DOCUMENT RESUME

ED 441 698		SE 063 822
AUTHOR	Perkins, David N.; Grotzer, Tina A.	
TITLE	Models and Moves: Focusing on Dimensions of Causal Complexity To Achieve Deeper Scientific Understanding.	
SPONS AGENCY	National Science Foundation, Arlington, VA.	
PUB DATE	2000-04-00	
NOTE	24p.; Based on the work of the Understandings of Consequence Project. Paper presented at the Annual Meeting of the American Educational Research Association (New Orleans, LA, April 24-28, 2000). For a related paper on the Understandings of Consequence Project, see SE 063 823.	
CONTRACT	REC-9725502	
PUB TYPE	Reports - Descriptive (141) -- Speeches/Meeting Papers (150)	
EDRS PRICE	MF01/PC01 Plus Postage.	
DESCRIPTORS	Biology; College Students; Ecology; Electric Circuits; Evolution; Higher Education; *Inquiry; *Models; Science Education; *Scientific Concepts	
IDENTIFIERS	Food Webs; National Science Foundation; Natural Selection	

ABSTRACT

This paper presents the results of a research project based on the Understandings of Consequence Project. This study motivated students to engage in inquiry in science classrooms. The complexity of the models is divided into four categories--underlying causality, relational causality, probabilistic causality, and emergent causality--and provides several examples, including electrical circuits, static electricity, natural selection, and ecosystems for scientific conceptions, to show evidence of the Models and Moves framework for learners. (Contains 23 references.) (YDS)

MODELS AND MOVES

Focusing on Dimensions of Causal Complexity to Achieve Deeper Scientific Understanding

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Presented at the American Educational Research Association annual conference, New Orleans, April 24- 28, 2000

This paper is based on the results of research carried out during the first year and a half of the Understandings of Consequence Project. We are continuing to research and develop the ideas presented here. If you have feedback for us or would like to keep in touch with developments on the project, please check our website at http://pzweb.harvard.edu/Research/UnderCon.htm or send us an email at Tina_Grotzer @PZ.Harvard.Edu.

This paper is based upon the work of Understandings of Consequence Project, which is supported by the National Science Foundation, Grant No. REC-9725502 to Tina Grotzer and David Perkins, Co-Principal Investigators. Any opinions, findings, conclusions or recommendations expressed here are those of the authors and do not necessarily reflect the views of the National Science Foundation.

MODELS AND MOVES

Focusing on Dimensions of Causal Complexity to Achieve Deeper Scientific Understanding

SCIENCE IS MORE BAFFLING THAN MAGIC

A magician locks his comely assistant into a cabinet and waves a wand. When he opens the cabinet, the assistant has disappeared—only to reappear in a cabinet on the other side of the stage. Breaking tradition, the magician asks the audience to explain how it was done. Most people say, "A trap door." The magician invites people to tour the stage. No trap door is apparent, but still they say, "A trap door." The magician decides to reveal all. He explains that there are twin assistants. The first assistant is still inside the first cabinet; the second was already hidden in the second cabinet. He shows the audience the two assistants side by side. Most are convinced for the moment. But a week later, many are saying, "You know, it was a trap door."

This story does not have a very plausible middle and end. People examining the stage would probably be convinced that there was no trap door. People seeing the twins side by side would probably not relapse to the trap door theory. It is not a plausible scenario for the magician's audience. However, just such a tale unfolds again and again in science classrooms throughout the world. Students are invited to engage in inquiry. They make up their own initial theories—so far so good—but then they cling to those theories stubbornly in the face of apparent counterevidence. Students hear the received theory and examine supposedly persuasive evidence for it. For a while, they may be convinced, but next week or next month they relapse to their initial views. What's not such a plausible scenario for the magician's audience happens all the time in science learning. For many a learner, science is more baffling than magic.

Why is this the case? One possible answer points to the specific difficulties posed by particular concepts and theories. This certainly is part of the story. However, more general factors may figure in learners' troubles. In the story of the magician, notice how accessible the twins explanation is. It is no more exotic than the trap door explanation, making a shift from the trap door view to the twins view relatively easy. Both reflect the commonsense world of everyday things and actions. In contrast, most scientific models go well beyond causal explanations of ordinary events. They posit invisible entities like electrons, rule systems like Ohm's law that govern the global behavior of systems, and large scale patterns of action that are "emergent" from small-scale interactions, as with the gas laws.

This paper argues that the difficulty of scientific concepts can be explained in large part by two general factors. The first is the limited models of causality most learners have. Their relatively simple styles of causal modeling contrast with the esoteric character of scientific models, what we refer to as *complex causality*. The second is the process of inquiry as learners understand it. They typically have little experience or comfort with *epistemic moves* such as remaining alert to gaps in a causal story or seeking disconfirmation for theories—moves that lead toward more complex models. With complex causality and epistemic moves in mind, we call this theory *Models and Moves*.

