Mr. Vetro: A Collective Simulation Framework

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Abstract: Growing science apathy at the K-12 education level represents an alarming development with potentially devastating consequences at individual, societal and economic levels. Surprisingly, student apathy is increasing while the general public increasingly reads popular science books and watches science TV programming. We have begun creating a new kind of infrastructure, called *Collective Simulations,* uniquely combining *social learning pedagogies* with *distributed simulation technology*. This infrastructure creates immersive learning experiences based on wirelessly connected handhelds. As part of the Mr. Vetro prototype, students learn about physiology through technology-enhanced role-play. Each group controls physiological variables of a single organ on their handheld computer. A central simulation gathers all the data and projects them. Collective Simulations allow students to learn about the intricacies of *interdependent complex systems* by engaging in discourse with other students and teachers.

Problem: Science Apathy and Its Consequences

Education has never been more important. The information society thrives on the ability to acquire, grow and process knowledge. However, our perceptions of knowledge are gradually changing. Thanks to information technology, factual knowledge is now easy to access. The quality of information may vary widely, but by and large most facts taught at K-12 institutions can be accessed through a Web search engine such as Google. In contrast to many hopes and predictions, the mere accessibility of factual information has had little impact on students' interest in science. In 1994, when the Web had practically no presence in public education, The Scientist [1] reported that researchers were alarmed by the public's lack of scientist knowledge. In 2004 The Scientist [2] reported little change, at a time when 92% of public schools have Internet access for instructional purposes [3]. Young students are turned off by mathematics and science. This science apathy is an imperative problem at a number of levels:

Personal level: Health science apathy can lead to bad decisions in early life regarding physical exercise, nutrition and habits such as smoking and drinking. Obesity, for instance, has become a worldwide crisis. For the first time in human history, as many people are over-nourished people as are undernourished.

Economic level: Science apathy negatively impacts the economic leadership of this country. Apathetic K-12 students are not motivated to enroll in science-oriented university programs. Dropping science enrolment aggravates the scientific personnel shortage in vital and growing industries such as biotech. The software development outsourcing phenomenon threatening the US Information Technology industry may soon be joined by scientific outsourcing. The lack of trained individuals is already increasing industrial scientific recruitment from countries such as India, which put a much larger emphasis on science education than does the United States [4].

Next generation teaching level: The consequences of science apathy for teaching are perhaps even more worrisome. Students that dislike science are not apt to become science teachers. This will have long-term consequences that are still hard to qualify, but certainly pose an amplifying effect that could turn an already bad situation even worse.

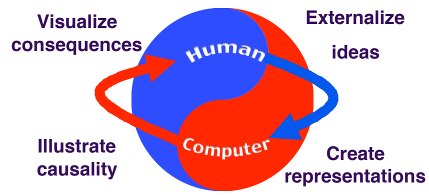
However, there is some good news. The general public's strong and growing interest in science illustrates that science apathy is not intrinsic to science, but is instead perhaps a consequence of how science is experienced in school and how tools such as information technology are being used. Our educational institutions need a new combination of pedagogy and tools that genuinely excites K-12 students about science, and helps them understand highly complex and interacting systems such as a human being.

Solution: Collective Simulations

Our goal is to create *Collective Simulations* as a conceptual framework that integrates *social learning pedagogical models* with *distributed simulation technical frameworks* in order to enable *meaningful learning*. This conceptual framework both allows and actively encourages meaningful learning by supporting discovery-oriented social learning processes. In a Collective Simulation, an entire group of students and their teacher – acting as a discourse facilitator – participate in a distributed simulation that unfolds in real time on a set of networked computers running distributed simulations. These computers are smart artifacts or tools that augment discourse and support the discovery-oriented scientific process.

Why Simulations?

