Promotion Reasoning About Complex Chemical Systems: Consequences of an Exploring Agent-Based Computer Models

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Abstract

This study studied middle school students' learning of the gaseous phase in chemistry through an emergent complex systems perspective as compared with learning through a normative disciplinary view. We explore the students' progression in reasoning about complex chemical systems in terms of generic systems thinking components. Seventh grade students' understanding of Gas Laws and KMT was studied using pre- and post-test questionnaires and interviews. 47 experimental group students learned with a 12-lessons curriculum that includes exploration of agent-based modeling (ABM), based upon a complex systems approach. 45 comparison group students learned with a normative commonly-used 12-lessons curriculum. we have found strong advantage to the learning environment based on exploring agent-based computer models for promotion reasoning about complex chemical systems. Additionally, we have found a prevalent and coherent mental model for making sense of complex chemical phenomena that goes beyond the expert/novice divide, intermediate in sophistication to the two extreme poles. It is typified by thinking in levels but not stochastic behaviors and emergent structures of causality. Another finding of this study indicates that there is an interaction between learning chemistry as a field of knowledge and general system thinking.

Keywords: Systems thinking, Agent-based modeling, Complex systems, Mental models, Chemistry education.

Introduction

This paper describes students' progressive reasoning about complex chemical systems in terms of generic systems thinking components. A body of research describes students' understanding of complex systems. This research has primarily studied students' understanding of complex phenomena in terms of expert/novice differences (Hmelo-Silver & Pfeffer, 2004; Jacobson, 2001; Wilensky & Resnick, 1999; Chi, 2005, 2012). However, processes of learning may take a number of interesting turns on the way. Knowing the starting point and destination do not necessarily provide us with enough information to understand and support learning. We have found a prevalent mental model for making sense of complex chemical phenomena that goes beyond the expert/novice divide. We have found a stable and coherent third form of reasoning, intermediate in sophistication to the two extreme poles. As we will show, it is typified by some features of expert thinking: thinking in levels and decentralized control; but not others: stochastic behaviors and emergent structures of causality.

We investigate seventh-grade students' reasoning about complex chemical phenomena. We report on questionnaires and interviews conducted while they were studying with experimental and traditional curricular units. The experimental intervention provided an emergent complex systems perspective and supported learning with manipulative computer models (Figure 1).

Complex systems are made up of many elements (or "agents"), which interact among themselves and with their environment. The interactions of numerous elements result in a higher-order or collective behavior, the system self-organize in coherent global patterns (Holland, 1995; Kauffman, 1995).

A visual, dynamic and linked representation that brings micro- and macro-levels closer and helps attend to the multiple, parallel and interacting nature at the micro-level is provided through agent-based modeling, platforms, such as NetLogo (Wilensky, 1999). ABM is an extensively used computational modeling paradigm, which simulates dynamic systems by simulating each of their many autonomous and interacting entities (named agents) (Holland, 1995; Kauffman, 1995; Bar-Yam, 1997). By experimenting with agent behaviors and interactions, we view how collective behavior results from individual behaviors and interactions. The current study examined learning with ABM to promote systemic thinking.

This body of research into people's reasoning about complex systems points out various biases, which divert people from attending to bottom-up processes of emergence. In some of the papers, educational interventions have been shown to change this state of affairs, such as constructing and exploring agent-based computer models (Klopfer, 2003; Levy & Wilensky, 2009a,b; Repenning, Ionnidou & Zola, 2000; Rates et al., 2016; Resnick, 1994; Wilensky, 1995, 1997, 1999a; Wilensky & Reisman, 2006; Wilensky & Resnick, 1999) and through role-playing participatory simulations (Colella, 2000; Klopfer, Yoon & Perry, 2005; Resnick & Wilensky, 1998; Soloway et al., 2001; Wilensky & Stroup, 1999ac, 2000).

