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Students' Learning with the Connected Chemistry (CC1) Curriculum: Navigating the Complexities of the Particulate World

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Abstract The focus of this study is students' learning with a Connected Chemistry unit, CC1 (denotes Connected Chemistry, chapter 1), a computer-based environment for learning the topics of gas laws and kinetic molecular theory in chemistry (Levy and Wilensky 2009). An investigation was conducted into high-school students' learning with Connected Chemistry, based on a conceptual framework that highlights several forms of access to understanding the system (submicro, macro, mathematical, experiential) and bidirectional transitions among these forms, anchored at the common and experienced level, the macro-level. Results show a strong effect size for embedded assessment and a medium effect size regarding pre-post-test questionnaires. Stronger effects are seen for understanding the submicroscopic level and bridging between it and the macroscopic level. More than half the students succeeded in constructing the equations describing the gas laws. Significant shifts were found in students' epistemologies of models: understanding models as representations rather than replicas of reality and as providing multiple perspectives. Students' learning is discussed with respect to the conceptual framework and the benefits of assessment of learning using a fine-tuned profile and further directions for research are proposed.

Keywords Chemistry education · Computer models · Agent-based models · Concept formation · Complex systems · Gas laws

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Introduction

Complex systems challenge our understanding, calling for reasoning at different levels of description and relating between these levels in *specific* and *causal* ways (Wilensky 2001; Wilensky and Resnick 1999). Chemical systems are a prime example of such systems and understanding them involves shifting focus between molecular interactions and experienced phenomena. In an associated paper in the current issue (Levy and Wilensky 2009) we present a conceptual framework underlying the design for learning about complex chemical systems and demonstrate it through the first chapter in the Connected Chemistry curriculum, which we abbreviate herein as CC1 (Levy et al. 2006). The main contributions of that paper are a theoretically motivated design for learning about complex chemical systems, and a corresponding fine-tuned assessment of students' learning in light of this same conceptual framework. This paper focuses on students' learning with CC1 through the lens of this conceptual framework. As we will show, students' understanding grows along several dimensions; however, it is more pronounced with regard to the submicroscopic particles' behaviors and interactions, and their relation to global phenomena, the very crux of reasoning about complex systems.

Encouraging students to distinguish between levels and relate between them, carefully observe individual actions and local interactions as well as global patterns is prominent in CC1. This is the first chapter of a model-based high-school chemistry curriculum targeting the topics of (macro) gas laws and (submicro) kinetic molecular theory (KMT). CC1 uses NetLogo agent-based computer models, models that compute a system's behavior and evolution from its components' properties, rules of action and interaction (Wilensky 1999a, 2001). These models are embedded in a Pedagogica script (Horwitz and Christie 1999) that provides several forms of guidance, assistance, and assessment, while logging students' actions and responses to questions. Over the previous decade, Wilensky and colleagues had developed several forms of the Connected Chemistry curriculum (Stieff and Wilensky 2003; Wilensky 1999b, 2003; Wilensky et al. 1999). The Modeling Across the Curriculum project (Gobert et al. 2003) that engages high-school students in learning science with computer models, provided an opportunity for a new form of the curriculum, CC1, that embeds the models in a scaffolding script.

The gas laws are macroscopic descriptions in symbolic-equation form, relating the volume of a container, the number of gas particles inside it and the gas' temperature to the pressure of the contained gas (e.g., Boyle's law relates pressure to volume when all else is kept constant). KMT is a submicroscopic theory that explains the forces between molecules and their kinetic energy in terms of the rules governing particles' behaviors, such as their random continual straight-line motion and the elastic nature of their collisions. Understanding and relating these two models requires reasoning about chemical systems along several dimensions: (1) gaining a conceptual understanding of the system by *focusing on* and *shifting between* the submicro- and macro-levels; (2) bridging between this conceptual understanding and the symbolic equation forms; and, (3) distinguishing and transitioning between physical experiences, such as opening a coke can or pumping up a bicycle tire, and their representations in both the gas law mathematical models and through the KMT-based conceptual model. Johnstone (1993) has succinctly laid out this intricate array of reasoning about chemical systems, naming it "thinking within the triangle". On one hand, he describes expert scientists as flexibly shifting between the submicro, macro and representational descriptions of the system at hand. On the other hand, he also describes the formidable challenge involved in supporting students in such learning and reasoning. The CC1 curriculum embraces this challenge of supporting students' construction of a runnable mental model of the system that connects with both its symbolic representation and with physical experience.

A conceptual framework (Fig. 1) was created to address supports for learning about chemical systems through model exploration and is elaborated and demonstrated in the accompanying paper (Levy and Wilensky 2009). The framework depicts three spheres of knowledge: *conceptual understanding* of how molecular interactions result in a system's global behavior in a variety of conditions and under various constraints, *symbolic-mathematical*