Simulations become enormously powerful learning tools [5] when they effectively combine human abilities with computer affordances. In an effective educational simulation, humans and computers complement each other in the cyclic process of exploration that is the heart of discovery-oriented learning. In our computer-augmented version of this process, humans externalize ideas and create representations, and computers illustrate causality and visualize consequences. As learners repeat this cycle they often uncover inconsistencies that revise their initial ideas. Professional scientists often construct and use simulations to aid their own scientific understanding. Simulations let learners actively engage in authentic scientific investigations; they can understand underlying processes by observing patterns that emerge as they manipulate simulation parameters.



Simulations can help illustrate intricate relationships between individual behavior and the aggregate behavior of a large group. In the case of an ecosystem, it may be easy to describe the behavior of an individual animal but quite challenging to predict the complex behavior of the entire system. An ecosystem simulation environment that lets learners express theories about how they think certain animals behave enables constructivist learning activities that can help *make thinking visible* [6]. Simulations illustrating the intricate relationship between individuals and aggregates are relevant to a large number of complex systems [7, 8] that include biological, social, economic, political, organizational, weather, and traffic systems.

If simulations are so powerful, why have they not had a greater impact on education? Pilot training and many other workplace-training applications already rely heavily on simulations. Evidence from K-12 contexts shows that computer-based simulations could provide a much more effective learning approach than drill-and-practice applications [9]. In spite of this potential, most simulations used in K-12 classrooms do not really engage students. We believe that simulations can become effective learning vehicles addressing this problem through a combination of *a) social learning pedagogy* and *b) distributed simulation technology*.

a) Social Learning Pedagogy: Making Learning Meaningful

The current situation cannot be improved without understanding the *social processes* and the *context* in which educational simulations will be used. The pedagogical dimensions of social processes are key indicators of the usefulness of a simulation in a classroom context. Joel Michael's notion of *Meaningful Learning* is based on ideas of a social process that includes active externalization of ideas and engagement in discourse [10]. He talks about the challenges of complex system comprehension in the context of human physiology education:

> "One of the most 'active' ways to help students to challenge with their own mental models is to get them to 'talk physiology.' Discussing, justifying, or explaining their answers to questions with one another, or with the instructor, is a powerful way to encourage meaningful learning."

Active externalization, reflection and discourse as learning processes are highly consistent with Piaget's notion of constructivism [11]. Learning is the process of adjusting our mental models to accommodate new experiences. Simulation-based learning processes are also consistent with Papert's notion of constructionism, in which learning is the result of a externalization-as-construction process of physical and conceptual artifacts [12].

The social aspect of Michael's notion of meaningful learning is implied by his focus on communication. Vygotzky's theory of social construction of knowledge [13] indicated that a learning process is substantially aided by active collaboration that includes discourse. Hutchins' theories of distributed cognition add the notion of tools and artifacts. He points out that human cognitions are not just a framework confined to individuals; they are distributed across individuals, tools and artifacts in an environment [14]. Discovery-oriented educational software can enormously benefit from this distributed framework. As educators and technology builders, we can and should depart from the viewpoint that a classroom is simply a container of isolated technology pieces used by individuals and move towards a socio-technical cooperative infrastructure that actively facilitates a social learning process.

b) Distributed Simulation Technology: Experiencing Interdependent Complex Systems

The comprehension of interdependent complex systems is an enormous challenge to learners. We reviewed physiology teaching materials at middle, high school, and university levels; we included textbooks, interactive CD-ROMs and Web-based sources and investigated titles offered by major publishers such as Pearson (http://www.aw-bc.com/info/ip/). We found a ubiquitous absence of explanations for how systems *interact*. All the materials we reviewed structured the human body into decoupled subsystems (e.g., respiratory and circulatory) isolated in separate chapters or animations with little, if any, connection. These neglected interactions are central to understanding how the human body works. Indeed, the general need to comprehend interactive systems is part of the current standards [15]. Realizing the need for more rigorously teaching about the interactions of systems instead of systems in isolation, many medical schools have changed or are in the process of changing their curricula to reflect a more integrated systems approach. Despite its importance, the integrated approach is largely ignored because of the inadequacy of traditional K-12 teaching media. *Collective simulations* are a technological infrastructure that can address this problem by creating an immersive learning environment that lets students collaboratively *experience* system interactions. While our examples are of a medical nature we want to stress that they apply to wide range of domains. These same interactive system concepts pertain to scientific domains such as economics, ecology, and biology. The overall system behavior of these domains cannot be understood by simply examining and explaining the behavior of individual parts in isolation.