Resnick and Wilensky (1993; Wilensky & Resnick, 1995; 1999) have described a pattern of thinking that makes it difficult for people to make sense of complex systems. They call this thinking pattern: the "deterministic-centralized mindset" (DC mindset). In this mindset, when people see a group of individuals arranged in some pattern, they tend to assume the pattern arises through the control of one individual or results from centralized control even when such coordination and control does not exist. When they try to explain such patterns, people make use of deterministic causal explanations, and do not invoke the role of stochastic processes in creating patterns. Penner (2000) has found a similar bias among middle school students as they reason about flocking geese and traffic jams at the start of an educational intervention. Jacobson (2001) has observed the "DC mindset" among university students, novices in the field of complexity, as they reasoned through eight different emergent processes. Wilensky & Resnick (1999) have pointed to "levels confusion," where the attributes of one level are "copied" onto another level. In addition to DC control assumptions, they found that many students (and researchers) failed in recognizing the distinctiveness of levels of description.

The current study builds upon and extends this body of knowledge, offering a developmental perspective in learning about complex systems.

Research Questions

1. How does students' reasoning about complex chemical systems change while learning in an environment that includes guided exploration of computer models and laboratories?
2. How does students’ reasoning about complex chemical systems compare with learning the same topic with more traditional means of lecture/textbook/laboratory?

Method

Research Approach and Design

We have used a mixed methods approach combining quantitative analysis of questionnaires and qualitative analysis of interviews. The research was planned as a non-randomized controlled quasi-experimental pre-test-intervention-post-test design.

Participants

104 seventh grade students participated in the study: 70 males, 34 females. Experimental group: (a) one class (n=30) from a rural secular elementary school; (b) one class (n=23) from an all-male religious state-funded school; Comparison group: (c) one class (n=19), same school and teacher as (b); (d) one class (n=30) from an urban low-SES school. Five experimental group students and seven comparison group students were selected for interviews by their teachers, as having a greater verbal-expressive ability. In all classes, the teachers have an undergraduate degree in science education and several years of teaching experience. Research went through the Ministry of Education approval process. All participants' parents completed consent forms.

Procedure

Before and after the activities, spaced 2-3 weeks apart, all students completed identical content knowledge questionnaires. 30 minutes were allotted for completing the questionnaire. The two experimental group classes engaged with the "Who Understands the Gas?" learning environment (Samon & Levy, 2017) as part of their seventh-grade science course, replacing the topic of Gas Laws and KMT. Two comparison group classes learned the same topics during 12 lessons with the normal curriculum that is based on lectures, laboratories and textbook-based learning. The interviews took place before and after the implementation and were recorded with a video-camera and voice recorder. The duration of each interview was about 20 minutes.

Who Understands the Gas? Curriculum

The "Who Understands the Gas?" learning environment (Samon, 2011) is made up of five activities, 12 lessons long. It includes guided exploration of agent-based NetLogo (Wilensky, 1999) computer models, laboratory experiments and class discussions. It is based on the Connected Chemistry curriculum that targets Kinetic Molecular Theory (KMT) and Gas Laws. It was adapted for younger junior-high students by excluding the mathematical representations, fine-tuned in response to previous research (Levy & Wilensky, 2009b) and enhanced with laboratory activities and the topic of diffusion. We describe the curriculum in greater detail in another paper (Samon & Levy, 2017).

Data Collection Tools

Two main data collection tools were used (Table 1): a content knowledge questionnaire and a protocol for a semi-structured interview. The questionnaire is based on that used in previous research on learning Gas Laws and KMT (Levy & Wilensky, 2009b) and diffusion (Odom & Barrow, 1995). Additional items were created in-house to obtain more information on students' reasoning about diffusion. The items were evaluated by five experienced science teachers, to ensure content-alignment and appropriate level. It includes 24 multiple-choice questions and two open-ended questions. An interview protocol was created and first pilot-tested with four students.