Support for the idea that students' causal models and epistemic moves are less than adequate for learning complex science concepts can be found in the research literature. Driver, Guesne, and Tiberghien (1985) outlined characteristics of student thinking that impede students' ability to grasp scientific concepts. A number of these concern how students reason about causality, for instance focusing on changes as opposed to steady states and subsequently failing to see a need to explain systems in equilibrium, or, for instance, the tendency to engage in linear causal reasoning by looking only for sequential chains of causes and effects when systemic patterns are in play. For another source, diSessa (1993) introduced the concept of phenomenological primitives (p-prims), small knowledge structures that people use to describe a system's behavior. These schemata come into play as ready explanations or components of explanations. While often considered to be self-explanatory and to need no justification, p-prims in their very accessibility can lure children and adults into mistaken explanations.

Similarly, Brown (1995) refers to core causal intuitions that can lead students astray regarding a variety of difficult science concepts. Brown focuses on core intuitions about how people attribute agency and how they assess responses to agency. He identifies a number of types—initiating, initiated, reactive, and so on. Andersson (1986) draws upon Lakoff and Johnson's (1980) notion of an experiential gestalt of causation as a possible underlying element in scientific misconceptions. He considers how students extend the primitive notion, learned in infancy, of an agent that physically affects an object to a sense of "the nearer, the greater the effect." Andersson outlines how such primitive notions play a role in difficulties students have in learning various science concepts. Kuhn (1991, 1993) reports research that identifies a number of shortfalls in students' general and scientific reasoning, including difficulty in generating counterevidence and perseveration in a favored theory despite blatant counterevidence. In summary, such research suggests that how we reason about causality influences how we analyze specific instances of causation in science class and beyond.

The Models and Moves theory asserts that learners tend to assimilate scientific concepts to a limited repertoire of causal models that are relatively simple in ways to be specified, and that learners lack a sophisticated repertoire of epistemic moves with which to challenge and perhaps improve their simple models. An important instructional implication follows: Learners will find whole ranges of complex science concepts more accessible when the instruction familiarizes them with the types of models involved and the types of moves that lead toward those models.

The following sections sketch the Models and Moves framework, offering four dimensions of complexity for causal models and four important phases of inquiry for the epistemic moves, with associated pitfalls and remedies. Then learners' initial levels of modeling and reasoning as they first encounter a phenomenon are examined. Such observations provide one kind of evidence for the models and moves theory. For further evidence, interventions designed to introduce learners to more sophisticated models and moves are discussed.

THE MODELS FRAMEWORK

The central notion behind the models framework is *complex causality:* Some explanations are more complex than others in fundamental categorical ways. However, a clarification of terminology is in order. In this line of inquiry, "complex causality" is the umbrella term for our area of interest, and does not always imply complexity in the common sense of intricate or causality in the common sense of A causes B. For instance, Ohm's law neither is particularly intricate nor of the form A causes B. Yet, it sits with other constraint system explanations at a high level of complexity in the framework, as will be seen.

Table 1 presents four dimensions of complexity in models: *Underlying Causality, Relational Causality, Probabilistic Causality,* and *Emergent Causality.* Relative to these dimensions, the causal explanations that people offer for everyday events are simple in several senses. Recall again the accessibility of the twin theory (or for that matter the trap door theory) about the magic trick. The twin theory depends on a *surface generalization,* a simple generalization from previous experiences involving twins and the difficulties of discriminating them. The twin theory proposes a *simple linear* causal relationship: The similarity of the twins causes people to think it's the same person who appears on the other side of the stage. The confusion is seen as nearly *deterministic*—almost anyone would think that the same person had disappeared and reappeared. A *central agent,* the magician with the collusion of the twins, brings about the effect.

In contrast, scientific models exhibit greater complexity, usually on more than one of the four dimensions. Evolution explained by natural selection and elementary electrical phenomena explained by Ohm's law and the behavior of electrons offer apt examples. Italics refer to categories in the framework:

- ***Underlying Causality.*** This dimension refers to the causal mechanisms invoked in an explanation. At their simplest, they take the form of (not necessarily correct) *surface generalizations* from experience, like "animals learn their necks need to be longer" or the token use of labels like "the balloon sticks to the wall because of static electricity." Scientific explanation typically involves one or more levels of *underlying mechanism* involving properties, entities, and rules that are not part of the surface situation, as with DNA or electrons and the rule systems that govern them

- ***Relational Causality.*** This dimension refers to the patterns of interaction between causes and effects. At their simplest, such patterns take the form "A causes B," as in "They needed wings and grew them" or "Electricity makes the bulb light." In contrast, natural selection offers an account of evolution that involves *interactive causality* and *re-entrant causality,* as in for example the co-evolution of bees and flowers. Ohm's law, a *constraint-based* system, addresses electrical circuits.
- ***Probabilistic Causality.*** This dimension refers to expectations about the level of certainty in causal relationships. At their simplest, such relationships are deterministic, consequences inevitable. In contrast, contemporary natural selection recognizes evolution as a *chaotic system.* Ohm's law treats electrical circuits as a deterministic systems, but it is *order from chaos,* averaging effects smoothing out atomic-level events into large scale orderly patterns
- ***Emergent Causality.*** This dimension refers to agency and to the compounding of causes and effects in ways that lead to new and not easily anticipated outcomes. The simplest level here involves central agents with immediate influence: The ducks needed webbed feet; the battery makes the current flow. In contrast, from the perspective of current science, species are *emergent entities* of evolution. Electrical circuits display *self-organizing* characteristics, where circuit configurations can yield unexpected (if you are not in the know) large-scale regularities, as in oscillations.