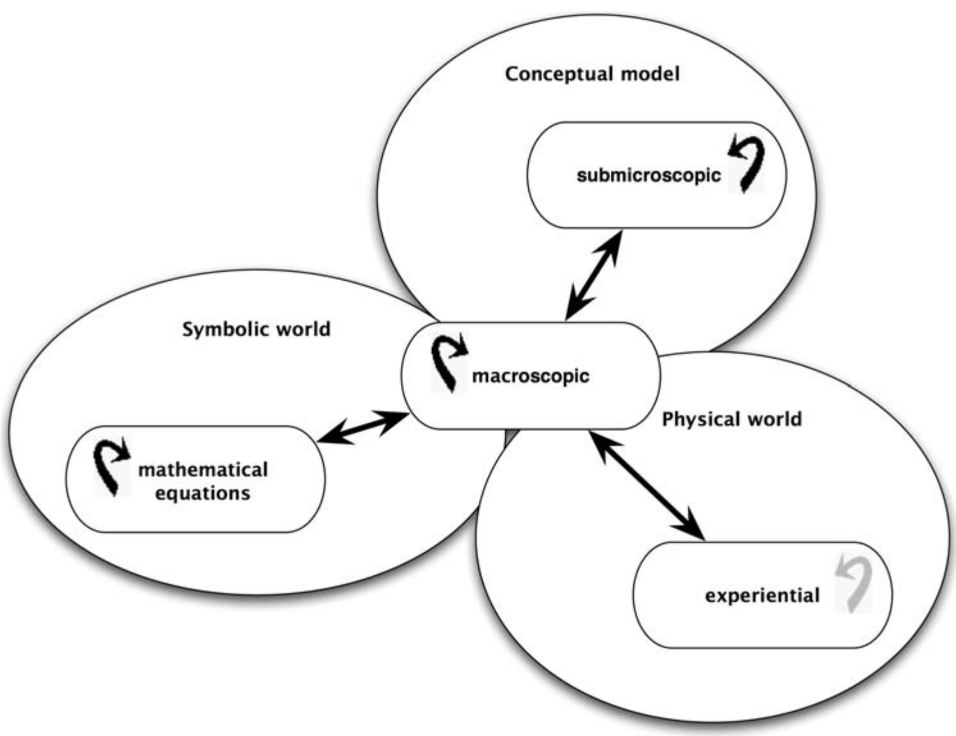

Fig. 1 Conceptual framework for supporting learning through model-exploration in the Connected Chemistry curriculum (CC1). *Larger circles* signify spheres of knowledge; *smaller ones* are forms of access to understanding the system; *arrows* signify the activities' learning goals—understanding each form of access in itself and bridging among them

expressions of the system's behavior and *physical experiences* of the explored phenomenon. Learning about the gas laws and KMT is typically conceptualized through four canonical forms of access: submicro, macro, mathematical[1] and experiential. The framework is *anchored at the experienced macroscopic level* that is common to the three spheres of knowledge. The CC1 activities employ the macro-level as a hub and encourage reasoning within each form of access (intra-level experiences), as well as bidirectional transitions among these forms (inter-level experiences). The framework can be illustrated by an example: consider how the pressure inside a container relates to changing its volume. This phenomenon can be experienced through action on everyday objects such as balls or bicycle tires. It can also be described in the form of Boyle's law, as an equation that connects these two macroscopic variables. Finally, a conceptual model can be described by using notions such as the motion of individual gas particles and their distinct collisions and how these relate to rates of collision, diffusion and pressure. The motivating hypothesis for the design of Connected Chemistry is that an educational setting that combines activities which foster an understanding of each form of access into describing the chemical system with activities that promote multiple bidirectional transitions along the three bridges anchored at the experienced macroscopic; constitutes a rich and fertile environment that supports a deep and integrated understanding of the chemical system at hand. The current study sets out to test students' learning through the lens of this framework.

This conceptual framework is part of a broader view we have developed that concerns multi-dimensional experiences with the submicroscopic world. The molecular level can be approached via all spheres of knowledge: by providing access to the symbolic representations related to molecular entities and enabling virtual experiences with these submicroscopic entities. Complementing the framework described in Fig. 1, which is anchored at the macro-level, such learning experiences would provide for a deeper and better connected understanding of the system.

Helping students learn about gas laws and KMT has attracted the efforts of chemistry educators and researchers from middle school to undergraduate courses. This attraction may result from the unique opportunity to combine and relate several forms of reasoning about a chemical system at an introductory level: a rule-based form in describing the gas particles, relatively simple equations at the macro-level, that can be related with real-world experiences. Moreover, the movement and interactions of a single gas particle is not too far removed from our daily experience with moving bodies, enabling easier conceptual access to the motions and interactions of invisible particles. It stands to reason that approaching a conceptual understanding that bridges between everyday experiences with inflated objects, such as basketballs, and a particulate model of bouncing submicroscopic particles is within reach. To this goal, several types of curricular interventions have been reported: supporting students as they develop the gas laws themselves (e.g., Bopegedera 2007; Laugier and Garai 2007), laboratories that help connect to the physical world, promote questioning and fine-tuning of the theoretical models (e.g., Ashkenazi 2008; Ivanov 2007) and the use of computer simulations to explore the system in a large variety of conditions (Lee et al. 2006; Liu 2006; Pallant and Tinker 2004; Sanger et al. 2000).

Among the reports that do elaborate on curricular interventions aimed at learning about gases, only few conducted comprehensive research into students' learning. When learning gains are described, they are portrayed as an aggregate score that does not discriminate between distinct ways of understanding such systems. Lee et al. (2006) manipulated the visual representations used in their computer models to change the cognitive load of the learning environment and tested for learning and transfer. It is difficult to tell what kind of learning was tested; however a sample item shows a focus on macro-level phenomena. Pallant and Tinker (2004) describe Molecular Workbench, a model-based curriculum focused on the topic of states of matter in middle school; in their interview samples they ask about both submicro- and macro-levels of description and transitions between them; however their analyses aggregate the results into a single global compound and the items themselves are not described. The current study portrays a more discriminating profile of students' learning, by breaking it down into its distinct forms of access and transitions among them. We propose that such a differential approach supports a more fine-tuned understanding of what students have learned and how different learning environments may support diverse kinds of learning.

Review of the Literature

A body of literature has been developed in the field of chemistry education addressing students' understanding and learning of chemical systems. Major findings include students' difficulties in relating submicroscopic molecular behaviors and macroscopic phenomena (e.g., Dori and Hameiri 2003; Treagust et al. 2003), the importance of using multiple (submicro-, macroscopic and symbolic) representations to further a deeper understanding of systems in chemistry (e.g., Gabel 1998; Dori and Hameiri 2003), that activities involving students' explorations of

[1] When we use the term mathematical here, we refer to aggregate mathematical descriptions such as equations or graphs.

manipulable computer models with multiple representations are related to greater learning gains (e.g., Ardac and Akaygun 2004; Kozma 2000; Snir et al. 2003) and the role of supports in this learning (e.g., Ardac and Sezen 2002; de Jong and van Joolingen 1998). For a detailed exposition of this literature please turn to the accompanying paper (Levy and Wilensky 2009). Building upon this extensive work, we expand to include mathematical modeling of the system's behavior, focused observations of individual particles, and partial access to the underlying mechanisms in conjunction with guided exploration of agent-based models. We now turn, in particular, to review the literature on students' understanding of the gaseous phase: from its particulate nature to the gas laws, topics explored by the students in the current study.