Table 1. Sample Items from the Questionnaire and the Interview Protocol

Data Source	**Targeted Concepts**	**Sample Items**
Questionnaire	KMT Micro-level	When two gas particles collide both their speed and direction will change. their direction can change but not their speed. their speed can change but not their direction. neither their speed not direction will change.
	Gas Laws Macro-level	Two basketballs have the same volume and are at the same temperature. The pressure in the first ball is larger than the pressure in the second ball. How is the number of air particles in each ball related to one another? The second ball has more air particles The second ball has less air particles The two balls have the same number of particles One cannot know which basketball has more particles
	KMT, diffusion Micro-macro bridge	Read the following section and answer the questions. A girl spread some perfume on her neck. Her mother, who was standing at the other side of the room called out: "What a good scent!" Describe in drawing, how the perfume particles reached from the girl's neck to the mother's nose, which is at the other side of the room. Use small circles to depict particles. Explain your drawing in detail. Describe in words how the perfume particles reached from one side of the room to the other. Explain how all the individual entities participate in the process.
Interview	KMT, pressure Micro-macro bridge	A blown-up plastic bag is placed before the participant. Let's look at the blown-up bag/ What is inside? If we could wear magic glasses that would let us see this at a million times this size, what is inside the bag? What would we see? Can you draw this? Explain your drawing with words. What are the objects that you've drawn? What do they do? What is between them? What is their size? Are they heavy? What is their shape? Is their shape constant?
	Gas Laws, pressure Macro-level	Two empty plastic bags are placed before the participant. I will now add air into one bag. What do you think will happen while the bag is being blown up? What is the difference between the empty bag and the blown-up bag?

Findings

In a different paper based on the same dataset we report on students' science learning (Samon & Levy, 2013). We have described the experimental group students' large learning gain (*M* = 80%, *SD* = 54) with respect to the comparison group (*M* = 28, *SD* = 45), showing a strong effect size (Cohen's *d* = 1.05). This difference in learning gains results mainly from enhanced learning of the concepts diffusion, density and KMT. The concepts pressure, temperature and Gas Laws were learned comparably with the two curricula.

Learning Gains

Sample size reduced to n = 92, as some students didn't complete one of the questionnaires. The questionnaire responses were coded as correct or incorrect. An overall score reflected equal status to each item. A learning gain was computed to compensate for differences in prior knowledge: ((post-score)–(pre-score))/(pre-score), the proportion of change with respect to initial understanding. The questionnaire's items were categorized into those that relate to the micro-level, those that address the macro-level and those that require moving between the two levels (Table 2).

Table 2. Pre-test and Post-test System Reasoning Scores (%), Learning Gains and Statistical Tests for Both Groups

		Pre-test (%)		**Post-test (%)**		**Learning gain (%)**		**Statistical tests**	
System dimension	**# items**	**Exp** *M (SD)*	**Control** *M (SD)*	**Exp** *M (SD)*	**Control** *M (SD)*	**Exp** *M (SD)*	**Control** *M (SD)*	**Unpaired *t* (91)[1]**	**Effect size, Cohen's *d***
Overall	24	45 (53)	43 (50)	75 (43)	54 (50)	80 (54)	28 (45)	4.95**	1.05
Micro	6	39 (49)	42 (49)	74 (44)	43 (50)	122 (110)	13 (85)	5.22**	1.12
Macro	8	58 (55)	52 (50)	80 (34)	65 (48)	81 (112)	40 (97)	1.83	0.43
Micro-Macro	11	58 (50)	42 (50)	76 (43)	58 (49)	85 (140)	56 (130)	.93	0.21

[1] - * marks significance of $p < .05$; ** marks significance of $p < .01$

Learning gains were higher for the experimental group on all dimensions. The comparison group advanced in some dimensions as well: the macro-level and micro/macro transitions. The experimental program was significantly higher with a strong effect size only for understanding the micro-level of the gas particles.

Finding the "model in the middle"

In this section, we describe how we discovered the "model in the middle". One of the items in the questionnaire (described in full in the method section) asks the participants to draw and explain how perfume from the neck of a girl may reach her mother's nose at the other side of the room. They were prompted to use a micro-level particulate description. To analyze reasoning about systems, we have coded for the following dimensions, based on the work of Jacobson (2001) and Levy & Wilensky (2008): multiple levels, emergence, decentralized control, stochastic behavior and equilibration processes. The dimension of multiple levels was further subdivided into three: conceptual distinction among levels (use of appropriate concepts with respect to each level), distinction among levels' actions (distinction among actions taking place at each level) and transitions among levels. Each dimension for each questionnaire was coded as sophisticated (1) or simplistic (0). Table 3 presents these coded dimensions with examples.

