Leveraging Fourth and Sixth graders' Experiences to Reveal Understanding of the Forms and Features of Distributed Causality

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ABSTRACT

Phenomena in science and in everyday life often involve effects in which agency is distributed across a number of actors whose individual-level behaviors converge to result in collective outcomes in what is known as distributed or decentralized causality. Research (e.g. Chi, 2005; Chi et al., 2012; Jacobson, 2001; Penner, 2000; Resnick, 1994; 1996; Wilensky & Resnick, 1999) suggests that students find it difficult to reason about macro-level properties that emerge as a result of micro-level interactions. Levy and Wilensky (2008) found that students were able to understand a form of distributed causality related to "scattering" in familiar contexts by constructing mid-level models. This study further investigated students' understanding of scattering and considered two additional forms of distributed causality, converging and spreading. It analyzed the types of information related to pattern and mechanism that students engaged as they reasoned about the features of each form. In-depth interviews, focused on concepts in contexts that the students would be familiar with, were conducted with eight students in fourth and sixth grade. Two interviews were conducted with each student; intervening instructional sessions conducted with both classes were designed to illuminate features of distributed causality. Students displayed more distributed reasoning than anticipated, and also included related forms of reasoning: hybrid and flexible reasoning. They reasoned primarily in the direction of agents towards populations and as would be predicted, increasing interactivity/synergy between agents gave them the most difficulty. They reasoned from lower-level rules as well as agent-based mechanisms related to the endogenous features of the particular agents.

INTRODUCTION

Certain phenomena in science are characterized by a causal structure in which agency is distributed across multiple actors whose actions collectively result in broader outcomes. Tiny ants build massive structures as do termites, bees and other insects. Some of these outcomes have effects that interact and become synergistic in ways that the collective outcome is much more than an aggregation of the contributions. For instance, hundreds of single organisms collectively move and behave together to constitute the super-organism known as a slime mold. Other examples exist at the intersection of science and human behavior, for instance the emergent outcome of global warming as a result of many individuals unintentionally contributing small amounts of carbon emissions. How we understand these distributed and decentralized processes affects our ability to understand human impacts on our environment, as well as our individual and collective motivations for mediating our behavior.[1]

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[1]Distributed causality and the related feature of emergence have been framed as essential features of complexity (Levy & Wilensky, 2008; 2011; Chi, 2005; Chi et al., 2012). The view adopted here is that systems can be complex in many ways (for instance, in terms of spatial and temporal scales; the inferred or obvious features of the variables;

However, research has been mixed on students' ability to reason about instances of distributed causality. A significant body of research suggests that students struggle to reason about decentralized processes; they tend to assume that centralized structures control and direct outcomes and are often surprised by the emergent outcomes (Resnick, 1994; 1996). Students often apply the causal rules operating at the agent level to the broader outcome in direct, linear forms (e.g. Chi, 2005; Chi et al., 2012). Even when using computer models designed to illuminate the connections between interactions at the level of individual actors and the emergent population effects students struggle to think between these levels (e.g. Penner, 2000; Wilensky & Resnick, 1999) More recent research suggests that building upon students' experiences leads to more distributed thinking (Levy & Wilensky, 2008) and that even young children may meet with some success in learning about distributed causality (Danish et al, 2011).

Distributed causality can result in a variety of patterns at the population level, including spreading, scattering, and converging forms. Some of these have been more studied than others. Distributed causality can also entail features that further complicate reasoning. For instance, actors may exist in the same temporal and spatial frames such that they are aware of each other or may be distributed over time and space such that they are not. There may or may not be coordinated intent. The resulting outcomes may have no connection to the intentions of the individual actors and, in some cases, to the intent of the collection of actors such as is the case with actions that contribute to the accumulation of carbon resulting in climate change. These features characterize the dynamics of many complex issues facing humanity and yet little is known about how they interact with understandings of distributed causality. Further, key issues related to the learnability of aspects of distributed causality and the most promising pedagogical paths, as elaborated below, are in debate (e.g. Levy & Wilensky, 2008; Chi et al., 2012). What is not in debate is the importance of the concepts and of expanding our knowledge of how they are understood and learned (e.g. Hmelo-Silver & Azevedo, 2006). The study reported here is an attempt to contribute to that knowledge base.

BACKGROUND

Centralized Mindsets as a Human Tendency

Seminal research by Wilensky and Resnick (Resnick, 1994; 1996; Wilensky & Resnick, 1999) suggested that people hold a "centralized mindset"—the tendency to assume that top-down control structures manage actors' or objects' behaviors. They argued that this tendency made it difficult for subjects to see instances of distributed, decentralized causality. They tested students' understanding in the context of StarLogo, a digital modeling environment that allows learners to consider the relationship between individual behaviors of the distributed agents, such as the birds that collectively make up a flock, ants that make up an ant colony, or cars that collectively contribute to a traffic jam. Students can manipulate the *lower level rules* which refer to the principles that motivate or guide the behavior of individual agents (e.g., in the case of the cars: slowing down when a police car is present, or speeding up when there are no cars in front of you). In some models, students are also able to manipulate parts of the environment, such as how

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potential non-linearities, and so forth (e.g. Fredericksen & White, 2000)) and that distributed causality and its emergent properties is one form of complexity that is critical to understanding many complex systems.

much grass is growing or how many wood chips are available. Intervening to manipulate the lower level rules enables students to observe how individual agents' behaviors can collectively contribute to the outcomes at a population level. These population level outcomes were often highly surprising to the middle school and high school students whom they studied.

Thinking Between Levels

One of the reasoning difficulties that Wilensky and Resnick (1999) identified relates to the challenges of thinking between the levels, those of the individual agents and those of the collective. The causal rules and behaviors at one level were not necessarily the causal rules[2] at another level. For instance, the individual cars on a highway move in a forward direction, but at the emergent level, a traffic jam moves backwards. While agent-based reasoning can occur from the perspective of the agents as participants in the causal system (in which the rules and actions that direct agents' behaviors are discernible), aggregate-based reasoning, is dependent upon the lens of birds-eye view observers (metaphorically speaking) who may "detect spatial and temporal patterns related to the population" (Levy & Wilensky, 2008, p.35). Aggregate-based reasoning focuses on group-level properties, flows between groups, or rates of change of a population (p. 4). Other research has substantiated the difficulties in reasoning between these levels; researchers found that students often brought the lower level rules forward and used them to try to explain the broader level outcomes (Chi, 2005; et. al, 2012).

Much of the research on distributed causality refers to the two levels using the terms "micro" and "macro." However, we use the terms "agent level" and "population level." A significant body of research exists in the learning of ecosystems science (e.g. Hogan & Fishkeller, 1996) on how students reason about microscopic phenomenon and the specific confusions that they grapple with. It is possible to have distributed causality where both the "agent level" and "population level" effects are on a microscopic scale. The choice of terms here is intended to avoid confusions related to this earlier research and to serve in instructional contexts in ways that do not invite confusions about scale.

Defining Aggregation and Emergence

One of the key challenges implicit in thinking about the relationships between the levels has to do with the concept of emergence. Emergence is generally used to refer to the broader level outcomes that are produced by the interactions of the collective individual agents. However, the definitions of emergence and what is involved in an interaction are described somewhat differently in the literature and these differences will become important in how distributed causality is defined and in the discussion of our results. Levy and Wilensky write, "the group level patterns arising from the interactions among the individuals are referred to as "emergent phenomena" (2008, p. 2). Interaction is a key aspect in the framing by Chi et al., (2012) as well. According to Chi and colleagues (2012), "For all processes, the behavior at the agent level can and should be considered as interactions between agents rather than actions of individual agents." (p 6). Further, Chi describes inter-level attributes (ones that characterize the

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[2] Chi does not consider the emergent (or pattern level as she calls it) to be causal and has focused (2005) on a distinction between causal processes and emergence which she deems "acausal" as a reason for students' difficulties. Ina 2012 paper, she uses the term cause but in apostrophes.

relationships between the agent level interactions and the resulting population outcomes) that are chaining, composite, or additive in nature as part of a sequential, direct causal process rather than an emergent one. In this framing, it is possible to have distributed agency with collective outcomes that are not considered emergent; emergence is a possible feature of, but not a defining feature of distributed, decentralized causality.

If one accepts the framing of Chi and colleagues, a number of questions arise about how to differentiate mere collections from those where the aggregate is more than a sum of the individual outcomes. The additive nature of wood chips in a termite tower in Star Logo has this quality. The key question is, at what point does an outcome become "emergent?" Is an additive, collective effect that is unintended by the individual agents, but the result of their collection, an emergent phenomenon? What defines a new level as a different entity—a crowd instead of a collection of people; a slime mold instead of set of one-celled organisms? Further, it can be difficult to decide when agent level interactions actually begin to interact with one another. Take for instance, people jockeying for position to be able to see something in a crowd. At first, their actions may interact in straightforward ways, but soon their interactions may begin to interact as the jockeying if one group of people interacts with the jockeying of others. Chi et al. (2012) describe the interaction of interactions or "second order interactions" as a feature of emergence in which the focus is on agents' interactions relative to other agents' interactions and reserve the term emergence for these instances. This equates emergence with synergistic outcomes. Each of these instances involves a different level of cognitive task with varying levels of cognitive load and dynamic causality. How the findings in the literature are interpreted depends partly upon the level at which one accepts that a phenomenon is emergent.