A corpus of research in science education points to students' difficulties in understanding the gaseous phase of matter. Some of these difficulties can be related to what Wilensky and Resnick call "levels confusion" (1999), where the properties of the macro-level are incorrectly ascribed to the submicro-level and has been reported in research of chemistry learning as well (Ben-Zvi et al. 1986; Nakhleh 1992; Nussbaum 1985; Treagust et al. 2003).

The literature reports a variety of alternative notions about gases such as ordered packing and weightlessness. Nussbaum (1985) summarizes his extensive research into students' understanding of gases that has found that while most high school students believe that a gas is composed of invisible particles, only 20% explain various phenomena based on accepted particulate ideas. At least a third use alternative ideas such as the gas particles expanding and contracting, getting hot and melting, and animistic notions of particles' behaviors. Lin and Cheng (2000) replicate these findings and add to these alternative concepts: molecules being pushed down by atmospheric pressure and staying away from heat. Mas and Perez (1987) report on views of gas as weightless; Stavy (1988) has even found that a significant portion of high school students regard gas particles as having a *negative* weight. Many of these concepts do make sense, when considering our macroscopic daily experiences, easy to sense and perceive: gravitation towards the earth, boiling water rising out of a pot and the expansion of substances upon heating; however, they point to students' misapprehension of the particulate nature of matter and their use of such everyday experiences to make sense of the submicroscopic level. Finally, students' explanations of phenomena such as diffusion do not incorporate the idea of random particle motion in a gas or liquid (Westbrook and Marek 1991; Novick and Nussbaum 1981) and they attribute gas particles with attractive and repulsive forces even when they are not close together (Novick and Nussbaum 1978).

Several researchers demonstrate how students may be capable of solving problems that involve using equations to predict the properties of gases under a variety of conditions; nevertheless their conceptual understanding lags far behind this "algorithmic" understanding (Niaz and Robinson 1992; Nakhleh 1992; Russell et al. 1997). However, even such "algorithmic" understandings may be limited when the problems do not fall into familiar and practiced problems. Students' understanding of the macroscopic principles of the gaseous phase, expressed in the gas laws is incomplete as well (Lin and Cheng 2000). Even after learning these topics in advanced placement classes, many students (and teachers!) did not make appropriate use of the gas laws to explain and predict the outcomes of various changes to gas-containing systems. As the authors describe: "The subjects tended to blindly choose a gas law equation if it had the variable they wanted, and make odd rearrangements of it in order to match the statement of the problem." (there, pp. 237).

The literature clearly shows that students have significant difficulties in understanding the gaseous phase in terms of both its molecular properties and interactions and its global behaviors. Our response to the reported difficulties is to design instruction that employs a complexity approach, explicitly distinguishing a system's levels of description and bridging between them. We have seen that students' understandings of symbolic and conceptual representations of such systems are not connected. This has led us to focus on helping students understand and bridge between such representations of chemical systems. In the paired paper (Levy and Wilensky 2009), we have reviewed how computer models have been used to advance such learning and presented the complexity view that backgrounds our approach of learning about systems, and more specifically—chemical systems. These conclusions have been important in our construction of a comprehensive conceptual framework to support and assess students' integrated understanding of chemical systems.

Focus of the Study

This study explores students' learning with the Connected Chemistry (CC1) curriculum. It is part of a broader investigation into various aspects of the students' processes of learning and includes their patterns of action/observation and inquiry strategies when exploring computer models (Levy and Wilensky 2006a) as well as a more detailed exploration of how understanding evolves through interacting with the curriculum (Levy and Wilensky 2006b). The present study targets students' learning with respect to three forms of access and three bridges in the described conceptual framework (Fig. 1):

What learning is evident among students who are engaged with the Connected Chemistry (CC1) curriculum within the submicroscopic, macroscopic and symbolic forms of access; and across submicro/macro, conceptual/math models, and models/physical world bridges?

Method

Participants

The sample included 904 students who had taken both the pre-test and the post-test. It includes 48.9% male students and 51.1% female students; 13% in 9th grade, 22% in 10th grade, 61% in 11th grade; 4% in 12th grade. The students learned with the curriculum as part of their chemistry course, 41.3% in a regular class, 30.4% in an honors class, 17.2% in a pre-AP class, 7.6% in a college-level class and 3.5% were unspecified. These students come from 12 diverse high schools across the United States who participated in the Modeling Across the Curriculum project (Gobert et al. 2003). In the sections presenting students' learning *during* the activities, the sample is reduced to sizes ranging from 250 to 746 due to technical difficulties in data collection and extraction.

Procedure

The students engaged with CC1 as part of their high school chemistry course during the 2004–2006 years, replacing the topic of gas laws and KMT in their normal curriculum. They participated in the seven activities usually on consecutive school days in the computer laboratory. Before and after the activities, spaced about 2–3 weeks apart, the students filled out two identical questionnaires, targeting their (1) content knowledge; (2) understanding of models in science. The students' interactions with the computerized environment, answers to open and closed questions and manipulations of the models were logged through the Pedagogica environment (Horwitz and Christie 1999), saved on a server and made available to the researchers.

Instruments

The questionnaires and the activity items are described. The conceptual framework (Fig. 1) was used to design the CC1 activities. The several forms by which the design relates to the conceptual framework are outlined, detailed and demonstrated in the accompanying paper (Levy and Wilensky 2009). As we will describe, the assessment items were aligned with the designed curriculum, thus reflecting the conceptual framework.

