Learning from Self-Explaining Emergent Phenomena

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Abstract: To date, relatively little work has explored how students learn about a particular class of processes, namely emergent ones. The research that has investigated these processes has primarily employed a case-study methodology. Here, we report on a controlled experiment comparing how students learn about the emergent topic of diffusion from self-explaining vs. from reading. In contrast to a prior study that found self-explanation was not associated with learning about emergence, students learned significantly more in the self-explaining condition. To shed light on how different types of self-explanations are related to learning, we analyze the content of students' explanations and their association to learning outcomes; we also present qualitative analysis of students' misconceptions and how these relate to existing theories of emergent attributes.

Introduction

Many science processes can be classified as being *emergent*, including diffusion (Chi, Roscoe, Slotta, Roy, & Chase, 2012), crystal growth (Blikstein & Wilensky, 2009), and natural selection (Dickes & Sengupta, 2013). Briefly, in an emergent process many micro-level agents behave according to simple rules to produce a more complex, macro-level outcome or pattern (Levy & Wilensky, 2008). In contrast to other "sequential" processes like the circulatory system, emergent processes correspond to a decentralized system, in that there is no controlling agent directing the behavior of the micro agents (Resnick, 1996). Moreover, in an emergent process, visible patterns at a given level (e.g., micro) do not necessarily correspond to patterns at another level (e.g., macro) – for a detailed comparison of emergent and sequential processes, see (Chi et al., 2012). To illustrate emergence using diffusion, suppose some blue dye is added to water. The micro-level agents correspond to the dye and water molecules, and these follow the simple rule of continuous, random motion. The macro-level outcome that arises from the molecular motion is a flow of the dye into water prior to equilibrium or a stable, unchanging light blue solution at equilibrium.

Given its prevalence in various phenomena, it is paramount that students understand emergent processes (Jacobson & Wilensky, 2006). Unfortunately, emergent concepts are very challenging (Asterhan & Schwarz, 2009; Chi et al., 2012; Meir, Perry, Stal, & Klopfer, 2005). For instance, some students, even at the university level, believe that during diffusion, molecules stop moving at equilibrium because the solution appears to be a uniform, unchanging color (Meir et al., 2005). This misconception suggests that students think the pattern at the micro-level must correspond to the pattern at the macro level, when in fact it can be disjoint for emergent processes. Reasoning connecting the micro and macro levels is also called *inter-level* reasoning (Blikstein & Wilensky, 2009; Chi et al., 2012), and some propose it is especially challenging for students in the context of emergence (Chi et al., 2012).

As we describe below, the majority of work exploring learning of emergence has focused on the utility of computer simulations depicting emergent phenomena, and a methodology corresponding to case studies (Blikstein & Wilensky, 2009; Levy & Wilensky, 2009b). While our work also involves simulations, our focus is instead on the role of student *self-explanations* about diffusion and their association with learning outcomes.

In general, self-explanation, i.e., the process of explaining and clarifying instructional material to oneself, is highly beneficial for learning (Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Fonseca & Chi, 2011; Muldner & Conati, 2010; Nokes, Hausmann, VanLehn, & Gershman, 2011; Renkl, 1997). Since the seminal Chi et al. (1989) study, there has been a great deal of research on self-explanation, for instance to investigate individual differences in self-explanation behaviors (Renkl, 1997), instructional manipulations such as the effect of introducing gaps into examples (Atkinson, Renkl, & Merrill, 2003), and the relationship of various types of self-explanation prompts (Nokes et al., 2011). Moreover, the self-explanation effect has been shown to exist in various kinds of domains, including procedural ones like probability (Atkinson et al., 2003) and physics (Chi et al., 1989) as well as conceptual domains like biology (Gadgil, Nokes-Malach, & Chi, 2012).

To date, however, very little work has explored how students learn from self explaining about emergent processes, which as we mention above correspond to a specific class of phenomena that students may find especially challenging. To the best of our knowledge, there is only one study that investigated whether self-explanation helped learning of emergent topics. Specifically, Asterhan and Schwarz (2009) analyzed explanations produced by pairs of students collaboratively learning about natural selection. The results from a correlational analysis showed that self-explanations were not associated with learning in this domain. This finding is somewhat surprising, since one would expect at least some benefit of self-explanation, and so we believe further investigation and replication are needed.

