Introduction: Motivation and Goals

In science education, a fundamental challenge remains: how do we help children to understand complex, emergent systems? The obvious strategy of having a child interact with a computer-based simulation has not been particularly successful (Lowe, 2004; Rieber, Tzeng, & Tribble, 2004; Tversky, Morrison, & Betrancourt, 2002). Why hasn't the community seen a more positive impact of simulations on enabling understanding? It is our hypothesis that current computer-based simulation environments do not provide a rich or broad enough set of experiences to enable children to develop an understanding of the myriad of issues involved in the behavior of a complex system. The canonical case places *a* child in front of a desktop computer-based simulation, which we will refer to as a Centralized, Single-device Simulations (CSS). For example, with a CSS application that simulates a forest ecosystem, the child could vary a number of parameters in the simulation and observe the changes that result. Empirical studies have shown that this approach seldom results in substantial learning gains over traditional classroom instruction (de Jong & van Joolingen, 1998; Swaak, van Joolingen, & de Jong, 1998). Even adding scaffolds (i.e., supports for learning), such as prompts that encourage students to make predictions before varying parameters, do not seem to support a broad range of learners in developing an understanding of the intricacies of the complex system. Currently, there is a lack of formal understanding of how to ensure educational simulations reach their promised potential. We suspect that once this legwork is done, learning gains will follow.

The Center for Highly-Interactive Computing in Education (HI-CE) has worked for over 7 years with over 10,000 students in 30 middle schools to improve science education. In the classrooms where our educational programs are used, we have found that student achievement improves by almost 15% on standardized tests, when compared with other science reform efforts in the Detroit schools. We attribute this remarkable level of improvement to one underlying concept: alignment (Smith & O'Day, 1991). We have worked exceedingly hard to bring a range of factors into technological, social, and instructional alignment (Blumenfeld et al., 2000; Fishman et al., 2004). Take the case of Model-It, our dynamic systems modeling and simulation application. Although Model-It has been shown to produce learning gains (Jackson et al., 1996), Model-It becomes effective only when the following alignments occur:

- teachers are provided with effective and sufficient professional development,
- curricular materials and Model-It highlight the parallel subject matter,
- teachers employ instructional strategies that reinforce Model-It concepts,
- teachers employ instructional strategies that engage the students in instructional activities(e.g., in using collaborative learning techniques), and
- assessment techniques examine the same concepts that the curriculum and the technology are meant to teach.

While developing our understanding of how to create all that alignment was costly and time-consuming, we feel we have learned how to do it and we can apply that understanding to a new situation. Thus, the research proposed here builds directly on HI-CE's experience in creating "aligned" technology-enhanced experiences for children. What is new in this proposal is the technology. In particular, we propose the exploration of a computer-based simulation environment, described below, that takes advantage of newly emerging handheld technologies in order to provide a rich, broad set of experiences for children as they grapple with understanding complex systems.

The CSS (Centralized, Single-device Simulations) paradigm does not accommodate the new forms of communication and interactivity afforded by personal computational devices like handhelds and cell phones. Emerging to exploit those technologies is the Distributed, Multi-device Simulation (DMS) paradigm. In a DMS, the simulation itself is distributed over multiple devices that would allow collocated users to view and manipulate different aspects of the simulation simultaneously. The one-to-one student-to-device ratio allows each student to interact with the simulation personally, while the coordination of those devices (via wireless or other means) ensures that the students are all participating in the same simulation at the same time. This trend is in alignment with an increased demand for better collaborative learning tools with which to perform inquiry-based learning tasks, and we are far from the first research team to explore it.

Figure 1a **Figure 1b**

Figure 1. Illustrations of MUSHI-Life natural selection simulation, Figure 1a depicts three students simultaneously participating, while Figure 1b highlights the use of a handheld as a "magnifying lens."

Our contribution to DMSs (Distributed, Multi-Device Simulations) has been to design a software development framework, Multi-User Simulation with Handheld Integration (MUSHI). In a MUSHI type system, multiple students, each equipped with a handheld computer, interact with each other and with a simulation running on a central computer (such as a TabletPC). In Figure 1a, we see three students, each with a handheld, exploring a simulation of a self-contained ecosystem. The MUSHI Framework facilitates the creation of simulations that enable children to: **(1) view** multiple learning representations and **(2) capture content** from the larger simulation, in order to **(3) inspect** and **(4) manipulate** that content on their handheld device, and in turn **(5) inject** the altered content back into the larger simulation. The form-factor of the devices also allows for students to **(6) discuss** their actions with one another, and to move about physically. Students can pass their handhelds to each other for viewing without interfering in the simulation. Additionally, students can jump from one simulation running on a particular TabletPC, to another simulation running on another TabletPC, with each TabletPC acting as a collaborative anchor. In Table 1 we give a relatively short series of examples of the types of learning affordances that the MUSHI Framework supports, in the context of a natural selection simulation, MUSHI-Life, that simulates a self-contained ecosystem. In Section 2.1, we will present a longer, more in depth, scenario.

The goals, then, of this three-year proposal are:

- **Design Guidelines:** A set of interface design guidelines for DMSs that are both theoretically-motivated and empirically-based, which will lead to the construction of a usable software simulation environment that supports children in learning about the underlying complex system.
- **Software Development Kit:** We feel strongly that our research effort needs to produce tangible tools that the community can use to further investigate the issues we explore. Thus, a deliverable from this effort needs to be a software development kit (SDK) that enables third-parties to develop MUSHI-based simulations that include the interface elements that promote usability and learning.

Learning Affordance	Example
Anchored Collaboration The tablets provide a natural focal point for students to meet and interact (Figure 1a).	Three students **log in** to the ecosystem simulation on a tablet by lining up their handheld's IR port with the tablet's IR port. Once logged in, they are able to **simultaneously explore and interact** with the ecosystem. Although they are free to pursue individual tasks with their handhelds, the fact that they are **gathered around** and interacting with a **shared ecosystem** leads to **discussion**, and with scaffolding, **collaboration**.