Mr. Vetro: the Human Physiology Collective Simulation

Mr. Vetro[1] is an early prototype of a Collective Simulation for human physiology that we have built. In this prototype, different systems or organs of Mr. Vetro are simulated on wirelessly connected handheld computers, while a central simulation aggregates parameters from the organs and computes Mr. Vetro's vital signs (Figure 1)[2].

At the beginning of an activity, handheld devices that run simulations of Mr. Vetro's organs are handed out to students. One group receives the heart, another group the lungs. Using the distributed simulations running on the handhelds, students control Mr. Vetro's organs. The lung group can vary parameters such as breathing rate and tidal volume in response to changing conditions such as exercise or smoking. The heart group can vary parameters such as heart rate and stroke volume. The teacher can act as the decision-making part of Mr. Vetro's brain to control decisions such exercise intensity. An initial discussion explores the students' own experiences with heart rates and breathing rates to get a sense of what meaningful numbers are.

One computer connected to a video projector communicates wirelessly and aggregates all the client simulations – in this case the heart and the lungs – into a composite representation that includes visual and audio elements. The heart and lungs show up as part of the 3D human visualization. The simulation begins. Mr. Vetro begins to breathe. The class sees the heart and lungs moving, and hears Mr. Vetro's heartbeat and breathing. Changes to physiological variables such as the breathing rate on a handheld computer simulation immediately update the entire distributed simulation. The students operating the lung will see the update on their handheld computer but everybody else will see and hear the update on the projected 3D model of Mr. Vetro.

A life signs monitor keeps track of Mr. Vetro's vital signs and displays them in the form of graphs or numerical values. ECG, heart rate, breathing rate, oxygen saturation, and oxygen delivered to tissue are some of the physiological variables calculated and displayed. The Collective Simulation does not automatically balance Mr. Vetro's life signs. As Mr. Vetro begins to jog (controlled by the teacher), his need for oxygen goes up. The heart and lungs teams have to collaborate to keep Mr. Vetro in a healthy state. If carbon dioxide is too high, can the heart compensate for a small breathing rate by beating faster? If the breathing rate is significantly low, when will hypoventilation begin?

The Collective Simulation is dramatically different from the traditional use of technology in education. Traditionally, the entire activity takes place in a computer lab—with a one-to-one mapping between students and computers. In a Collective Simulation, the simulation cannot be operated without discourse. The heart team cannot directly control the lungs. If the heart team feels that the lungs are operating too slowly, then they must communicate with the lungs team and involve the entire classroom. Requests need to include justifications. Misconceptions get externalized and discussed. This collective simulation infrastructure fosters a social style of learning that emphasizes distributed cognition.

C^5 Technical Approach

The Collective Simulation infrastructure creates an unobtrusive learning environment that enables new kinds of discovery-oriented, social, simulation-based learning activities.

A regular desktop computer with an attached video display operates as Collective Simulation server communicating with all the handheld computers. The communication is established as XML-based messages delivered through TCP/IP sockets over Wi–Fi or BlueTooth. The same computer also runs the main Collective Simulation which is an

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[1] Translated from Italian, "vetro" means "glass". The name is derived from Mr. Vetro's glass skeleton.

[2] An interactive flyer of Mr. Vetro can be found at: http://agentsheets.com/research/c5/documents/interactive%20flier/c5-flier.html.

agent-based 3D (OpenGL) simulation engine used also in other AgentSheets Inc. projects. The handhelds run client software (Java, C++, and Flash) communicating asynchronously with the collective simulation server.

