Tracing the Development of a Haptically- enhanced Simulation for Teaching Phase Change

James Minogue
North Carolina State University
Raleigh, NC 27695, USA
James_minogue@ncsu.edu

Shengyen Tony Chen
North Carolina State University
Raleigh, NC 27695, USA
stchen@ncsu.edu

David Borland
RENCI, University of North Carolina at Chapel Hill
Chapel Hill, NC 27517, USA
borland@renci.org

Marc Russo
North Carolina State University
Raleigh, NC 27695, USA
merusso@ncsu.edu

Abstract
This paper traces the research-design-develop-test cycle of a haptically-enhanced science simulation designed to teach upper-elementary students core ideas about matter, phase change, and the role of intermolecular forces. We describe our focus group work, usability testing, and small-scale pilot testing. We also detail the technical work behind the creation of our simulation. Our project combines Unity® (a popular cross-platform game engine and integrated development environment) with the Novint Falcon® haptic force-feedback device to reach beyond typical teaching methods in today's classrooms. Most of the opportunities to learn during elementary school science take place at the visible concrete (macro) scale, side-stepping the underlying invisible (micro) scale mechanisms. We share our efforts to pinpoint the cognitive influence of haptic force-feedback and present a novel framework that assesses learners' agility moving between macroscale and microscale representations, along with their mechanistic thinking.

Author Keywords
Gaming Technology; Haptic Feedback; Science Education; Basic Chemistry

ACM Classification Keywords
H.5.2 [Information interfaces and presentation]: Haptic I/O; K.3.1 [Computers and Education]

Modified Children's Beliefs about Matter Interview protocol

1. Take a look at this sugar cube. What do you think it is made of?
2. Is it just one big piece of material or is it made of smaller parts/bits? How big are they? What shape are they? How are these pieces similar to the original sugar cube? How are these pieces different from the original piece of sugar? Do you want to draw them?
3. Take a look at this water. What do you think it is made of?
4. Is it just one big piece or is it made of smaller parts/bits? How big are they? What shape are they? How are these parts/bits similar to the cup of water? How are these parts different? Do you want to draw them?
5. Why do you think the sugar holds its shape but the water flows?
6. Tell me how ice is made.
7. What do you think this ice cube is made of? Why do you think the ice cube holds its shape but the water flows?
8. If you leave this ice cube on the table, it starts to melt. Why does it melt? What do you think might be happening to the parts/bits of water? Do you want to draw them?

Introduction

Current force-feedback haptic technology enables the augmentation of computer-generated images with a simulated sense of touch. Our work combats "reasoning thin" elementary science curricula by building and pilot testing a haptically-enhanced simulation for learning that provides "conceptual encounters" with the invisible aspects of phase change. In this paper we describe the theoretical and practical work that took place during our design-develop-test cycle. Work in progress (WIP) includes the validation and application of our domain-specific mechanistic thinking scoring schemes that we describe later in this paper.

Designing the Simulation

The design of our Intermolecular Forces (IMF) simulation was driven by our research into student thinking about the particulate nature of matter (PNM), phase change, and chemical bonding [4, 11, 7, 8, 9, 10, 15, 17], and in-depth focus group work with 9-11 year olds. Most research suggests that an appreciation for the PNM is foundational to understanding chemistry, but conceptual difficulties persist throughout all levels of education. One often cited reason for these difficulties is the abstract microscopic nature of the actors (atoms and molecules) and mechanisms. Studies looking directly at changes of state have shown that learners do not intuitively explain these changes in terms of particle interactions. Rather they may suggest that the particles are embedded in continuous stuff/matter or that the particles themselves melt [10]. In regard to chemical bonding, studies have shown that inter- and intramolecular forces and bonds are often confused and anthropomorphized [15]. The literature makes it clear that the content we targeted is complex and rife with conceptual difficulties.

The affordances of haptics may help bridge some of these conceptual gaps and lead to a more complete understanding of phase change and intermolecular forces. The full simulation enables students to move between macroscale and microscale representations of water in its solid, liquid, and gas phases and feel the differing intermolecular forces at play (e.g. in the solid phase the molecules feel 'stuck in place'). We provide more detail in the Pilot Testing section.