For our purposes here, and our interest in investigating how students understand distributed causality, we have used three tiers. The first tier includes collections that are additive; there is straightforward adding up of contribution towards an outcome. This level includes aggregates resulting from additive effects that result in a broader outcome than would otherwise be enabled by individual efforts. For instance, the resulting termite mound in Star Logo is enabled by the aggregate effort. Even an aggregate of people, merely adding a bunch of individual actors, if they are all yelling, singing a song, or talking on their cellphones, can lead to deafening noise that is the result of distributed causality. We then consider two tiers related to interaction. Putting a bunch of people in a room might cause them to interact—they talk to each other. At this first level, the interaction between the agents leads to outcomes that are equal to or more than the result of just adding people to the room. These are first order interactions. Then we talk about synergy and synergistic outcomes. These occur when the interactions interact. For instance, someone talks louder to the person next to them to be heard over the other people who are interacting. Others follow suit and soon there is an escalating noise level. While we respect that it can be argued that these have different ontologies, we consider all of these to be a part of understanding distributed causality and to emerge from local level rules even if they are not the form of emergence that Chi et al. (2012) refer to. Therefore, we more broadly define emergent outcomes as outcomes that are not the direct result (intended or not) of the actions of individual agents. We found these distinctions to be useful in operationalizing how to assess children's understanding. Given the students' focus on agency, intentionality, and what they can control, this notion of emergence as a variable beyond their control seemed to gain traction in their reasoning. Here we use synergistic interactions to fit with the definition of emergence used by Chi and colleagues. We elaborate further on these choices below.

Grasping synergistic interactions or emergence as Chi describes it, is challenging. Chi (2005) and colleagues (Chi et al., 2012) investigated students' reasoning and found that students tend to reduce emergent phenomena, interactions, and equilibration processes in self-organizing systems either to linear causality, a centralized model, and/or a deterministic framework. Jacobson (2001) found that students assume a "Clockwork Mental Model" that characterizes phenomena as reductive, with centralized control and single causes. This Clockwork Mental Model, in contrast to the Complex Systems Mental Model (CSMM) that experts tend to use, also involves predictable actions with the magnitude of effects consistent with the magnitude of the action (e.g., small actions can cause small, but not big, effects). Students using the Clockwork Mental Model also focus on static structures and events, as opposed to a process of equilibrium that more complex causal reasoning tends to exhibit.

One of the cognitive challenges of dealing with synergistic interactions involves the cognitive load of holding the actions of many individual agents in mind and reasoning dynamically about how their interactions interact. Programs such as StarLogo are helpful in downloading some of this cognitive. Research on students' interactions with StarLogo suggests that instructional supports can be developed to help students progress in their understanding of distributed causality. Other programs focused on helping students see these outcomes have been used in instructional contexts (e.g. Collela, 2000; Hmelo-Silver et al., 2007; Klopfer, Yoon, & Perry, 2005).

Prior Experience as a Cognitive and Epistemic Resource

While many of the primary institutions and experiences in children's lives—families, schools, sports teams—do have centralized features (Resnick, 1996), many also have decentralized features. Despite the many "top-down" control structures in schools, decentralized control of behavior is an expectation, from how children conduct themselves on the playground to quieting themselves for a school assembly. These experiences vary in their inherent features. For instance, in a noisy cafeteria or assembly hall, individual intent may focus on being heard by the person next to you, but the collective outcome is escalating noise (typically unintended at all levels). The collective behavior embeds distributed agency and a diffusion of responsibility and juxtaposes individual responsibility against those collective outcomes. Students reasoning about these experiences can offer insight into their implicit assumptions about distributed causality.

Levy and Wilensky (2008) argue that students might reveal more understanding in familiar contexts and that these experiences can be recruited to further learning. They explored ways to build upon sixth graders' current experience and reasoning in order to address their difficulties reasoning between levels, from agent-based causality to aggregate forms of causality involving emergence as they define it. First, they interviewed 10 sixth graders' to assess their "predispositions" about a common P.E. class activity called "scattering" in which teachers say, "Spread as far out as you can so that you all have enough room without hitting each other." In this scenario the individual agents act independently, but their behaviors result in a collective outcome at the systems level. The process, therefore, can be examined at two distinct levels: at the level of the child (agent level), or at the level of the spreading through the room (What Chi et al., 2012 refer to as the 'pattern level'). Following these interviews, they offered class activities and discussions related to the spread of rumors and disease.

Levy and Wilensky (2008) then re-interviewed students using a process of increasingly scaffolded reflection on the agent-based and aggregate levels. They found that students engaged in *"Mid-Level Model Construction"* or subgroupings between the level of the individuals and the emergent phenomena to help them in reasoning dynamically about what happened (Levy & Wilensky, 2008, p. 4). For example, they found that, in the scenario of scattering in gym class, students described rows or developed little clusters; in spreading a rumor, they described a process in which each child told a subgroup composed of 3-4 children, and in the spreading of a disease throughout a deer population, the students talked about families of deer. In a later analysis of this data set (Levy & Wilensky, 2011), they found that students used these little groupings to reason about the emergent outcomes that might occur on a smaller scale. They termed this process "paralleling" which describes how this practice might offer a pathway or "steppingstone," a term from the learning progressions research (Wiser, Smith, Doubler, & Asbell-Clarke, 2009), towards understanding the emergent outcomes of the broader population.

Danish, Peppler, Phelps, and Washington (2011) investigated whether younger students can learn about distributed causes and how they interact. They used Bee Simulation software to help first and second graders learn about the complex interactions within the hive. They showed population patterns and individual agent behaviors in contrast on the top and bottom of the same screen and contrasted two behaviors: collecting nectar individually or communicating about it using the bee dances. This allowed students to examine the cases side by side to evaluate the effectiveness of the behaviors. The focus on the bee dance and the interaction of the bees was designed to help students see the effectiveness of these behaviors through the use of contrasting cases (e.g. Bransford & Schwartz, 1999). They found an increase in students' ability to reason about the aggregate behavior levels and to articulate some of the mechanisms by which bees collect nectar. While these results are promising, it is difficult to discern the avenue along which the students reasoned: whether students actually reasoned from lower-level to higher-level rules, or just saw that the bee dance resulted in faster nectar collection.

Incommensurate or a Developmental Pathway? These results can be viewed as Levy and Wilensky have argued—that these studies suggest that it is possible to build upon students' understanding as developmental pathways for learning about distributed causality and emergent phenomena. Wilensky and colleagues (e.g. Wilensky & Reisman, 2006) argue that agent-based approaches to understanding emergent phenomena are developmental and that a focus on agency is developmentally prior. They also argue that agent-based approaches are pedagogically preferable (2008). Alternatively, Chi and colleagues claim that emergence is such a different concept that students do not have a model of it and therefore it must be taught directly. They (2005, 2012) argue that there is a bias towards directed causality and that these schema are incommensurate with notions of emergence—a "you can't get there from here" argument. In this framing, prior experience would be unlikely to offer a cognitive or epistemic resource because it is ontologically unfamiliar—in other words, without explicit training in emergent schema (because the schema is so different) students would have reduced it to a direct linear relationship. We return to this broader question of agency in the discussion section.

Chi and colleagues (2012) attempted to demonstrate this incommensurability empirically. They pre- and post-tested students and used a general process module focused on the structures of emergent processes in contrast to a nature of science “filler” module as an intervention intended to offer an equivalent time commitment. They then taught two concept-specific diffusion modules: one focused on diffusion as an emergent process to the students who participated in the general emergent process module and the other without reference to emergence to those who participated in the filler module. There were no statistical pre-test differences and both groups made significant pre- to post-test gains, but the process module students showed gains with a somewhat larger effect size (d = 1.233 as compared to d = 0.748). On the diffusion pre-tests, they do not report significant differences between the groups, so one assumes that the process-general module learning did not transfer without further direct teaching. However, on the post-test, the diffusion as an emergent process group did outperform the group taught diffusion without emergence by approximately an effect size of one, though both groups made significant learning gains. These results suggest that direct teaching of the schema can be helpful whether or not they offer strong evidence for the incommensurability claim.

We argue here, however, that no matter whether you expect that former experiences will lead to bias as Chi suggests or will offer a cognitive resource as Levy and Wilensky suggest (2008), it has the potential to interact with the instructional equation. Therefore, revealing how students’ reason about prior experience can be an important endeavor. The study by Levy and Wilensky (2008) demonstrates the feasibility of using students’ experiences to make explicit, their implicit assumptions about the nature of distributed phenomena.