Multiple Linked Representations Handhelds allow students to independently view the simulation at various levels of granularity (Figure 1b).	The tablet presents an ecosystem at a **macro level** of granularity, which presents **visible emergent behaviors** of ecosystem denizens, e.g. herding. Each student's handheld simultaneously displays a **micro-level** view of the student's virtual location within the ecosystem, e.g. they can view an individual denizen and its **micro-level characteristics** such as its mandible type.
Mobility Students can see what other groups are doing and even collaborate with neighboring groups to solve more complex problems.	After thoroughly exploring the ecosystem on one tablet, some students from each station are directed to move to different stations. The students who remained can share their earned knowledge of the station's ecosystem with the newcomers. The group membership shake-up prevents one person from always dominating a group, and the **privileged knowledge** encourages **reticent students to share their ideas verbally**. The students are directed to **make comparisons** between the new station's ecosystem and the one they studied previously.
Parallel Interactions Students can simultaneously collect information on a variety of phenomena, facilitating complex collaboration tasks.	The students are instructed to discover which kinds of foods each breed of bug is able to consume. Half of the students are asked to observe different types of food and to **collect numerical data** on which and how many bugs feed upon each food type. The other half is asked to observe different types of bugs to **catalogue** the different mandible types. Then the students are directed to share their information, to **make generalizations** about the relationship between mandible type and food consumption.
Scaffolding The multi-device nature allows for a new type of scaffolding, synergistic scaffolding, to be employed to support both (1) the learning across different devices and (2) the social interactions of the students.	As the students work, insects may cluster in some areas and move away from others. The scaffolding system can draw student attention to these patterns by using signaling on both the handhelds and the tablets. To be **synergistic**, the scaffolding system will prompt each of the students to engage in an **individual, complementary task** in order to study the flagged pattern. The task assignment can be predicated on past task performance, so students are not challenged to perform too far outside their **proximal development zone**. The scaffolding system can subsequently scaffold collaborative student **discussion** after task completion, where each student shares his or her individual findings.
Content Extraction and Injection Students are able add and remove objects from the simulation in order to better understand how the objects affect the simulation and vice-versa.	In order to test their theories, students will be asked to develop their own experiments. An ecosystem supports a population of small-mandibled bugs that exclusively eat berries, but nuts also exist in the ecosystem. The students **hypothesize** that the ecosystem can support twice as many bugs if some of the bugs can eat nuts. They capture a large-mandibled, nut-eating bug from another station's ecosystem and inject it into their own to **observe** the results. The newly-imported bug species thrives, and the ecosystem in fact does support twice as many bugs – however, the population is exclusively comprised of the new species. The students are then challenged to understand why the berry-eating bugs died out – further experimentation will tell them that although the large-mandibled bugs can eat nuts, they prefer to eat berries – a lesson in invasive species.

Table 1. Brief overview of some of the learning affordances of our MUSHI framework.

Intellectual Merit: Supporting children in coming to deeply understand complex, emergent systems is a core challenge in science education. As low-cost but powerful handheld computers have become available, there is an exciting opportunity to fundamentally rethink how we can construct simulations of complex systems so as to allow children to access and manipulate the elements in the simulated system and, in turn, productively interact with each other. The particular computer-based simulation architecture we propose has a number of unique affordances that, based on the literature, should lead to dramatically improved student understanding. To insure that outcome, we know from our previously successful efforts that we must align the technology with more traditional, but critically important educational factors, such as curriculum, teacher preparedness, standardized tests, etc. Inasmuch as we have a solid track record of producing educational technology that has resulted in significant gains in student achievement, we feel poised, with this project, to again enable children to make significant gains in understanding important science issues.

Broader Impact: With little or no access to ePaper and ePencil, our society is guaranteeing that there is no economic advancement in the future for children caught in the digital chasm. Our proposed learning technology, however, exploits low-cost but powerful handheld computers to enable significantly enhanced learning. Thus, that architecture is especially relevant to schools and homes that are economically challenged. Moreover, we have explicitly planned from the outset that the fruits of the research can be readily transitioned out of the university into the commercial sector, thereby enabling broad distribution and availability – at low cost. In sum, we have consciously attempted to create the conditions for our R&D efforts to have the type of broad impact that NSF envisions for its best science research.

The organization of this document is as follows:

- Section 2: Here we provide a brief description of the status of our work in developing an initial implementation of MUSHI
- Section 2.1: Here we provide an extended scenario of students interacting with several MUSHI-based simulations.
- Section 3: In this section we provide a tabular presentation of work related to MUSHI; our goal is to highlight the specific differences between our work and that of the others in the field.
- Section 4: In this section we briefly present highlights of previous sponsored NSF research.
- Section 5: Finally, we lay out a three year R&D effort directed to achieving the two goals presented above

Section 2: Current Research

The MUSHI framework evolved out of a communicable disease simulation called "Cooties" and a prototype genetics simulation called "PocketGen". We knew that handhelds provided a certain level mobility that would allow a more face-to-face approach when students worked together. In Cooties, students arbitrarily exchanged IR signals, some of which carried a communicable disease. In PocketGen, students raised virtual pea plants, and used IR beaming to cross pollinate between devices. Unfortunately, as we continued at add features, we quickly realized that the limitations of a handheld's form factor would become a dampening factor. Charts and tables require a great deal of screen real-estate and processing power. To address this issue, we began experimenting with wireless synchronization between handhelds and desktop sized computers. Initially, the simulation continued to run primarily on handhelds, while the desktops were reserved for displaying large graphs and family trees. However, with our next simulation, an economics game called "Choc-Econ", we offloaded even more computation onto the desktop device. Building from a sort of local / global framework, we realized that the majority of our learning tasks did not require that the handhelds communicate directly. The idea of a community interface was proposed; it would provide a working area that can be explored and controlled simultaneously by a group of students, as opposed to a single individual. Thus, the MUSHI framework was born.