Student Focus Groups

During the first student focus group (N=12;9-10 year old) a researcher interviewed individual students using a modified *Children's Beliefs about Matter Interview protocol* (see sidebar) [7]. Results showed that none of the students exhibited a *macrocontinuous* view (i.e. materials cannot be broken down). Seventy-five percent (75%) had *macroparticulate* views (i.e. made of little pieces/parts) and 25% *microparticulate* (i.e. molecular view of matter). Several children knew the term "molecule" but attributions of this term varied greatly; evidence of understanding of the term was thin. The bulk offered *macroprocess* explanations of why ice melts. They recognized that temperature was a part of the process (the entity) but few offered any mechanism (activity) for the melting. Sample responses included: "*if water gets cold it freezes*" and "*if ice gets warm it melts*". Only 2 students (17%) gave any signals of *microprocess* thinking (i.e. a molecular view of the process). Recognition of any sort of molecular forces at work was non-existent [2, 8, 14, 16].

The second student focus group was conducted with nine 9-10 year olds. Here they interacted with various virtual objects that modeled different macroscopic physical properties (viscosity and hardness/compliance)

Student Focus Group

Figure 1. Our setup

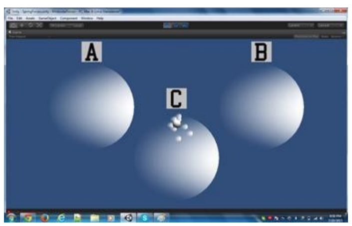

Figure 2. Liquid models with different viscosities.

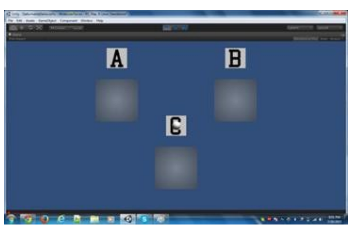

Figure 3. Solid objects differing in hardness.

and intermolecular forces between molecules at different temperatures. Students first used the haptic device to feel a series of virtual spheres simulating different viscosities. Students described what they thought they were feeling and matched the objects with corresponding real-world fluids (peanut butter, honey, and cooking oil). Students did the same thing with virtual blocks of different hardness. A key goal here was to see if the users could discriminate between the forces of varying magnitudes. Finally, users were asked to feel haptically-enhanced molecular models of water in three different phases and match them with the correct term (solid, liquid, and gas). Figures 1-3 show some of this work. Findings for these core interactions showed that most students had an easier time understanding what our macroscale solid models were trying to show them. Here 67% correctly matched the steel, 89% correctly identified the dough and rubber, and 75% correctly matched all 3 solid models with their real-world substances. Their work with the liquid models was not as accurate. Here only 33% correctly matched the peanut butter, 44% matched the honey, and 67% matched the oil. Only 33% correctly matched all 3 liquid models with their real-world targets. We suspect that these difficulties arose because the students have had less experience feeling viscosity in their everyday life. These outcomes suggested that our solid models were working well but pointed us to needed improvements for the haptically-enhanced models for viscosity. Engaging with our viscosity models seemed less intuitive to them. We were encouraged to find that most students (78%) were able to perceive force magnitudes and correctly identify the strongest and weakest force. This suggested that our models were working well on this key dimension. When students felt prototype simulations of our zoomed-in haptically-enhanced molecular models approximating the various phases of water, 56% correctly matched all three models with their phases. The remaining 44% got only the solid correct, confusing liquid and gas. Findings for this core interaction showed that our microscopic haptically-enhanced simulations were understandable to many of the users. All users understood the task and seemed able to make some of the translations from the invisible microscopic models to their visible macroscopic phase/state. This also suggested that students of this age do indeed have, or can quickly acquire, some concept of the particulate nature of matter (PNM) and may be well positioned to work with our full simulations.

Usability Testing

During the usability testing session (Figures 4-5) a new group of 9-10 year olds (N= 8) tried out a set of more refined/further developed haptic interactions for our IMF simulation. These included the modeling of three different hardnesses and viscosities at both the observable/macroscale and zoomed-in invisible microscale. The goal here was to see if the haptic feedback was perceivable and behaving as we designed it to do. Users were able to 'feel' the various macro/micro renderings of solids and liquids and were asked to describe what they thought they were feeling. We were also interested in users' agility moving between the two scales so we had them feel the models again and try to match the two different levels of representation.

Our findings suggested that users recognized that they were "feeling" hardness and they were readily able to sense the different hardnesses at the macroscale. The sensing of viscosity at the macroscale still proved more

Usability Testing

Figure 4. A student during usability testing.

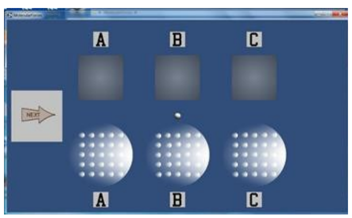

Figure 5. A screenshot of our prototype IMF simulation. Students were tasked with matching the macroscopic representation (top row) with the corresponding microscopic representation (bottom row)

difficult for the users. While several students suggested that they were feeling "thickness", differentiating among the objects on this dimension was more challenging. The zoomed-in molecular level models were less intuitive (as we anticipated). Students' responses here pointed to some confusion about what they were supposed to be feeling, which may stem from their lack of experience thinking about solids and liquids on a molecular level.