Exploring a Broader Set of Population Level Patterns

Scattering is one type of distributed causal pattern. What other types exist and what are their related features? This next section considers common forms of distributed causality that we anticipated students might have experience with. We considered the inherent features of each and ways that might be complexified by other variables related to spatial and temporal scales, the types of agents, and so forth. Each type is framed from and labeled at the resulting population pattern. The forms are not mutually exclusive in a defining way; rather, they represent common characteristics (Smith & Medin, 1991). We considered four forms of distributed causality: scattering (e.g. PE class); spreading (e.g. rumors; civil unrest; trends); converging (e.g. traffic jams; termites building a mound; everyone buys water /batteries before a natural disaster; fireflies lighting; flash mob; riots); and equilibrium (e.g. ecosystems: rabbits and grass, algae in ponds) models. We chose not to investigate equilibrium forms (beyond the aspects of these models inherent to scattering) as part of this study given the considerable focus and extensive research basis related to them in ecosystems education (e.g. Hmelo-Silver et al, 2007; Jacobsen, 2001; Klopfer, Yoon, & Perry, 2005). The list below is not intended to be exhaustive, but rather to capture instances that might be common in the lives of K-6 students. This discussion is a result of an a priori analysis that was conducted in order to guide the development of the study instruments and classroom supports as elaborated below. Following the a priori analysis, observation in four K-6 classrooms (Kindergarten, Grades 2, 4, and 6) and playgrounds was conducted in order to develop interview questions related to common experiences that invite students to reason about the types of distributed causality and the various features. We looked at experiences beginning in Kindergarten because we wanted to focus on situations that students would hold a wealth of experience with.

1) *Scattering Forms:* These forms have been carefully studied and elaborated above in the work of Levy and Wilensky (2008). They involve a process of moving out, often to the confines of a defined space (even in gym class on an open field, if students scatter "too far," teachers will call them back and impose parameters). Scattering forms can be seen in animal communities (e.g., birds in a nesting spot, penguins on an Antarctic landscape), when using community resources (e.g., patrons in a library, umbrellas on a beach), and in the sciences in aspects of the gas laws. Scattering forms emphasize spatial relationships, resource allocation, and depend upon a variety of mechanisms from those related to the nature of matter (e.g., simplification of the Pauli Exclusion Principle for a Newtonian World: Matter takes up space; No two objects can occupy the same space) to social conventions around personal space. They may involve simultaneity or may occur in a temporal sequence (for instance, as students enter a room to take a test and find a space away from everyone else who is already seated, or birds landing on a beach.) There may be subgroupings in scattering forms, or each agent might behave homogeneously in response to those around it. The interactive aspects are largely in relation to the dynamic movement of other agents: when the spacing (packing) problem is satisfied, the interaction stops. How extended and interactive the process is depends in part on the homogeneity of the lower level rules. If, for instance, most students are just trying to find a place on the field, it might occur quickly. If, however, some are trying to find a place that is also near a friend, and others are intentionally trying to complicate the process, it may cause the interaction between the agents to be more intense and more drawn out.

2) *Spreading Forms:* These forms are similar, in some respects, to scattering because they involve an outward movement from a precipitating source. For instance, rumors may be traceable to a given source, trends, disease, and civil unrest may spread from an identifiable, "ground zero," provocative event, misunderstanding and so forth. However, the underlying mechanisms may be very different. They may involve forms of physical and social contagion and these may result in synergistic, second level interactions when emotion and actions become woven together. They also have a temporal or sequential quality in that domino-like and branching relationships may unfold over time. These aspects of spreading forms of decentralized causation should be accessible to students according to Chi (2005; 2012) because they share an ontological structure with directed forms of causality. The synergistic, emergent outcomes as the second level interactions unfold would presumably require holding an emergent causal schema.[3]

3) *Converging Forms:* These forms exhibit the opposite population pattern and result in the drawing together of the distributed agents towards a collective outcome. It could be a termite mound, ant hill, flash mob or fireflies lighting to signal others. These forms can also have a "tragedy of the commons" (Hardin, 1968; Senge, 1990) character such as when everyone converges on the roads at the same time, overpopulates the best beach, or all rush out to buy water and batteries before a natural disaster. These forms may involve many different

[3]Chi et al. (2012) would not consider the aspects of sequential contagion to be emergent, but resulting simultaneous contagion might be, however, the feedback loop in escalation requires a sequentiality that probably puts this form of synergy outside their definition of emergent.

mechanisms, termites as builders, creative collaboration, resource desirability, panic, greed (as suggested by Senge, 1990) and so forth. The convergence may extend or be condensed over time. This form may serve productive goals, such as the building that results from termites or the light from groups of fireflies for example; alternatively, civil unrest and riots may lead to destructive outcomes.

The Role of Complexifying Features

Instances of distributed causation can be influenced by variables that complicate the relationships between levels along a number of dimensions. Dimensions such as these can result in complex behaviors that violate students' assumptions (e.g. Hmelo-Silver & Azevedo, 2006). Common complexifying features include the following:

Spatial distribution. Reasoning across spatial scales becomes especially complex when confounded with distributed causality. The agents may be spread out within a given space such that they are still aware of one another or they may be far flung from one another. How close they are can impact how much they interact with one another. It is possible, however, to have synergistic outcomes even in instances when agents are highly spatially distributed. Spatially distributed agents can substantially increase the cognitive load of reasoning about distributed causality; agents are difficult to hold in mind from an attentional stance and, in cases where they interact with one another, it can be challenging to conjure up what those interactions might be like, especially if the mechanisms for their interactions are unfamiliar. (Alternatively, people may know just enough about how a mechanism works to enable them to project the interactions despite the spatial distribution. For instance, the basic rules for how the internet enables spatially distributed agents to interact would be common knowledge in most societies today.)

Temporal distribution. When the temporal distribution between agents' actions increases, it can reach a point where the many distributed actions are difficult to hold in mind and reason about collectively. The tendency to focus on temporally contingent actions makes it more likely that earlier actions will be missed with those actions closest to the collective outcome taking on the most salience. In order for distributed causality to occur across temporal spans, there need to be ways to bring the collectivity of the actions forward. How easily the distributed causality is detected depends upon the perceptibility and salience of these mechanisms.

Interactivity/ Synergy. Interactivity and synergy as features can be contrasted with simple aggregation. An example here is the difference between just adding more people in the cafeteria example above, the aggregation will result in noise as an population outcome, versus people's tendency to try to speak over each other in order to be heard, so the lower level rules shift and the emergent outcome is also increasing noise. A collection or aggregation without interaction is easier to anticipate the outcome of than an interacting one. This includes amplification and dampening (e.g. accumulating garbage, using less water during a drought) and tipping points at which aggregation is no longer straightforward and certain values have greater impact than others. Interactivity and synergy relates to the discussion above about how emergent outcomes are defined. Here, we define emergent outcomes as outcomes that are not the direct result (intended or not) of the actions of individual agents. By this definition, aggregate outcomes that emerge from the collection of individual actions are considered emergent, though not interactive or synergistic. Note that this differs from concepts of emergence put forth by Chi and colleagues (2012) in which emergence is the result of relations amongst relationships and therefore are a second-order effect. Focusing on emergent effects that are and are not synergistic enables us to differentiate cases where there are collective outcomes of distributed actions (often to the surprise of the individual agents) and those that have the added complexity of synergistic, interactive effects.

Heterogeneous Agents and Rules. In some instances of distributed causality, the distributed agents are homogeneous and behave according to similar rules, such as bouncing molecules in the air. This simplifies the dynamics involved in imagining their interactions and the emergent outcomes. Other instances involve agents that differ and/or follow different rules. Hmelo-Silver and Azevedo (2006) consider heterogeneity of components as a characteristic of complex systems. In the cafeteria example above, there are a range of agents in the cafeteria including teachers, younger students, older students, etc. They may behave in different ways. For instance, some students may react differently to the rule of using indoor voices. Teachers, queen bees, and "leaders" of other types may follow the same lower level rules at some times, but then may step outside of those rules and follow different rule at other times (potentially resulting in more centralized outcomes that pull against one's ability to imagine decentralized processes). This complicates the process of imagining how different agents interact to result in emergent effects. Some of the research has focused on the status between agents. Chi et al (2012, pg.10) allows for heterogeneity in that agents "can behave in disjoint or non-matching ways" as long as "all interactions have equal status with respect to the pattern. (There is no leader or a subgroup of agents whose interactions are more controlling than others.)" Here status appears to be about level of control only. However, this is difficult to operationalize because different kinds of impacts are likely to have different levels of impact, thus different levels of control in different instances. Imagine one or two boys in the cafeteria who are exceptionally loud compared to the others. Even though they share the same status, they would have a differential impact on the emergent outcome. In this sense, the definition of emergence would be dependent upon the particulars of the situation.