Table 3. Systems Reasoning Dimensions and Examples in the Students Responses

	Sophisticated Systems Reasoning		**Simplistic Systems Reasoning**	
Dimension	**Definition**	**Example**	**Definition**	**Example**
Multiple levels	Distinction among macro- and micro-levels	*As a result of the particles' motion the mother could smell the good scent [of the perfume]*	Confusion among levels, use of descriptors of one level regarding another	*The mother smelled the particles*
Emergence	The whole is more than the sum of its parts.	*First, the particles are concentrated in one place... The particles move randomly in all directions. As a result of their collisions with each other and with objects, they reached the mother's nose.*	The whole is the sum of its parts	*The perfume particles reached from one side of the room to the other because the particles move.*
Decentralized control	Decentralized control, the macro-phenomenon results from random actions and interactions at the micro-level	*The particles move independently in a straight line until they hit a body/particle/wall. And that's how the perfume fills the whole room.*	Centralized control. Causality results from a single source.	*The nose is like a smell magnet, so the smell is attracted to it.* *The particles try to go where it's empty... That's how they reached the mother.*
Stochastic behavior	The agents' behavior is random and unpredictable.	*The particles moved in all directions randomly. As a result of collisions with the objects and with each other, they reached the mother's nose.*	Purposefulness, the agents' behavior is completely predictable.	*The perfume particles pushed the air and that's how they reached the other side of the room.* *They [the particles] spread quickly in all directions and then they slow down; they move from a high concentration to a low concentration.*

	Sophisticated Systems Reasoning		Simplistic Systems Reasoning	
Dimension	**Definition**	**Example**	**Definition**	**Example**
Equilibration	Local dynamic processes, which result in the system approaching equilibrium. These processes continue after reaching equilibrium.	*When the girl spread perfume all the particles were close to her. And then they started mixing with all the air particles in the room and collided with each other and spread in all directions on the area of the whole room*	There is no equilibrium, or, a process is described as intended to create equilibrium; Purposeful motion from high to low concentration	*There is a path, a precise path, from the girl's neck to the mother's nose, on which the particles are more dense.*

To test for possible clustering, an integration of dimension codes that "go together", codes for each one of these seven dimensions were set as members of a vector that described the student's reasoning about systems. Table 4 presents the results of a two-step cluster analysis, with the dimensions in descending order of importance in segregating among the clusters, according to chi-square tests.

Table 4. Two-step Cluster Analysis of the Students' Reasoning about Diffusing Perfume in the Questionnaire

Systems reasoning dimension	Relative importance[1]	Cluster 1[2] (n = 62)	Cluster 2[2] (n = 43)	Cluster 3[2] (n = 24)
Emergence	1	0	2	100
Conceptual distinction between levels	0.7	0	74	92
Decentralized control	0.7	0	51	100
Distinction among levels' actions	0.5	24	81	100
Stochastic behavior	0.4	1	2	58
Transitions among levels	0.4	0	16	62
Equilibration	0.3	29	70	100

[1] Importance of clusters distribution dimension

[2] Numbers in cells are proportion (%) of questionnaires in this cluster that show sophisticated complex systems reasoning regarding the particular dimension

We can see three forms of reasoning about the system, which reflect different levels of sophistication in understanding complex systems. Three dimensions are most important in distinguishing between these forms: emergence, conceptual distinction among levels and decentralized control. The first cluster displays mainly non-sophisticated reasoning regarding the three. The third cluster exhibits mostly sophisticated reasoning with respect to the three dimensions. The second cluster, the "model in the middle", shows sophisticated reasoning about levels conceptually, but not emergence, while decentralized control does not typify the cluster one way or another.

To summarize, we have seen three modes of reasoning about complex systems.

Mode 1, hence "simplistic complex systems reasoning": non-sophisticated reasoning about systems in all dimensions, some distinction between levels, but only regarding actions.

Mode 2, hence "model in the middle": non-sophisticated reasoning about emergence, stochastic behaviors, sophisticated reasoning regarding conceptual distinction among levels and distinction among levels' actions, and understanding of equilibration processes. Decentralized control does not typify this mode one way or another.