A pre- and post-test *content knowledge questionnaire* assesses students' understanding of the gas laws and KMT. It is related to two of the three spheres of knowledge in the conceptual framework: the conceptual model and the mathematical model, as well as the links and bridges between the different forms of representation. A pre- and post-test *epistemologies of models questionnaire* was used to test for the bridge relating the models (both conceptual and mathematical) to the physical world. *Embedded content knowledge assessment* items in the activities were used to address most of the same forms of access and bridges as those assessed by the content knowledge questionnaire (apart from their understanding of the mathematical model). Students' *construction of the gas law equations within the activities* was analyzed as reflecting their understanding of the mathematical model. These instruments are detailed below.

The *content knowledge questionnaire* (see Appendix A in Supplementary material) includes 19 multiple-choice items assessing the main concepts and some of the skills targeted by the curriculum. In the process of designing the questionnaire, a two-dimensional analysis of all the questions addressed to the students in the activities was conducted. One dimension describes the main content addressed in the curriculum: KMT as the submicroscopic component of the conceptual model; gas laws in qualitative form as the macroscopic component of conceptual model; gas laws as equations stand for the symbolic world in the form of a mathematical model; submicro/macro transitions reflect this bridge within the conceptual model; conceptual/symbolic transitions express the bridge between the conceptual model and the mathematical model. Appendix B (see Supplementary material) describes the correspondence between the components of the conceptual framework and the items in the questionnaire. A second dimension involves Shavelson et al. (2002) (Ayala et al. 2002) categories of knowledge: declarative, procedural, schematic and strategic. Each question and task in the curriculum was coded for these two dimensions. The proportion of each type of questions in the two-dimensional array was calculated. The same proportions were used to plan the questionnaire. This is true for all but one category: the procedural form of knowledge. We have included a smaller proportion of this category, as direct analysis of this knowledge in the activities is possible via logging, and in the interest of brevity. Some of the items were selected from research studies that targeted specific misconceptions in the field. Items 1–2 are an adaptation of an item developed by Noh and Scharmann (1997) targeting students' conceptual model of gas particles. Items 13–17 regarding Boyle's law was previously developed and researched by Bowen and Bunce (1997). The other items were invented "in-house" to address the activities' topics and specific confusions we had detected among students in our previous design-based research of the activities. In the process of writing the questionnaire, the draft underwent several reviews by the team at the Center for Connected Learning and Computer-based Modeling, as well as researchers at the Concord Consortium. It was revised twice in accord with the development of new activities and lessons learned from analysis of the previous versions.

Students' understanding of models and how these relate to the physical world were evaluated with the *epistemologies of models questionnaire*, an instrument developed by Treagust et al. (2002) named the students' understanding of models in science survey (SUMS). It contains 27 statements about scientific models and students are asked to indicate their agreement with these statements using Likert scales. In Treagust et al.'s research using this instrument, the authors administered the survey to 228 students in grades year's 8, 9 and 10 from two schools in Australia. Analyses of the data collected revealed a five-factor solution that represented measures of five constructs. These are: (1) models as multiple representations (MR), (2) models as exact replicas (ER), (3) models as explanatory tools (ET), (4) uses of scientific models (USM), and (5) the changing nature of models (CNM).

During the activities, several questions were posed framing the activity, promoting learning and then assessing it. The latter 24 *embedded content knowledge assessment* items describe students' learning within the context of the activities while the computer models are available for exploration. These assessment items were coded with respect to the conceptual framework as addressing its different components: the submicro and macro forms of access and the submicro/macro and conceptual/mathematical models bridges. In Appendix C (see Supplementary material), the items and their coding are described: the first column describes the framework component, the second column the activity in which the item is embedded, and the third column is the item itself.

Students' understanding of the symbolic representations was assessed through their *construction of the gas law equations within the activities*. During the activities, the students constructed three mathematical representations of the gas laws by exploring the models, collecting and analyzing data. They selected a functional form describing the relationship and typed out an equation to describe it (see Fig. 11 in Levy and Wilensky 2009 and the accompanying description). The students' selection of the functional form of the relationships (linear, reciprocal or quadratic) and their constructed equations served to assess their understanding of the related mathematical model.

All questionnaires and activities were scripted and the students' answers were made available for analysis.

Data Analysis

Data analysis focused on the content knowledge and model epistemologies pre- and post-test questionnaires and on the embedded assessment items. Both the content knowledge questionnaire and the embedded content knowledge assessment items' responses were coded as correct or incorrect. A total score was averaged, omitting students who did not complete at least two-thirds of the items. A mean score of the sub-scales corresponding to the components of the conceptual framework was calculated for each student. Paired *t*-tests and Cohen's effect size (Cohen 1988) were used to compare the pre-test results with those of the post-test and those of the embedded assessment.

The models epistemologies questionnaire was recoded on a scale of 1 (disagree) to 3 (agree). For each sub-scale, a mean rank was calculated for every student. The mean of students' scores across the individual items that comprised each sub-scale was calculated and used to represent students' score on each measurement sub-scale. Paired *t*-tests and Cohen's effect size were used to assess the significance and the magnitude of the effects.

The students' constructions of the symbolic relations for the gas laws in functional form and as equations were coded as correct or incorrect. Regarding the ideal gas law that involves four variables, an equation was considered correct if it included at least three of the four variables in the appropriate mathematical relation. To understand the complexity of the mathematical representations the students could construct, the number of variables included in their equations, regardless of their correctness was coded.

Findings

Students' learning gain profiles are presented through results from the two pre- and post-test questionnaires and the embedded assessment, with relation to the conceptual framework that distinguishes submicro-, macro- and mathematical representations and highlights bridges among them.