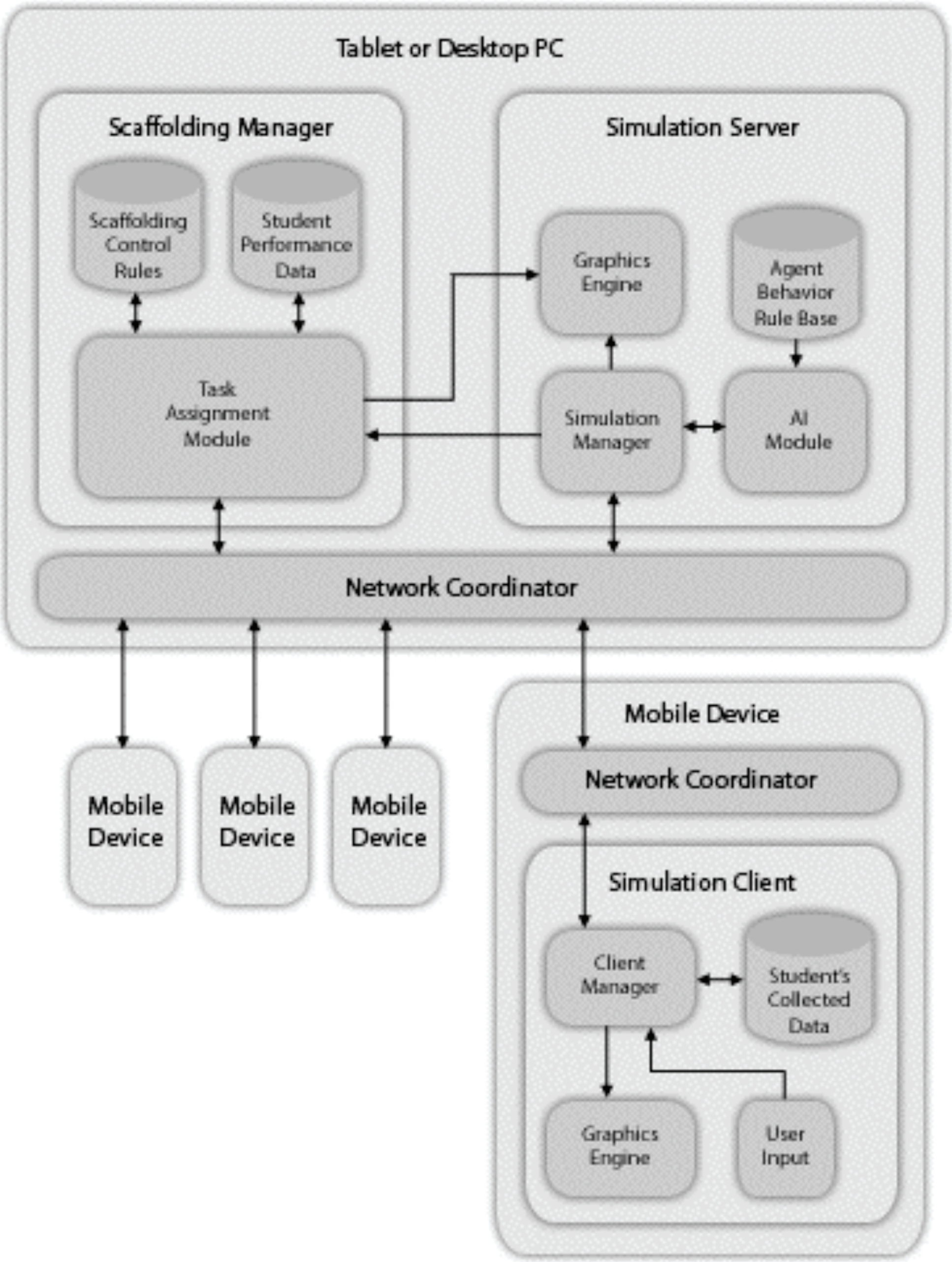

Figure 2. Current MUSHI software architecture.

The MUSHI framework is in a preliminary stage of development. We have recently completed the proof-of-concept system for the MUSHI-Life simulation described in Section 2.1 (Lee et al., 2005; Vath et al., 2005). MUSHI-Life is our test application to determine the both the technological and educational strengths and weaknesses of the MUSHI framework. Primary amongst our technical concerns were: (1) the allocation of processing tasks- to devices, (2) the reliability and bandwidth of wireless networking, (3) the conservation of memory on the handheld devices, and (4) the usability of multi-device interfaces. Additionally we had several educational concerns, including: (5) finding the optimal modalities for synergistic scaffolding, (6) providing affordances for inquiry learning and (7) providing affordances for effective collaboration.

The MUSHI architecture (Figure 2) takes the above seven concerns into account; separating each of the challenge areas into its own discrete problem with as little overlap with the other problems as possible. The majority of the computation occurs on the desktop device, although for the sake of bandwidth, some simple data processing is off-loaded onto the handheld. Some amount of data processing (in lieu of storing data like pre-composited image files) also helps to keep the memory footprint of the system down to a reasonable level. Due to its complexity and inconsistency, networking is separated as much as possible from the other key systems. A separate scaffolding manager helps to both guide inquiry learning, and to foster natural collaboration activities between multiple users**.**

2.1 Extend Scenario of a MUSHI-Based Simulation

This scenario is set in a seventh grade classroom, wherein 20 students are about to begin a biology unit that deals with natural selection. The presentation of core ideas underlying the process of natural selection is articulated in national science education benchmarks (American Association for the Advancement of Science, 1993). These benchmarks suggest middle-school students should understand that: (1) there exist variations in body plans and internal structures across different organisms; and variations in environmental resources (including food, space, water, air, and shelter) that influence both (2) individual survival and (3) population survival. We can see that even in this first introduction to natural selection, students must build an understanding of what occurs on a local, micro level (goals 1 and 2) and on a global, macro level (goal 3), and how these two levels influence one another. Thus, a natural selection simulation that presents a complete ecosystem at both the local and global levels would be a good candidate for our MUSHI framework. In conjunction with this simulation, which we will call MUSHI-LIFE, the following equipment will be needed: 6 desktop or tablet PCs, 20 handheld computers, and 1 wireless access point (see Figure 3).

