research that are exploring a range of *designs for invention* and *designs for innovation*. We next provide an overview of the chapters, followed by a consideration of a set of thematic strands that emerged as we look across these chapters.

Chapter Overviews

In Chap. 2, Blikstein and Wilensky discuss the *MaterialSim* project in which engineering students program their own scientific models using the NetLogo agent-based modeling tool to generate microlevel visual representations of the atomic structure in various materials being studied. NetLogo also provides a multiagent modeling language to program rules defining the behaviors of agents in a system, which in the case of this research, consisted of the interactions of individual atoms. Of central importance in this chapter is the dramatic distinction between NetLogo-enabled visual and algorithmic representations versus the more typically used equation-based representations of the materials studied in these types of engineering courses, which based on classroom observations of a university level engineering materials science course consisted of 2.5 equations per minute in a typical lecture! An important argument advanced in this chapter is that the isomorphic visual and algorithmic representations of the relatively simple microlevel interactions of particular phenomena a computer-modeling tool like NetLogo affords may lead to dramatically enhanced learning compared to the highly abstracted mathematical representations typically used in traditional engineering education. Put another way, this research argues that *representations profoundly matter for learning*. Further, providing tools for learners to construct and shape these representations as part of modeling activities perhaps might matter even more.

The third chapter by Horwitz, Gobert, Buckley, and O'Dwyer presents research on "hypermodels," which builds on earlier work involving *GenScope* (Horwitz & Christie, 2000). *GenScope* was a "computer-based manipulative" representing genetics at different levels from microlevels of DNA and genes to macrolevel phenotypic and population expressions of organism traits. Learners may manipulate settings at the DNA and gene level in *GenScope* and then view how different traits would look on an organism. As is discussed in this chapter, however, just providing learners with a representationally rich, interactive, and open-ended (i.e., unstructured) environment such as *GenScope* did not necessarily lead to enhanced learning of genetics in many classrooms. In response to earlier mixed empirical findings, this research team worked on new ways to support or scaffold learners using an open-ended model or simulation tool using *hypermodels*. Briefly, a hypermodel provides a "pedagogical wrapper" around the core model or simulation engine that specifies particular sequences of learning activities involving the model or simulation engine for students as well as scaffolds for learning important conceptual aspects of the domain being represented. A centrally important aspect of this new research involves *model-based reasoning* (MBR), in which learners form, test, reinforce, revise, or reject mental models about the phenomena related to their interaction with hypermodels and other representations. This chapter reports on research involving the *BioLogica* hypermodel environment and its use to scaffold or structure genetics learning activities in classroom settings.

Ketelhut, Clarke, and Nelson, in Chap. 4, describe the main elements of three design cycles for the *River City* multiuser virtual environment (MUVE) that took place over 8 years. Conducted in the form of a design-based research project involving almost 6,000 students, the development of *River City* was driven by comparisons between "experimental" classes that used *River City* and conventional classes, all taught the same curriculum. One of pivotal design intentions was to let students themselves identify "factors" that might be causing diseases simulated in *River City* as part of science inquiry activities. The *River City* research team was able to explore important questions concerning the value of "immersive" science inquiry learning given their opportunity to experiment with thousands of students over a number of years. For instance, regarding the possible novelty affect of having students use a new approach such as a virtual world to learn, it was found that most students extended their engagement with the activities in *River City* beyond the first hours of using the system. It was also found that students who were academically low achieving profited from this kind of learning compared to traditional classroom instruction. In the last design cycle (2006–2008), a potential issue from the previous cycle – that of higher achieving students benefitting less compared to low-achievers – was addressed by incorporating a learning progression into the design of the environment in which some content was only accessible after certain prerequisite objectives had been achieved. Interestingly, the content then made available at this stage is not a higher "game level," as would be the case for a typical entertainment game, but rather was made available in a "reading room." This design approach thus raises interesting questions about the relation to – and possible synergies with – conventional text content and related learning activities and those activities with which students are engaged "in" a virtual world for learning.

In Chap. 5 – by Jacobson, Kim, Miao, Shen, and Chavez – discusses a number of design dimensions and research issues for learning in virtual worlds as part of the *Virtual Singapura* (VS) project. VS provides a virtual experience for students to engage in science inquiry skills, similar to *River City*, but the scenario is based on historical research into disease epidemics and cultural contexts in nineteenth century Singapore, rather than the fictional contexts of *River City* or *Quest Atlantis* (Barab, Thomas, Dodge, Carteaux, & Tuzun, 2005). In addition, the synthetic characters in VS are based on the diverse cultural groups in Singapore during that period. Intelligent agent technology is used so the synthetic characters may adaptively respond to interactions with the avatars of the students, providing different information about the scenario based on changing class activities in VS on different days and on the behaviors of the students in the virtual world. Research findings from two studies are reported, with the first study discussing the initial pilot testing of VS and the second study exploring the issue of learning in a virtual world for transfer to new problem and learning settings. A discussion is provided at the end of the chapter about ways to enhance learning in virtual worlds through different pedagogical trajectories for unstructured and structured virtual learning experiences and through nonvirtual activities.