Content Knowledge Questionnaire (Submicro, Macro, Mathematical, Submicro/Macro, Conceptual/Mathematical Models)

The students' growth in understanding was assessed with identical pre- and post-tests spaced 2–3 weeks apart (Table 1). The test score is the proportion of questions in the test answered correctly. From pre-test to post-test, the students' score rose from 56 to 66% with a medium effect size. When broken down by components, we can see significant improvement for all. However, different

Table 1 Descriptive and comparative statistics of students' content knowledge in the Connected Chemistry curriculum (CC1) with respect to the conceptual framework

Conceptual framework component (# of items in questionnaire)	Test		Paired t	Effect size
	Pre M (SD)	Post M (SD)		Cohen's d (95% CI)
All (19)	56 (17)	66 (19)	−17.61**	0.55 (0.46–0.65)
Form of access				
Submicro (3)	45 (28)	60 (31)	−13.14**	0.51 (0.41–0.60)
Macro (3)	76 (29)	82 (27)	−6.01**	0.21 (0.12–0.31)
Mathematical (1)	42 (49)	58 (49)	−8.21**	0.33 (0.23–0.42)
Bridge				
Submicro/Macro (8)	56 (21)	65 (22)	−11.72**	0.42 (0.33–0.51)
Conceptual/Mathematical models (4)	56 (28)	62 (29)	−6.83**	0.21 (0.12–0.21)

Scores are mean percentages of correct answers on pre-test and post-test questionnaire. $N = 904$

** $p < 0.01$

components elicited stronger and weaker effect sizes. Among forms of access, greater improvement was seen in the students' understanding of the submicroscopic level; among the bridges, greater improvement was observed for the submicro-macro transitions.

Embedded Assessment of Content Knowledge (Submicro, Macro, Submicro/Macro, Conceptual/Mathematical Models)

During the activities, several questions were posed framing the activity, promoting learning and then assessing it. The latter assessment items describe learning in situ and offer an observation of how students' post-test questionnaire responses compare with those that are contextualized in the activities with the models available for exploration (Table 2). The results show the students' greater success along all dimensions when the questions are embedded in the activities rather than dis-embedded in the subsequent post-test questionnaire. A strong effect size (Cohen's $d = 1.09$, 95% CI 0.99–1.19) paints a positive picture regarding the students' learning with CC1. Stronger effects are seen for the submicroscopic level and the submicroscopic-to-macroscopic bridge. However, a ceiling effect may be responsible for the less than strong effect size regarding the macroscopic level.

Table 2 Comparison of students' content knowledge between embedded assessment and the pre/post-test questionnaires assessment with respect to the conceptual framework

Conceptual framework dimension	n	Assessment		Pre-test/embedded	Effect size
		Embedded M (SD)	Post-test M (SD)	Paired t-test t	Cohen's d (95% CI)
All	746	77 (2)	66 (19)	25.34**	1.09 (0.99–1.19)
Form of access					
Submicro	250	90 (30)	60 (31)	20.47**	1.76 (1.56–1.95)
Macro	609	91 (20)	82 (27)	10.69**	0.57 (0.46–0.68)
Mathematical	–	–[a]	58 (49)	–	
Bridge					
Submicro/Macro	821	78 (30)	65 (22)	20.63**	0.97 (0.86–1.07)
Conceptual/Mathematical models	540	71 (34)	62 (29)	12.40**	0.63 (0.51–0.75)

Scores are mean percentages of correct answers on the post-test questionnaire and on the embedded assessment items in the activities. $N = 904$ for the post-test questionnaire. n's are variable across items in the embedded assessment

[a] Understanding the symbolic representations separate from the conceptual model is assessed separately in the section describing the students' construction of the equations describing the gas laws. It cannot be compared with the post-test as the latter did not include similar items

** $p < 0.001$

Epistemologies of Models Questionnaire (Models/Physical World Bridge)

Students' epistemologies of models were assessed with the SUMS instrument; pre-test and post-test results are presented and compared (Table 3). Several significant changes are seen in how models are perceived. Students' appreciation that models can provide a variety of perspectives (MR) increased from pre-test to post-test, their predilection to view models as exact replicas of reality (ER) decreased, and their understanding that models serve to provide explanations (ET) decreased. Results regarding students views of how models are used in science (USM) and their understanding the changing nature of models (CNM) show no significant changes from pre-test to post-test.

Construction of the Gas Law Equations (Mathematical Model)

During the activities, the students constructed mathematical representations by exploring the models, collecting and analyzing data. Based on a scatter-plot of their data, they selected the canonical functional form of the relationship. They then proceeded to type out an equation they considered appropriate to describe this relationship. The results show that they were more successful in selecting a canonical functional form than in writing out an equation (Table 4). They were more successful with the linear pressure–temperature relationship than with the inverse pressure–volume or the complex ideal gas law. However, it is important to note that half the students succeeded in constructing the equations. The mean number of variables the students included in their ideal gas law equations, regardless of whether they were correct, is between three and four, $M = 3.39$ (SD = 0.86).

Table 4 Students' construction of the gas laws during the Connected Chemistry (CC1) activities

Gas law[a]	Symbolic form	
	Canonical function	Equation
$P = kN$	73	–[b]
$P = kT$	83	69
$P = k/V$	78	52
$PV = kNT$	–[c]	50[d]

Scores are percentage of students that constructed correct equations. $n = 206$

[a] The symbol P represents pressure, N is the number of particles, T is temperature, V is volume and k is a constant

[b] In the first activity, constructing an equation was demonstrated

[c] This question was not asked

[d] A correct equation was considered as one that had at least three variables, and all the dependencies are correct

Discussion

Our goal in creating the CC1 unit of the Connected Chemistry curriculum was to help students form an integrated understanding of a complex chemical system: a collection of gas particles interacting among themselves and with their local environment forming global system-wide patterns. As described more extensively in the introduction, teaching this topic has been fraught with difficulties (e.g., Nussbaum 1985; Lin and Cheng 2000). We turn to discuss the extent to which CC1 measures up to its own goals. The main contributions of this work is are a theoretically motivated design for learning about complex chemical systems, and a corresponding fine-tuned assessment of students' learning in light of this same conceptual framework.