Unaligned Intentionality. Issues of intentionality complicate the process of thinking between levels. The resulting emergent outcomes are often entirely unaligned with the lower-level rules guiding the behavior of individual actors. Climate change offers a good example. People drive their cars intending to go about their daily affairs, but the collective emergent outcome is the increased carbon precipitating climate change. Chi and colleagues argue that in order to be an emergent process, "Interactions are undertaken by the agents with the intention of achieving local goals only without any intention of causing the (changes) in the pattern. The pattern emerges from the local interactions of all the agents" (2012, pg. 10). This rules out instances of distributed causality that have aligned local and global outcomes, including efforts to make local changes with the intention of impacting global outcomes such as moderating our production of carbon in service of doing ones' part about the issue of climate change. It implies that awareness of the broader outcomes and attempts to align ones' local and global actions actually changes the nature of the process or phenomenon. Here, we consider unaligned intentions to be a source of cognitive challenge and surprise, but not a definition of the process itself as emergent or not. The goal of our instructional efforts is to teach students to better anticipate the emergent outcomes and to align their local actions with those outcomes.

The relationship between pattern and mechanism

The causal induction literature looks at both patterns of covaration and mechanism and the role that they each play in children's causal reasoning (e.g. Gopnik & Schulz, 2007; Sobel & Buchanan, 2009). The patterns that students notice can be contingent upon the mechanisms they believe are involved and their assumptions about how those mechanisms behave. For instance, if students conceive of the mechanism in electrical flow as being substance-like, they may be more likely to produce direct, linear consumer-source models (Perkins & Grotzer, 2005; Shipstone, 1985, Sudbury et al. 2000). Focusing on weight as the mechanism in sinking and floating often leads to direct linear instead of the relational models driven by density-focused mechanisms (Raghavan, Satoris, & Glaser, 1998). Even distinctions such as whether students view the agents as homogeneous or heterogeneous can hinge upon background mechanism knowledge. For instance, teachers often refer to molecules in the air and their behavior as homogeneous, but if students know that air contains molecules (such as oxygen) and atoms (such as hydrogen) toms (or any of the noble gases), then they are viewed as heterogeneous. The same is true with the underlying theories of how girls and boys would behave differently (as in the example of scattering in gym class in Levy & Wilensky, 2008.)

Here we are interested in what students know about the nature of causality referring to the particular schema and rules in play. However, we anticipate that by studying instances of causation (Pazzanni, 1991), how students think about the mechanisms in particular instances will impact how they understand and explain the population level patterns. Therefore, how they integrate this information and how it differs across problem types is of interest in the study.

RESEARCH QUESTIONS

This study treated everyday experiences as potential cognitive and epistemic resources the way that Levy and Wilensky (2008) do that might be recruited towards instructional goals. It sought to explore children's thinking about three different distributed causal models (defined at the population outcomes level) and to use children's experiences to consider implicit assumptions that they might hold. The overarching research questions that it asked were:

1. Which forms (scattering, spreading, converging) and features of distributed causality might students reveal aspects of understanding in contexts designed to elicit, enable, and scaffold their expression and learning?
2. What characterizes these understandings?

It also sought to further illuminate the following questions:

3. What is suggested about the learnability of the concepts and/or their incommensurability with forms of reasoning in their experience?
4. What are the implications for leveraging children's everyday experiences as cognitive and epistemic resources in learning about distributed causality?

The probes and analysis were designed to illuminate aspects of pattern and mechanisms that students engaged and how they reasoned about each. The focus was on studying the reasoning of a small number of students in depth over multiple sessions in order to gain insight into how they framed their interpretations.

METHOD

Design

Over a four-month period during the 2011-2012 school year, two classes of students (n = 40) from public schools, a fourth grade class in Cambridge, MA and a sixth grade class in Lawrence, MA, participated in pre- and post-assessments and a set of curricular activities designed to illuminate aspects of distributed causal understanding and to support students' understanding.

Both schools serve diverse communities in terms of ethnicity and SES, have significant populations with limited English proficiency and special learning needs. In Cambridge, 45% of students are economically disadvantaged and the ethnic mix is 35% Caucasian, 35% African American, 15% Latino, and 15% Other. Approximately 40% of students are eligible for free or reduced lunch. The school in Lawrence serves a population that is approximately 86% Latino, 10% Caucasian, 3% African American, and 1% Asian. One fourth of the students have limited English proficiency and one fifth has special learning needs. Approximately 65% of students are eligible for free or reduced lunch. The study included fourth and sixth graders because in related research in which one would have expected developmental differences (and would have predicted an increase in ability) we found that the fourth graders gave more sophisticated answers in some respects possibly due to the effects of the school curriculum or cohort effects due to their age or the particular group (reported in Grotzer, Duhaylongsod, and Tutwiler, 2011).

Each class participated in four to five classroom sessions (depending upon the amount of time available in each session—ranging from 45 to 60 minutes in length). Four students from each class participated in pre- and post-interviews—lasting approximately 40 minutes in length (n = 8). Teachers selected two students from each gender to represent a balanced group across achievement levels. The interviews focused on common student experiences and the curriculum activities. All of the sessions were video and audio-taped. The interviews were transcribed for later analysis.

Interviews

Students were presented with scenarios from different domains and were asked to explain the causal processes taking place. The interview scenarios focused on content that students would be familiar with from their own experiences, such as escalating noise in a cafeteria, things that go viral on the Internet, or how children space themselves evenly on a rug during classroom meeting time, and invited students to discuss the features of distributed causality. The questions were balanced across the forms of distributed causality as indicated in Table 1. The questions invited students to reason about the complexifying variables as listed. Some questions also included near transfer questions such as how birds distributed themselves evenly on a nesting site. First a pre-interview was conducted in order to observe students' initial thoughts and to provide a baseline of comparison for the post-interview. The post-interview scenarios also introduced some new scenarios that reflected both the classroom interventions, and students' evolving thinking.

Interviews proceeded from an open-ended to an increasingly structured format (e.g., forced-choice format) in order to assess both how students framed the concepts on their own and how they addressed specific aspects of the concepts. For example, students were first shown a picture and asked, "What do you think is going on here?" The questions then became partially structured and drew students' attention to the patterns: after showing the students a picture of birds in their nests spread out evenly on the beach they were asked, "See these birds in their nests? How do you think they got that way?" After they responded students were then directed to "Look at how neatly spaced out they are. No bird built their nest on top of another bird's. Each bird has space around its nest. Have you seen anything else that spreads out like this? How do you think it got that way?" Eventually the interview became highly structured so students were eventually asked to state a preference between a forced choice set of responses: "I asked two other students how the kids got spread out on the rug. One kid said that the teacher told kids where to sit. The other kid said that the kids decided where to sit. Which do you agree with most—that the teacher said where to sit or the kids decided? Please explain your choice." The structured multiple choice format made it possible for students to choose distributed causal responses even if they were unable to generate them. We anticipated that students might use agency-based reasoning more in the versions of questions with human agents than animal agents given the powerful nature of agency-based reasoning (Carey, 2010; Meltzoff, 2008; Wilensky & Reisman, 2006).

Table 1. Alignment of Interview Topics with Distributed Causal Form and Complexifying Variables

Distributed Causal Form			**Complexifying Variables**
Scattering	**Spreading**	**Converging**	
• Birds on a beach • Kids on a rug • Gym class	• Marching (Hup 2,3,4) • Catch-phrase* (Z&F) • Viral*	• Ants • Termites • Cafeteria*	• SSA (Spatial distribution) • 4-Square (heterogeneous agents) • Cafeteria (amplification or dampening)* • Catch-Phrase (amplification or dampening)* • Viral (temporal and spatial distribution; exponential growth)

*Questions that invited students to reason about synergistic interactions.
Note: Placement of an interview question is also dependent upon the level at which it is interpreted and upon the lower level rules that give rise to it. For example, the cafeteria problem could be an example of converging (many people ending up in one spot) or equilibrium (not studied here) if students are instructed to wait in line when too many people are in the cafeteria at once. And so on.

Class Activities

The students participated in a set of classroom activities focused on the dimensions of distributed causality. The number of sessions ranged between four and six, and were 45 to 60 minutes in length depending upon the available time (and accounting for the differences in the number of sessions), and focused on the four concepts as described in the next paragraphs . The sessions were taught by a researcher and the classroom teacher. The intervention components included activities that engaged students in distributed interactions with emergent outcomes: 1) as participants where they were a part of the pattern and could feel a sense of agency and; 2) as on-lookers where they were able to see the overall pattern as it emerged from the distributed interactions. Some activities were designed to fit with the curriculum at that grade level. For instance, the sixth graders studied slime molds and the fourth graders studied erosion. Other activities were designed to support learning of the distributed causal features but not specific curriculum content, such as sequencing and clapping interactions or the interactions of termites and ants. A full curriculum developed from these sessions will be available at: http://gse.harvard.edu/uclab/

Introducing a Distributed Causal Schema. The first focus introduced phenomena that involved clear examples of distributed causal schema. It considered variation in how distributed causality plays out and that distributed causality is not just part of the non-human world but also a part of the human world (e.g., crowd behavior). Students were asked to abstract the deeper structure by reasoning analogically between multiple cases (e.g. fire ant rafts, termites, and flocking birds).