In Chap. 6, Reimann and Kay address the question of how net-based team collaborations can be augmented beyond the provision of basic communication and document management facilities so that the students are provided with information that helps them to coordinate with each other and to learn more over time. This work involves undergraduate computer scientists who are conducting their capstone project in programming teams, and with graduate students who are working in teams that engage in prototypical research activities (e.g., building a model, writing a report). Teams in these projects use a variety of communication and documentation technologies such as wikis and file repository systems. Reimann and Kay describe a number of approaches that all build on providing mirroring and/or visualization feedback information about aspects of the teams' work in a visual format back to the teams. The rationale for this approach is provided in terms of an analysis of research on teaching team skills in general and team writing in particular. One type of visualization focuses on participation in terms of students' contributions to the *Trac* collaboration that combines a wiki, a ticketing system, and a file repository system. The authors describe how various aspects of participation in a programming team can be visualized with a combination of time lines (i.e., Wattle Trees), social network diagrams, and a visualization type based on Erikson and Kellog's (2000) social translucence theory. An exploratory study is discussed that showed this type of information was effective and largely acceptable to students, in particular to those students who had a leadership role in their team. Reimann and Kay report further on developing visualizations for the overall structure of a wiki site, taking the form of a kind of hypertext network overlaid with participation information (WikiNavMap). They also describe visualizations that are not based on participation data or the linking of wiki pages, but make use of the information contained in the text as it develops over time in the form of multiple versions of individual wiki pages. Their chapter closes with a discussion of techniques that provide textual and graphical feedback on the content of wiki pages (and other online document formats such as Google Docs) and how formative feedback to learners and teams might be connected to new ways to provide summative feedback such as grades.

In Chap. 7, De Jong, Hendrikse, and van der Meij describe a study that deployed mathematical simulations developed with the *SimQuest* authoring tool in 20 classes from 11 Dutch schools. The simulations were closely linked to chapters on functions in the mathematics textbook used in these classes, which were covered over a 12-week period. Despite the fact that the *SimQuest* simulations plus the support materials were carefully studied in trials with more than 70 students of the same age group as targeted in the study in conjunction with teachers, the take-up in the schools was subject to many variations, some productive and some not. De Jong and colleagues discuss two main obstacles for the use of *SimQuest* inquiry tasks in the participating Dutch classrooms. First, there were severe time constraints in classrooms that led teachers to skip specified activities that relied on technologies if there were technical difficulties. Second, the textbook used in the classes was not optimally aligned to the *SimQuest* inquiry activities. Interestingly, the time devoted to design the curriculum and the classroom alignment (what Roschelle et al., this volume, call activity design) was of the scale of months, whereas the development of the *SimQuest* software took years of a calendar time (and many more person years).

Chapter 8, by Peters and Slotta, describes opportunities that the Web 2.0 (a combination of technologies and ways of using these technologies) offers for educators. In addition to the affordances of immersive environments such as Second Life, they identify collaborative writing with media such as wikis and blogs as particularly relevant for knowledge construction purposes. To be useful for learning and knowledge construction in a school context, Web 2.0 technologies need to be carefully structured and related to tasks, activities, and content. Peters and Slotta propose their Knowledge Community and Inquiry (KCI) model as a pedagogical framework. KCI combines elements of collaborative knowledge construction with scripted inquiry activities that target-specific learning objectives. Of particular consequence in KCI pedagogy is sequencing, which begins with a (comparatively) unstructured phase during which students collaboratively generate a shared knowledge base in the form of a set of wiki pages, for instance, followed by a phase with guided inquiry activities. In the first study that Peters and Slotta describe, students generated a number of wiki pages concerning human diseases without any “seed” knowledge provided to them and without intervention from the teacher. Only after this student-generated knowledge base was generated did the students engage in more structured inquiry tasks, building on and using the student-generated content, in addition to normative curriculum materials. The first study they report showed that this approach led to deeper domain knowledge (assessed in terms of students’ examination scores) compared to a group with conventional teaching regarded by teachers involved in the intervention as yielding good learning and classroom practices. Interestingly, students asked for more guidance concerning the open phase because they felt that a graded task should be accompanied by more structure. To accommodate this need and to potentially deepen the engagement of students even further, a second study is reported where the open phase was more structured, not in terms of steps, but in terms of the structure of the collaboration product (a document), which led to good learning results. However, challenges are discussed regarding the time required of the co-design process, and the productive use of data logs as a means for student assessment.

The challenge of large-scale integration of innovative learning technologies into schools is the focus of the research reported in Chap. 9 by Roschelle, Knudsen, and Hegedus. They suggest that any “advanced” technology design needs to include the means “...for bridging the gap between new technological affordances and what most teachers need and can use.” An advanced design in this sense focuses on one or more of three levels (building on Kaput & Hegedus, 2007): (a) representational and communicative infrastructure, (b) curricular activity system, and (c) classroom practices and routines. The chapter focuses on long-term research in the *SimCalc* project regarding the question of how the *MathWorlds* software (the “infrastructure”) can be connected to a curricular activity system. To develop an activity system, the first step is to identify a *rich task* that is pivotal to the curriculum and that brings together a number of concepts relevant to the curriculum. At the same time, the task should allow for a learning progression over a clearly specified amount of time that fits into the usually tight school agenda. In addition to taking into account the demands of the curriculum, a rich task should contribute to the long-term development of students’ engagement with a body of knowledge. Roschelle and associates discuss two examples of such rich mathematics and learning tasks. The second step in activity design involves developing *support materials* for teachers and students. In the model put forward in this chapter, this comprises the development of teacher guides, student workbooks, and workshops for teacher development. Finally, the chapter contains examples of how to design such materials and measures, and describes experiences with the method from a number of *SimCalc* studies.