While each of the four scales ranges from a simple to a complex extreme, no claim is made about strict order of difficulty or of developmental stages. Indeed, the levels of the scales are themselves categories and allow simpler and more complex variations. For example, entirely within the *mediating cause* category of Relational Causality, A causes M causes B seems a more accessible relationship than M catalyzes A causes B. The general claim is the looser one that difficulty increases roughly with complexity along on the scales.

Moreover, it is important to recognize that explanations falling low on the four complexity scales are not necessarily wrong. They may be entirely suited to the phenomenon at hand. The point, rather, is that typical scientific explanations routinely involve more complexity because the target phenomenon demands it, and often learners do not manage to get there.

THE MOVES FRAMEWORK

The central notion behind the moves framework concerns the epistemic moves that serve scientific inquiry, and indeed inquiry in general. The moves framework identifies four broad aspects of inquiry, characterizing each in terms of typical trouble spots and specific moves that address those trouble spots. Table 2 describes the scheme. A characterization of each of the four aspects follows:

Seeking a gapless model. A plausible model does not leave gaps in the causal story it advances. It does not, for instance, beg the question with a *convenient assumption* or posit one thing causing another when it's not clear how or whether the one thing might cause the other, a *missing link.* Efforts to examine a model for gaps and to adjust or abandon the model are part of good inquiry.

Putting the model at risk. Good inquiry also involves putting the model at risk. This includes, for example, being cautious about *positively biased* evidence and about *excusing and patching*—making excuses in the face of seeming counterevidence and patching the model in ad hoc ways.

Detecting flawed evidence. Misleading evidence can lead to the rejection of sound models and the acceptance of unsound ones. Part of good inquiry is detecting flawed evidence, for instance a *very limited sample* that may accidentally mislead or *confounded variables* that do not discriminate which variable wields influence.

Building from counterevidence. Genuinely sound counterevidence for a model does not necessarily imply rejecting the model altogether. If, for example, the model shows *minor discrepancies in central cases* or *erratic performance in the "same" circumstances,"* the model often can be repaired.

While the moves framework includes four categories for completeness, in the studies reviewed and reported here only the first two figure as it happens. Preserving science examples for later discussion, it's worth illustrating the first two by bringing back the magician once more. Explaining the magician's trick with a trap door may risk *convenient assumptions,* such as that the stage truly had a trap door, or even had space beneath it. Facing this challenge, examining the stage, and finding nothing, a proponent of the trap door explanation might *excuse and patch it:* "Well, probably the seam is too fine even to see." As this very ordinary example reminds us, in everyday argument, people commonly make convenient assumptions, excuse and patch favored theories, and so on (e.g. Kuhn, 1993; Voss, Perkins, & Segal, 1991). Sometimes such moves may be legitimate. Frequently they are not.

The moves of good inquiry often drive toward more complex models of the phenomenon being explained. Even the patched trap door explanation makes this apparent: A hard-to-detect trap door demands further explanation about how a trap door could be so seamless. In scientific inquiry, efforts to eliminate gaps, put the model at risk, detect flawed evidence, and build from counterevidence routinely lead to highly complex models of the sort that dominate contemporary science.

EVIDENCE FOR MODELS AND MOVES: LEARNERS' INITIAL LEVELS

With the Models and Moves framework outlined, questions of evidence invite attention. One prediction says that initial conceptions of scientific phenomena should be low on the complexity scales. Notice the issue is not whether the initial conceptions are mistaken by the measure of contemporary science. They almost always would be, given the sophisticated knowledge behind received theories. However, it's possible that initial conceptions would show medium or higher levels of complexity, mistaken or not. Such a finding would disconfirm the Models and Moves theory. Relatedly, the theory implies that initial conceptions should display moves-related problems, the neglect of which allows learners to persist in those models despite shortfalls.

The investigators tested these implications by examining initial conceptions of several science concepts, both in the literature and through classroom-based studies. The results support the Models and Moves theory.

Electrical Circuits

As students learn about simple circuits, they typically find it hard to focus at the level of the system, instead analyzing effects locally (Shipstone, 1985). They commonly offer what might be called a "cyclic sequential" causal account for current flow. They envision the circuit as initially empty. The circuit fills with a "substance-like material" (Slotta & Chi, 1997) that eventually reaches the bulb and causes it to light. For instance, a typical student explanation sounds like this: "The electrons travel into the wire and they go to the bulb and then it lights. The electrons keep going until they are back in the battery and can travel around again. If the wire were longer, it would take longer for the bulb to light because it takes longer for the electrons to reach the bulb."