Thus, the goals of the present study are to investigate the impact of self-explanation for an emergent topic, as well as to explore (1) the relationship of different *types* of self-explanations and learning, and (2) the particular misconceptions students have about emergence as evidenced by their self-explanations.

Related Work

The majority of research exploring student understanding of emergent phenomena has involved qualitative case studies. Levy & Wilensky (2008) present analysis from interviews with 10 students that probe their understanding of emergent features of everyday phenomena, such as a crowd scattering. The focus of the analysis was on student reasoning related to the inter-level processes and how different types of reasoning (e.g., bottom up vs. top down) fostered understanding of the mid-level attributes.

Penner (2000) performed a series of case studies to investigate students' emergent reasoning. These case studies involved groups of students as they engaged in model building activities centered around representing and investigating emergent processes. The analysis includes excerpts of students' micro- and macro-level descriptions. Others have also explored the use of model building exercises, i.e., through simulations, for emergent processes. Typically, these exercises involve having students model the micro-agents using a set of rules (e.g., atoms move randomly), for instance in the NetLogo environment, which allows them to observe the resulting macro-level pattern emerge. Wilensky and Reisman (2006) describe two simulations of biological systems involving the impact of predator-prey on population dynamics and the coordinated behavior of fireflies and how they can be used to learn about emergence. Blikstein and Wilenski (2009) present case studies of students' experience with several simulations showing emergent phenomena related to materials science. The paper presents qualitative description of students' models and their high level reasoning related to these.

Other work on supporting learning about emergent processes with simulated environments has focused on the design of activities and guided prompts to guide students (Levy & Wilensky, 2009a, 2009b). These prompts targeted the macro, micro and inter-level aspects of emergence. The strongest effects in terms of learning outcomes were found for prompts that targeted the micro and inter-level concepts. While informative, this work did not gather data on students' self-explanations.

Chi et al. (2012) provided students with micro and macro simulations of emergent processes and prompts for emergent concepts during related activities. No correlation was found between learning and responses to prompts related to the macro simulation, but there was a high correlation between learning and responses to prompts related to the micro simulation – thus, the conjecture was made that students already knew the macro concepts. As was the case with the Levy and Wilenski work cited above, in this study students were not prompted to provide verbal explanations, instead being asked to type answers to questions in the learning materials at fixed intervals. Written explanations generated in response to text-embedded questions can be considered different from ones verbally produced, since the focus for self-explanations is to try and understand the instructional materials rather than to generate a coherent answer to a question (e.g., Chi 2000). Moreover, this study did not analyze how self-explanations in general, and specific explanations in particular, did (or did not) enhance learning of emergent concepts.

Study: Student Self-Explanations in Emergent Domains

The goals of the present study were to investigate the following three key aspects:

(1) the utility of self-explanation for learning about an emergent domain, compared to reading
(2) the nature of students' self-explanations and which types of explanations are beneficial for learning about emergence
(3) student misconceptions as highlighted by their self-explanations

Materials

The study involved the following materials related to diffusion:

- two diffusion simulations
- a diffusion text
- a diffusion pre-test and post-test

To help students understand inter-level concepts, the two simulations showed diffusion occurring on the visible level (*macro* simulation) and at the molecular level (*micro* simulation); see the left and right panel of Figure 1 for the macro and micro simulation, respectively. The simulations were interactive (for instance, clicking the "start" button in the micro simulation resulted in molecules bouncing and colliding).