In Chap. 10, Hamilton and Jago discuss learning environments that provide customization and interpersonal connections as *personalized learning communities* (PLCs). They propose a set of design principles for PLCs, explain the rationale for each principle, and then illustrate how the PLC design principles are being used as part of the ongoing ALASKA project (Agent and Library Augmented Shared Knowledge Areas). ALASKA is designed to be a PLC in which students learn mathematics – currently precalculus – using a tablet computer that accepts pen or touch input. Intelligent agents interact with the learners via simple dialogs and can answer a set of domain-specific questions. Additional features of ALASKA include a library of applets and tools and a communication system that provides thumbnail and full-size views of student screens and the ability to arrange peer tutoring between students to teachers. This system is presently under development, so the “Miriam Scenario” is described to illustrate a hypothetical situation in which the ALASKA system is used as an instantiation of the PLC design principles and representative interactions.

The final chapter is an Afterword by Reimann and Jacobson that considers issues related to how research into the design of learning environments as discussed in the chapters of this volume might inform perspectives on the transformation of learning more generally. Fostering transformation of learning will require, at least, attention to assessment methods and teaching practices. Future learning environments, it is argued, should enable formative assessments that provide dynamic feedback about both individual learning and the learning of groups. These environments should also augment the pedagogical palette that teachers have available for enabling new ways of teaching and learning. Although technology-based innovations may be necessary for certain types of future learning environments, they are unlikely to be sufficient, and therefore must be aligned with pedagogical approaches, content, and assessments. Affecting learning transformations of educational systems may result from large-scale “top down” policy initiatives. An alternative, one perhaps more likely, is in a manner similar to how fads and “hits happen,” from the accumulation of many small examples of transformational learning that stimulates future interest in and adaption of such approaches that may be amplified and propagated across entire educational systems.

Thematic Strands

The chapters in this volume each focus on different research issues and types of learning. While they are diverse, they share perspectives and thematic strands that link them together within a community of research practice. At a general level, these chapters reflect different aspects of research in the field of the learning sciences in terms of various theoretical frames and methodologies employed in these research projects. In addition, as discussed in the first section of this chapter, there is a shared interest in design, although some focus on *designs for invention* and others on *designs for innovation*. Three chapters discuss work that involves certain inventions – such as the use of intelligent agent technology in the *Virtual Singapura* project in Chap. 5, the deployment of data mining technologies outlined in Reimann’s and Kay’s Chap. 6, and the pedagogical agents and set of design principles for personalized learning communities described by Hamilton and Jago in Chap. 10. The majority of the chapters in this volume are best regarded as designs for innovation, which we believe provide opportunities to do research that contributes both to theory as well as to use-inspired issues – the so-called Pasteur’s Quadrant (Stokes, 1997).

We have identified three other thematic strands across these chapters: *advanced representational affordances*, *advanced designs for interaction and participation*, and *advanced educational designs*. Whereas there may important be elements of all three of these themes in all of the chapters, we next discuss the chapters that seem most closely aligned with each of these themes.

Advanced Representational Affordances

The range of technologies used in chapters in this volume range from globally distributed multimedia web pages (i.e., with text, digital video, images, and animations and computer modeling, simulation, and visualization tools) to relatively newer technologies such as virtual reality worlds, intelligent agents, and data mining systems.

Collectively, these technologies greatly expand the *representational affordances* (Kozma, 2000) that are available to designers of learning environments compared to traditional instructional modalities. We view the notion of "affordances" in a way similar to the perspective of Norman (1988) as *possibilities for action that are readily perceivable by individuals* using artifacts, which provides a cognitive nuance to Gibson's (1979) ecological articulation of this term as *opportunities for action*. Multiple, often dynamic, and interlinked representations provide *possibilities for learning* that different design approaches may leverage for various types of learning environments. Further, multiple and often linked representations are not just cosmetic and felicitous, but rather, *foundational* given views that expertise in many areas requires not just abstract conceptual knowledge but also *representational flexibility*, which is the ability and facility to use various representations and to link across them as part of discipline-oriented activities (Kozma, Chin, Russell, & Marx, 2000).

Whereas the use of advanced representational affordances of various learning technologies is reflected in all the research discussed in this volume, the *MaterialSim* project nicely illustrates this thematic strand. For example, multiple representations using NetLogo consist of the visualization of the behavior of atoms in the materials being modeled, graphical and quantitative output of the model runs with different parameter settings (i.e., designed affordances), and the computational rules in the NetLogo programming environment. These representations may then be linked to the relevant abstract mathematical models, which in traditional instruction are the *primary* representation provided to the learner, despite their nonisomorphic relationship to the microlevel behavior of atoms in materials studied in engineering courses such as this. A deep understanding of the physics of materials science requires learners not just to memorize complex formulas, but also to be able to link various representations across micro- and macrolevels of phenomena and different types of symbolic coding and representational forms in conjunction with constructing appropriate mental models about the behavior of the atoms that interact to form various materials and structures. The chapter discusses important research toward achieving such transformative learning gains.