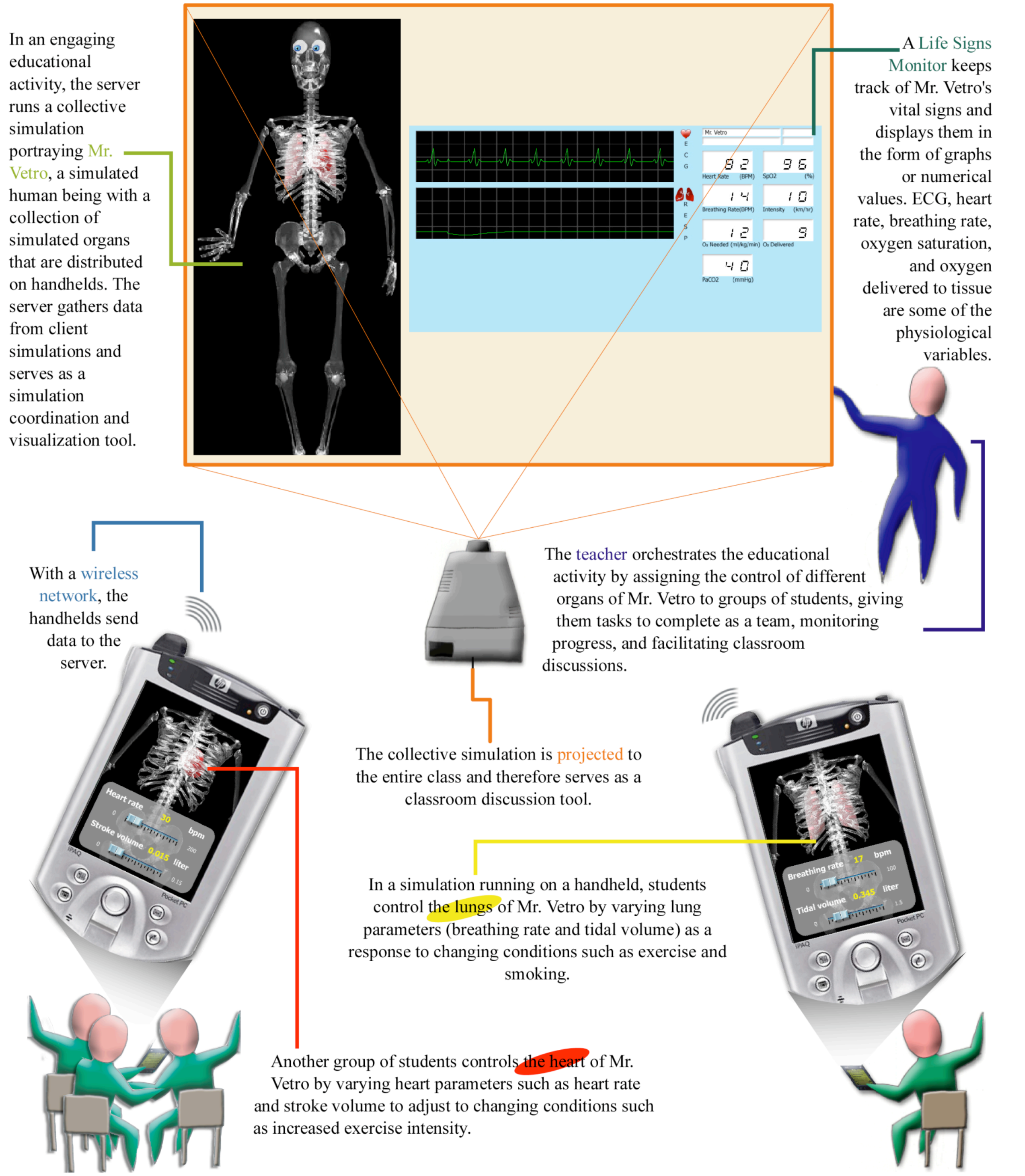

Figure 1: Mr. Vetro Collective Simulation

The underlying architecture (called C[5]) is an Information Technology infrastructure that uniquely combines the following five principles:

1) ***Collective***: Complex simulations can unfold on two levels. For instance, Mr. Vetro's organs run on individual handhelds, but the collective simulation of the entire human being runs on the server aggregating all the signals from the individual organs. This aggregated simulation calculates life signs and projects them to the entire classroom. A social simulation of one household might run on a single handheld controlled by one user. A collective simulation modeling an entire city could run on a server and aggregate the behaviors of individual households.