Mode 3, hence "sophisticated complex systems reasoning": sophisticated reasoning about systems in all dimensions, slightly less so for stochastic behaviors.

Group and Test Effects on Mode of Systems Reasoning

After coding the questionnaires for mode of reasoning about systems, these modes were tested for group and test effects (Figure 1).

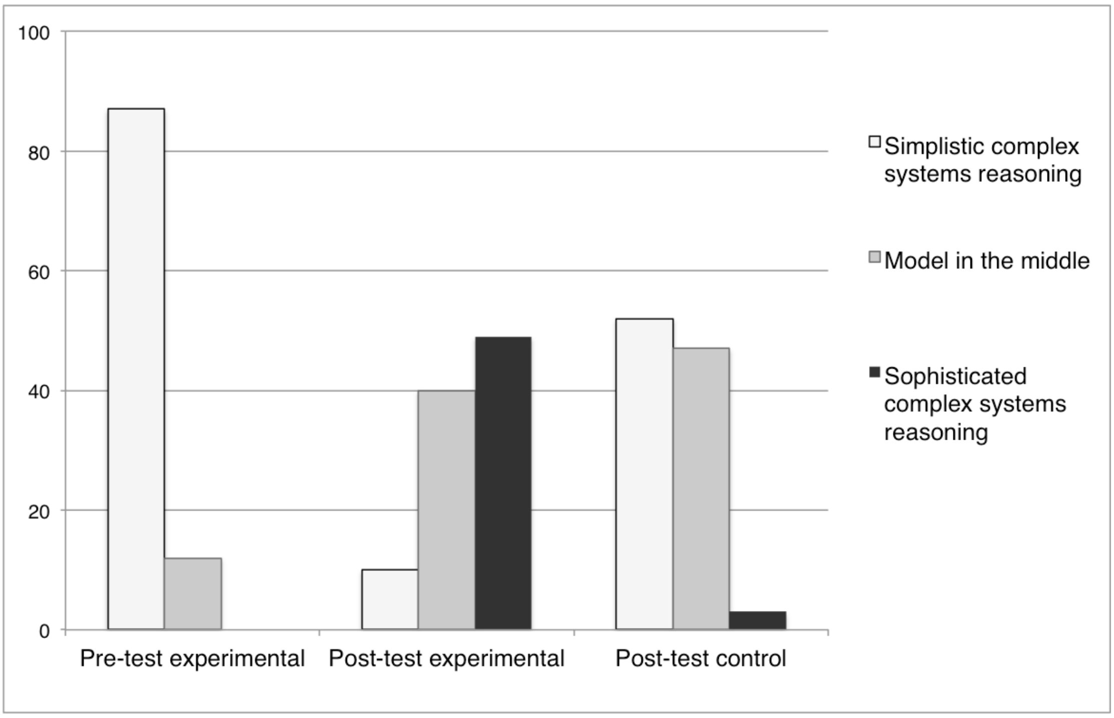

Figure 1. Association between group and test and mode of systems reasoning

In the pre-test, most participants held a simplistic model of reasoning about complex systems. In the post-test, most of the experimental group shifted extremely to a fairly even distribution between a sophisticated model and the model-in-the-middle. About half of the comparison group progressed in the post-test to more sophisticated reasoning, however to model-in-the-middle reasoning rather than sophisticated reasoning about systems. Unpaired t-test is $t(91)=6.17$ ($p<.01$) for group and test distribution among modes. Cohen's $d=1.4$ for distinction among groups regarding this distribution shows a strong effect size.

A Qualitative View into the Modes of Reasoning about Chemical Complex Systems

Following this finding regarding model-in-the-middle the interviews were re-analyzed regarding these modes of reasoning. In the interview, participants were asked to explain several phenomena: inflating a bag, sucking air out of a bottle, spread of perfume in an air bag, warming up air. These phenomena demonstrate pressure change, temperature change and diffusion. Results are shown for two participants (Tables 5 and 6).