The Horwitz, Gobert, Budkley, and O'Dwyer research involving *Hypermodels* also exemplifies advanced representational affordances, in particular, those that are *readily perceivable by individuals*. Not only does *BioLogica* provide representations of microlevels of genotypic representations (e.g., DNA, genes), but these are also linked to macrolevel phenotypic trait expressions of organisms. These representations and affordances for learning were also available in the earlier *GenScope* system (Horwitz & Christie, 2000), but in an open-ended and unstructured way that the researchers believed resulted in mixed learning findings in earlier studies. Hence their chapter here details design decisions that were intended to constrain the affordances options for learners so that more salient representations for particular learning activities were likely to be selected, which their research suggests resulted in enhanced learning outcomes. Other chapters in this volume provide interesting perspectives about the theme of advanced representational affordances and learning, such as the *River City, Virtual Singapura*, and *SimQuest* projects.

Advanced Designs for Interaction and Participation

A second theme in this volume pertains to interaction, participation, and collaboration. Reimann and Kay's chapter deals with this issue in a general form, while Ketelhut et al. and Jacobson et al. come to it from the perspective of how to foster science inquiry in schools. The chapter by Roschelle and associates contributes to this theme by researching classroom activities that extend mathematical operations into students' interaction with networked handheld devices.

Computers may promote science learning by engaging large numbers of students in scientific inquiry without the logistical difficulties and dangers associated with experiments involving real materials in real laboratories. The "virtual laboratory" is a frequently used metaphor in educational simulation designs, which are exemplified in the chapters on the *SimQuest* (De Jong et al., this volume) and *BioLogica* (Horwitz et al., this volume) projects. Whereas these chapters focus on teaching scientific thinking in general (e.g., variable control, hypothesis testing), and on the interaction with domain-specific representations such as the Punnett Square in *BioLogica*, also represented in this volume is the genre of *inquiry environments*, such as *River City* and *Virtual Singapura*. These inquiry environments are not only three-dimensional, but also inherently "social" as they build on the metaphor of an *inhabited* virtual world, with the population being made up of the students themselves (represented through *avatars*), plus *nonplayer or synthetic characters*. It is the participatory nature of virtual inquiry worlds that distinguishes them from simulation environments that may well employ 3D technologies as well, but are designed for supporting individuals' interactions with the simulated entities and processes.

Virtual worlds specifically designed for education (for another example, see *Quest Atlantis* (Barab et al., 2005)) are different from the more general case of open virtual worlds (such as *Second Life*) in that they incorporate specific scenarios, such as the presence (or absence) of a sewage cleaning system in the world, and that they have their own dynamics, such as things developing over time in the virtual world with or without user interventions. In addition, inquiry-oriented virtual worlds typically include specific research tools, such as virtual microscopes, which learners may use as part of the inquiry activities they are engaged in.

Virtual worlds provide for representational richness (if well-designed) and make it easy for learners to interact and communicate with each other. The research reported in the chapters on virtual worlds in this volume suggests that learners are engaged, including students who do not relate well to textual resources, as in the *River City* research (Ketlehut and associates, this volume). All this should lead to better learning and improved learning outcomes, and there is increasing evidence – part of which is provided by chapters in this book – that this potential materializes. However, there are substantial costs involved in producing high quality virtual worlds for learning, which may be offset by relatively low costs for dissemination of these learning environments if appropriate computers and infrastructures are available. Certainly policy decisions about implementing future learning environments will be informed by cost–benefit analyses of development and deployment expenses of new types of environments such as virtual worlds with alternatives such as traditional classrooms. We note even traditional classrooms such as those for science also may have significant costs associated with specialized laboratory equipment (and sometimes hazards), and thus hope these analyses also consider *benefits* such as the potential for enhanced learning gains, motivation, and engagement, as well as the safety and flexibility of laptop and mobile technologies.

Another aspect of designs for interaction and participation is to bring digital content into the physical world – *augmentation* – rather than to attempt to simulate the physical world in a digital form – *virtualization*. Augmentation may be seen in the *SimCalc* project, where students engaged with mathematical content that is "in" their classroom rather than "in" a virtual space. There are many situations where virtualization is advantageous, for instance, in situations where the objects of learning are difficult to experience, such as *MaterialSim* and *BioLogica*, or dangerous. We expect that designs for augmentation and virtualization will be important approaches for types of future learning environments in areas such as science, history, and geography.

In addition, even with the important interest in visual representations now possible with virtual worlds and computer visualizations, we should not dismiss textual formats. It is important to remember that in the rhetoric about multimodality, the "multi" includes textual notation formats, which are, of course, powerful representational forms at the core of knowledge creation and communication for over three millennia. For instance, Ketelhut, Clarke, and Nelson began to address this issue by equipping *River City* with a "level" that targets those who quickly progress through the game-like elements. As noted above, the new content that is then made available is *not* virtual, but rather is text available in a "reading room." This raises the interesting question of the relation between conventional text content (and related learning activities) and experiences in interactive and immersive 3D environments. Furthermore, Reimann and Kay demonstrate that text written by students does not have to be treated as a static product, but rather that the processes of creating text can be dynamic when provided with sources of continuous feedback.