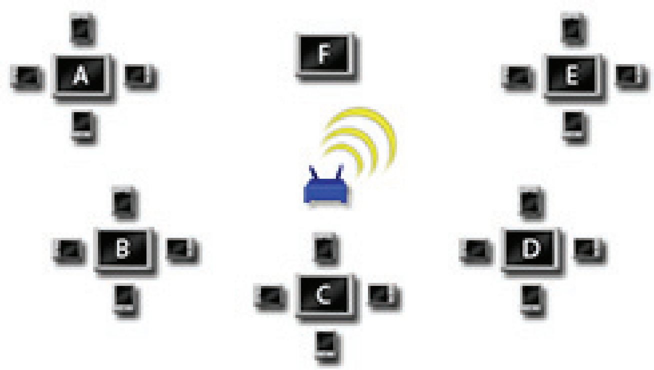

Figure 3. A schematic depicting the use of MUSHI-LIFE in a classroom of 20 students. The students each have a handheld computer and are divided into five groups of four. These five groups each surround a tablet or desktop PC running MUSHI-LIFE, ~~labelled~~labeled A-E. The remaining tablet or desktop PC, F, is reserved for the instructor's use. A wireless access point allows the devices and PCs to communicate with one another wirelessly.

The students are broken into five groups of four. Each group gets their own ecosystem; this ecosystem will be run on one of the 5 desktop or tablet PCs placed at a lab station. The sixth desktop or tablet PC will optionally be used by the teacher, to manage tasks (e.g. the assignment of habitat type to each station's ecosystem). Every ecosystem has a distinct combination of environmental factors, including: temperature, precipitation frequency, terrain features, native bug[1] varieties, food types, and predators.

[1] Notice that we use the term "bug" in lieu of more scientifically correct terminology like "insect". Much like the designers of GenScope with their "dragon" populations, we are not attempting to use a "real" population of insects because some phenotypes and behaviors have been exaggerated to make the educational topics easier to grasp.

Every student has a handheld device which simultaneously acts as a: moveable probe, microscope, Petri dish, quick reference guide, lab notebook, bug transport “crate”, and collaboration/cooperation manager.

The students will use their handhelds to access and explore their ecosystems at a “zoomed-in” local level, while the station’s display depicts the “zoomed-out” global level of the ecosystem. To begin this exploration, every student:

1. Picks up a handheld
2. Enters their name
3. Swipes the handheld in front of their station’s infrared port, automatically logging them into the station’s ecosystem simulation.

As each student logs in, a small “view frustum” icon appears on their lab station, displaying that student’s virtual location. Students will notice that their handhelds display a magnified view of the region of the ecosystem underneath their “view frustum” icon. (See Figure 1b).

To explore the ecosystem, the students at a station may:

- **Move** their view icons around the ecosystem, using the directional pad located at the bottom of their handheld. As the students move their icons, their magnified handheld views will adjust to display their new virtual locations.
- **Inspect** an item of interest (e.g. a piece of fruit) in greater detail by tapping it with their stylus. This action will bring up a corresponding encyclopedia reference for that item.

After a period of exploration and familiarization, the groups are given the following broad learning goal:

Discover the optimal combination of traits required for bugs to survive in each of the ecosystems.

Students can observe both the global environment and its bugs by **viewing** the station display and their personal handheld display, respectively. Bugs within their handheld view are magnified – allowing the students to observe their bugs’ specific characteristics and behaviors. Students are prompted via the scaffolding system to:

- **Observe** global characteristics that might impact the survival of the bugs – for example, the distribution of food about the ecosystem.
- **Share** their findings with their group members. They can do this through **discussion** and by passing their handhelds back and forth, using the handhelds as a sort of conversational artifact.

4a **4b** **4c**

Figure 4. Illustration of multi-device, synergistic scaffolding. In Figures 4a and 4b the scaffolding system is attracting the attention of the student. Figure 4c depicts an individualized task assignment. Students can be given unique tasks based on their past task performance. The unique tasks are complementary, to better scaffold collaborative discussions after the students complete their individual tasks.

The scaffolding system in MUSHI-LIFE is a ***synergistic*** one, meaning that the different aspects of the scaffolding work together across the different devices (Tabak, 2004). For example, there are times when interesting behavior patterns **emerge**, but are only visible on the global station display. A simple example might be that bugs begin clustering in certain regions that are plentiful in a particular food source: a hard-shelled seed. In such a situation, the **synergistic scaffolding system**[2]:

- **Directs student attention** to the global station's depiction of the clustering. It can do this by simultaneously providing visual cues on the station display (e.g. a glowing, blinking circle surrounding the area of interest on the station display, see Figure 4a) and textual cues on the handheld devices (e.g. directions to inspect the food type found in the circled region, see Figure 4b).
- **Gives complementary directions** to the students to facilitate cooperation and collaborative learning. There is no reason that the students' textual directions (delivered by their handheld devices) must be the same: instead, the group's students may each be given a different, complementary task (see Figure 4c). (For example, , one student may be assigned the task of inspecting the food source, and another may be given the task of inspecting the mandibles of the bugs found in the circled region).
- **Gives individualized directions** to the students. The task distribution also may depend on past performance by the individual, so that students with lower past performance are not asked to perform too far outside of their demonstrated range, in accordance with Vygotsky's theory of proximal development.