Turning to the Models framework, from the standpoint of Underlying Causality such learners are explaining electrical flow with a *token agent.* Even when they refer to electrons, the electrons simply fit into a story of flow, rather than the flow reflecting a set of rules that apply to electrons. From the standpoint of Relational Causality, the students' accounts reflect *mediating causality* at best: The battery pushes the electrons and the electrons in turn light the bulb. Regarding Probabilistic Causality, the system is seen as *deterministic.* Regarding Emergent Causality, there are *central agents,* the battery and in turn the electrons. Turning to the Moves framework, students' token agents implicate a serious shortfall in seeking a Gapless Model: a problem of *missing mechanism:* The students tell a story in which the electrons move and light a bulb, but without any account of why they move or how they light the bulb. It is difficult for them to Put the Model at Risk from such a point of departure since a token agent account makes virtually no predictions.

Scientists, on the other hand, might envision the system as described by a "cyclic simultaneous" kind of causality, where electrons already exist throughout the wire. Hooking the wire up to a battery causes flow, the excess negative charge in the battery repelling nearby electrons, which repel other electrons. The current flows all at once, more like the movement of a bicycle chain. The scientists' account involves an elaborated *underlying mechanism* and *interactive, re-entrant (as the circuit reaches equilibrium), and constraint-based (Ohm's law) causality.* "Constraint-based processes" were studied by Chi and colleagues (e.g. Chi & Slotta, 1993) as an area with which learners have difficulty. Constraint-based processes function according to certain laws, such as Ohm's law or Newton's laws; lack an internal causal agent; have no obvious beginning or ending; have interacting components; and have equilibrium as a goal state. Scientists would view the circuit's behavior as deterministic at the macro-level. However, regarding Emergent Causality, the circuit's behavior reaches its steady state through a *self-organizing* process, the equilibration of the charges involved.

Static Electricity

Our own investigations across a number of topics also support the claim that students bring impoverished causal models to their attempts to learn scientific concepts. For example, as well as confirming the above findings on circuit electricity, we interviewed students on static electricity. From the standpoint of received science, elementary electrostatics involves an *underlying mechanism* of electrons, electron displacement, the repulsion of like charges and attraction of different charges, and so on. This mechanism implicates *interactive causality* and also *re-entrant* causality through the process of reaching equilibrium. In contrast, students' explanations in response to basic electrostatics demonstrations tended to take very simple and efficient forms, for example: "I think it happened because the electricity went to the paper to make it stay." "I think it happened because of static electricity." "I think it happened because the electricity from the wool gave it to the balloon." "I think it happened because when you rub the cloth to the balloon something happens to the balloon to make it stick."

Such responses plainly involve *token agents* and *simple linear causality.* Once in a while, students made comments that referred to *interactive causality,* for instance, "There is an attraction between the wall and the balloon. Something about the wall and something about the balloon have been changed and it makes them attract." The interactive causal explanations that students offered were not necessarily scientifically accurate. For example, one student described air pressure as "pushing" the balloon to the wall while the wall "sucks" the balloon towards it using static cling. However, our investigation emphasized not the correctness of the explanation but its causal form. Concerning the Moves framework, the token agents students employed brought along problems of *missing mechanism* and little opportunity to Put the Model at Risk for lack of predictions from the essentially empty account via a token agent.

Natural Selection

Ohlsson (n.d.) offers an interesting set of findings about initial conceptions of evolution. Ohlsson conducted interviews of a number of college students, collecting their explanations for adaptive changes in species over time. Responses recounting Darwinian natural selection were rare. Ohlsson classified the responses into seven categories as follows: *environmentalism,* traits develop when the circumstances present a demand or opportunity; *survival,* the relevant trait and its opposite are in the population, and members without the trait die; *creationism,* God creates the trait; *training,* organisms learn or adapt during their lifetime and pass on traits (Lamarckian); *mutationism,* the trait suddenly appears in small numbers and spreads in the population; *mentalism,* animals decide, discover, learn, or are taught new behaviors or how to give themselves new traits; *crossbreeding,* traits arise via interbreeding between species; *dissemination,* organisms with the trait gradually increase in numbers generation by generation, displacing those lacking it.

The current investigators analyzed these categories from the perspective of the models dimensions. Concerning Underlying Causality, most responses were *composite explanations,* accounting for evolution by piecing together phenomena at the same level as adaptations themselves, rather than underlying level, as with genetics. It should be noted that Darwin's own theory of natural selection was a composite theory—he had no accompanying theory of genetics—albeit one much more complete than the students offered. Concerning Relational Causality, the explanations were mostly *simple linear,* as for instance with *environmentalism*, where the circumstances somehow cause the trait to develop. Concerning Probabilistic Causality, most accounts were deterministic: The adaptation would follow inevitably. Concerning Emergent Causality, there was some recognition of *aggregate effects,* adaptations dominating in a population over time, but also sometimes *central agents with immediate influence,* again as with *environmentalism* where the environment causes the adaptation.