Advanced Educational Design

The theme of *advanced educational design* weaves several perspectives about learning environments reflected in different chapters in this volume. The distinction proposed by Roschelle, Knudsen and Hegedus (Chap. 9) for three levels of learning technology design that has influenced their research – (a) representational and communicative infrastructure, (b) curricular activity system, and (c) classroom practices and routines – may be applied to other chapters in this book. For example, all chapters contribute to (a) by necessity, and many make direct or indirect contributions to (b). However, there are relatively few contributions to (c). In particular, the attention given to curricular activity systems, and hence to addressing the gap between what technology can do and what teachers and students see as its affordances, is significant. This is a central theme in the chapters by Roschelle and colleagues and by Peters and Slotta, and figures prominently also in the chapters by Ketelhut, Horwitz, and De Jong, and their respective coauthors.

With most technology innovations, initially there is a relatively large gap between the *affordances perceived by the users* of a new technology-enabled learning environment and the *affordances the designer intended.*[1] As discussed above, we suggest that from the perspective of designing educational environments, affordances may be viewed as *possibilities for learning* that encompass pedagogical and assessment decisions that directly influence learning activities. Since teachers will likely perceive innovative learning environments and pedagogies through the lens of their current classroom practices and routine activities, the perceived affordances of learning innovations will likely be a way to enhance aspects of these established practices rather than to initially try out new learning and teaching opportunities that probably were intended by designers. The chapter by De Jong and associates illustrates this tendency as they found teachers did not use the *SimQuest* system in ways intended by the researchers due in part to the perception of a lack of alignment with the textbook that was being used. Unfortunately, this "possibilities perception gap" for affordances is frequently not recognized nor addressed by learning environment designers and developers. On a positive note, when this gap is recognized, as we believe it was in the Roschelle and associates chapter, the research suggests that appropriately designed and implemented infrastructure changes can, in fact, change classroom practices and transform learning.

We see other examples of the third design level – classroom practices – in this volume exemplified in the chapters by Ketelhut and Jacobson with their respective colleagues. Both groups are involved in designing not only for content and activities, but also for the enactment of these activities where students interact with content, each other, and synthetic characters in virtual learning environments with distinctive affordances relative to conventional classrooms. Since the relevant parameters of these virtual worlds are designed in advance, and can be better controlled at "run time" than is the case for real classrooms (and other learning settings, such as museums or laboratories), these research projects illustrate perhaps the greatest design opportunities for learning environments that implement innovative practices such as multiuser interactions and collaborations, varying pedagogical approaches, different degrees of structure and openness in learning activities, monitoring profiles of behavior and accomplishments of learners in the virtual worlds, and providing formative and summative assessments to individual as well as collaborative groups and teachers.

Another aspect of the theme of *advanced educational design* concerns design decisions related to the nature and sequencing of *structure* provided to the learner. For example, in the research reported involving the virtual worlds of *River City* and *Virtual Singapura*, guided inquiry approaches were used in which there was initially high structure provided in terms of scaffolds and constrained learning tasks, whereas over time, the scaffolding was reduced for more open-ended

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[1] As noted above, this conceptualization of affordances is influenced by the work of Norman and Draper (1986) on user-centered design, but here we generalize from just the design of the computer interface to the design of overall environments for learning.

activities (i.e., less structure was provided). As Jacobson and associates discuss in Chap. 5, guided inquiry may be regarded as a "high-to-low structure" sequence. Jacobson and his colleagues note that most research to date involving learning in virtual worlds has employed guided inquiry or high-to-low structure sequences of learning activities. They speculate that future work with these types of environments should also investigate virtual learning in which low-to-high pedagogical trajectories are employed, such as is suggested in research involving "productive failure" (Jacobson, Kim, Pathak, & Zhang, 2009; Kapur, 2008).

In reflecting on advanced educational designs, we suggest that there is emerging a 10-year (±2) rule for successful designs of educational learning environments. As reflected in chapters in this volume, many of the learning tools and environments considered a success in terms of research and implementation have been iteratively developed for over a decade. For example, KCI research that built on the earlier environment Slotta helped develop, WISE (*Web-based Inquiry Science Environment*), *BioLogica* and the earlier *GenScope* systems of Horwitz and associates, the *SimCalc* project of Rochelle and colleagues, and the *River City* project that Ketlehut and associates discuss, with another important technology-based environment not reflected in this volume, *Knowledge Forum* (Scardamalia & Bereiter, 2006), having evolved its design over almost two decades. It is perhaps not surprising that developing sophisticated technology-enabled learning environments would require a decade-long time frame to evolve from "learning inventions" of promise initially researched in a few classrooms to innovations that in turn are iteratively revised and implemented in larger numbers of classrooms and diverse educational settings as part of extended (and costly) research initiatives. Indeed this decade range timeframe is comparable to innovation processes in other fields (Shavinina, 2003).