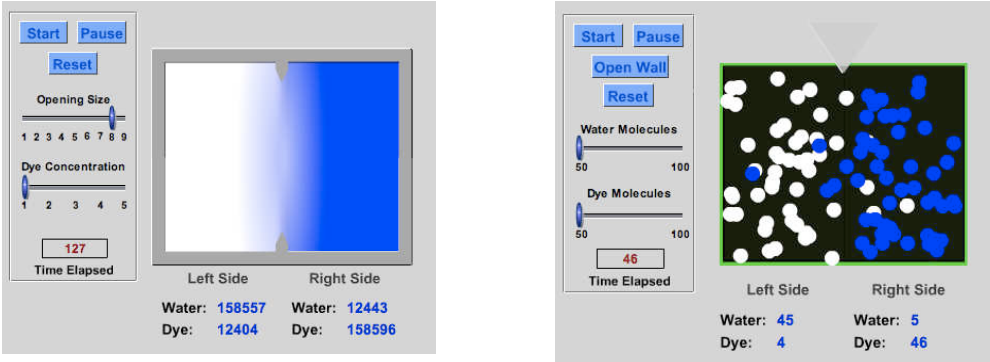

Figure 1: Macro level (left) and micro-level (right) simulations of diffusion

The diffusion text was printed on 8 by 11 sheets and was based on text used in earlier studies (Chi et al., 2012). The text described the diffusion process and also included information on emergent features and attributes, but without directly referring to emergence. The first two pages of the text were intended as a warm up, and so discussed non-emergent aspects of diffusion related to the properties of gases, liquids and solids. We followed the procedure used in (Chi, de Leeuw, Chiu, & LaVancher, 1994) to design two versions of the text: one with prompts reminding students to self-explain (*prompted text*) and one without prompts (*unprompted text*); otherwise, the content of the text was identical between the two conditions. The prompted text included a total of 52 generic prompts to self-explain (corresponding to "EXPLAIN" prompts, see Tables 2 and 3, top, for examples; 9 of these prompts were in the warm-up text). These prompts were embedded throughout the text (typically after each sentence or several sentences; whitespace was inserted between a given prompt and the next batch of text to clearly highlight what needed to be explained). Both versions of the text (prompted, unprompted) concluded with a description of the diffusion simulations and suggestions to use the simulations. In the prompted text these suggestions corresponded to 11 specific self-explanation prompts (e.g., "*What are the molecules doing during equilibrium?*"), while in the unprompted text, the suggestion was an invitation to use the simulation in free exploration mode.

The pre- and post-tests assessed students' diffusion knowledge and were based on tests used in prior studies (Chi et al., 2012; Muldner, Lam, & Chi, 2013). The tests included questions that probed understanding of emergent aspects of diffusion at the micro, macro, and inter levels, but without explicitly mentioning emergence. For instance, to assess the inter-level *disjoint* attribute, one question asked "*As the dye diffuses away from where it was originally dropped into the water, can some dye molecules bounce back towards this original place?*" The pre-test included 25 multiple-choice questions, while the post-test included the same 25 questions and six additional questions for a total of 29 questions (10 *inter-level*, 8 *micro*, 2 *macro*, and 9 *other*).

Participants

The participants were 42 college students, who participated in the study to fulfill a psychology credit.

Design

The study included one independent variable with two conditions: *reading* and *self-explaining*. We used a stratified random sampling procedure based on pre-test performance to equalize prior knowledge between the two conditions.

Procedure

Each session was conducted individually in a private room that included a table and a desktop computer. Students signed the consent form (5 min.), filled in the pre-test (15 min.), and then read the diffusion text (*reading* condition) or read and self-explained the diffusion text (*self-explaining* condition). Students in both conditions were told to read out loud at their normal pace. Students in the self-explanation condition were also told to

> follow the "explain" prompts to explain what the information means to you. For instance, you can explain what new information does each line provide for you, how does it relate to what you've already read, does it give you a new insight into your understanding of how diffusion works, or does it raise a question in your mind. Tell us whatever is going through your mind - even if it seems unimportant.

Table 1: Pre-test and post-test mean student performance (N = 42)

	pre-test %	ANCOVA-adjusted post-test %
self-explaining condition (*n* = 23)	*47.0%*	*76.4%*
reading condition (*n* = 19)	*47.4%*	*68.9%*

To ensure students in the self-explaining condition followed instructions to explain, they were prompted if needed by an experimenter, who sat behind them to avoid interfering with the task. It turned out that as in prior work (Chi et al., 1994), students rarely needed reminders to self-explain because they spontaneously followed the prompts that appeared in the text. To control time on task, students in the reading condition were asked to read the text twice, following the procedure in (Chi et al., 1994).