2) ***Compact***: C^5 simulations have a small memory footprint and fit onto small computing devices. These devices include Pocket PCs, next generation calculators, and cell phones. Compactness is essential for classroom management, since simulations may need to be downloaded through a network into a device. This could be a serious issue in a large classroom, if many students use the network simultaneously. Since handheld devices are physically compact, simulations need to work with small display sizes, and with pen or thumb-keyboard based input. Physically compact handheld computers let the technology adapt to the classroom, rather than demanding the classroom adapt to the technology. This helps avoid leading classes to a computer laboratory, and creates interaction dynamics that enable social learning.

3) ***Connected***: C^5simulations are not limited to a closed world, where students must manually feed the simulation. The Internet and physical sensors provide immense sources of live, dynamically updated, information that is highly relevant to educational simulations. Collective Simulations let students turn existing Web pages into information sources. Candidate Web pages might contain numerical information such as current weather information. In some activities, a simulation could be connected to inexpensive commercial sensors such as Polar's heart rate monitor. The C^5 architecture wirelessly connects these information sources to student simulations, and automatically feeds the simulations new data in real time.

4) ***Continuous*****:** Simulations that run in real time or are connected to real world events can run in a continuous mode. In contrast to most current educational simulations, a continuous simulation can run for extended periods of time—possibly 24 hours a day, 7 days a week. Mr. Vetro's continuous nature could manifest itself when running the simulation in modes other than real time. At the moment, learners see the immediate effects of changing organ parameters. However, a continuous simulation could fast forward to the future to see the long-term effects of actions such as smoking or abusive drinking. Exploring and contrasting short versus long-term effects of substance abuse is intriguing and has numerous applications.

5) ***Customizable***: While small, pen-based displays limit complex end-user authoring schemes, next-generation handhelds could support simple end-user user programming; students can customize existing simulations themselves. New simulations would not have to be created from scratch. Mr. Vetro's profile is easy to customize, so students can explore case-based scenarios where Mr. Vetro assumes different profiles.

Why Handhelds?

Experiences in classrooms [16] (including our personal observations) indicate that form factors and unit pricing of regular desktop computers can have detrimental consequences to information technology supported learning, especially when they lead to computer labs instead of regular classroom use. Handheld devices such as the Palm Pilot are quickly emerging as low-cost information technology and educational delivery platforms that are highly relevant for education. Next generation handhelds such as the HP iPAQ have capabilities that include:

Speed: they are fast enough to run complex interactive simulations;

Networking: they have fast wireless networking capabilities (Wi-Fi and Bluetooth) that let them participate in a connected network of collective simulations; and

Display: they have high-resolution color displays that, despite their small size, can both represent and manipulate intricate interactive content.

This new generation of handhelds leads to educational applications that move qualitatively beyond electronic versions of paper and pencil applications. Advanced applications include hyperlinked note taking, scheduling, and graphing. Interactive simulations move one step further by enabling individuals to explore complex learning subjects and perform "what-if" experiments on their personal handheld devices. A collection of wirelessly connected handhelds can create distributed simulations that conceptually collect individual decisions into aggregate phenomena.

Pilot studies

As part of our project we explored building a variety of distributed simulations. Example simulations included ecological, e.g., the economic footprint of a community, and ecosystems role-play activities. We held multiple planning meetings with teachers, in which we collaboratively investigated teacher needs and the potential applicability of technology in their courses. Most relevant to this proposal was the finding that many biology teachers found themselves to be challenged with teaching physiology and anatomy using existing curriculum materials. At these meetings, several teachers strongly encouraged us to create distributed simulation of a human being that could be used both in biology and anatomy classes. Moreover, our classroom colleagues directly contributed specific ideas and suggestions for the simulation's functionality and form. This collaboration led to the creation of Mr. Vetro.