Concerning Moves, various Gap and Risk shortfalls appeared, reflecting the very partial nature of the explanations students offered. One was the Gap problem of *convenient assumption.* In *survival, crossbreeding,* and *dissemination,* the relevant trait conveniently appears or is already in the population. Both *environmentalism* and *training* suffer from *missing mechanism.* In the first case, somehow the environment draws out the adaptation; in the second, somehow the acquired traits are passed along. In summary then, these initial conceptions of evolution fall at the simple ends of the complexity scales and implicate Moves problems as well.

Ecosystems

Research suggests that most teachers consider ecosystems and the related concepts of food webs and food chains important topics for students to learn (Barman & Mayer, 1994). However, this research also found that teachers consider these topics to be relatively easy for students. The wealth of investigations examining students' misconceptions about ecosystems contradicts this belief. A full scientific account of ecosystems is a formidable construct, involving *underlying mechanisms* such as bacteria (Underlying Causality scale), *interactive causality and re-entrant causality* (Relational Causality scale), *chancy* and *chaotic systems* (Probabilistic Causality scale), and *causal webs, trigger effects,* and *self-organizing systems* (Emergent Causality scale). However, students' typical accounts capture hardly any of this complexity.

For example, research shows that when reasoning about effects in ecosystems, students usually miss the connectedness within the system and the implicit complex causal relationships (e.g. Griffiths & Grant, 1985; Webb & Boltt, 1990). For instance, Barmen, Griffiths, and Okabukola (1995) interviewed 32 students from senior high schools in the USA, Australia, and Canada. Students were asked to respond to hypothetical situations regarding populations influencing other populations and the overall impact on the food web by manipulating "cut-outs." They found that students believed that a change in one population will not be passed along several different pathways of a food web and that a change in one population will only affect another population if the two are related predator-prey. Griffiths and Grant (1985) found similar misconceptions previously in a study of grade ten biology students. Grotzer (1989, 1993) found that the tendency to ignore indirect effects was somewhat age-related. Seven year olds were less likely than nine and eleven year olds to detect indirect effects on their own. However, instances where indirect effects were ignored or explicitly rejected occurred with fairly high frequencies across the age groups.

Students do not easily recognize interactive causal relations on their own. Most students break these patterns apart and miss the reciprocal aspects of them. According to Green (1997), although many systems in our world (economic, human relationships) involve complex chains of cause and effect encompassing two-way causal processes, people tend to construct one-way linear chains when explaining them. He found that when twenty-year olds were cued in terms of a predator-prey relationship, sixty percent gave two-way causal accounts. Uncued, only sixteen percent gave two-way causal accounts. Similarly, forty percent of his subjects used two-way causal models when explaining a two-level problem. However, only nine and a half percent used two-way causal models when explaining a three-level problem. Such data suggest that more complex problems elicit fewer two-way causal models. Barman and Mayer (1994) found that, although the students defined a food web as a more realistic representation of feeding relationships, when probed as to what would happen to an ecosystem if the fox population was reduced or the rabbit population doubled, the students' responses revealed a lack of understanding of the mutual relationships within a food web. The students tended to believe that a change in the size of a prey population has no influence on its predator's population, and that a change in the population of a first-order consumer will not affect one or more produce populations.

Such shortfalls are striking. Food webs basically allow for what is called *composite explanation* within Underlying Causality, invisible factors like bacteria and energy budgets aside. In other words, the story can be told in terms of familiar agents such as foxes and rabbits and their familiar actions. In terms of the Moves framework, this creates ample opportunities for Putting the Model at Risk through common-sense reasoning that seeks disconfirmatory instances, challenging *positively biased evidence.* Yet students generally do not make such moves.

EVIDENCE FOR MODELS AND MOVES: IMPACT OF INTERVENTION

The Models and Moves theory predicts that students tend toward very simple causal explanations as gauged by the Models framework, with few sophisticated moves as gauged by the Moves framework. While the studies reviewed support that prediction, one can still question whether the results reflect shortfalls in learners' repertoire of causal models and epistemic moves. Indeed, a distinction can be drawn between instances of causation and the rules of causality (Murayama, 1994; Pazzani, 1991). Causation refers to explanations of cause and effect in specific instances—the particular mechanism in play and so forth—while causality refers to the rules of cause and effect relationships. Perhaps the former and not the latter creates students' difficulties: Perhaps the strangeness or intricacy of particular topics such as electricity or evolution somehow masks or suppresses models and moves actually in students' repertoire or easily enough arrived at with less vexed content.