For both conditions, the diffusion text was provided on paper, while the diffusion simulations that the latter part of the text referred to were presented on the desktop computer; students could interact with these simulations (e.g.,. pressing the "start" button began the simulation of the diffusion process on the macro or micro scale in the macro and micro simulations, respectively). All sessions were video recorded, and student utterances following the warm-up session in the self-explaining condition were transcribed.

Does Self-Explanation Foster Learning of Emergent Topics?

To determine if self-explanation fostered learning of emergence over reading, we used an ANCOVA with the *pre-test %* as the covariate and *post-test %* as the dependent variable. This analysis showed that overall, students performed significantly better on the post-test in the self-explaining condition as compared to the reading condition ($F(1, 39) = 4.98$, $p = .03$, $\eta^2 = .086$; see Table 1 for details). Thus, in contrast to Asterhan & Schwarz (2009), in our study self-explanation was beneficial for learning of emergent topics.

Since one of our primary goals was to gain insight into the relationship between the content of students' self-explanations and learning of emergent topics, for the remainder of the paper we focus on the self-explaining group.

What Types of Self-Explanations are Associated with Learning?

To investigate whether *what* students explained was associated with learning, we labeled each student self-explanation in the transcribed protocols as follows (see Table 2 for examples):

- *macro-level* self explanations expressed ideas about the "big picture" visible level of diffusion that one could see with the naked eye
- *micro-level* self-explanations referred to molecules and/or their interactions
- *inter-level* self-explanations connected micro-level concepts to the visible macro level
- *other* self-explanations related to concentration and miscellaneous topics

Table 2: Excerpt of the diffusion text (top) and examples of corresponding self-explanations (left) and self-explanation type (right)

[Text]: Eventually, the ink molecules are spread evenly throughout the beaker, and the diffusion process appears to have come to an end. [**EXPLAIN**]

Um eventually the whole thing of water will be one color	macro level
It appears that it's .. it's stopped because it the entire beaker is like the same color there is no more mixing I guess	macro level
So this is when the dye molecules of eventually collided in every area possible in the container which causes the ink molecules to disperse	micro level
the molecules are always moving and they are always gonna be sliding past each other and colliding so I don't know if diffusion ever comes to an end per se	micro level
So it's all done equilibrium is reached and then they [the molecules] are still moving but you cant really tell cause it's all the same color	inter level
Pretty much spread out the whole thing and once you see the beaker a certain color because the molecules from the ink has evenly divided with the water	inter level

Table 3: Excerpt of the diffusion text (top) and examples of corresponding of paraphrase (left) and paraphrase type (right)

The macro level pattern of diffusion is fairly clear: The initial dark concentration of ink in one area of the beaker gradually spreads out until the whole beaker becomes evenly – but not as darkly – colored. **[EXPLAIN]**

Um that when you drop the beaker in that's where the flow of dye starts to go	Macro Paraphrase
So from the direction where the dye was dropped or where they dropped the dye into the water that is the starting point from where it moves on and then it swirls around	Macro Paraphrase

As far as the grain size of the coding, following an explain prompt in the text, students tended to express an explanation that encapsulated a single, high-level idea. Thus, for the vast majority of cases, the grain size for the coding was the entire explanation a student provided following such a prompt. If the content of a student's explanation involved a given level (e.g., micro), then it was coded as such even if the text included a macro-level idea (e.g., see *micro level* rows in Table 2). The rationale behind this choice was that unless students made explicit the link between levels, there was no way to objectively identify when they were reasoning in an inter-level fashion.

As a starting point, we relied on the definition in (Chi, 2000) and did not differentiate between self-explanations that were paraphrases vs. ones that included inferences beyond information in the text snippet students read prior to generating the explanation (the latter are referred to *self-explanation inferences, SEI* (Chi, 2000)). Instances not considered self-explanations corresponded to cases where students merely re-read the passage verbatim, or expressed a fragment that did not include sufficient information to determine a code.

If we consider all four categories of explanations (including the *other* category), there were a total of 1087 explanations, or 47.2 on average per student. Since there were a total of 54 prompts after the warm up (43 generic and 11 specific prompts), this analysis shows that on average, students responded to the prompts with some type of self-explanation in the majority of cases.