Table 5. In-depth Analysis of Interviews with Respect to Modes of Systems Reasoning (A)

	Pre-test		**Post-test**	
Phenomenon	**Explanation**	**Systems View**	**Explanation**	**Systems View**
Inflating a bag/balloon	*He [the air] takes up place in the balloon and the balloon slowly, slowly grows.*	References macro-level alone Direct causality: The air takes up space in the bag, as a result it inflates ➔ Mode 1	*The pressure on the bag's walls causes it to inflate, [the pressure results] from their [the particles'] motion and their collisions with the bag's walls.*	Micro- and macro-levels are distinct; separate actions for each: pressure on the walls, collisions among particles. Emergence: pressure results from particles' collisions with the walls. Distinction among levels (conceptual, actions, transitions), pressure emerges from collisions, decentralized control. No mention of stochastic (random) behavior) or equilibration ➔ Mode 3
Sucking air out of a bottle	*[was not used in pre-test interview]*		*There's less pressure… [pressure] is the particles' collisions with the walls.*	Decentralized control: The bottle shrinks because there are less particles' collisions with the walls. Distinction among levels, emergence, decentralized. No mention of stochastic (random) behavior) or equilibration ➔ Mode 2

	Pre-test		**Post-test**	
Phenomenon	**Explanation**	**Systems View**	**Explanation**	**Systems View**
Warming up air	*Nothing happens to the air when you warm it up.*	References macro-level alone, thus there is no change in the air after heating it ➔ Mode 1	*The pressure will rise.. because the particles move faster [and the bag] will inflate.*	Distinction among levels in terms of concepts and actions taking place at each level. Emergence: Heating results in the particles becoming faster (micro), and thus the pressure (macro) increases. Distinction among levels, emergence, decentralized. No mention of stochastic (random) behavior) or equilibration ➔ Mode 3
Spread of perfume in air	*You put it [the perfume] inside and it will settle down.. The air will push it downwards.*	References macro-level alone Assigns volition to the particles Centralized control: The air pushes the perfume and as a result, it moves downwards. Direct causality ➔ Mode 1	*They [the particles] will spread out all over the bag... with collisions. The particles begin moving.. [draws dots with a pencil, takes an orange color and inserts dots in-between the air particles. Distribution is even]. (Do the perfume particles move all the time?) Yes.*	Dynamic equilibrium: the particles move continuously, collide and distribute evenly in the bag. Emergence: Collisions among the particles result in their even distribution in space. Distinction among levels, emergence, decentralized, dynamic equilibrium. No stochastic behavior ➔ 3

Table 6. Analysis of Interviews with Respect to Modes of Systems Reasoning (B)

	Pre-test		**Post-test**	
Phenomenon	**Explanation**	**Systems View**	**Explanation**	**Systems View**
Inflating a bag	I: I have a bag here. I'm about to add air into it, inflate it. What will happen during inflation? B: *Air goes in.* I: Why does it take this shape? [shows blown up shape of bag] B: *Because you added more particles inside.* I: And then? B: *Then it took up more space, inflated.* I: Why? B: *They* [the particles] *need space between them, when you put in more, the space becomes smaller.* I: What happens when the space becomes smaller? B: *Then they* [the particles] *try to push each other.* I: What happens from the moment they entered that causes the bag to inflate? B: *They push each other and then it inflates.* I: But they're pushing in the	Distinction among levels: air and particles. Decentralized control: macro-phenomena result from local micro-level interactions. Distinction among levels, decentralized control, volition of particles. No emergence, equilibration or stochastic behavior ➔ Mode 2	I: I have here an empty bag. I added air and it inflated. Can you tell me what the air did that caused the bag to inflate? B: *The particles collided with the walls.* I: Can you show this to me with coins? What did the particles do to make the bag inflate? B moves a number of coins in straight lines going at different directions. When they hit the wall of the bag, they reflect and change direction. B: *Hit the walls.* I: When the pressure is greater, what does that mean? B: *More collisions with the walls.* I: The pressure is greater only when there are more collisions with the walls? Are there additional causes? B: *When there are more particles, there are more collisions.*	Distinction among levels: air and particles. Emergence: pressure results from particles' collisions with the walls. Stochastic behavior: demonstrated with the coins moving randomly in a variety of directions. Distinction among levels, decentralized control, stochastic behavior, emergence. No equilibration ➔ Mode 3.