Table 3 Descriptive and comparative statistics of students' epistemology of models in the Connected Chemistry curriculum (CC1)

SUMS sub-scale	Test		Paired t	Effect size
	Pre M (SD)	Post M (SD)		Cohen's d (95% CI)
Models as multiple representations (MR)	2.63 (0.360)	2.70 (0.407)	−3.090*	0.18 (0.03–0.34)
Models as exact replicas (ER)	2.68 (0.307)	2.60 (0.400)	3.592**	0.22 (0.07–0.38)[a]
Models as explanatory tools (ET)	2.62 (0.360)	2.53 (0.426)	3.685**	−0.23 (−0.38 to −0.07)
Uses of scientific models (USM)	2.75 (0.445)	2.74 (0.440)	0.370	−0.02 (−0.18–0.13)
Changing nature of models (CNM)	2.65 (0.448)	2.68 (0.469)	−1.231	0.07 (−0.09–0.22)

Scores are mean ranks on pre-test and post-test questionnaire. Ranks range 1–3, 1 disagree, 3 agree. $N = 321$

[a] The effect size was inverted as this sub-scale, different from the others, describes more mature model epistemologies as relating to smaller values on the Likert scale

* $p < 0.05$

** $p < 0.01$

A conceptual framework was developed to structure our view of how to design chemistry learning experiences for students. The framework describes three spheres of understanding: a conceptual model, the symbolic world and the physical world. Activities were designed to foster students' understanding within each sphere separately and in juxtaposition, aiming to promote an integrated view of the system. The macro-level descriptions were used to bridge between the three spheres and support these shifts.

We have studied students' learning with CC1 using this conceptual framework to discriminate between these different components of understanding the system. While some aspects have shown considerable learning gains, others have been less successful. As described in the introduction we have found no previous research into students' learning of the topic of gas laws and KMT using this more fine-tuned approach. Such a profile of learning supports a more balanced view of the particular advantages offered by the learning environment, realizing its strengths as well as parts that need further development or pairing up with complementary materials. Moreover, such discriminating assessment tools can be used to compare several learning environments and map out the specific benefits of each to advance students' integrated views of chemical systems.

Before discussing the conclusions from this investigation, we state some qualifications based on limitations of the investigation. Studying students' long term learning would have benefited from additional testing after a larger time interval. Moreover, comparison with a control group studying the same content with a more traditional curriculum would afford testing for the unique advantages and disadvantages of CC1. A control group would have been desirable to assess the relative merits of the standard curriculum and CC1: the constraints posed by the NSF-funded project, within which CC1 was only a small part, did not enable us to use controls. Finally, the chemistry learning questionnaire included several items created by the authors and reviewed internally, but was not vetted with a population similar to that studied.

We turn to discuss some of the main results.

Among the conceptual framework's components, stronger effect sizes were found regarding students' understanding of the submicroscopic level and its bridging to the macroscopic level. Through engaging with CC1, students gained a deeper understanding of the particulate world. Weaker effects were found with respect to students' reasoning about the system at the macro-level; however, this results from a ceiling effect, as the post-test results were close to the possible maximum. The CC1 design included several experiences that focused on particles, encouraging careful observation of their behaviors and interactions, selecting their rules of interaction and programming some of their behaviors. Some of these activities may seem irrelevant to learning goals associated with the topic. For example, students are asked to articulate a single particle's history of motion, speed and collisions using several visual and mathematical representations. The strong effects regarding students' comprehension of the particulate level support the claim regarding this unique aspect of the curriculum. Moreover, we have also seen an increase in the students' ability to relate the submicro- and macro-levels of the system. This supports our claim that activities that involve specifying the particles' behaviors against the backdrop of the macro-level phenomenon help students form the connections between these two levels of description. Furthermore, based on our previous work on students' spontaneous strategies of constructing "mid-levels" in reasoning about complex systems (Levy and Wilensky 2008), CC1 introduces models with a small number of particles through which one can capture some of the patterns that emerge more clearly at the macro-level. These types of activities support creating a more nuanced understanding of how the two description levels connect.

With regards to the mathematical model describing the gas laws, between half and two-thirds (depending on the particular equation) of the students successfully constructed the gas laws, most engaging with the complex task of constructing the four-variable ideal gas law. However, solving problems with equations and relating between the mathematical model and the conceptual model in the post-test did not show strong effects. With respect to problem solving with equations and relating these to the conceptual model, undoubtedly, CC1 with its focus on model-based explorations invests more effort in advancing the associated conceptual understanding. We have suggested that the curriculum should not replace the practice of quantitative problems (Levy and Wilensky 2009), and the teachers' guide explicitly encourages further activities on the topic. Nevertheless, we are encouraged by the results showing that many of the students succeeded at constructing the symbolic-equation forms of the gas laws themselves. This is an uncommon experience in normal science learning that has been encouraged but not researched by innovative researchers working at the undergraduate level (Bopegedera 2007; Laugier and Garai 2007). Having demonstrated high-school students' abilities to construct, not only two-variable relationships, but also the four-variable ideal gas law with the supports in CC1, opens up an arena for further research that builds upon students' mathematical understandings to further their understanding of additional scientific phenomena. While the seven activities in CC1, not surprisingly, did not advance students' practice of solving problems with equations, we do believe that forming a deeper understanding of such symbolic representations may *later* serve to further integration of students' grasp of the domain. This is particularly true when such activities are in juxtaposition with those promoting greater conceptual understanding, thus addressing the frequent disjunct between "algorithmic" and conceptual understandings (Nakhleh 1992; Niaz and Robinson 1992; Russell et al. 1997).

Significant shifts were found in students' epistemologies of models. They grew to appreciate the representational nature of models, understanding that models do not need to exactly replicate the represented phenomenon and that different models can describe a single phenomenon. Wilensky's previous work on learning chemistry and physics with agent-based models (Wilensky 1999b, 2003) engaged students in constructing models, a powerful form of learning leading to deep understandings of the domain. Gilbert and Boulter (1998) have cautioned that using models in an exploratory rather than a construction mode may obfuscate students' understanding of the idealized and partial character of a model's representation of reality. In constructing computational models, students become part of a design process that includes selecting parts and properties from the phenomenon under study and deciding on rules of interaction. In CC1, students explore prepared models. However, several types of activities were designed to highlight the artificial and partial nature of these representations, such as gradually adding in parts and rules to the basic model and using simple NetLogo commands to access the symbolic representation of the submicro-level and change its visual representations. We are gratified to see that even though the students did not create the models, their understanding of the scope and limitations of models has increased. Further results strengthening these conclusions as to students' understanding of models in science and how models relate to the physical world are analyzed more discriminately with respect to the number of activities students completed, and compared with the other curricula developed in the MAC project will be reported in a forthcoming paper (Gobert et al. under review).