We were encouraged by the users' ability to make the translation between the two scales using our models. For the solids that varied by hardness, 62.5% were able to correctly match all three solid macroscale models with their microscopic analog. For the liquids of different viscosities, 50% were able to correctly match all three macroscale models with their corresponding microscopic model. In all but one case, if they got all of the solid blocks correct they also got all of the liquid spheres correct. The order that they progressed through the simulations did not impact their performance. This finding tells us that students do indeed have some agility in moving between the macro- and microscales. This is an important outcome, as our IMF simulation is being built to enable this movement between scales and it will attempt to leverage these multiple representations to improve their reasoning about phase change. This testing session also surfaced some technical issues including unwanted device vibration and excessive solid surface deformation.

Pilot Testing

Pilot testing of our IMF simulation involved a convenience sample of 50 new students (9-11 year olds). The final version of the simulation (shown in Figure 6) enabled students to use an electron microscope icon to move between macro- and microscale representations of different solids and liquids at the same temperature, and water at the solid, liquid, and gas phase, controlling the temperature using a slider At the macroscale haptic users could poke the block of ice to feel its hardness, feel the viscosity of the liquid water in a pot, and interact with water as a gas. At the microscale, haptic users could grab individual water molecules in the three phases and actually feel the differing intermolecular forces at play (e.g. in the solid phase the molecules feel 'stuck in place').

Students cycled through pre-assessments, simulation, and post-assessments individually. Participants were randomly assigned to a "haptic" or "no haptic" group, completed identical assessments, and used the same interface. For pilot testing we developed two novel paper-pencil assessment tasks (Figure 7). These were designed to detect the differential impact of haptic force feedback on students understanding of phase change (in particular the process of ice melting) and their ability to link observed physical properties to the underlying molecular make-up and intermolecular forces.

We have developed novel analytic frameworks (scoring schemes) to examine students' written products from the IMF testing. These frameworks look at students' movement between the two levels of representation, zeroes in on students' use of mechanistic thinking (or lack thereof) in their explanations [3, 6, 12, 13], and examines the relationship between the students' images and written explanations. Data analysis using these frameworks has just begun. Figure 8 shows the

Pilot Testing

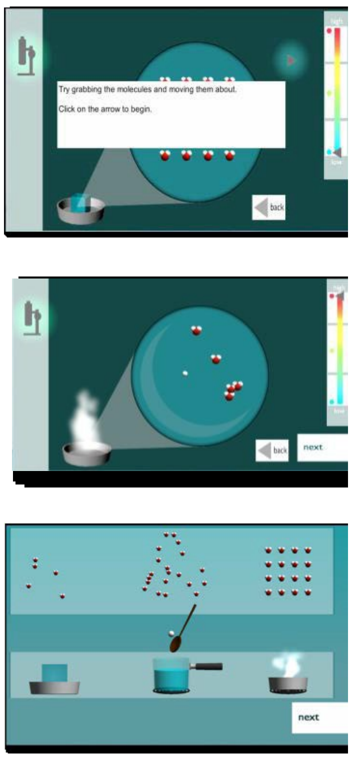

Figure 6. Representative screenshots of our IMF simulation used in pilot testing, with zoomed-in microscopic views (top, middle), and combined micro-and macroscopic views (bottom).

core of our analytic framework for our *Ice Melting* prompt.

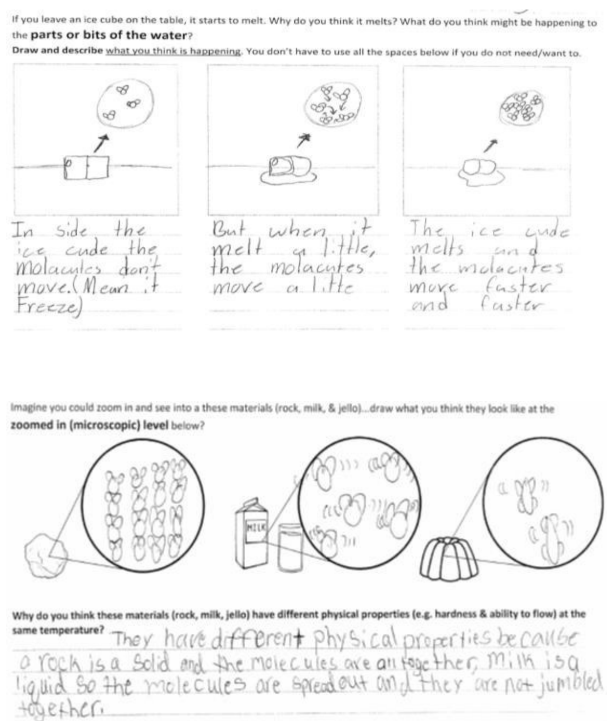

Figure 7. Images of our IMF simulation assessments. First the melting of ice and then the physical properties of different materials.