Accordingly, one way to test the Models and Moves theory further is to try to teach students models and moves, examining whether this expands their understanding. Therefore, we are conducting intervention studies in which some students hear introductions to and explicitly discuss the nature of causality—the specific causal rules and patterns in play—in the context of particular science topics. We are comparing their performances to those of students who do not engage in discussion of causal rules. Although this phase of our program of research is underway right now, we can report some preliminary results. The results analyzed to date leave the role of moves unexamined as an independent variable, focusing on models.

We predicted that we should see superior performance from students exposed to discussions about the nature of causality. Considerable support has emerged for that hypothesis. For instance, students studying elementary electrical circuits who participated in discussions about the nature of causality within the context of specific instances of causation (Causal Models Group) showed significantly greater conceptual change in their causal models of the electrical circuit than students who discussed specific instances of causation through activities designed to help them do so (Activities Only Group) and than students in a control group ($p < .05$). Students in the Causal Models Group also showed significantly superior understanding of science concepts related to their causal models of electrical circuits for which students typically hold misconceptions, gaining an average of 5.6 points, one standard deviation above the control group at 2.9 points and close to one standard deviation above the activities only group at 3.3 points, ($p < .05$). There were no significant differences between the control group and the activities only group. (These results are reported in detail in Grotzer & Sudbury, 2000.)

Similar results emerged from our study of students' understanding of the connectedness within ecosystems. The intervention condition significantly affected students' gain scores in the total number of connections that they detected within the ecosystem ($F(2, 26) = 3.63$, $p = .04$) and the causal models group significantly outperformed the control group ($t = 2.41$, $p = .02$). The Causal Models group outperformed the Activities Only group in trend though the differences were not statistically significant. The mean gain score for each group was as follows: Causal Models = 21.2; Activities Only = 12.9; and Control = 6.1. Students in the causal models group detected more two-way connections on the post-test than students in other groups. Cyclic connections were only found on the post-test and then, only in the causal models group. (These results are reported in detail in Bell-Basca, Grotzer, Donis, & Shaw, 2000.)

CONCLUSION

We began with a puzzle: Magic was easier to understand than science. A likely reason was not hard to find. The baffling accomplishments of a master magician, once explained and demonstrated, occupy the everyday world of commonsense causality. Even if a trick is complicated, each element has a comforting familiarity. In contrast, a scientific explanation that might even have fewer principal elements would often be more complicated in other senses—invoking an underlying mechanism, interactive, cyclic, or constraint-like relations among factors, probabilistic elements, and emergence of various kinds. Unfamiliar and uncomfortable with such causal Models, and not well equipped with the Moves needed to reason their way toward them, learners would often find themselves baffled and frequently backslide after a little progress.

We have found significant support for this Models and Moves theory from studies of students' initial conceptions and conceptions after conventional instruction. The causal models implicit in students' explanations tend to be quite simple by the measure of the four dimensions of the Models framework. Also, students rarely appear to deploy the moves of Seeking a Gapless Model and Putting the Model at Risk that would take them beyond these simple models. Moreover, efforts to explicitly teach students more complex models in the course of teaching particular science topics yield considerable gains in their understanding, in comparison with control groups that received only conventional instruction and activities groups that engaged in the activities associated with the causal model discussions, but without the explicit discussions.

While all this supports the Models and Moves theory, other important questions remain part of our ongoing research. For one, do Epistemic Moves make a contribution to students' science understanding and scientific reasoning independent of model repertoire—indeed, helping to expand that repertoire? Although some of the activities have folded in epistemic moves, we have not treated them as an independent variable. For another, when students appear to become acquainted with more complex models in the context of one science topic, do they transfer this to other science topics that may be quite different on the surface? We are hopeful that the answers to these questions will be positive, but all that can be said at present is that the work is in progress. Meanwhile, the findings to date are encouraging. If the Models and Moves theory is sound, even in considerable part, it promises much toward explaining more deeply the difficulties learners encounter with many topics in science, and toward educating them more effectively.

REFERENCES

Andersson, B. (1986). The experiential gestalt of causation: A common core to pupils' preconceptions in science. *European Journal of Science Education*, 8(2), 155-171.

Barman, C.R., & Mayer, D.A. (1994). 'An analysis of high school students' concepts & textbook presentations of food chains & food webs'. *The American Biology Teacher*. 56(3): 160-163.

Barman, C.R., Griffiths, A.K., & Okebukola, P.A.O. (1995). 'High school students' concepts regarding food chains and food webs: A multinational study'. *International Journal of Science Education*. 17(6): 775-782.

Bell-Basca, B., Grotzer, T.A, Donis, K. & Shaw, S. (2000). Using Domino and Relational Causality to Analyze Ecosystems: Realizing What Goes Around Comes Around. Paper to be presented at the Annual Conference of the National Association for Research in Science Teaching (NARST), New Orleans, April 28- May 1.

Brown, D. (1995). *Concrete focusing and refocusing : A cross-domain perspective on conceptual change in mechanics and electricity*. Paper presented at the Annual Meeting of the American Educational Research Association, San Francisco, April 18-22.