In light of the substantial effort over a significant period of time that is necessary to design high quality, theoretically grounded, and empirically validated learning environments, it would clearly be advantageous if these efforts were accompanied by the articulation of a *design methodology* that could inform designers of future learning environments. In the learning sciences, *design-based research* (Barab, 2006; Collins, Joseph, & Bielaczyc, 2004; Kelly, Lesh, & Baek, 2008; The Design-Based Research Collective, 2003) has been advanced to inform empirical research in real world contexts, but not necessarily the design of artifacts and environments themselves. In contrast, a *design methodology* for environments that help learners construct deep and flexible understandings of important knowledge and skills would, we propose, articulate a *language for design and representations of design* that are theoretically principled and empirically informed. Such a design methodology of "research-based" or "best practices" would allow a broader range of professionals to contribute to the development and implementation of innovative pedagogies and learning environments beyond the relatively small circle of influence of typical academic research projects in this area. The design methodology we envision is not dogmatic, but rather seeks ways to document different design processes and high-level design decisions. For instance, a design methodology might build on the work on educational patterns and pattern languages (Goodyear, 2005; Linn & Eylon, 2006; McAndrew, Goodyear, & Dalziel, 2006; Quintana et al., 2004) in terms of ways to document and communicate design ideas about different types of learning environments. Such a reification of design elements and approaches would, we believe, stimulate the coevolutionary iterations of design innovations for future learning environments.

Conclusion

The chapters in this volume are representative of international research efforts that are exploring ways in which environments for learning may help students achieve goals of importance in twenty-first century education. The centrality of *design* in its iterative and coevolutionary manifestations is of importance in several of the research programs discussed in this volume, in particular, those of longer duration. In addition, we hope that the thematic aspects of these programs of research – such as designing learning environments with rich representations and opportunities for interaction and participation, as well as pragmatic educational designs more broadly that encompass curricular activity systems and classroom practices and routines – may help provide perspectives from which to view not only the research in this volume but other work in the field as well. These chapters report on significant accomplishments for advancing our understanding of learning and teaching, as well as many lessons learned. In closing, our hope is that collectively these accomplishments inspire and the lessons challenge researchers and educators for *today*. After all, enhancing learning environments of the future is "simply" about how our students might better learn tomorrow.

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Chapter 2
MaterialSim: A Constructionist Agent-Based Modeling Approach to Engineering Education

Paulo Blikstein and Uri Wilensky

Introduction

For the past two decades, the engineering education community has started to come to terms with an unfortunate paradox: despite a view of engineering as the ultimate design profession, very little actual experience in design is incorporated into undergraduate engineering curricula. Recently, pressured by decreasing enrollment, unmotivated students, and an avalanche of new demands from the job market, several engineering schools have started to roll out ambitious reform programs, trying to infuse engineering design into the undergraduate curriculum. A common element in those programs is to introduce courses in which students design products and solutions for real-world problems, engaging in actual engineering projects. These initiatives have met with some success and are proliferating into many engineering schools. Despite their success, they have not addressed one key issue in transforming engineering education: extending the pedagogical and motivational advantages of design-based courses to theory-based engineering courses, which constitute the majority of the coursework in a typical engineering degree, and in which traditional pedagogical approaches are still predominant.

In this chapter, we describe and analyze a series of studies designed to address this exact issue, in which we investigate undergraduate students' learning of

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theoretical content in materials science through designing (i.e., programming) their own computer models of scientific phenomena. Our research design emerged from extensive classroom observations followed by a literature review of engineering and materials science education, as well as analysis of class materials, and interviews with students. Our observations (consistent with the literature review) indicated that students' understanding of the subject matter was problematic, and that the teaching was not up to the challenge of the sophistication of the content. Based on this diagnosis, we have iteratively designed constructionist (Papert, 1980) model-based activities for materials science - *MaterialSim* (Blikstein & Wilensky, 2004a; 2004b, 2005a; 2005b; 2006a; 2008) - a suite of computer models, learning activities, and supporting materials designed within the approach of the complexity sciences and agent-based modeling. The activities were built within the NetLogo (Wilensky, 1999b) modeling platform, enabling students to build models, and investigate common college-level topics such as crystallization, solidification, crystal growth, and annealing.

The studies consist of both design research and empirical evaluation. Over 3 years, we conducted an empirical investigation of an undergraduate engineering course using MaterialSim, in which we investigated: (a) The *learning outcomes* of students engaging in scientific inquiry through interacting with MaterialSim; (b) The *effects of students programming their own models* as opposed to only interacting with preprogrammed ones; (c) The *characteristics, advantages, and trajectories of scientific content knowledge* that is articulated in epistemic forms and representational infrastructures unique to complexity sciences; and (d) The *design principles* for MaterialSim: what principles govern the design of agent-based learning environments in general and for materials science in particular? Twenty-one undergraduates enrolled in a sophomore-level materials science course participated in three studies in 2004, 2005, and 2006, each comprised of a survey, preinterview, interaction with the prebuilt computer models, students' construction of new models, and a postinterview.

2.5 Min per Equation

Our classroom observations suggested that the ever-growing sophistication and extent of college-level content in engineering (and, in particular, materials science) pose a difficult challenge to current teaching approaches. One reason is that the important equations and mathematical models taught in undergraduate materials science courses are not only complex, but are connected in nontrivial ways to multiple sets of other theories, concepts, and equations. Teachers end up resorting to multiple equations and models to derive and explain a single canonical phenomenon, and those equations and formulas are oftentimes located in a different areas of mathematical modeling (statistical mechanics and geometrical modeling, for example). What is more, many "engineering theories" are combinations of empirical models or approximations, and not pristine, rigorous, and easy-to-describe theories.

