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Lifelong science learning: A longitudinal case study

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Abstract

How do students link school and personal experiences to develop a useful account of complex science topics? Can science courses provide a firm foundation for lifelong science learning? To answer these questions we analyze how "Pat" integrates and differentiates ideas and develops models to explain complex, personally-relevant experience with thermal phenomena. We examine Pat's process of conceptual change during an 8th grade science class where a heat flow model of thermal events is introduced as well as after studying biology in ninth grade and after studying chemistry in the 11th grade. Pat regularly links new ideas from science class and personal experience to explain topics like insulation and conduction or thermal equilibrium. Thus Pat links experience with home insulation to experiments using wool as an insulator. This linkage leads Pat to consider "air pockets" as a factor in insulation and to distinguish insulators (with air pockets) from metal conductors that "attract heat." These linkages help Pat construct a heat flow account of thermal events and connect it to the microscopic model introduced in chemistry. Pat's process of conceptual change demonstrates how longitudinal case studies contribute to the understanding of conceptual development. Future work will synthesize the conceptual change process of all 40 students we have studied longitudinally.

Introduction

Theories of scientific conceptual change offer a wide range of conjectures about lifelong learning (e.g., Linn, Songer, & Eylon, in press). Piaget conducted extensive cross-sectional studies to support his view that students develop a formal, abstract reasoning skill during adolescence and use it to advance understanding (e.g., Inhelder & Piaget, 1958; Piaget, 1952). Gagné 1968) studied mathematical problem solving to support the view that learning fits a hierarchical model where students master components before more complex ideas. Ausubel (1963) described how students build on their ideas and reorganize their thoughts. Research showing that students develop intuitive ideas based on observations of the natural world motivated McCloskey (1983) and others to hypothesize that student knowledge development in some sense recapitulates historical advance. Gentner and Stevens (1983) discuss the role of explanatory models in knowledge acquisition. diSessa (1993) among others shows that students entertain a range of ideas as they actively reformulate ideas to develop mature views. White and Frederiksen (1990) demonstrate that students benefit from learning a series of models of complex phenomena and Thagard (1992) analyzes how coherence influences conceptual change.

In this paper we examine how the student "Pat" develops understanding of thermal equilibrium over a five year period. Pat explains a range of familiar events such as why metal and wood feel different at room temperature. We analyze the contribution of class experiences, illustrating how Pat incorporates instruction about microscopic and macroscopic models of thermal events. During eighth grade Pat's physical science course relies on a heat-flow model. During high school Pat studies biological processes such as diffusion and encounters microscopic models of matter in chemistry.

To characterize conceptual change in these longitudinal interviews we identify explanations and models of thermal events as well as integrations and differentiations of scientific ideas. For this work we define a model as an explanation of scientific observations involving a mechanism. For example Pat accounts for conduction by positing that "metals attract heat." Research suggests that students often develop multiple explanations or models linked to specific contexts rather than seeking abstract principles that transcend context (Linn, diSessa, Pea & Songer, 1994). We describe the repertoire of models Pat uses in varied contexts.

We examine how Pat connects ideas to explanations by identifying differentiations and integrations. We define differentiation as the process of decomposing a scientific idea into two distinguishable scientific ideas each connected to an explanation. Weiser & Carey, (in Gentner & Stevens, 1983), describe the historical process resulting in the differentiation of heat and temperature. Siegler (1976) demonstrated that students struggling to understand the balance beam differentiated cases based on observable features of the situation. Similar differentiations occur as students struggle to understand thermal events. For example, Lewis (1991) reports that many students decompose objects into conductors (objects like aluminum foil that feel cold in a 25 C room) and insulators (objects like styrofoam wrap that feel neutral in a 25 C room) in the context of selecting a material to wrap a cold drink to keep it cold. Often students, based on experience, distinguish heating (adding heat) from cooling (cold flow) rather than seeing these as linked (diSessa, 1993). We define integration as the process of combining two or more scientific ideas into a single concept connected to a single explanation. For example, Pat integrates heating and cooling, saying that heat can flow into or out of an object. The process of integration and differentiation is complex and often varies by context. We seek to describe Pat's conceptual change in terms of models and explanations and in terms of integration and differentiation and to invite discussion of the implications.

Methods

Pat is one of 40 longitudinal participants selected randomly from the more than 300 eighth grade students in a middle school participating in the Computer as Learning Partner (CLP) curriculum during one school year. Pat makes average progress in eighth grade. While taking physical science, eighth grade students were interviewed for 30 minutes every three weeks. In the summer after ninth and 11th grade, students participated in 3 hour interviews in their former middle school classroom. Interviews were tape-recorded and transcribed. Students also responded to classroom tests, surveys, and written assessments. The school, located in a metropolitan area, serves middle income families from diverse cultural and linguistic groups. Following high school graduation, most of the students plan to attend a vocational program, two-year, or four year college; a minority seek jobs immediately.

All students study the CLP curriculum in a one-semester physical science course. CLP emphasizes thermal phenomena, takes advantage of real time data collection, and features an electronic laboratory notebook (Linn, 1992; Linn, in press; Ferguson, in press). The classroom is equipped with 16 networked Macintosh computers donated by Apple Computer, Inc. Classes of 32 students work in groups of two at the computers. Students use the CLP software to design experiments, predict outcomes, collect data in real time, design simulations, display results, record observations, and make reports.

The CLP curriculum introduces a heat flow model to help students make sense of their experiences. For example a principle relevant to thermal equilibrium states, "If two objects that differ only in initial temperature are placed in a cooler surround, heat energy will flow out of the object with the higher initial temperature more quickly." Although the heat flow principles could form the basis for student response to all the interview questions, students draw on a broader base of information. Because the principles are abstract students often find the details of the problems salient and draw on these to form explanations. Thus, Pat reflects on home insulation and develops explanations of explanations based on the fibers, the air between the fibers, or the holes between the fibers.