The synergistic scaffolding may also prompt students to:

- **Capture** the bugs for detailed observation. By pressing a handheld's "capture" button, a student is able to "scoop up" a nearby bug, effectively removing it from the global simulation and moving it to the handheld.
- **Inspect** the captured sample bug more thoroughly. When captured, a bug's phenotypical characteristics (and, in later exercises in the unit, its genotypical characteristics as well) are made readily apparent on the handheld device.
- **Discuss** their findings with other students engaged in parallel, complementary tasks.

Once again, different inspection tasks may be assigned to different students, with the synergistic scaffolding marshaling their inspection efforts and encouraging the students to share their individual findings with one another. So, for example, the student **inspecting** a bug **captured** from the cluster is directed to compare her bug with another student's bug **captured** elsewhere. Through **discussion**, the two students discover that the cluster bug has a much larger mandible than that of non-clustering bug. The student **inspecting** the food source at the clustering site is likewise prompted to discuss his finding, that the food source is a hard-shelled seed, with the other students. A fourth student has, in the meantime, been directed to **observe** which types of food are the most common in the ecosystem. From this, the group will more easily be able to make a hypothesis about which mandible type would be the best for survival in their ecosystem. Similar scaffolding strategies could be used to help students collaboratively form hypotheses about the other traits as well. This synergistic scaffolding of the collaborative learning experience would not be possible without the use of multiple, individual devices to deliver the cues.

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[2] It bears mentioning that the exact visual, auditory, and textual components of these synergistic scaffolds will be determined by preliminary empirical studies conducted during the first year of research on the MUSHI framework. Likewise, the synergistic scaffolding of student-student cooperation is as-yet untested, and the benefits of same will need to be verified and refined during the first year of testing.

Such synergistically-scaffolded collaborative learning need not take place only within the lab station, however. The mobility of the handheld devices allow for students to move from station to station. After being captured, the bugs can be:

- **Transported** from location to location within a station's environment, or from station to station, with the handheld acting as a sort of transport "crate."
- I**njected** back into an ecosystem simulation, perhaps an ecosystem at a different station.

In this manner, after learning all about the ecosystem at their own station, students can move to other stations, bringing along with them samples of their original ecosystem's bugs[3]. With this mobility, concepts such as competition for resources can be easily explored. Because the imported bugs can interbreed with the native bugs, inheritance and adaptation can also be addressed with MUSHI-LIFE. In later exercises dealing with inheritance, students may be allowed to **manipulate** the genotypes of the captured bugs, but this feature is left until students are familiar enough with the simulation and its practices that they can design and enact their own experiments within the simulation. As the students become more facile with the use of the MUSHI-LIFE simulation software, and with cooperating with one another, the synergistic scaffolding will fade.

Section 3: Results from Prior NSF-Sponsored Research

HI-CE has been awarded a number of NSF grants that are germane to the current proposal.

- In ~~the~~ The Center for Learning Technologies in Urban Schools (LeTUS) (NSF 0380 310 A605) we developed the notion of "alignment" – where the middle school science curriculum, employing learning technologies, worked well and where the human element – teachers, administrators, curriculum coordinators, technology managers, also worked well together, all in the context of a large, urban school district.
- In our KDI project, the ASSESS Project (NSF KDI-9980055) explored the effectiveness of software scaffolds for learners and worked to develop general design principles derived from these studies. That effort has resulted in numerous publications and the much-cited paper (Quintana et al., 2004) describing design guidelines for software-based scaffolds.
- In our ITR (NSF ITR-0085946 project (Information Technology Research: Learning-Centered Design Methodology: Meeting the Nation's Need for Computational Tools for K-12 Science Education) we developed design guidelines for computer-based learning environments to provide learners with rich cognitive and social experiences as they carried out inquiry-based science activities. In particular, a suite of learning tools for handheld computers was developed under ITR funding. Those tools were licensed from the University of Michigan to GoKnow, Inc. (www.goknow.com) which has promoted the tools in K-12. Currently, those handheld tools, which have won several national awards, are recognized as the leading tools for handheld computers in K-12 and are running on over 15,000 handheld computers in 35 states and 4 countries.

Section 4: Related Research

There have been a number of efforts to provide students with computer-based environments for modeling and simulating complex systems. We would argue that MUSHI, as an example of a Distributed, Multi-device Simulation (DMS) system, engenders two specific types of activities that can significantly lead to increased learning: increased manipulation of the elements in the simulation (Table 2) and increased social interaction (Table 3). The literature (Bransford, Brown, & Cocking, eds., 2000; Mayer & Chandler, 2001) supports our claim as to the efficacy of these activities. The challenge, of course, is enabling the

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[3] Again, the most beneficial modality for this migration of students between stations must be determined experimentally. For example: should all of the students rotate to a new station, thus preserving the group structure, or should half of the group rotate at a time, so that the students who remain behind can help the incoming students "catch up" by sharing their earned knowledge of the station's ecosystem through **discussion**?

children to take advantage of those affordances. Our strategy will be to develop a broad range of scaffolds – scaffolds that are in software (traditional and synergistic), and also scaffolds that are enacted in the classroom, by teachers and by peers. While there is definitely prima facie evidence that we can develop effective scaffolds and thereby leverage the affordances of a DMS, the proof is in the pudding – we must carry out the studies proposed in Section 5.