As a result, what takes place in a typical engineering theory course lecture is not a linear progression of equations, from simple to complex. Conversely, when a new phenomenon is taught to students, a very large number of new connections with previously learned topics will likely arise on multiple levels, generating even more specialized equations to account for those connections. The sheer number of equations generated makes a comprehensive exploration infeasible in the classroom. Our classroom observations revealed that, in a typical 30-minute period, students would be exposed to as many as 12 unique equations with 65 variables in total (not counting intermediate steps in a derivation) – or approximately 2.5 minutes for each equation and 45 seconds for each variable!

This overloading with equations and variables seems a likely candidate for explaining the students' difficulties described above. We decided to investigate this hypothesis and investigate: what kind of understanding did this multiplicity of explanation levels and the "overloading" of equations foster in students? In addition to understanding the consequences of the traditional pedagogical approaches, we wanted to explore possibilities of an alternate approach, and examine the consequences of using agent-based models (Collier & Sallach, 2001; Wilensky, 1999a; Wilensky & Resnick, 1999) enacted as microworlds (Edwards, 1995; Papert, 1980) for students' understanding of materials science content since our previous research suggested that using such a modeling approach might be a better match of content to student cognition.

The agent-based modeling approach, as we will explain in detail, enables modelers to employ simple individual-level rules to generate complex collective behaviors. These simple rules capture fundamental causality structures underlying complex behaviors within a domain. Wilensky, Resnick, and colleagues (Wilensky, 1999a; Wilensky & Reisman, 2006; Wilensky & Resnick, 1999) have pointed out that such rules could be more accessible to students than many of the equations describing the overall, macroscopic behaviors of a system. The agent-based approach is also a better fit with the constructionist pedagogical framework (Papert, 1991). The history of constructionist pedagogy has included three principal modes of learner activity: (a) designing and programming computational artifacts (programming-based constructionist activities – PBC); (b) exploring computer-based microworlds (microworlds-based constructionist activities – MBC); and (c) engaging in the first two modes with computationally augmented physical structures (tangible-based constructionist activities – TBC). Agent-based modeling can be used in any of these three modes. In the second mode, models can function as constructionist microworlds, as agent-based models can represent the underlying logic of a system, enabling students to investigate and modify features of that structure and explore the consequences of those changes, and through that exploration and investigation come to understand the domain. In the first mode, students design and program their own agent-based models and gain a deep sense of the design space of domain models. In the third mode, students can connect physical sensors and motors to agent-based models and let the models take input from real world data and drive real world action (*bifocal modeling*, Blikstein & Wilensky, 2007). In the MaterialSim project, we have designed artifacts and activities to engage students in each of these three modes. In this chapter, we will explore the first two modes, i.e., microworlds-based (MBC) and programming-based constructionist activities (PBC).

The conjecture that using agent-based modeling (ABM) would be a better cognitive match for students is based on research that suggests that this approach fosters more generative and extensible understanding of the relevant scientific phenomena. In the case of materials science, instead of multiple models or numerous equations, this framework focuses on a small number of elementary behaviors that can be applied to a variety of phenomena. Instead of a *many-to-one* approach (many equations to explain one phenomenon), we attempt here a *one-to-many* approach (one set of local rules to explain many phenomena), through which students would see diverse materials science phenomena not as disconnected one from the other, but rather as closely related emergent properties of the same set of simple atomic or molecular rules. A second major focus of our study was to determine: What kind of understanding do students develop of the materials science content when they study it from this agent-based, *one-to-many* perspective?

In addition to those two driving questions, we wish to explore one further dimension of this pedagogical approach. There have been several recent studies of students using ABM to learn science; in many of these studies the approach taken was to design sequences of models and microworlds for students to explore (e.g., Levy, Kim, & Wilensky, 2004; Stieff & Wilensky, 2003). We extend this approach to the domain of materials science but mainly we wish to find out what the effect will be from *moving beyond microworlds and enabling students to choose phenomena of interest to them and construct their own models* in the domain of material science (for another such approach, see Wilensky & Reisman, 2006).

In this chapter we are focusing on the interviews and laboratory studies prior to the classroom implementation (subsequent design experiments on classroom implementations are reported in Blikstein, 2009). We report on a particular pedagogical design and present evidence in the form of excerpts and samples of students' work, which demonstrates that the experience with MaterialSim enabled students to identify and more deeply understand unifying scientific principles in materials science, and use those principles to effectively construct new models.

Materials science is one of the oldest forms of engineering, having its origins in ceramics and metallurgy. In the nineteenth century, the field made a major advance when Gibbs found that the physical properties of a material are related to its thermodynamic properties. In the early twentieth century, the field of materials science concentrated on metals and university departments were often called "metallurgical engineering departments." The field has since broadened to include polymers, magnetic materials, semiconductors, and biological materials and since the 1960s has been called materials science. Today, with the explosion of research in nanotechnology, alternative energy, and new materials, it has gained a very significant role in the realm of technological innovation. However, the teaching of materials science has not kept up with the rapid advances in the field. Therefore, before diving in to the study, we step back and contextualize the teaching of materials science within the landscape of engineering education, its recent critique, and calls for reform.