For the reminder of the paper, we focus on the macro/micro/inter-level explanations. Note that these three levels are not unique to emergent processes – in fact, Chi et al. (2012) describes how other types of processes also can be characterized by these levels. However, the characterization of emergent processes at each level as well as across levels is unique, as compared to, for instance, sequential processes (for a full description, see Chi et al. (2012)).

Students expressed a total of 993 self-explanations related to macro, micro and inter-level concepts, with each student producing on average 43.1 total such explanations. On average per student, inter-level explanations were least common (M = 8.5, SD = 4.5), followed by macro-level explanations (M = 12.9, SD = 4.4), and micro-level explanations (M = 21.7, SD = 3.5). Students generated significantly fewer inter-level explanations than macro-level explanations (paired test $t(22) = 2.6$, $p = 0.01$, $d = .6$) or micro-level explanations (paired test $t(22) = 12.9$, $p < 0.01$, $d = 2.7$); students also generated fewer macro-level explanations than micro (paired test $t(22) = 5.9$, $p < 0.01$, $d = 1.2$).

How were different types of self-explanation (macro, micro, inter-level) associated with learning outcomes? To address this question, we conducted a correlational analysis between each type of explanation and pre- to post-test gains (calculated using the difference between pre-test and post-test, i.e., *post-test % - pre-test %).* Macro-level explanations were negatively associated with pre- to post-test gains ($r = -.46$, $p = .029$), while both micro- and inter-level explanations were positively associated with pre- to post-test gains ($r = .43$, $p = .04$ and r = .44, $p = .04$, respectively).

As we reported above, the post-test did not include many purely macro level questions, and so one possibility is that we are simply not measuring learning related to these concepts. This conjecture doesn't explain, however, why macro-explanations may have interfered with learning as suggested by the negative correlation. We propose an alternative interpretation, namely that macro-level self-explanations are straightforward for students to generate (as was also found, for instance, by Levy and Wilensky (2009b). This is because macro-level concepts relate to visible phenomena that students are exposed to in daily activities (e.g., dye swirling in a liquid after it is dropped in), and so likely know about already. This conjecture can be strengthened by investigating the number of correct vs. incorrect explanations generated. This coding confirmed that macro-level explanations are clear-cut compared to the other types of explanations, in that students expressed significantly fewer incorrect macro-level explanations, as compared to the number of incorrect micro-level explanations ($t(22) = 2.6$, $p = 0.02$, $d = .6$) or incorrect inter-level incorrect explanations ($t(22) = 2.8$, $p = 0.01$, $d = .6$). Thus, by generating explanations about macro-level concepts that they for the most part likely already knew, students were missing opportunities to explain about aspects that they did not know related to micro and inter-level phenomena.

Self-Explanation Inferences (SEIs) versus Paraphrase Explanations

While in general there is evidence that self-explanations foster learning, this should be particularly true for explanations that include content that goes over and beyond the text the student read previously to generating the explanation, i.e., that *SEI* > *SE* as far as learning of diffusion is concerned. To address this question in the context of an emergent domain, we labeled each macro/micro/inter-level explanation as follows:

- *SEI* if the explanation contained domain-relevant material over and beyond what was provided in the text associated with the explanation, and
- *paraphrase* otherwise

Table 2 provides examples of SEIs (content over and beyond what was provided in the text underlined), while Table 3 provides examples of paraphrase explanations. On average, students expressed the following number of each type of SEI explanations: macro (M = 10.2; SD = 4.1); micro (M = 17.1; SD = 4.6), inter-level (M = 8.3; SD = 4.6); for paraphrases explanations, students expressed the following number of each type: macro (M = 2.7; SD = 2.7), micro (M = 4.6; SD = 2.8), inter-level (M = .2; SD = .4). Overall per student, a large proportion of explanations were SEIs (on average 81.5%), highlighting that students were constructive in the self-explaining condition. To see how SEIs vs. paraphrases influenced learning outcomes, we re-ran the correlational analysis from the previous section for each type of explanation. As far as the SEIs are concerned, this analysis confirmed our above results related to micro and inter-level explanations: micro and inter-level SEIs were positively associated with pre- to post-test gains (r = .46, p = .03 and r = .42, p = .049, respectively). The macro SEIs were not significantly associated with learning (p = .23). As far as the paraphrase explanations are concerned, none were reliably associated with learning, although there was a trend for the macro-level paraphrases being negatively associated with pre- to post-test gains (r = -.35, p = .105).