<table>
<tr><th rowspan="2">System categories</th><th rowspan="2">Example tools</th><th colspan="3">Interacting with simulations</th></tr>
<tr><th>View and inspect</th><th>Control and modify</th><th>Capture and inject</th></tr>
<tr><td rowspan="5">Centralized, Single-Device Simulations: Simulations can be viewed and/or manipulated on a single device</td><td>GenScope (Hickey et al., 2003) ChemSense (Kozma 2000; Kozma, 2003)</td><td>Students can view and inspect parameters in a model. The system displays the model at multiple levels of scale simultaneously, but is limited by the device's screen space.</td><td rowspan="2">Students can modify different parameters in a model (e.g., changing the chromosomes of an organism, controlling the temperature of a reaction, indicating the rate of flow in a stream model) through a graphical user interface.</td><td rowspan="8">However, there is no sense of capturing a portion of a centralized model for individual study to allow different students to explore different parts of the model.</td></tr>
<tr><td>Model-It (Jackson et al., 1996)</td><td>Students can view and inspect parameters in a model. There is no way of displaying multiple levels of a complex system – only one level can be depicted at a time.</td></tr>
<tr><td>NetLogo (Wilensky & Resnick, 1999)</td><td>Students can view and inspect parameters in a model. Only the global level of the system is depicted; the local level is represented by a programming language.</td><td>Students can modify model parameters (e.g. the behavior of local-level entities) by altering the programming code governing the local level.</td></tr>
<tr><td>The Sims</td><td rowspan="2">Students can view and inspect local parameters in a model (i.e. the psychological states of the residents). Global level patterns must be inferred.</td><td>Students can modify model parameters (e.g., the behavior of local-level entities) through a graphical user interface.</td></tr>
<tr><td>MMOGs (Massively Mutiplayer Online Games)</td><td rowspan="2">Students can modify different parameters in a model (e.g., the behavior of local-level entities) by assuming the roles of local-level entities.</td></tr>
<tr><td rowspan="4">Distributed, Multi-Device Simulations: Simulation can be viewed and/or manipulated on multiple, coordinated devices</td><td>Geney (Danesh et al., 2001) Cooties, Thinking Tags (Collella et al., 1998)</td><td>Students can view and inspect the state of the local-level part of the model that the represent. Students only way to "view" the global state of the model is to consider what is happening to the other people participating in the simulation.</td></tr>
<tr><td>HubNet (Wilensky & Stroup, 2000)</td><td rowspan="3">Students can simultaneously view different parts of a system on their different devices (e.g., a desktop computer displays the global system, while handhelds display the local). Different levels of the system can be displayed without the screen "real-estate" constraints of multiple representations on a single display.</td><td>Students can use different devices (e.g., networked calculators) to control simulation parameters.</td></tr>
<tr><td>C5: Mr. Vetro (Repenning, 2003)</td><td>Students can control different simulation parameters, but only those that are pre-assigned to their individual device.</td></tr>
<tr><td>MUSHI (Lee et al., 2005; Vath et al., 2005)</td><td>Students can use different devices (e.g., wireless mobile devices) to control simulation parameters.</td><td>Rather than be restricted to a pre-defined aspect of the simulation, students can capture different aspects of the simulation from the global view into their individual devices, & take a more local, detailed look.</td></tr>
</table>

Table 2: Engendering Highly-Manipulative Activities

System categories	Example tools	Levels of social interaction
Centralized, Single-Device Simulations: Simulations can be viewed and/or manipulated on a single device	**GenScope** (Hickey et al., 2003) **ChemSense** (Kozma 2000; Kozma, 2003)	Students can work alone to focus on their particular learning activity. Difficult for multiple student-student and classroom-teacher interactions since the simulation is housed on one device. Students might pair up on a device, but even then, one student has control of the simulation at any given time.
	Model-It (Jackson et al., 1996)	Same as GenScope
	NetLogo (Wilensky & Resnick, 1999)	Same as GenScope
	The Sims	User interaction is mediated through the networked sharing of simulation elements.
	MMOGs (Massively Mutiplayer Online Games)	User interaction is mediated through networked, typed communiqués or through real-time voice transmissions.
Distributed, Multi-Device Simulations: Simulation can be viewed and/or manipulated on multiple, coordinated devices	**Geney** (Danesh et al., 2001) **Cooties, Thinking Tags** (Collella et al., 1998)	Student-student interaction is the focus of participatory simulations. It is incumbent on the teacher to help students understand the global impacts of their activities at the local level.
	HubNet (Wilensky & Stroup, 2000)	Student-student interaction can arise, but it is not inherent to the simulation since students are simply controlling a part of the simulation and not necessarily interacting with each other.
	C5: Mr. Vetro (Repenning, 2003)	Student-student interaction can arise, but it is not inherent to the simulation since students are simply controlling a part of the simulation and not necessarily interacting with each other. Also, since each student controls a specific part of the overall simulation, there is a danger for certain students to dominate the simulation activity.
	MUSHI (Lee et al., 2005; Vath et al., 2005)	Students can gather around a device (e.g., the tablet) in small groups (more than pairs) to look at and discuss the global level of the simulation. Students can work individually on inspecting and modifying captured pieces of the simulation, and then re-engage with other students as they all inject their changes back into the global system.

Table 3: Engendering Social Interaction

Section 5: Proposed Research

In this section, then, we lay out a three-year plan of research and development with the goal of producing:

- **Design Guidelines:** A set of interface design guidelines that are both theoretically-motivated and empirically-based that leads to the construction of a usable software simulation environment that supports children in learning about the underlying complex system.
- **Software Development Kit:** We feel strongly that our research effort needs to produce tangible tools that the community can use to further investigate the issues we explore. Thus, a deliverable from this effort needs to be a software development kit (SDK) that enables third-parties to develop MUSHI-based simulations that include the interface elements that promote usability and learning.

In order to produce these two deliverables:

- we first identify the research questions underlying their production,
- next, we lay out our R&D work plan, and then
- we close by describing our management plan and our dissemination plan.

5.1 Research Questions

In order to build MUSHI-based simulations, and ultimately in order to build a MUSHI Software Development Kit (SDK), there are two crucial themes that we need to explore: that of usability design, for which will follow a User-Centered Design (UCD) approach (Norman, 1986), and that of learning design, for which we will follow a Learner-Centered Design (LCD) approach (Quintana, Soloway, & Krajcik, 2003):

- **Usability Design: What kinds of visual, auditory, and textual feedback are necessary to help students comprehend and navigate a MUSHI-based simulation?** For example, we need to understand how to:
    - Help students make the connection between what they see on their handheld devices and what they see on the larger station display,
    - Help students map the simulation controls to device buttons and/or on-screen elements, and
    - Help attract students' attention to relevant simulation events (e.g., via multi-device imagery or auditory stimuli, or both) without disrupting an active workflow.