Chi, M.T.H. & Slotta, J. (1993). The ontological coherence of intuitive physics. Commentary on A. diSessa's "Toward an epistemology of physics." *Cognition and Instruction, 10*, 249-260.

diSessa, A.A.(1993). Toward an epistemology of physics. *Cognition and Instruction* 10(2 & 3), 105-226.

Driver, R., Guesne, E., & Tiberghien, A. (1985). Some features of children's ideas and their implications for teaching (pp. 193-201). In R. Driver, E. Guesne, & A. Tiberghien (Eds.), *Children's ideas in science*. Philadelphia: Open University Press.

Green, D.W. (1997). 'Explaining and envisaging an ecological phenomenon'. *British Journal of Psychology*. 88: 199-217.

Griffiths, A. K. & Grant, B.A., (1985). 'High school students' understanding of food webs: Identification of a learning hierarchy and related misconceptions'. *Journal of Research in Science Teaching.* 22(5): 421-436.

Grotzer, T.A. (1989). *Can children learn to understand complex causal relationships?: A pilot study.* Unpublished qualifying paper. Cambridge, MA; Harvard University.

Grotzer, T.A. (1993). *Children's understanding of complex causal relationships in natural systems.* Unpublished doctoral dissertation. Cambridge, MA: Harvard University.

Grotzer, T.A. & Sudbury, M (2000). Moving Beyond Underlying Linear Causal Models of Electrical Circuits. Paper to be presented at the Annual Conference of the National Association for Research in Science Teaching (NARST), New Orleans, April 28- May 1.

Kuhn, D. (1991). *The skills of argument.* New York: Cambridge University Press.

Kuhn, D. (1993). Connecting scientific and informal reasoning. *Merrill-Palmer Quarterly, 39*(1), 74-103.

Lakoff, G. & Johnson, M. (1980). *Metaphors we live by.* University of Chicago Press: Chicago.

Murayama, I. (1994). Role of agency in causal understanding of natural phenomena. *Human Development, 37*, 198-206.

Ohlsson, S. (n.d.). Acquiring an explanatory schema: A preliminary model and related data. Unpublished paper.

Pazzani, M. (1991). A computational theory of learning causal relationships. *Cognitive Science, 15*, 401-424.

Shipstone, D. (1985). Electricity in simple circuits (pp. 33-51). In R. Driver, E. Guesne, & A. Tiberghien (Eds.), *Children's ideas in science.* Philadelphia: Open University Press.

Slotta, J. D. & Chi, M. T. (1999, March). *Overcoming robust misconceptions through ontology training.* Unpublished paper.

Voss, J. F., Perkins, D. N., & Segal, J. W. (1991). *Informal reasoning and education.* Hillsdale, NJ: Erlbaum.

Webb, P. & Boltt, G. (1990). Food chain to food web: A natural progression? Journal of Biological Education, 24(3), 187-190

Table 1: Dimensions of Complexity in Models

Underlying Causality From a same-level account of a phenomenon to an inferred underlying mechanism	*Relational Causality* From A causes B to complex reciprocal relations and constraint systems	*Probabilistic Causality* From deterministic causality to chaotic and quantum systems	*Emergent Causality* From a central and direct agent to highly emergent causality
Surface generalization: Simply describes the regularity under consideration in a generalized way (often incorrect). Often variants of "More's law"—more of this means more of that. ***Token agent:*** Some agent, intentional or not, made things come out that way. Agent's behavior parallels phenomenon, no real differentiation. ***Composite explanation:*** Describes or explains in terms of objects and processes that are part of the system in question rather than underlying it. (Such theories can sometimes be illuminating. Natural selection is a composite explanation.) ***Analogical model:*** System explains target phenomenon by analogy and analogical mapping (e.g. electricity as fluid flow). ***Underlying mechanism:*** Properties, entities and rules introduced that are not part of the surface situation but account for it (e.g. Ohm's law; and underneath that electrons and their rules of conduct. *Note: There are often two or three levels of underlying mechanism, each underlying the previous*).	***Simple linear causality:*** A impinges on, pushes, influences B. A typically seen as not affected. (e.g. A pushes, pulls, initiates, resists, supports, stops B. A may be active as in pushing or passive as in resisting). ***Multiple linear causality:*** Multiple immediate causes, multiple immediate effects, necessary and sufficient causes etc. This often adds previously neglected agents of lower saliency to the causal story. ***Mediating cause:*** At least three agents in play, M mediates the effect of A on B (e.g. A affects M affects B, M is a barrier to A affecting B, M is a catalyst to A affecting B). ***Interactive causality:*** Mutual interaction of two or more agents (e.g. mutual attraction, net effects as in lift) ***Re-entrant causality:*** Simple causal loops as in escalation and homeostasis. ***Constraint-based causality:*** Behavior of system reflects a set of constraints that the system "obeys"—constancy, conservation, and covariation rules (e.g. conservation of energy, Ohm's law, law of gravitation)	***Deterministic systems:*** As in Ohm's law, law of gravitation. ***Noisy systems:*** Basically deterministic systems perturbed by random or unanalyzed factors (air friction, turbulence on thrown objects) ***Chancy systems:*** At certain junctures, things might go one way or another with a certain probability. ***Chaotic systems:*** Fundamental unpredictability in long term due to "butterfly effects" (e.g. the weather) ***Order from chaos:*** Averaging effects smooth out chaotic systems into highly orderly large-scale patterns (e.g. gas laws). ***Fundamentally uncertain systems:*** As in quantum theory, uncertainty build into the nature of objects and events, even for very small systems in the very short term.	***Central agents with immediate influence:*** One or a very small number of key factors fairly directly yield the result. ***Long causal chains, branching structures, cycles:*** E.g. as in ripple effects of an ecological disaster. ***Aggregate effects:*** Cumulative effects over time (e.g. erosion). ***Causal webs:*** Complex web of interactions as in ecologies. ***Trigger effects.*** A modest influence "topples" a complex system into a new state or pattern of activity. ("Tipping points.") ***Self-organizing systems.*** Seemingly messy systems evolve into clear patterns over time without an external agent or an internal blueprint. ***Emergent entities and processes:*** As with the emergence of new species, chemical compounds, etc.