Mapping Between the Agent and Population Levels. A second focus was on reasoning between agent and population levels. Students were given an opportunity to participate in an activity (simulating the BOIDs program from StarLogo) in which they were an agent in a decentralized process and were asked to reflect from both the agent and population levels.

Contrasting Cases. A third focus explicitly contrasted cases of decentralized and centralized processes for accomplishing a task. Students participated in an activity that used each schema. The discussion included reflection on the differences and considered the predictability of each as well efficiency with which each schema "worked" for a lining-up task.

Transferring to Concepts in the Curriculum. The fourth focus connected back to topics that they were learning in the classroom and considered them through the lens of distributed causality. The fourth graders focused on erosion and concepts related to environmental science, whereas the sixth graders focused on slime molds and climate change.

ANALYSIS

The data sources included audiotapes and transcripts from each interview session and students' reflections upon previous sessions in later ones. Students' comments often include examples from the classroom-based activities so the analysis includes that content. Our analysis included: 1) a grounded analysis (Charmaz, 2006) designed to surface emic patterns in students' reasoning. Narratives were developed of how the students changed in their explanations of the task, accompanied by detailed task analyses and consideration of leverage points that may be useful in teaching concepts that embed the causal concepts. It also included an 2) etic analysis of the student interview transcripts to quantify the prevalence of centralized or decentralized reasoning in students' responses. Statements where students indicated that a single agent (or a subgroup of agents) directed the other agents to achieve a local and/or global (pattern-level) goal were coded as centralized reasoning, and statements that suggested that multiple, distributed agents contributed to the emergent outcome were coded as decentralized reasoning. Statements that had no clear causal pattern were coded as ambiguous. Two independent coders scored the data, using ATLAS.TI, until they reached 90% agreement (.79 Cohen's Kappa) with one coder coding 100% of the data and the other coding 25%. Disagreements in coding were discussed until agreement was reached.

FINDINGS

The results are presented in two parts. The first section presents how students reasoned about distributed causality in relation to centralized causality in the pre- and post-interviews. These findings are the result of the etic analysis that looked for particular patterns in students' reasoning in relation to what is already known about the structure of the concept of distributed causality and how it is defined. It also draws upon the results of the emic analysis that revealed patterns in students' reasoning between the two: 1) reasoning in both directions, from agent to population and vice versa; 2) collective interdependence; 3) hybrid reasoning (includes features of both centralized and decentralized reasoning) and; 4) flexible reasoning. The second section offers insights into how students reasoned—the types of information that they depended upon the most and how understanding of pattern and mechanism interacted. Each section considers affordances and limits in students' thinking and discusses differences, where they were evident, between the fourth and sixth graders. How student reasoning appears to have been impacted by the supporting classroom activities is integrated into the discussion of the results with caveats about the suggestive, but inconclusive nature of both sets of findings based on the small, intensive focus of the study.

What did the findings reveal about students' ability to reason about distributed causal forms?

To a much greater extent than anticipated based upon the earlier research (e.g. Resnick, 1994, 1996), students used decentralized reasoning in the pre-interview to explain their answers, regardless of the form of the distributed causal pattern (scattering, spreading, or converging) that the target question anticipated. The earlier research suggested a strong tendency towards centralized causal interpretations. However, on questions designed to enable students to reveal their implicit understandings of inherently distributed causal phenomena, they revealed more ability than anticipated. The counts of the number of centralized versus decentralized responses on the pre-interview shows that students tended to give distributed causal responses in 73% of the instances. The post-interview is not significantly different in response pattern with 78% of the instances resulting in decentralized responses. (See Figure 1.)

Four patterns emerged from the emic analysis that characterized how students typically reasoned. These patterns are described below.

Reasoning from Both Directions: Agent vs. Population Levels. Students described decentralized processes reasoning from both agent- and population-based reasoning forms. Agent-based descriptions were more common which makes sense since students were given the population

Figure 1. Pre- and Post-Interview Counts of Centralized and Decentralized Statements

Pre-Interview Centralized/Decentralized Counts

	Centralized	Decentralized	Totals
Jake	4	11	15
Marcie	3	13	16
Faye	7	19	26
Luke	9	10	19
Shaniqua	3	14	17
Lakeshia	6	16	22
Jim	3	16	19
Jiang	7	15	22
Totals	42	114	156
Percent	27%	73%	

Post-Interview Centralized/Decentralized Counts

	Centralized	Decentralized	Totals
Jake	4	15	19
Marcie	8	21	29
Faye	5	23	28
Luke	9	16	25
Shaniqua	2	18	20
Lakeshia	1	16	17
Jim	4	23	27
Jiang	10	19	29
Totals	43	151	194
Percent	22%	78%	

level effects and were asked to explain them from that direction. There may be other reasons, considered in the discussion, for why agent-based explanations were common.

Agent-based reasoning: The following examples typify agent-based reasoning, where the phenomenon is perceived through the perspective of the participant (and his rules and behaviors). Jiang, a sixth grader, on her pre-interview exemplifies a typical response across the interviews in the bird spreading scenario. It reveals agent-based reasoning where each individual bird chooses a spot, and does not necessarily work with other birds to collectively make a decision. The interviewer asks: "Okay, so they're sitting on their nests. How do you think they got like this?" Jiang replies, "They all picked their own place to settle down so they could keep their egg warm… On her post-test, Faye, a fourth grader, clearly sees the agents as participants in the act of making the cafeteria get louder. She offers the individual-level rules for why they get louder:

> Um, so first someone's talking, they're like "doodoodoloodoo, blah blah blah" whatever. And a couple other kids start talking, and the first group of kids have to talk louder so, um, whoever they're talking to can hear them. And then those more kids start talking, and then they have to be louder to… so other people can hear them. And everyone has to be louder, and louder and louder, so each person they're talking to can hear them.

Aggregate-based reasoning: Fourth grader, Jake uses aggregate-based reasoning on his post-interview when he repeats the emergent outcome of the students getting louder. Despite the experimenter probing about the agent-level rules, he continues to focus on the population level.

J: Um, the kids already in the cafeteria are just getting louder.
I: Mm-hmm. And how are they getting louder?
J: They're like raising their voices.

I: Okay, and so what's happening when they're raising their voices that is hap—that is making it louder and louder?
J: Like, they, they talk like, like, much louder, so like, so it gets louder.

During the pre-interview, fourth grader Marcie refers to the population patterns saying that the birds "look like an array," and that they are in rows with "the same, like, kind of space [between them]." She reasons that this equal amount of space between birds is necessary because of the vast number of birds, and due to the limited amount of land available: "And there's a lot of birds, then you have to make it into rows" (a mid-level construction as per Levy & Wilensky, 2008)). Later, she maps the population level to the agent level without additional prompting. She says, "And, it's like, one person will go here, and then they know the amount of space like—well, bird—they know the amount of space that they need. So one will go here, and like, one will go here." She also identifies the lower-level rules that allow the agents to choose their spots when she says, "they each need a certain "amount of space."

Collective Interdependence. A second reasoning pattern relates to discussions of collective interdependence. Some students, particularly when developing analogies between the behaviors of ants and termites, focused on the idea that when the agents help one another, they help the whole group. These explanations suggest that students connected the levels, realizing that what happens on one level holds consequences for what happens on another. For example, Lakeshia, a sixth grader, says, "Because to help each other out, like to help each other like do something for all of them. I think it's helping all of them and stuff."

Students also emphasized agents collectively contributing to an outcome. This is less complex than actually predicting an emergent outcome because the examples are in the context of explaining outcomes that have already happened or that are readily predictable. However, it reveals students make connections between the actions at one level and the outcomes at another. Jiang demonstrated this reasoning when he spontaneously offered an analogy of a soccer team winning a state championship:

J: Well…soccer teams, they all try to make it into the goal and make it, win games, and win games, so they could, maybe, win the state championship or win the grand…the, like a golden cup or something. And then they have to try hard and they have to work as a team so they can they can get, achieve, what they want to get. So they all have to work together to pitch in, like in football they have to, everybody has to work hard so they could win a touchdown or win, go to the Super Bowl and win that thing that they win.
I: Hm. And how does that remind you of the ants and the termites?
J: Well, they're all trying to work together. And football they all try to work together to get this goal and the termites are trying to…their own goal, is kind of like, to keep refreshed and live long, I think. And their own working hard to build their home together, and then achieve a goal, this goal, I do not know what that goal is.