  Complementing the design activity expressed in this question, we have an assessment question:
- **Usability Assessment:** To what extent do students effectively use multiple devices and other interface elements in a MUSHI-based simulation?

But, creating a usable system is not enough: a child could manipulate parameters in the simulation and still not learn anything about the underlying complex system. The learning technology community's strategy (Quintana et al., 2004) is to provide scaffolds to help motivate, support, and direct learners in coming to understand the intended content. Thus, there is another research theme that needs to be explored:

- **Learning Design: What scaffolding strategies are needed to support students using MUSHI-based simulations?** For example, we need to better understand how to:
    - Coordinate scaffolds across multiple devices so as to make their interoperability seem seamless
    - Identify and codify task characteristics to better be able to match tasks to student abilities
    - Deliver social scaffolding so that students become engaged in conversing with one another
    - Properly fade the social scaffolding once students begin cooperating

Again, complementing the design activity expressed in that question, we have an assessment question:

- **Learning Assessment:** To what extent do MUSHI-based simulations help middle-school students develop a deep understanding of complex systems?

5.2 R&D Method

As we argued in Section 1, "alignment" is a key to making effective learning technologies.

- For example, in inventing potential scaffolding strategies we need to draw both on theoretical studies of how children learn and on classroom observations of children actually having difficulty in learning. As well, we need to understand what scaffolding strategies are best implemented in software, in a MUSHI-based simulation and what scaffolds are best left for a teacher or even a fellow student to provide. Still further, we have to understand what scaffolding strategies are specific to a particular area (e.g., MUSHI-Chemistry) and which strategies cross simulation lines, so to speak. And still further, we need to be sensitive to the actual curriculum being used in the classroom and the types of assessments that the children will be given: our MUSHI-based simulations take up class time and thus using a MUSHI-based simulation must prepare the children for the state (and local) standardized tests or we won't be allowed back into the classroom! In sum, then, we researchers need to take seriously the myriad of issues that impact student learning as we create our technology.

While there is a distinct cost to being sensitive to school issues and aligning one's efforts appropriately, the upside is that we will produce research and technology that has a better fit, from the outset, with real classrooms and thus it is easier to transition the fruits of the research into the classroom – and thus there is a greater likelihood of a broader impact of the research on real learning situations.

We will employ two types of empirical studies:

- **Focus Groups:** Here we will examine specific design features of a MUSHI-based simulation using 4-6 students over a short period of time.

- **Classroom Tests:** In middle school classrooms[4], where we will be able to test the software over an extended period of time, we will be able to conduct "in-situ" tests of our MUSHI-based software.

We have employed these types of studies in previous research and are familiar with the issues - – and pitfalls – involved in these methods.

Assessing the Effectiveness of Scaffolds
Of central importance is assessing the effectiveness of the scaffolds: we want to see how students use scaffolded MUSHI tools to perform their various science activities.

"Effects With" Assessment
We use an "effects with" (Salomon, Perkins, Globerson, 1991) assessment method (Quintana, 2001; Quintana, Krajcik et al., 2001) to consider how scaffolds effect the work of learners over time. Our specific "effects with" method involves assessing every instance when a learner uses different scaffold to do a task. We then summarize the different assessments to see how different learners used each scaffold and how a given learner's work patterns changed over time. Each scaffold assessment uses a specific set of previously formulated assessment criteria (Table 4) ~~we formulated previously~~ (Quintana, Fretz, Krajcik, & Soloway, 2000). The criteria consider both traditional usability issues and "task do-ability" issues to describe whether different scaffolds supported learners to work in a correct, mindful, increasingly expert-like manner—something traditional usability criteria do not address. We can formulate metrics describing how each criterion applies to each scaffold to explain each aspect of scaffold use and track how those aspects change over time (Quintana, Krajcik et al., 2002b).

"Effects With" Assessment Criteria	Description
Accessibility	Could students find a particular scaffold in the tool interface?
Use	Did students use an accessible scaffold?
Efficiency	Could students use a scaffold efficiently to complete the supported task?
Progression	Did students use a scaffold to do the supported task in a linear (i.e., novice-like) or more non-linear (i.e., expert-like) manner?
Accuracy	Did students perform a supported task correctly and appropriately using a scaffold?
Reflectiveness	Does the scaffold support learners in spending time to reflect on a supported task?

Table 4: "Effects with" Assessment Criteria

In terms of the proposed project, we are going to look at the effects with each of the scaffolding features that we develop for the different MUSHI simulations.

"Effects Of" Assessment
We also want to look at whether learners learned the material supported by the software and the extent of the learning or the size of the learning gains that may or may not have occurred. For "effects of" assessment, we can compare the growth in process and domain knowledge of individual learners. For example, a pre/post test approach looks at the learner's knowledge before and after using the software. Learners are given a pre-test about the work activities before using scaffolding software to measure their current knowledge. After using the software for some time period, learners would be given a post-test to measure their domain knowledge after the software use (or at different intervals throughout the software use).

[4] We will return to Ms. Monique Shorr's 6th grade classroom in Hartland, MI to carry out these classroom studies. We have worked with Ms. Shorr for 4 years now. A letter of support, signed by Ms. Shorr's principal, Keenan Simpson, is provided in the "supplementary materials."