This version of Connected Chemistry did not engage with physical world experiences, such as laboratory investigations. Such experiences would provide a central activity in deepening student's experiential learning and are an important component in the conceptual framework. This design was a compromise necessitated by the larger project's definition. Connected Chemistry is an evolving curriculum and has been implemented in several different forms. In earlier and later versions of the curriculum, laboratories play an essential role. In a study that included testing the separate and combined effects of learning with simulations and through laboratory work, it was found that incorporating the two contributed to learning more than each separate type of activity (Liu 2006). Future research could test whether this is true for CC1 as well.

Finally, we have found a strong effect size regarding students' learning in situ, and a medium effect size for learning assessed with the post-test content knowledge questionnaire. Embedded assessment is related to "learning effects *with* technology" (Salomon et al. 1991), those occurring while people work in partnership with the technology, in our case, exploring models. They describe learning effects *of* technology as lasting changes in understanding, subsequent to interaction with technology, when the student is away from the computer; in our case, the post-test questionnaire is removed from the activity but does not test for lasting effects, as it took place shortly after the short intervention we had created. As expected, the impact of the curriculum is stronger when the students are in partnership with the computer models, as these extend their reasoning and even help project to new situations. It is important to note the duration of the students' participation in the activities—seven lessons. We assume, a proposition worthy of further research, that more extensive curricula across different domains would help students transition to an "emergent" stance in reasoning about systems with greater and possibly generalizable and lasting effects.

We have seen students' understanding grow along several dimensions, more pronounced with regard to the submicroscopic particles' behaviors and interactions, and their relation to global phenomena, the very crux of reasoning about complex systems. We have also seen growth in their understanding of scientific models and in their ability to construct mathematical representations through model exploration. Learning from the relative strengths and weaknesses this study has elucidated regarding CC1, the conceptual framework we have created may be adapted to the learning of other complex systems that incorporate physical experiences, mathematical models and complexity-based conceptual models. Further research would test the generality and applicability of this approach.

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References

Ardac D, Akaygun S (2004) Effectiveness of multimedia-based instruction that emphasizes molecular representations on students' understanding of chemical change. J Res Sci Teach 41:317–337. doi:10.1002/tea.20005

Ardac D, Sezen AH (2002) Effectiveness of computer-based chemistry instruction in enhancing the learning of content and variable control under guided versus unguided conditions. J Sci Educ Technol 11(1):39–48. doi:10.1023/A:1013995314094

Ashkenazi G (2008) Similarity and difference in the behavior of gases: an interactive demonstration. J Chem Educ 85(1):72–77

Ayala CC, Shavelson RJ, Yin Y (2002) Reasoning dimensions underlying science achievement: the case of performance assessment. Educ Assess 8(2):101–121. doi:10.1207/S15326977EA0802_02

Ben-Zvi R, Eylon B-S, Silberstein J (1986) Is an atom of copper malleable? J Chem Educ 63:64–66

Bopegedera AMRP (2007) An inquiry-based chemistry laboratory promoting student discovery of gas laws. J Chem Educ 84(3):465–468

Bowen CW, Bunce DM (1997) Testing for conceptual understanding in general chemistry. Chem Educ 2(2):1–17. doi:10.1007/s00897970118a

Cohen J (1988) Statistical power analysis for the behavioral sciences, 2nd edn. Lawrence Erlbaum, New Jersey

de Jong T, van Joolingen WR (1998) Scientific discovery learning with computer simulations of conceptual domains. Rev Educ Res 63:179–201

Dori YJ, Hameiri M (2003) Multidimensional analysis system for quantitative chemistry problems: symbol, macro, micro, and process aspects. J Res Sci Teach 40(3):278–302. doi:10.1002/tea.10077

Gabel D (1998) The complexity of chemistry and its implications for teaching. In: Fraser BJ, Tobin KG (eds) International handbook of science education. Kluwer, Great Britain, pp 233–247

Gilbert JK, Boulter CJ (1998) Learning science through models and modeling. In: Fraser BJ, Tobin KG (eds) International handbook of science education. Kluwer Academic Publishers, Great Britain, pp 53–66

Gobert J, Horwitz P, Tinker B, Buckley B, Wilensky U, Levy ST, Dede C (2003) Modeling across the curriculum: scaling up modeling using technology. Paper presented at the 25th Annual Meeting of the Cognitive Science Society, CogSci 2003, Boston, Massachusetts, USA, July 31–August 2, 2003

Gobert J, O'Dwyer L, Horwitz P, Buckley B, Wilensky U, Levy ST Examining the relationship between students' epistemologies of models and conceptual learning in three science domains: Biology, Physics, & Chemistry (Easton) (under review)

Horwitz P, Christie M (1999) Hypermodels: embedding curriculum and assessment in computer-based manipulatives. J Educ 181:1–23

Ivanov DT (2007) Experimental verification of Boyle's law and the ideal gas law. Phys Educ 42(2):193–197. doi:10.1088/0031-9120/42/2/011

Johnstone AH (1993) The development of chemistry teaching: a changing response to changing demand. J Chem Educ 70:701–705

Kozma RB (2000) The use of multiple representations and the social construction of understanding in chemistry. In: Jacobson MJ, Kozma RB (eds) Innovations in science and mathematics education: advanced designs for technologies of learning. Lawrence Erlbaum, New Jersey, London, pp 11–46

Laugier A, Garai J (2007) Derivation of the ideal gas law. J Chem Educ 84(11):1832

Lee HL, Plass JL, Homer BD (2006) Optimizing cognitive load for learning from computer-based science simulations. J Educ Psychol 98(4):902–913. doi:10.1037/0022-0663.98.4.902