Thus, as reported in the above section, while in general micro and inter-level self-explanations were associated with learning, only when students provide additional inferences in their explanation (i.e., an SEI) was this association reliable.

Do Low and High Gainers Differ in their Self-explanation Patterns?

Another way to examine the association between self-explanation and learning is to divide students into low and high learners based on pre- to post-test gains, and examine their explanation behaviors. To do so, we took the low and high tails of the gain distribution, ignoring the middle group of students. The latter was done since the gains were normally distributed and so doing a straight median split did not correspond to a true low/high gain population, i.e., the students around the middle were not truly low or high gainers.

When we analyzed self-explanations as a whole, without distinguishing SEIs from paraphrases, we found that the high-gainers (n = 7) had significantly more inter-level self-explanations than the low gainers (n = 6; 12.0 vs. 5.2, respectively, $t(11)$ = 3.1, p = 0.02, d = 1.9) and marginally more micro-level explanations (22.3 vs. 18.6, respectively, $t(11)$ = 1.8, p = 0.098, d = 1.1). In contrast, the high gainers had significantly fewer macro-level explanations (10.4 vs. 15.8, $t(11)$ = 2.5, p = .03, d = 1.5). As far as the SEIs, this pattern for the most part held, in that the high gainers had significantly more inter-level SEIs (11.7 vs. 5.0, respectively, $t(11)$ = 2.8, p = 0.02, d = 1.7) and more micro-level explanations (18.7 vs. 12.6, respectively, $t(11)$ = 2.2 p = 0.048, d = 1.3, respectively); there was a trend that high gainers also had fewer macro SEIs but this did not reach significance. Thus, these results support the correlational analysis above that micro and inter-level explanations are associated with learning but macro-level explanations may interfere with it.

What Kinds of Misconceptions Are Present in Students' Self Explanations?

Prior work has indicated that emergence is a challenging domain. Thus, to gain insight into student misconceptions as expressed by their self-explanations, we checked students' macro/ micro/ inter-level explanations for the presence of misconceptions. Students generated a total of 96 incorrect ideas in their explanations; on average per student, 0.68 incorrect macro-level ideas, 1.95 incorrect micro-level ideas and 1.59 incorrect inter-level ideas. However, if we look at the proportion of misconceptions, on average per student, there was a similar proportion of micro and inter-level misconceptions (on average, 39.6% vs. 40.1%), while the proportion of macro misconceptions was lower (on average, 20.3%).

Some of misconceptions pertained to students' incorrect belief that molecular motion is not random (randomness is one of the characterizing features of the agents corresponding to an emergent process (Chi et al., 2012)). For instance, after reading that a water molecule goes to the right side, a student expressed that "I'm guessing a water molecule goes to the other side", i.e., that the molecules exchange places to maintain equilibrium. Along a similar vein, another student expressed that "as one is crossing over, the other ones start shooting over too because there is not enough space for them in that same spot" - this was said despite the fact he was looking at the micro simulation, which clearly portrayed random motion of the molecules.

Another feature of emergent processes is that the agents at the micro level do not intend to cause the macro level pattern (Chi et al., 2012), and that in general, none of the agents embody "intention". As expected, some students expressed explanations contradicting this fact, related to all three levels. For instance, one student explained that "at micro level again molecules are just - water molecules are just *trying* to grab the ink molecules and …. ink molecules are *trying* to grab the water molecules". Other students explained that the "dye molecules just go to the other side *trying to find space*" or that a molecule "crosses to the other side because there is a lower concentration of dye molecules on that side". As another example, a student also generated an inter-level explanation that "once equilibrium has been reached the visible changes at the macro level don't seem to change but suggesting that um at the micro level the molecules are constantly in motion *which I'm guessing is to maintain that equilibrium*".