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Table 2: Epistemic Moves toward Better Models, with their Cues (Moves marked by ">" lead to more complex models)

Seeking a Gapless Model	*Putting the Model at Risk*	*Detecting Flawed Evidence*	*Building from Counterevidence*
Missing mechanism with in a surface generalization or token agent Moves: > Articulate a composite or analogical explanation or an underlying mechanism. >Elaborate token agent with an underlying mechanism. ***Centrist model without an obvious central agent.*** Moves: >Clearly identify the control mechanism and how it works. >"Decentralize" the model, looking for emergent effects. ***Convenient assumption*** begs the question. Moves: Abandon the model. >Add an explanation of the presence of the lucky element. ***Missing link in causal story.*** Moves: Reject model. Seek compelling empirical evidence, even if link not understood. >Elaborate link. ***Effects at a distance, or much delayed.*** Moves: Reject model. >Elaborate with mechanisms of propagation, persistence. ***Instantaneous effects.*** Moves: Accept as within paradigm. >View as brief unanalyzed transient. >Elaborate model to describe what happens in a brief interval.	***Counterevidence not possible.*** As formulated, nondisconfirmable in principle. Moves: Reject model. Revise model and/or expectations to make disconfirmable. ***Positively biased evidence.*** Moves: Seek disconfirmatory instances. Formulate rival model and compare evidence. ***Excusing and patching,*** excusing through dismissal of counterevidence or patching to accommodate counterevidence, often because model is so intuitively appealing or alternatives unappealing. Moves: Formulate rival model. Resist excuses, evaluate based on evidence and close reasoning, use of extreme cases, etc. Seek completely new model. >Seek reorganized, rather than patched, model. ***Same account of contrasting cases.*** The similarity may be suspect. Moves: Critique the similarity, look for crucial differences, revise model. ***Different accounts of similar cases,*** e.g. cases that are continuous variants of one another or that simply involve a change of frame of reference. Moves: Discard one model and extend the scope of the other. Try to unify the models.	***Apparent sources of noise in observations.*** Moves: Improve instrumentation, observation conditions. Use many observations, averaging, to filter out random error. >Extend model to include the "noise" as part of the system. ***Apparent sources of bias, including human bias.*** Moves: Use ways of detecting bias, filtering out biased data, correcting for it. Hedge claim. Strengthen claim when bias would seem to be *against* it. >Extend model to include bias as part of system. ***Very limited sample.*** Moves: Larger or repeated samples. Wider, deliberately disparate range of cases. Statistical methods to test adequacy of sample, reliability of conclusions. ***Confounded variables.*** Moves: Control of variables. Using "natural" experiments. Statistical methods to unconfound. ***Questionable whether observation predicted by model.*** Moves: Check logic of prediction and simplifying assumptions. Check that observation falls within scope of model. ***Correlation taken for causation (post hoc, propter hoc).*** Moves: Consider coincidence, different direction of causal arrow. >Elaborate strong persuasive mechanism. >Consider more elaborate models, e.g. a common cause for two correlated effects.	***Blatant disconfirmation on central cases.*** Moves: Abandon model. >Elaborate to accommodate additional factors. ***Minor discrepancies on central cases.*** Abandon model. Reframe as approximation. >Elaborate model to accommodate additional factors. ***Central core of cases okay, disconfirmation on other cases.*** Move: Abandon model. >Narrow scope of model by a systematic criterion. >Elaborate to accommodate problematic cases. ***Erratic performance in "same" circumstances.*** Moves: Abandon model. >Develop a systematic criterion for when model applies. >Elaborate model to accommodate previously unrecognized differences in circumstances. >Elaborate model to include probabilistic elements.

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