The resulting prototype was used in a preliminary educational activity developed with the help of a biology high school teacher. During this activity, students subjected Mr. Vetro to different levels of exercise and controlled the heart and lungs to optimize his physical condition. In some scenarios Mr. Vetro was a smoker, and students simulated the effects of smoking and nicotine on the lungs' via its tidal volume and the heart's stroke volume. The students simulated various situations, and observed Mr. Vetro's physiological variables. Students recorded their data and used their parameter values to reach conclusions and answer questions prepared by their teacher. The teacher was surprised to see a high degree of engagement of the students and an almost ER-like atmosphere including vivacious discussions and a sense of real-time drama.

We found that while students had some understanding of each separate organ, they did not have a clear sense of the connection between the circulatory and the respiratory systems. Moreover, collaboration through the use of handhelds was very natural. Groups of students gathered around the central simulation and were controlling the parameters of each organ. They engaged in the activity, discussed changes, and collaboratively explored the questions posed by their teacher. This preliminary user testing illustrated that the C^5 architecture can instigate a unique collaborative style of simulation-based discovery-oriented learning.

Demonstrations, follow-up brainstorming sessions with teachers, and workshop presentations all produced a large number of suggestions and comments that made it clear that our Collective Simulation framework can be used for a wide range of activities. High-level suggestions for Mr. Vetro included: exploring connections to nutrition and physical education, long-term simulations about alcohol and substance abuse, and the use of heart rate monitors and other sensors to make simulations more personal.

Related Work: Physiology Simulations & Multi-User Simulation Architectures

In the process of creating Mr. Vetro we have examined physiology software and participatory simulation systems.

SimBioSys (http://www.critcon.com/ccipublic/products/clinics.php3) uses simulated Emergency Room situations as training context. It exposes students to real-time situations based on patient case studies. Without the proper treatment a patient is likely to die. SimBioSys does not deal very directly with physiological variables; it is more concerned with the process of quickly determining which sensors to use and what kind of medication to administer. Mad Scientist (http://madsci.com/) offers similar training software. Its Emergency Room training title "Cardiac Arrest!" includes links to on-line book texts, video resources and "algorithm flowchart." The Logal Science Explorer Series by Riverdeep (http://www.riverdeep.net/) is much more K-12 oriented. It provides a set of activities in a science curriculum that covers key concepts in biology, chemistry, and physics. Through what Riverdeep calls "computer simulation activities," students can discover and understand scientific concepts. We have specifically explored the Riverdeep units on the cardiovascular system and the respiratory system. Logal activities provide good content on individual systems. Students interact with simulations through worksheets that encourage them to predict and estimate feasible value ranges of physiological variables. However, these explorations are focused on variables of the same system, e.g., the lung volume over time, and do not support interactions between different systems. The JavaMan Project (http://www.health.adelaide.edu.au/paed-anaes/javaman/) includes a Web-based computer model of human physiology. It lets users explore the Respiratory and Vascular systems of the human body. The model can deal with a large set of variables. An abstract, mostly textual interface, does not include a visualization of a human being, and does not allow the simulation to be distributed. Participatory simulations [17] involve people using or building simulations collaboratively. Desktop, handheld and wearable computing devices can be connected in various ways to support participatory simulations. In HubNet, collaborating students explore math functions [18] by providing individual data points to a continuous mathematical function. A central server collects these data points and represents them as points on a plot visible to the entire class. In the Science Theater project [19], groups of elementary school children learn about ecosystems by building simulations that include designing and exchanging animal agents [20] over the Internet through the AgentSheets Behavior Exchange [21]. In the MIT Thinking Tag Virus simulation game, each player wears a small computational tag that can communicate with nearby tags through infrared links [22]. This hardware is used to create a role-playing game in which a group explores the mechanism of virus transfer. Similarly, the Geney project [23] uses Palm Pilot handheld devices to "simulate the breeding of a species across a distributed population. The Cooties system simulates the spread of viral disease through Palm Pilots

[24]. Multi User SimCity (http://www.dux.com/simctyux.html) is a networked version of the popular Maxis SimCity simulation game that lets a group of environmental design students play city planning games.