On her post-test, Marcie reveals an understanding of the need to have multiple agents who contribute to an emergent outcome, such as the ants building a raft and the termites building a termite mound:

M: Because they all stick together like a puzzle piece, one of my classmates said. And umm, so like if one person's like, "there's a hole here" and they say, "Oh, I need to go there." But they don't really say that, they just kinda know, like, when to go. And the termites, it's the same, like one termite can't build like that whole one big thing, because it's huge, like it would take a lot of time like an ant it would just drown, but a termite, it would probably take like years if one termite did that. But if one, like, if like hundreds of termites do that it might take like a day or like a week or something.

This type of reasoning illustrates students' awareness of the separate agents contributing to the collective outcome and that the resulting entity is not possible without the collective effort. In reconciling the differences between students' reasoning here, and that in the earlier decentralized causality research, it is important to keep in mind that students are not being asked to predict emergent outcomes in this work: the end states (in some instances, framed as goal states) are known and so the task is one of reasoning between them and not predicting one from the other.

Hybrid Reasoning. Students' explanations often included aspects of *both* centralized and decentralized reasoning, labeled here as "hybrid" reasoning. In some cases, they used a centralized agent as a catalyst for a decentralized process, or vice versa. For example, when asked how students distribute themselves during gym class, Lakeshia said they "randomly… go to [their] own spaces" (decentralized). When probed further, she said that they do this in response to the teacher's (centralized) directions: "We would be listening to the teacher." Lakeshia hints at this mixed interaction when she says, "we're going to have to know how much space we're going to need to do whatever we have to do in the spot." Jiang demonstrates offers a post-interview explanation with decentralized behaviors (looking at the teacher) that reflect learned expectations of centralized control when he describes being in the auditorium as noise escalates and students respond and get quiet:

J: And then other people, they can't hear their conversation, so they get louder. Yeah, but, we usually, like, I'll be quiet. We just look at the teacher and then we all be quiet for some reason. I don't know why.
I: Yeah? So tell me about that, um, like, who looks at the teacher or what…
J: I think it's, someone hear something or they just look at the teacher 'cause they think the teacher said to be quiet, but the teacher never says to be quiet. It's just, like, they just look at her. I don't know why…for some reason. Yes.

These hybrid examples illustrate that students are able to detect centralized and decentralized features within real world problems. This type of reasoning also mirrors real life: emphasizing that there is often more than one causal pattern at play.

Flexible Reasoning. This type of reasoning is different from hybrid reasoning in that students give at least two different potential responses (e.g., a centralized *and* a decentralized example) for how a population level pattern can unfold. Students often leveraged their own personal examples when describing how events unfold. For example, in the "kids on a rug" scenario, Jiang straightforwardly offers two different options on his pre-interview for how the spreading could have manifested: "Um, they could've either picked the seat, or the teacher could've told them where to sit." Jake demonstrates flexible thinking on his post-interview as he gives a centralized example and then a decentralized example in describing similarities in the ants' and termites' behavior: "I think it's the same because they all follow their instincts and the job is, like, maybe their queens assign them what to do, or it's maybe they just do like random jobs, they just help, they just all like come together into one big bunch and they all help build it…" Jake is able to identify that a centralized agent, such as a queen, can give orders, or that the ants can decide what to do in a more decentralized manner.

Overall, the findings suggest that when given scenarios that have the potential to elicit decentralized reasoning and that students are familiar with, students are able to respond with decentralized explanations. When given the population patterns, they were able to reason towards them from the agent-level rules and could make connections between the levels. They were able to reference centralized and decentralized patterns in situations that encompassed both. Further, with additional scaffolding and support such as a curricular intervention, students are able to describe how events can unfold in multiple ways.

What insights can be gleaned into how the students reasoned and what information they drew upon to support their interpretations?

Reasoning from Lower Level Rules. Above, we discussed how students often adopted an agency-based perspective in reasoning about distributed causality. A common, related tendency was for the students to describe the relevant lower level rules from the agents' perspective. In general, all of the students used lower level rules rather consistently when describing the various scenarios. These scenarios often elicited lower-level rules of wanting to be heard, personal space, comfort, and meeting biological needs. It makes sense that the lower-level rules would be a point of focus because these are connected to the individual, agent-based perspective with which students would be most familiar. Common responses to the scattering scenarios include Jiang's in response to the bird scenario, "They probably like, looked, looked around for a right place to put their egg. And then to have it hatch there, because they don't want a bumpy place or like…yeah." And Shaniqua's in response to the gym scenario, "To say—yeah, to say to other people that that's where you're being, and if they're touching you, then they just need to spread a little bit more." Jake gives an example of a lower-level rule in response to this ants/termite question—a converging causal form scenario. He claims that when the agent realizes that the structure is not sturdy, s/he goes to make it sturdier: "Like, if like something's unsteady, like oh, I need to go build the—I need to go and need to like make this sturdier or something like that. In the cafeteria scenario, another converging phenomenon, most students gave the lower-level rules of wanting to be heard as a reason for the noise increasing. Jiang describes each student getting louder in order so that everyone can hear what others are saying, "Well, each kid, like I said, they can't hear each other so they have to get louder so they can listen to the conversation, what each other is saying."

Reasoning from Mechanisms. Consistent with the research findings on causal induction (e.g. Schlottman, 1999) many students reasoned from mechanisms to explain what they thought might happen. Many of these addressed endogenous features of the agents, including instinct and contagion. As elaborated in the third section, students were more likely to use different mechanisms (communication vs. mimicry) based upon the type of question and form of population outcome. Students are merely attending to the method of communication that is naturally associated with the act (i.e., one isn't likely to mimic someone watching a You Tube video, but rather tell someone to watch it). Below, we elaborate on the most common forms:

Contagion as a Mechanism: The emic analysis revealed that students tended to use forms of contagion to describe decentralized processes: contagion by communication (involves a process of passing information or knowledge from agent to agent) and contagion by mimicry (the "followers" model the behavior of an individual or group of individuals without being told to do so). It was primarily found in spreading forms. It is possible that understandings of contagion have been documented from understanding of disease and germs as it is well-documented that children begin to develop these concepts in the preschool and kindergarten years (Kalish, 1996, 1997; Keil, Levin, Richman & Gutheil, 1999). In the post-interview, for example, Jim describes a process of contagion by communication across spatial gaps when asked how things "go viral":

> "Because people, like, maybe some person in Canada saw it and then they were telling their friends. And then a lot of people in Canada saw it and then maybe one of those people moved and they recommended it to someone in the US or they recommended it to someone in India. And they move or they can call them or they can, uh, email them.... And then it would go all around the world."

Other students suggest that the contagion spreads via communication when they directly tell other agents to look at You Tube videos, or they "[pass] it on from kid to kid" as Jake says. Students in both grades commonly described the Hup-2-3-4 scenario as contagion through mimicry. Three of the four sixth-grade students mentioned contagion by mimicry when explaining the Hup-2-3-4 scenario, saying things such as "They copied each other because they thought it was cool" (Jim), or "They all were following the people who started it … It kept catching on." (Jiang). Jim described contagion as occurring because of both communication and mimicry, acknowledging that contagion is a complex process that does not necessarily occur through one mechanism. He described how he taught his sister how to kick (communication) and then other people saw how they did it and began to copy them (mimicry): "When me and my brothers… I showed some of them, I showed my sister how to kick and then my brother sees it and he would do it and then my other brother would do it. And it would keep going on."

Instinct as a Mechanism: Some students use instinct as a type of mechanism to describe what fueled the pattern-level outcome. Various degrees of instinct were used, ranging from language that might be suggestive of instinct (e.g., "They don't—I don't think they really decide, they just do it" (Jake, post-interview), to the actual use of the term but with various associated explanations. In some cases it is difficult to tell whether students have a deep understanding of what instinct is, or whether they are merely using it as a token explanation. In either case, being able to identify instinct—an endogenous, agent-based mechanism—suggests that students can reason from the agent to explain the population-level outcome. The tendency to utilize instinct as a mechanism was most commonly used to explain the pattern-level behavior in the birds and ants and termites scenarios. Three out of the four 4th grade students (Jake, Luke, and Faye) attributed instinct as a mechanism in the ants/termites scenario in the ants/termites and birds post-interview questions. Faye, in particular, clearly illustrates her understanding of instinct:

> "Something that no one taught them, they just know it from when they're born. Example: sea turtles, they go to the nearest light on the water. So that's why they have to be born at night time because if they're born at daytime they'll just go anywhere in the water and they'll just like crawl around [mimes with hand gestures]. "Oh, where am I going?"

Instinct was not necessarily used only as a decentralized mechanism. Students used it to reason for both centralized and decentralized causality, for instance Jake says:

J: Well, like, [the queen] also might have the instinct to like, tell them what to do to be able to build the thing that they need to build, in order to um, build what they need to build.
E: Hmm. Yeah. Can you tell me what you mean by instinct?
J: Like, like they know, like an instinct is like they know what to do without anyone telling them to do it.