Aside from looking at pre/post tests, we will also conduct artifact analysis at periodic intervals to see the quality of the artifacts that students create (e.g., generated hypotheses or concept maps) over time. Looking at the quality of the artifacts (scored by teachers as per the classroom metrics they would use for grading student work), we can see how well students are completing the overall tasks being supported by the scaffolded tools. This gives us another measure of the of the scaffolded tool's effectiveness. Additionally, we can correlate the "effects with" and "effects of" information to see how use of individual scaffolds (via "effects with" assessment) may have contributed to the overall learning seen in the "effects of" assessment.

YEAR ONE: ESTABLISH BASELINE	YEAR TWO: EXPAND SCAFFOLDING AND SYSTEM	YEAR THREE: DEVELOP SCAFFOLDING GUIDELINES & SDK
USABILITY AND LEARNING ACTIVITIES		
ACTIVITY: DESIGN		
• **UCD:** Design user interface ideas for MUSHI-Life simulation; produce usability guidelines.	• **UCD:** Modify user interface for MUSHI-Life and design user interface for MUSHI-Chemistry; modify usability guidelines.	• **UCD:** Modify user interface for MUSHI-Life and MUSHI-Chemistry as needed; design user interface for MUSHI-Weather; finalize usability guidelines.
• **LCD:** Design initial scaffolding features for MUSHI-Life simulation drawing on traditional software scaffolding approaches; produce scaffolding design guidelines.	• **LCD:** Modify existing scaffolding and design "synergistic scaffolding" for MUSHI-Life and design scaffolding features for MUSHI-Chemistry; modify scaffolding design guidelines.	• **LCD:** Modify scaffolding for MUSHI-Life and MUSHI-Chemistry as needed; design scaffolding for MUSHI-Weather; finalize scaffolding design guidelines.
ACTIVITY: ASSESS		
• Focus group testing of the MUSHI-Life simulation with small group (4-6) of students	• Classroom testing of the MUSHI-Life simulation in a single classroom. • Focus group testing of MUSHI-Chemistry simulation with a small (4-6) group of students	• Classroom testing of MUSHI-Life in multiple classrooms • Classroom testing of MUSHI-Chemistry in single classroom • Focus group testing of MUSHI-Weather simulation with a small (4-6) group of students
• **UCD:** Make initial usability assessment	• **UCD:** Continue usability assessment	• **UCD:** Continue usability assessment
• **LCD:** Conduct "effects with" and "effects of" scaffolding assessment, with special emphasis on multi-device scaffolds	• **LCD:** Conduct "effects with" and "effects of" scaffolding assessment, with special emphasis on the social scaffolds	• **LCD:** Conduct "effects with" and "effects of" scaffolding assessment, for both multi-device and social scaffolds
TECHNOLOGY ACTIVITIES		
• Alpha MUSHI SDK	• Beta MUSHI SDK	• MUSHI SDK
• MUSHI-Life v0.1 natural selection simulation	• MUSHI-Life v1.0 natural selection simulation	• MUSHI-Chemistry v1.0 chemistry simulation
	• MUSHI-Chemistry v0.1 chemistry simulation	• MUSHI-Weather v-0.1 weather simulation
		• Pass SDK to outside development group for development of new MUSHI simulations

Table 5: Three Year Work Plan

5.3 Work Plan

The table below outlines a plan for what we will do over the three year period. The activities, of course, are directly related to the research questions. For example, over the three year effort, we will continue to refine the interface guidelines, based on the above "usability" criteria in addressing the User-Centered Design (UCD) research question. To ground and inform our efforts, we will design and build three very different simulations over the course of three years: MUSHI-Life, the aforementioned natural selection and evolution simulation, MUSHI-Chemistry, a chemical reaction simulation, and MUSHI-Weather, a weather simulation. Because these content areas require different types of visual representations and scaffolding, we anticipate that we will be able to use them to triangulate the most essential features that need to be included in the final MUSHI SDK deliverable. While the schedule in Table 5 is ambitious, we feel we can carry out the activities effectively.

5.4 Management Plan

The responsibilities of the various team members are outlined below.

- **Elliot Soloway:** Project Director and responsible for overall project management. He will also focus on scaffold design, and software design and engineering in this project.
- **Christopher Quintana:** Co-PI and responsible for the empirical assessment of the MUSHI-based software. He will also contribute to the design of the scaffolding guidelines.
- **Joseph Chigwan Lee:** Joe is a PhD student in CSE, will co-design the MUSHI framework, and will be primarily responsible for the construction of the MUSHI-Life simulation.
- **Leilah Lyons:** Leilah is a PhD student in CSE, will co-design the MUSHI framework, and will be primarily responsible for MUSHI-Chemistry; she will also contribute to the empirical usability assessments.
- **Graduate Student from School of Education:** This student will be primarily responsible for the assessment of the MUSHI learning environment. This student will be assisted by both Lyons and Lee, and will be directed by Quintana.

5.5 Dissemination Plan

As we mentioned earlier, we feel that after spending upwards of $1,000,000 in a university lab, it is incumbent upon us to try to make our research efforts more broadly available in the United States. To that end, we will employ a range of dissemination strategies:

- **Research publications**: We will, of course, publish our findings in scholarly conferences and journals. The ACM CHI (Computer-Human Interaction) Conference and the International Conference for the Learning Sciences are two prominent venues, as are journals of these organizations.
- **Website**: We will create a website and make available, as soon as possible, demos of MUSHI-based simulations, and will also post our research publications (when appropriate) on the site.
- **Commercialization:** In the recent past, the University of Michigan has licensed software developed in HI-CE to a university spin-off, GoKnow, Inc.[5] GoKnow has been able to successfully market university-developed educational software – after significant rewriting, documenting, etc. We feel that MUSHI's Software Development Kit should be ready for a third-party to use in Year 3 of this effort and, if the economic terms are appropriate, GoKnow will likely license the MUSHI SDK and use it, at their expense, to produce MUSHI-based simulations.

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[5] Respecting full disclosure, the University of Michigan owns 10% of GoKnow, Inc. Elliot Soloway is a co-founder and Acting CEO of GoKnow, Inc.