This list is by no means comprehensive. Earlier multi-user simulation systems had to make difficult trade-offs between pedagogy and technology. Multi user simulations in education were either powerful or running on handhelds. Collective Simulations uniquely join regular desktop and powerful handheld computers into sophisticated, yet economically feasible classroom simulations. The resulting combination of social learning pedagogies with distributed simulation technology is not just a means of more efficient learning; it enables new approaches of learning not previously possible without information technology.

Discussion

The prototype of Mr. Vetro provides an interesting starting point for further research in the educational viability of a collective simulation infrastructure. To this end, we need to create complete educational modules and evaluate them in educational settings. We are working with medical experts, professors and students at the Harvard Graduate School of Education, local teachers, and Shodor Foundation to create and disseminate complete collective simulation-based educational modules for physiology courses. Medical experts provide the physiological expertise behind the simulation; educational experts inform the development of pedagogical approaches that deal with distributed simulations in classrooms; local teachers write new curriculum around the simulations and design activities to integrate the simulations into classroom lessons; and the Shodor Foundation runs regular computational science workshops on the use of simulations in education.

There is a setup overhead associated with each distributed, handheld-based simulation modules that is introduced into a classroom. In general, there is too much setup overhead to justify using such modules for only a single class period. For distributed simulation activities to be worth their overhead, they should be used over a large part of the course duration (semester or trimester). Ultimately, the most effective way for the educational market to adopt C^5 technology will be to use a suite of modules that covers an entire course curriculum. Therefore, we will need to embed C^5 simulations into a more general framework that includes activity management. Activity management tools will help us effectively deliver polished, stand-alone educational activity units that educators can use.

Future work will also consist of exploring potential real-time data sources for Mr. Vetro, such as sensors and probeware. Useful data for Mr. Vetro could come from heart rate monitors, such as wrist size heart rate monitors — these devices are commercially available to consumers at an affordable price. Consumer monitors typically target amateur and professional athletes, as well as people undergoing cardiac rehabilitation. They provide biofeedback data that help regulate the intensity and quality of a workout and keep performance within safe ranges. We could use such data to implement scenarios where users use real-time sensors to create information such as their heart rate, upload the data, and display the results on Mr. Vetro. In this scenario, they could change parameters such as breathing rate and tidal volume to determine how they could improve their performance. The use of physiological sensors would extend the scope of medical applications of Collective Simulations to physical education.

Other future enhancements could include *simulation-based Web indexing*. Collective simulations could access the Web on demand by enabling conditions in the running simulation that trigger opening a relevant Web page. Mr. Vetro's health condition can be connected to definitions, treatments, and other related web-based material. For instance, when Mr. Vetro's partial pressure of carbon dioxide falls below some threshold, the simulation can then offer a collection of links related to hyperventilation. It could offer definitions of hyperventilation, or information on hyperventilation and remedies from sites such as WebMD. The ability to bring up information connected to the current simulation state delivers Web-based information that is immediately relevant to the activity context.

In addition to exploring high-end PDAs as a hardware platform for collective simulations, we also explore other hardware possibilities to evaluate economic and technical characteristics of emerging products. Particularly interesting are cell phones and game consoles. Most new cell phones run Java or Macromedia Flash content; they often have wireless network capabilities and feature color displays that are sufficient for useful simulations. Prensky, highly controversially, asserts, "cell phones – not computers are the future of education" [25].

Acknowledgments

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[3] Opinions expressed are those of the authors and not necessarily those of NSF

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