He uses instinct as he considers possible centralized and decentralized explanations:

> "I think it's the same because they all follow their instincts and the job is, like, maybe their queens assign them what to do, or it's maybe they just do like random jobs, they just help, they just all like come together into one big bunch and they all help build it and just, and I don't think… ….Um, they probably tell each other like, to handle that place and to handle this place. And like, and for the ants, they tell them to go there, to go there, yeah" (post-interview).

Reasoning from External/Environmental Triggers and Structures.

Students also spoke of circumstances external to the agents within the environments that interacted with the population level outcomes. These either; 1) acted as "event-like" triggers or; 2) guided agents' behavior due to structural guidance within the environment. Both of these responses fit with earlier research. Resnick (1996) claims that individuals often think of things as initiated via a leader (by lead), or a seed—"some preexisting, built-in inhomogeneity in the environment"—that gives propels the pattern (p. 14). He found that students focused on "seeds" (e.g., "an accident or a broken bridge") when describing how traffic jams begin. Each of these responses involves a focus on external causes that impact the outcome more than the lower-level rules and related internal mechanisms. Resnick (1996) claims that acknowledging the active role of the environment is a feature of decentralized reasoning. Chi refers to "distinct conditions and parameters" controlling behavior at each level but argues that these conditions are different at the agent and population levels. In this sense, constraint-based reasoning alone does not signal an understanding of emergence.

<u>External Triggers:</u> Here, we use the term "triggers" to refer to an external cause that behaves as an event-like influence to initiate certain outcomes in the system. Here, on her pre-interview Faye is aware that external forces can prompt the agents to do a task:

E: … And for the termites they are triggered by the morning, they gotta start working, they gotta build it, they gotta do. And then it's decentralized because each ant knows what they're gonna do, they're going to attach to each other, but they know where to go. And then each termite knows that one, like this group of termites is going to build, this group of termites is going to find water, this group of termites is going to do this. Yeah. So one part's centralized, one part is decentralized. …

Likewise, the flood triggers the ants/termites to escape:

E: I'm not sure that would happen because it's kinda like a rare thing, not for the termites but for the ants because they don't really make the raft that much, it's kinda like an emergency thing when floods happen or when they need to escape quickly in the water.

Environmental Structures: Students also attended to environmental features that structured the agents' experience and behavior. This behavior was unanticipated given the primacy of events in structuring what we attend to and how we parse experience (e.g. Avrahami & Kareev, 1994; Davidson, 1969; Minsky, 1977; Neisser, 1986; Nelson, 1986; Strickland & Keil, 2011). However, Resnick writes, "In Sciences of the Artificial, Herbert Simon (1969) described a scene in which an ant is walking on a beach. Simon noted that the ant's path may be quite complex, but the complexity of the path is not necessarily a reflection of the complexity of the ant. Rather, it may reflect the complexity of the beach. Simon's point is this: Do not underestimate the role of the environment in influencing and constraining behavior. People often think of the environment as something to be acted on, not something to be interacted with. People tend to focus on the behaviors of individual objects, ignoring the environment that surrounds and interacts with the objects." (Resnick, 2009).

The term "external structure" is used to portray the role of environment as exogenous to the agents but to influence the agents' behaviors. (Furthermore, here the environment is viewed as a potentially dynamic element in the system in influencing the outcome and/or agents' behaviors.) It is not termed as a constraint because even if such structures often constrain behavior they can enable behavior. Two common examples involved referring to the role of the cafeteria walls and seats in influencing behavior. For instance, on his post-interview, Luke, a fourth grader says:

L: Um, it's like, because the sound of the, of all the kids in the cafeteria, they probably like, bounce off the walls.

I: Yeah. Okay, so it bounces off the walls and then what happens?

L: And then it goes, like, into one spot, and then it keeps bouncing off the walls, and goes to that spot, and that's where it gets louder and it affects the whole entire cafeteria.

Later, he adds:

L: And then, when we, like, go to our tables, we, well, we have assigned seats, so we, we know where to sit, and, and when I look at like, the chairs, they're all, like apart from each other. They, so, so that we can have a lot of space for ourselves and that we can all have our own space and we can like, all-- …Maybe that's how they were made. Like, maybe the people that made it thought that it would be a good idea if the chairs were spread apart so all the kids can have their own space and they won't, and they won't complain about how much space they get.

Fourth graders tended to address external structures more frequently than the sixth graders in this sample and drew upon their experiences of echoing cafeteria walls, the lines on the gym floor, or naturally-occurring structures on the ground.

Reasoning from concrete and abstract mid-level constructions.

Student responses also included mid-level constructions that bridged the individual and population levels of phenomena, as found in earlier research by Levy and Wilensky (2008). Students used more abstract mid-level constructions (e.g., quiet vs. loud kids, groups of conversations) to more obvious mid-level constructions (e.g., “birds in rows,” “flocks,”). On his pre-interview, Jiang emphasizes groups of conversations in a type of mid-level construction, explicitly bridging the individual level to the population outcome:

I: Okay. Is it—who are the kids? Is it all of them, or some of them, or one of them?
J: It’s probably all of them because it sounds like all of them are yelling at once. And talking in different conversations.
I: Oh, they’re talking in different conversations?
J: Yeah, like, and it’s all making one loud noise.

On her pre-interview, Shaniqua groups at the table level in the cafeteria question when she says, “Because they – conversations grow louder and louder, and it can be happening at more than one table.” On his pre-interview, Jake divides birds into flocks and groups:

J: Um, like, maybe like, kind of like, kind of like communicated. Kind of like, like flock, like each flock for their own little space.
E: Hmmm. So they communicated?
J: [nods]
E: Um, what do you mean, each flock got their own space?
J: Like, maybe there was—it wasn’t just one, like all those birds in like one group, maybe there were different groups.

In these cases, the behavior of the mid-level groups can be described by paralleling, a process written about by Levy and Wilensky (2011), in which the behaviors of the groupings holds similarities to the interactions in the broader process.

Not all grouping was constructed in service of describing decentralized processes. Students also named groups that participated in centralized control. Jiang offered this example:

> “I think that the queen ant tells them what they’re supposed to do. They kind of, like, have different leaders, like in the army, they have, there’s captain and there’s a general and he has his leaders and they tell other people what they’re supposed to do if they’re not doing it right. Like, the queen ant, she might have other royal blood ants and they’re telling the ants what to do.”

What about Synergistic Interactions?

The research above suggests that students are able to reason about distributed causality. There were many instances of reasoning across the first two tiers described earlier: 1) collective, additive, and aggregate phenomenon; and 2) reasoning about interactions between agents. There were many fewer instances of the third tier in which students recognized interactions amongst interactions or synergistic outcomes (what Chi et al., reserve the term “emergence” to explain). This supports what Chi and colleagues (2012) have written about the difficulties of understanding these ontological forms.

Reasoning from the lower-level rules to the population level may be effective when the outcomes are merely additive, but as soon as they become complex in terms of interactions and synergies, one would expect students to struggle with predicting effects as Wilensky and Resnick found (1999). Synergistic reasoning was not common and more often students gave explanations that indicated that they stopped short of describing synergistic interactions. For instance, on his post-interview, Luke gave a number of ways that the noise in the cafeteria might add up, but none of them entail interactions between the interactions of the agents. Asked why there was more noise in the cafeteria, he said,

> “Um, kind of three reasons. One is maybe there’s more kids entering. And two, is maybe each kid, maybe the loud kids are talking even louder. And three is, maybe the kids are just talking, and then, like the sound of them talking is vibrating off the walls, and going into, like, just probably the middle of the cafeteria, and it keeps-- and so it gets louder.”

In another instance, Lakeshia is able to describe the population-level outcome, but she struggles to identify the synergistic interactions between the agents who share videos. She says, “Like for example, on Facebook and stuff, like a video would be posted. Um, videos, music videos and stuff, then like everybody else sees and listens to it, and then they share it, and then like it keeps on going.” When pushed to explain her ideas further, S still focuses on the population-level outcome without detailing the synergistic behaviors between agents: “Just one person listens to a song and then like they post it on youtube, um if we listen to it and then we like it, then we usually “like it” or share it.” [Ok. And so you share it to your friends. And then what happens?] “And then it goes viral, and then everybody else likes it and then they share it.”

There were many examples in which the pattern of reasoning that students engaged could be defined as direct or sequenced. For instance, Marcie refers to an assembly line metaphor as a chain for the ants and termites scenario, invoking the Direct Causal Schema that Chi et al. (2012) discuss, when she says,

> “Yeah, I think people work together. They might not be as fast. They work together, like the assembly line I’ve heard about that, one person does their job and then they pass it to the next person, like you don’t really have to talk unless you’re having a conversation, you don’t have to say, “Okay, I’ll give this to you, and then you can give it to him.” You give directions once, and then you have an assembly line so you just keep going”

However, some students did spontaneously describe lower level rules with an awareness of the synergistic interactions that they would enable. On his pre-interview, Jim described how an individual's increasing volume affected the volume of others in the cafeteria: “Well, first people would start talking. And then another person near them would start talking and they couldn't hear each other so they talked louder. And then the next group who were talking did the same thing and then the next, and the next, and the next, and so everybody was talking really loudly" His explanation demonstrates that he understands how multiple agents can interact to contribute to the emergent outcome: the loud noise in the cafeteria.