	Pre-test		Post-test	
Phenomenon	**Explanation**	**Systems View**	**Explanation**	**Systems View**
	middle. How does it get to the bag? B: *No, they push in the entire bag.* I: What is pressure actually? B: *It's when the space between the particles is closer.* I: If I continue to blow up this bag, what will happen? B: *It will burst.* I: Why? B: *Because there are too many particles, more than necessary.* I: What do you mean? B: *That there are too many atoms that want to go out, and when you load more, it bursts.*			

From these analyses, we see shifts from pre-test to post-test. Participant A moved from a consistently non-sophisticated mode of reasoning about systems to sophisticated reasoning about a complex chemical system. Participant B shift from a model-in-the-middle form of reasoning to sophisticated reasoning about a complex chemical system.

Learning of system knowledge with a normative approach

The interviews with the students from the comparison group were conducted after the analysis of the findings and the discovery of the interim model. Table 7 presents an analysis of an interview that characterizes the intermediate model. This is to try understanding this way of thinking in more depth. In the interviews, students were asked to explain various phenomena.

Table 7. Analysis of Interviews that characterizes the intermediate model

Phenomenon	Explanation	Systems View
Opening of a bottle containing air	*Interviewer: (showing a 1.5-liter bottle "empty" plugged in) What's inside the bottle?* *student: Uh ... nothing, really air.* *Interviewer: Where is the air?* *student: At the top of the bottle* *Interviewer: What is the air made of?* *student: Particles* *Interviewer: Where are the particles?* *student: At the top* *Interviewer: What causes the particles to be only at the top?* *student: Because they're moving at constant speed, so they want to get to the top* *Interviewer: If we focus on one particle, does he want to reach the top?* *student: Yes* *Interviewer: What will happen if I open the plug?* *Student: The particles came out*	The student has a view of the air as a complex system. It distinguishes between levels both in terms of the proper use of terms and in terms of activities: At the macro level, the air takes up space in the bottle and at the micro level, particles that move at constant speed. It displays distributed control; the individual particle controls its movement. At the same time, she lacks the understanding of randomness in particle motion. As far as the particles are concerned, they want to reach the top, so they are only at the top of the bottle. Ron presents a conflict, on the one hand the particles have constant motion and on the other, they are at the top. A student with a random perception realizes that the particles move in all directions, as a result of this movement they would fill the entire volume of the bottle.

From these analyses, we see that the student presents an intermediate mental. She refers to the different levels in the system and knows how to distinguish between them in terms of concepts and in terms of operations. She lacks an understanding of the randomness and emergence. She did not refer to the interaction between the particles and consequently she cannot understand the emergence. She attributes intentions and desires particles, ie, decentralized control. This decentralization prevents her from understanding randomness.

Discussion

This paper describes students' progression in reasoning about complex chemical systems in terms of generic systems thinking components. We have observed a prevalent mental model for making sense of complex chemical phenomena goes beyond the expert/novice divide, a coherent third form of reasoning. It is typified by some features of expert thinking: thinking in levels and decentralized control; but not others: stochastic behaviors and emergent structures of causality. This supports a more continuous view of learning about complex systems. This study was conducted in the domain of chemistry learning and it remains to be explored whether this finding replicates to other domains. However, in the domain of chemistry we have come to realize that some systems reasoning components that can be learned through a disciplinary and not necessarily emergent perspective: distinguishing levels and viewing control as decentralized. The specific benefits of learning with such a perspective are in understanding how the randomness results in order at a higher level and emergence.

The qualitative analysis of the interviews, shows that students harnessed their tendency for ego centered-centralized thinking about systems for distinguishing between levels and understanding the decentralized character of the chemical system. These findings question a central theory regarding reasoning about complex systems. Resnick & Wilensky (1993; Wilensky & Resnick, 1995; 1999) describe novices' views of systems as entrenched in a deterministic-centralized (DC) mindset. Such a mindset pairs non-stochastic events and centralized control as both typifying such reasoning. (Grotzer, Derbiszewska & Solis, 2017). The current study, unties this pair. One can come to learn about decentralized control without noting the stochastic nature of the system. Thus, we can see two less sophisticated forms of reasoning, one the DC mindset, but one with only the D.

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