A New Scenario in Engineering Education

In 2007, approximately 400,000 students took college-level engineering courses in the United States alone (American Society for Engineering Education, 2007). As early as the 1960s, education researchers (Brown, 1961; Committee on the Education and Utilization of the Engineering, 1985; Jerath, 1983; MIT Center for Policy Alternatives, 1975; Panel on Undergraduate Engineering Education, 1986) have pointed out that engineering education lags behind in its adoption of newer approaches to teaching and learning. In recent years, there have been numerous calls for reform from the engineering education community and several schools have implemented reform initiatives (Einstein, 2002; Haghighi, 2005; Russell & Stouffer, 2005). The driving force behind engineering education reform programs were both new societal needs (Dym, Agogino, Eris, Frey, & Leifer, 2005; Committee on the Education and Utilization of the Engineering, 1985; Katehi et al., 2004; Tryggvason & Apelian, 2006) and technical advances. As basic science and engineering become increasingly intertwined in fields such as nanotechnology, molecular electronics, and microbiological synthesis (Roco, 2002), students and professionals have to deal with time scales from the nanosecond to hundreds of years, and sizes from the atomic scale to thousands of kilometers (Kulov & Slin'ko, 2004). This wide range of subjects and problems makes it prudent not to try to cover all the relevant knowledge so that students master the knowledge in each domain, but instead to help students develop adaptive expertise (Bransford & Schwartz, 1999; Hatano & Oura, 2003) that they can apply to new problems and situations.

However, most engineering curricula remain in coverage mode – curricula are still so overloaded with transient or excessively detailed knowledge that there is no time for fostering students' fundamental understanding of content matter (Hurst, 1995). This phenomenon of curricular overloading is not exclusive to higher education. Tyack and Cuban (1995) identified the "course adding" phenomenon in most of twentieth century reform initiatives across all levels of education – new courses are regularly added to the curriculum to satisfy new societal needs. However, the situation becomes more problematic as we envision engineering schools in two or three decades from now. At some point the limit is reached and if courses need to be added, others must be removed – but can we afford to exclude anything from the curriculum? A major challenge is in how to go about deciding what courses can be dispensed with (and what knowledge).

A common approach in many universities has been to add hands-on engineering design courses to the curriculum. Design-based courses represented one attempted solution to the overcrowding of courses as they enable multiple content domains to be taught together. Design courses have been highly successful (Colgate, McKenna, & Ankenman, 2004; Dym, 1999; Dym et al., 2005; Lamley, 1996; Martin, 1996; Newstetter & McCracken, 2000), but they are not the universal answer for all problems afflicting engineering education. First, a significant part of engineering education consists of basic science (physics, chemistry), engineering science (fluid mechanics, thermodynamics), and mathematics (calculus, linear algebra). It is challenging for design-based courses to focus on the core conceptual elements of these highly theoretical knowledge domains as the physicality of students' projects can be an obstacle for learning invisible or microscopic phenomena such as chemical reactions, pure mathematics, or quantum physics. Secondly, the technological tools used in those reform initiatives (such as modeling and design software) are the same employed by professional engineers in their everyday practice and not especially designed for learning. Using professional-based tools might be tempting as they enable students to achieve more rapidly the desired engineering design. In the specific case of materials science, however, this might not be the best choice. Most software tools used in engineering courses do not afford insight into the computation underlying their design and functioning. For engineering practice, indeed, a tool has to yield reliable and fast results – understanding what's "under the hood" is not necessarily useful. However, in materials science, this could be disadvantageous for learners. The computational procedures might embody an essential, perhaps crucial, aspect of the subject matter – *how* the conventional formulas and representations capture the phenomena they purport to model. Manifestly, no computer-modeling environment can uncover all of its computational procedures – it would be impractical example, to have students wire thousands of transistors to understand the underlying logic of the modeling environment. Nevertheless, we believe that most of these environments could be made profitably more transparent to students. However, the epistemological issues regarding the tools and knowledge representations in traditional engineering teaching run deeper.

First, in materials science, many of the traditional formulas *themselves* are opaque – they embody so many layers of accumulated scientific knowledge into such a complex and concise set of symbols that they do not afford common-sense insight and grounding of the causal mechanisms underlying the phenomena they purport to capture. Different from the basic sciences, engineering knowledge is a complex matrix of empirical "engineering laws," theories derived from fundamental mathematical or physical models, approximations, and rules of thumb. Making sense of this complex matrix is challenging for novices. Although using formulas and conventional engineering representations is perhaps conducive to successful *doing* (designing a new alloy, for example) it does not necessarily lead to principled understanding (knowing how each of the chemical elements interact and alter the properties of the alloy.[1]) Particularly, we are interested in "*extensible" understanding* – learning principles from one phenomenon that could be applied to other related phenomena.

Secondly, there is an important distinction to be made in how representations relate to the phenomena they purport to describe. We are not arguing that aggregate equational representations are intrinsically ill suited for learning engineering or science as there are many cases in which equational representations are fruitful for

[1] For more on design for learning versus design for use see, for example, Soloway, Guzdial, & Hay, 1994.