Explanation of Ice Melting
Macroprocess Explanation based on a perception of a macroprocess occurring, such as ‘water freezes and turns into ice’; phenomenon-based re-descriptions of the observed phenomenon
Macroprocess-heat Explanation based on a perception of a macroprocess involving heat, such as ‘ice melts when it gets warm’; a mechanism is suggested
Microprocess Explanation based on a molecular level process, such as ‘water molecules move apart’; no mechanism…considers only structural state
Microprocess-heat Explanation based on a molecular level process involving heat, such as ‘atoms spread out when you warm something’; a mechanism is suggested
Image-Text Relationship <u>Incompatible</u>: contradict each other; inconsistent <u>Compatible</u>: communicate the same idea or concept <u>Complementary</u>: work together to fill out or complete a narrative of the phenomena, mutually supplying each other’s lack

Figure 8. Our novel analytic framework for the *Ice Melting* task.

Technical Work

We have developed a Unity plugin for the Novint Falcon device that provides a high-level wrapper interface to Novint’s Haptic Device Abstraction Layer (HDAL) library, including various features to enable our simulations.

Microscopic forces. We have developed a piecewise linear approximation to an intermolecular force (IMF) curve based on a standard linear spring model. Multiple IMF effects can be added to simulate the attractive and repulsive forces between the haptic probe and multiple molecules in a scene. For each molecule the user specifies the position, spring rest length, point of maximum attractive force, spring strength, and a damping coefficient to reduce oscillatory motion.

Solid surfaces. We use the standard haptic approach of using spring forces to simulate surfaces [1, 5]. Unity's physics engine provides collision detection between the haptic probe and the objects in the scene. The collision surface contact point and normal generated by the physics engine are passed to our haptic plugin, along with spring and damping coefficients to determine the hardness of the surface. The contact point and normal define a plane used as a local approximation of the surface, enabling a much higher haptic update rate (typically 1000 Hz) than physics update rate (typically 50Hz), via a spring force applied perpendicular along the plane normal. In this manner adding haptics to feel the surfaces of complex scenes can be easily integrated by relying on Unity's existing physics engine for collision detection, while retaining the ability to feel stable forces. Surfaces are used to simulate macroscopic solids in our simulation.

Deformable surfaces. We have integrated haptics with the Impact Deformable plugin to visually represent the hardness or softness of surfaces. Our solution uses two probe objects, one that collides with and deforms the mesh, and another invisible probe which collides with an invisible non-deformable proxy of the mesh to generate forces as with a standard surface. Deformable objects are used to simulate macroscopic solids with different degrees of softness in our simulation.

Viscosity. We provide a standard viscosity effect when the haptic probe is inside designated objects in the scenario, used to simulate macroscopic fluids with different thicknesses, or viscosities, in our simulation.

Non-haptic mode. We provide a non-haptic mode for IMFs and viscosities that conveys the applied force visually. A configurable joint simulates a spring-like force connecting the haptic probe to a visible proxy object. Haptic force effects are calculated for the proxy object, making the user compensate by moving the haptic probe farther (producing a larger spring force) to counteract. The net force is thus conveyed visually to the user by producing a visible lag in moving the haptic probe and seeing the haptic proxy move. This approach is used to compare haptic and non-haptic conditions.

Significance

Our work impacts the disciplines of *science education*n and *human-computer interaction* (HCI), specifically targeting upper elementary students' learning about IMFs, phase changes, and mechanistic reasoning more generally. The analytic frameworks we have developed are significant because they are theoretically sound and easily adaptable by other researchers. From an HCI perspective, our Novint Falcon-Unity® plugin can be a tool for other developers in this area. We have also been building a set of *Design Guidelines for Haptically-enhanced Science Simulations*. This document has been fed by our design, development, and testing work. Such design guidelines include: target content areas that rely heavily on the concept of 'force' to explain the underlying mechanism of the observable phenomena; consider including explicit in-simulation prompts that direct users' attention to the haptic affordances; and minimize the amount overt in-simulation assessment including limiting the amount of typing required.

Acknowledgements

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