Levy ST, Wilensky U (2006a) Gas laws and beyond: strategies in exploring models of the dynamics of change in the gaseous state. In: Buckley B (Organizer), Gobert J (Presider), Kraicik J (Discussant), "supporting science learning and science education reform with information technologies". Paper presented at the National Association for Research in Science Teaching, San Francisco

Levy ST, Wilensky U (2006b) Emerging knowledge through an emergent perspective: high-school students' inquiry, exploration and learning in connected chemistry. Paper presented at the annual meeting of the American Educational Research Association, San-Francisco, 7–11 April 2006

Levy ST, Wilensky U (2008) Inventing a "Mid-level" to make ends meet: reasoning between the levels of complexity. Cogn Instr 26(1):1–47

Levy ST, Wilensky U (2009) Crossing levels and representations: the connected chemistry (CC1) curriculum. J Sci Educ Technol

Levy ST, Novak M, Wilensky U (2006) Connected chemistry curriculum, CC1. Evanston, IL. Center for Connected Learning and Computer Based Modeling, Northwestern University. http://ccl.northwestern.edu/curriculum/chemistry/. Download at http://mac.concord.org/downloads

Lin H-S, Cheng H-J (2000) The assessment of students and teachers' understanding of gas laws. J Chem Educ 77(2):235–238

Liu X (2006) Effects of combined hands-on laboratory and computer modeling on student learning of gas laws: a quasi-experimental study. J Sci Educ Technol 15(1):89–100. doi:10.1007/s10956-006-0359-7

Mas CJF, Perez JH (1987) Parallels between adolescents' conceptions of gases and the history of chemistry. J Chem Educ 64(7):616–618

Nakhleh M (1992) Why some students don't learn chemistry. J Chem Educ 69(3):191–196

Niaz M, Robinson WR (1992) From 'Algorithmic mode' to 'conceptual gestalt' in understanding the behavior of gases: an epistemological perspective. Res Sci Technol Educ 10(1):53–64. doi:10.1080/0263514920100105

Noh T, Scharmann LC (1997) Instructional influence of a molecular-level pictorial representation of matter on students' conceptions and problem-solving ability. J Res Sci Teach 34(2):199–217. doi:10.1002/(SICI)1098-2736(199702)34:2<199::AID-TEA6>3.0.CO;2-O

Novick S, Nussbaum J (1978) Junior high school pupils' understanding of the particulate nature of matter: an interview study. Sci Educ 62(3):273–281. doi:10.1002/sce.3730620303

Novick S, Nussbaum J (1981) Pupils' understanding of the particulate nature of matter: a cross-age study. Sci Educ 65(2):187–196. doi:10.1002/sce.3730650209

Nussbaum J (1985) The particulate nature of matter in the gaseous phase. In: Driver R, Guesne E, Tiberghien A (eds) Children's ideas in science. Open University Press, Philadelphia, pp 124–144

Pallant A, Tinker RF (2004) Reasoning with atomic-scale molecular dynamic models. J Sci Educ Technol 13(1):51–66. doi:10.1023/B:JOST.0000019638.01800.d0

Russell JW, Kozma RB, Jones T, Wykoff J, Marx N, Davis J (1997) Use of simultaneous-synchronized macroscopic, microscopic, and symbolic. J Chem Educ 74(3):330–334

Salomon G, Perkins DN, Globerson T (1991) Partners in cognition: extending human intelligence with intelligent technologies. Educ Res 20(3):2–9

Sanger MJ, Phelps AJ, Fienhold J (2000) Using a computer animation to improve students' conceptual understanding of a can-crushing demonstration. J Chem Educ 77(11):1517–1520

Shavelson RJ, Li M, Ruiz-Primo MA, Ayala CC (2002) Evaluating new approaches to assessing learning. Paper presented at the

Keynote Address: Joint Northumbria/EARLI Assessment Conference, University of Northumbria at Newcastle, Longhirst Campus, UK

Snir J, Smith CL, Raz G (2003) Linking phenomena with competing underlying models: a software tool for introducing students to the particulate model. Sci Educ 87:794–830. doi:10.1002/sce.10069

Stavy R (1988) Children's conception of gas. Int J Sci Educ 10(5):552–560. doi:10.1080/0950069880100508

Stieff M, Wilensky U (2003) Connected chemistry—incorporating interactive simulations into the chemistry classroom. J Sci Educ Technol 12(3):285–302. doi:10.1023/A:1025085023936

Treagust D, Chittleborough G, Mamiala T (2002) Students' understanding of the role of scientific models in learning science. Int J Sci Educ 24(4):357–368. doi:10.1080/09500690110066485

Treagust DF, Chittleborough G, Mamiala TL (2003) The role of the submicroscopic and symbolic representations in chemical explanations. Int J Sci Educ 25(11):1353–1368. doi:10.1080/0950069032000070306

Westbrook SL, Marek ED (1991) A cross-age study of student understanding of the concept of diffusion. J Res Sci Teach 28:649–660. doi:10.1002/tea.3660280803

Wilensky U (1999a) NetLogo. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL. http://ccl.northwestern.edu/netlogo

Wilensky U (1999b) GasLab: an extensible modeling toolkit for exploring micro- and macro- views of gases. In: Feurzig W, Roberts N (eds) Modeling and simulation in science and mathematics education. Springer, New York, pp 151–178

Wilensky U (2001). Modeling nature's emergent patterns with multiagent languages. Paper presented at the Eurologo 2001 Conference, Linz, Austria

Wilensky U (2003) Statistical mechanics for secondary school: the GasLab modeling toolkit. Int J Comput Math Learn 8(1):1–41. doi:10.1023/A:1025651502936 (special issue on agent-based modeling)

Wilensky U, Resnick M (1999) Thinking in levels: a dynamic systems perspective to making sense of the world. J Sci Educ Technol 8(1):3–19. doi:10.1023/A:1009421303064

Wilensky U, Hazzard E, Froemke R (1999) GasLab—an extensible modeling toolkit for exploring statistical mechanics. Paper presented at the Seventh European Logo Conference (EUROLOGO '99), Sofia, Bulgaria