Yet another feature of emergence is that the micro and macro patterns can be disjoint (Chi et al., 2012). However, some students explained that the molecules followed the macro pattern, e.g., "it shows how the dye molecules are slowly moving to the left side where the water was an the water molecules are slowly moving to the right side where the dye was", and that at equilibrium, "they are still moving but they don't really move that much any more cause the color is equally distributed". Another student echoed this sentiment explaining that "after a while it makes equilibrium and they don't move that much".

Other students thought that only one type of agent was responsible for the macro pattern when in fact all agents are (Chi et al., 2012), e.g., "it seems that the dye molecules are responsible for the flow pattern because they are the ones diffusion to the left side which contains the water molecules". We also saw evidence of so-called inter-level slippage (Blikstein & Wilensky, 2009), when students expressed explanations inappropriately attributing features of a given level to another. For instance, during diffusion, the molecules move randomly, but at the visible macro level, there is a predictable pattern where the dye spreads from high to low concentration. However, students would attribute the random attribute to the macro level, e.g., "it's a liquid so it's going in random directions". Another student reasoned in the opposite direction, by saying that "in the micro level the elements moving from the high concentration to the low concentrated part". Yet another explanation concluded that the molecules "are gonna diffuse as it says and it becomes one particle instead of two", which may be an indication of attributing the uniform color of the water at equilibrium to the molecules somehow combining into one type of molecule. Along a similar vein, another student explained that "eventually … all the molecules are the same color".

Discussion and Future Work

In this study, we focused on students' verbally-expressed self-explanations in an emergent domain. In contrast to prior work (Asterhan & Schwarz, 2009), we found that self-explaining was beneficial, more so than reading. One possible explanation for this difference in results between our and prior work may relate to the context, in that in our study, students worked alone, as opposed to the Asterhan and Schwarz study where students worked collaboratively (and so other constructs that were analyzed, like argumentation moves, may have overshadowed explanation effects). We do acknowledge that only the students in the self-explaining condition had specific prompts (related to the simulation), which may have had an especially beneficial effect. However, these types of prompts corresponded to about one quarter of the total prompts (i.e., the majority of the prompts were generic in the self-explaining condition), and so were unlikely to account for the majority of the explaining benefit.

Having determined that self-explanation is more beneficial than reading, we then focused on analyzing how the content of students' explanations related to their learning outcomes. We found that only micro and inter-level explanations were associated with learning. Differences between low and high gaining students mirrored this pattern, in that the high gainers preferred to generate explanations related to micro and inter-level concepts, while low gainers preferred generating macro-level explanations. This highlights that the types of explanations students generated were driven by individual differences instead of merely by the text students were reading. In a sense, the low gainers may have preferred to invest less effort and so deferred to explanations that were easier to produce (as is suggested by the lower error rate for the macro explanations, as compared to the micro and inter-level ones). Other work in non-emergent domains has also shown that low gaining students prefer to engage in unproductive behaviors, such as guessing and checking (Baker, Corbett, Koedinger, & Wagner, 2004), since these require less cognitive effort than trying to understanding the underlying domain.

Our work suggests that a fruitful future avenue for supporting emergent learning from self-explanation corresponds to encouraging students to generate micro and inter-level explanations, for instance via prompts embedded in digital environments. An open question, however, is whether in order to fully understand emergence, students need to acquire the necessary emergent schemas, and so require schema training, as proposed in (Chi et al., 2012). Others propose that students' exposure to emergent concepts through guided interventions may be sufficient (Jacobson & Wilensky, 2006). These avenues await future research.

References

Asterhan, C. S. C., & Schwarz, B. B. (2009). The role of argumentation and explanation in conceptual change: Indications from protocol analyses of peer-to-peer dialogue. *Cognitive Science, 33*, 373-399.

Atkinson, R. K., Renkl, A., & Merrill, M. M. (2003). Transitioning from studying examples to solving problems: Effects of self-explanation prompts and fading worked-out steps. *Journal of Educational Psychology, 95*(4), 774-783.