On his post-interview, he also gives a synergistic explanation when describing how the agents interact with one another to pass a video along, and thus make it go viral: "I think it means that they posted it on one of those video websites, like YouTube, or something. And then everybody's started watching it, and then everybody knew about it and they were telling their friends and their family. And then they started watching." When asked to explain more, he continues "And maybe some people would copy it and put it onto a different website. And then it would go all around the world." Next, he recognizes that this process can occur despite the spatial separation of the agents: "maybe some person in Canada saw it and then they were telling their friends. And then a lot of people in Canada saw it and then maybe one of those people moved and they recommended it to someone in the US or they recommended it to someone in India. And they move or they can call them or they can, uh, email them."

Finally, he articulates a mechanism for how the interactions between people become synergistic to form the population-level outcome of videos going viral:

I: So how, do individual people look for the video or do they hear about it or how do they find out about it?

J: I think they, sometimes they might hear about it and sometimes I think they're just looking online and they just see it right there and they just click on it and see it and watch it.

I: Okay. So when it goes worldwide is this different people looking for the video or, like…

J: Well, I think it's recommended. Like, a lot of people recommend it and then they can recommend it to family members and maybe they know other people in other places in the world. They tell them, they look at it, and then they tell other people, and it keeps going around and around. And then you get a lot of people looking at it from around the world.

I: Hm. Um, and do you think that when, kind of like, the first few people that see the video, do you think that it starts with one person or does it start with several people at the same time?

J: Well, I think, like, maybe like a few or…amount of people look at it and then, if more and more people like it, then they'll start telling them, like maybe, it starts like at a hundred or something. They might tell their friends, those hundred people might tell their friends to watch it and then if they like it they tell their other friends, and then it goes on and on.

DISCUSSION

The findings here reveal that students used more decentralized reasoning than earlier research would suggest. It replicates findings by Levy and Wilensky (2008) that drawing upon familiar experiences reveals affordances in students' thinking. Students were able to reason between the population and agent levels when the contexts are familiar and/or they were presented with the population patterns or given the patterns at both levels. They also readily adopted the language of centralized and decentralized causality and applied it to relevant instances.

Students use agent and aggregate-based decentralized reasoning. Agent-level reasoning, gathered from emic coding, seems to be more common in the data. This does not come as a surprise as students often emphasize that the pattern begins with one person. There were very few examples in which the students identified a group (e.g., “a group of kids”) as being the catalyst for the pattern. This is in line with other research (Centola, McKenzie, & Wilensky, 2000; Wilensky, 1993, 1997a, 1999a; Wilensky & Reisman, 2006) that suggests students can reason about more complex systems when they use agent-based reasoning, especially as it “leverages children’s intuitions about their own bodies, perceptions, decisions, and actions” (Levy & Wilensky, 2008, p. 9). As such, Levy & Wilensky (2008, p.9) argue “that agent-based reasoning is developmentally prior to aggregate reasoning.”

An important difference between the earlier research and the findings based upon students’ experiences is that the earlier work asked students to predict emergent outcomes is that in this work the end states (in some instances, framed as goal states) are known and so the task is one of reasoning between them, not predicting one from the other. Predicting unknown population outcomes from the agent-based interactions is a considerably more difficult task, involves lots of cognitive load and working memory resources (Feltovich, Coulson, & Spiro, 2001; Narayanan & Hegarty, 1998), dynamic processes, and is something that adults and experts struggle with (Dorner, 1989). There is no easy path between them based upon the cognitive load of predicting many parallel interactions that may have multiple levels of order of interaction between them (synergies).

It is likely that as students today access new technologies they will have experiences that enable distributed agency much more than in the past. This is especially true in the gaming community. Where highly distributed agency results in interactive games, the outcomes of which cannot easily be predicted. Research on members of the gaming community suggests that serious gamers develop both sophisticated knowledge of the games and sophisticated systems reasoning skills (e.g. Liu, 2013).

Students revealed understanding of interactions between agents but only a few students offered instances of synergistic interactions or “second-order interactions.” This relates to the key question of whether students understood the concept of “emergent phenomena.” The answer depends to some extent on how emergence is defined. If it includes the interaction between agents that is characteristic of the scattering activity used by Levy and Wilensky (2008), all of the students revealed some understanding. Chi has argued that these first order interactions fit with a direct schema not an emergent one. Some, such as spreading, were more likely to induce direct schemas. However, if emergence is defined as synergistic schemas or second order interactions, then it was present but to a much lesser extent. Indeed, this seemed to be the most difficult aspect of reasoning about outcomes and presented a hurdle for many students. Some sixth graders reasoned about second order interactions on the pre-test and while we can’t be sure that they have never been introduced to emergent schema formally, if it happened, it did not happen in the context of school according to the sixth grade science teacher. Here, we set out to investigate learning about distributed causal schemas, not solely understandings of emergence.

We consider the reasoning that students demonstrated as representative of distributed, uncoordinated agency to be strong aspects of distributed causal schemas whether or not students have also mastered embedded concepts of emergence.

Incommensurate or Resources to be Recruited?

The discussion above strongly suggests that students recruit their experiences to learn features of distributed causality. This argues that building upon students' knowledge is a strong instructional strategy for learning to reason about the differences between centralized and decentralized causality.

The question of incommensurability that was posed in the extant literature, focused specifically on learning concepts of emergence defined by second order interactions. Many of the tasks that we investigated, such as scattering and spreading by contagion, fit within Chi's notion of direct schema, therefore they do not raise issues of having a different ontology. Students' response to the cafeteria and viral video question do illustrate that some students are able to use notions that involve second order relationships—synergistic interactions—both pre- and post- interview at both ages. These findings show that a few students were able to leverage their everyday experiences to make sense of emergent phenomena whether or not they are ontologically distinct from non-synergistic forms of distributed causality. However, other research has shown that compelling schemas can indeed serve as biases that blind students to other possible schemas (e.g. Perkins & Grotzer, 2005). The compelling nature of agency makes it a candidate for being potentially blinding in some cases even as it may be enabling in others.

Developmental research shows that agency and agency-related schemas make important contributions to learning. Carey (2009) considers agency to be a core aspect of human cognition. Research shows that some of the most powerful learning for infants comes from their ability to carry out actions and to intervene—to be an agent (Meltzoff, 2007; Sommerville, 2007) and to observe the interactions of others (Gopnik & Schulz, 2004; Meltzoff, 2007). Babies also privilege intention and goal-directed behavior; they attend more to behaviors that offer information about an actor's goals than to other behaviors (Woodward, 1998). These abilities become increasing elaborate and textured as they grow (e.g. Woodward, 2003; Janovic, et al., 2007; Baldwin, Baird, Saylor & Clark, 2001). This strong focus on agency-oriented causality can make it difficult to notice forms of causality that are not characterized by this schema, for instance, non-agentive causality such as that in natural systems (Woodward, 2007). Infants "draw limited inferences when no causal agent is present" referring particularly to a human causal agent (Meltzoff, 2007). Goal-directed causality fits well with the direct schemas that Chi has argued characterize non-emergent phenomena. This work supports Levy and Wilensky's assertion (2008) that agentive schemas are developmentally prior. But is also raises the strong question of whether agency is prioritized to the point where it makes it more difficult to recognize other schemas. Chi et al. (2012) has argued that they are so counterintuitive that students have no familiarity with them and they need to be introduced.

Students were able to reason from compelling experiences, their intent, their knowledge of subgroups, etc. The research substantiates that agency, intervention, and the identification of goals is a powerful learning mechanism particularly in causal induction. This can compel interest and learning. Alternatively, it can make it difficult to ascertain instances where agency might lead one astray, where intention is unaligned at the population and individual levels. Knowing what assumptions students hold can be important to helping them to be aware of possible biases. It can be argued that no matter whether you expect that former experiences will lead to bias as Chi suggests or will offer a cognitive resource as Levy and Wilensky suggest (2008), it has the potential to interact with the instructional equation. Therefore, revealing student reasoning about prior experience is an important component of teaching complex concepts. The findings here do not reveal significant pre- post-test shifts in how much reasoning or each type students adopted. However, the instruction did not focus specifically on second order interactions or extracting the emergence schema. Other research suggests that being aware of them as a possible tendency offers students the possibility to be reflective about the schema that they invoke (Grotzer, Kamarainen, Tutwiler, Metcalf & Dede, 2013).

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