Baker, R., Corbett, A., Koedinger, K., & Wagner, A. (2004). *Off-task behavior in the cognitive tutor classroom: when students "game the system"*. In Proc. of SIGCHI Conference on Human Factors in Computing Systems (CHI'04), 383–390.

Blikstein, P., & Wilensky, U. (2009). An Atom is Known by the Company it Keeps: A Constructionist Learning Environment for Materials Science Using Agent-Based Modeling. *International Journal of Computers for Mathematical Learning, 14*(2), 81-119.

Chi, M. T. H. (2000). Self-explaining expository texts: The dual processes of generating inferences and repairing mental models. In R. Glaser (Ed.), *Advances in Instructional Psychology* (pp. 161-238). Hillsdale, NJ: Lawrence Erlbaum Associates.

Chi, M. T. H., Bassok, M., Lewis, M. W., Reimann, P., & Glaser, R. (1989). Self-explanations: How students study and use examples in learning to solve problems. *Cognitive science, 13*(2), 145-182.

Chi, M. T. H., de Leeuw, N., Chiu, M. H., & LaVancher, C. (1994). Eliciting self-explanations improves understanding. *Cognitive Science, 18*, 439-477.

Chi, M. T. H., Roscoe, R., Slotta, J., Roy, M., & Chase, C. (2012). Misconceived Causal Explanations for Emergent Processes. *Cognitive science, 36*(1), 1-61.

Dickes, A., & Sengupta, P. (2013). Learning Natural Selection in 4th Grade with Multi-Agent-Based Computational Models. *Research in Science Education, 43*(3), 921-953.

Fonseca, B., & Chi, M. T. H. (2011). The self-explanation effect: A constructive learning activity. In R. Mayer & P. Alexander (Eds.), *The Handbook of Research on Learning and Instruction*: Routledge Press.

Gadgil, S., Nokes-Malach, T. J., & Chi, M. T. H. (2012). Effectiveness of holistic mental model confrontation in driving conceptual change. *Learning and Instruction, 22*(1), 47-61.

Jacobson, M. J., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *Journal of the Learning Sciences, 15*(1), 11-34.

Levy, S., & Wilensky, U. (2009a). Crossing Levels and Representations: The Connected Chemistry (CC1) Curriculum. *Journal of Science Education and Technology, 18*(3), 224-242.

Levy, S., & Wilensky, U. (2009b). Students' Learning with the Connected Chemistry (CC1) Curriculum: Navigating the Complexities of the Particulate World. *Journal of Science Education and Technology, 18*(3), 243-254.

Levy, S. T., & Wilensky, U. (2008). Inventing a "Mid-level" to make ends meet: Reasoning between the levels of complexity. *Cognition and Instruction, 26*(1), 1-47.

Meir, E., Perry, J., Stal, D., & Klopfer, E. (2005). How effective are simulated molecular-level experiments for teaching diffusion and osmosis? *Cell Biology Education, 4*, 235–248.

Muldner, K., & Conati, C. (2010). Scaffolding Meta-Cognitive Skills for Effective Analogical Problem Solving via Tailored Example Selection. *International Journal of Artificial Intelligence and Education, 20*(2), 99-136.

Muldner, K., Lam, R., & Chi, M. T. H. (2013). Comparing Learning from Human Tutoring and from Observing. *Journal of Educational Psychology*, Advanced online publication. 18 pages.

Nokes, T., Hausmann, R. M., VanLehn, K., & Gershman, S. (2011). Testing the instructional fit hypothesis: the case of self-explanation prompts. *Instructional Science, 39*(5), 645-666.

Penner, D. E. (2000). Explaining systems: Investigating middle school students' understanding of emergent phenomena. *Journal of Research in Science Teaching, 37*(8), 784-806.

Renkl, A. (1997). Learning from Worked-Out Examples: A Study on Individual Differences. *Cognitive science, 21*(1), 1-29.

Resnick, M. (1996). Beyond the centralized mindset. *Journal of the Learning Sciences, 5*(1), 22.

Wilensky, U., & Reisman, K. (2006). Thinking like a Wolf, a Sheep or a Firefly: Learning Biology through Constructing and Testing Computational Theories -- an Embodied Modeling Approach. *Cognition and Instruction, 24*(2), 171-209.

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