Lewis (1991) created the interview questions and studied an earlier cohort in her dissertation research. The interviews included questions about thermal phenomena presented in the context of naturally-occurring problems. For example, students were asked, "If you were going to wrap a cold soda to take to school for lunch, what is the best thing to wrap it in?" or "You arrive at a ski cabin during the winter and no heat was left on. The room thermometer reads 5 degrees C. What can you predict about the temperature of the objects in the cabin? Why?" The interviewer then probed, asking about the main reason for the answer, evidence to support the answer, reactions to using materials such as wool or aluminum foil, and reflections on the character of the answer. The interviewer sought to determine students' views of insulation and conduction, heat flow, thermal equilibrium, as well as heat and temperature. If students contradicted themselves from the perspective of the interviewer, they were asked to explain how their ideas were connected. For example, during the interview after ninth grade Pat responded to the question about the best thing for wrapping a soda as follows:

Pat: Well, we found out last year that it's not aluminum. It would be like plastic wrap or bubble wrap I think was the best...

Interviewer (I): And why is that? ...

Pat: So whatever is in the little metal particles attract heat and so they would, the heat energy would kind of be sucked on to the can and would go into the soda and warm it.

I: But that a lot of people do wrap sodas in foil. ...But if you wrapped it in you were saying plastic wrap or bubble wrap, what would be different about that?

Pat: Because of the air pocket.

I: What would the air pockets do?

Pat: There's something with how the air is an insulator. If you have like um, let's say the Styrofoam wrap, that's really porous. So then the air kind of holds in the little holes and then it insulates against heat energy coming in.

To analyze Pat's conceptual change the authors each independently identified integrations/differentiations, and explanations/models used by the student. We then jointly reviewed the interviews and constructed the summary in Figures 1 and 2 to report the course of knowledge development in two aspects of thermal equilibrium. In the next section we discuss the models Pat uses to make sense of the topic and show how these models both help and hinder progress in understanding the material.

Results and Discussion

Results fall in three categories. First, we describe Pat's integrations and differentiations. Second, we analyze the models Pat develops to connect experiences both in school and in everyday life. Third, we discuss how Pat's models incorporate eighth grade instruction about thermal events and high school courses that relate to these topics but do not address them directly.

Integrations and differentiations

As shown in Figures 1 and 2 Pat makes a number of integrations and differentiations to sort out aspects of thermal equilibrium. For example, in the area of insulators and conductors, prior to instruction Pat predicted that wood and metal would behave differently in the context of a room and an oven. Salient information about insulators (made up of fibers, have holes like in thermal blankets) lead Pat to emphasize a class of insulators that rely on air pockets to contribute to their effectiveness. Pat contrasts these with metals and develops an explanation for conducting based on metals attracting heat.

To make sense of thermal equilibrium, Pat distinguishes the steady state of equilibrium from the process of temperature change to get to equilibrium. Since conductors change towards equilibrium much faster than insulators Pat initially predicts that conductors come close to equilibrium with their surroundings but that insulators remain closer to their starting temperature or "room temperature" when placed in an oven or refrigerator. Eventually Pat connects room temperature to a view of "rooms" as having any temperature saying, "An oven is like a room." In later interviews Pat connects any environment to the idea of a room and predicts that insulators and conductors will both reach the temperature of any "room." This results in two integrations: one involving conductors and insulators and another involving warm and cold rooms.

Pat struggles to explain why some objects feel colder than others in a room at thermal equilibrium. In early interviews, Pat takes the rate of conduction between the hand and the object as an indicator of the temperature of the object (see Figure 2). In later interviews, Pat integrates conduction with the "feel" of the object, adds the idea that the hand has a temperature of its own, and explains the feel of objects on the basis of temperature difference and rate of conduction.

Thermal equilibrium also involves realizing that heating and cooling are the same process in different directions. Natural scientists describe heat as flowing when there is a temperature difference. Pat generally employs a notion of heat flow starting at about the fourth interview. In the interview just prior to tenth grade, however, Pat also discusses a cold flow model as shown in this segment:

Pat: OK. The metal would kind of, like aluminum foil, would kind of pull the cold out of the soda into the air because um, it moved to the. The cold like, it just moved right out onto the metal because metal is the conductor and then it would be released into the air. I forget if it happened that way or if the heat in the air, like the metal pulled the heat in from the air into the soda. I forget if the cold left or if the heat came in, but it's probably both.

I: Does that make sense that there could be both? *[Reflection question]*

Pat: Yeah, it makes sense.

I: So cold could go out and heat could come in.

Pat: But it could also be just one. The heat could come in or the heat would leave depending on whether it was hot or cold.

I: Which sort of makes more sense to you? Or does it?

Pat: I really never kind of understood whether there was both or not.

Pat also differentiates heat flow in solids and gasses (air especially). In later interviews Pat begins to link all these ideas in a heat flow model and to distinguish materials on the basis of how fast heat flows through them.

Models

Pat's thermal models illustrate the course of scientific knowledge development as well as the role of personal and school experience. Pat starts with no model for thermal equilibrium but soon appropriates a model of metals attracting heat to explain why metals cool faster than wood and a separate model for insulation ("air pockets make heat energy not go"). Pat also posits a role for air, expressed as metals "pulling the heat in from the air." Pat describes insulators as porous and able to contain air, saying, "the air kind of flows in the little holes and then it insulates against heat energy coming in." Finally, Pat integrates a view of all things being at room temperature with the process of insulation and conduction, and connects all these ideas to the notion of heat flow emphasized in class instruction.

To explain everyday experiences Pat also employs the heat flow model. For example, to explain why metals and pottery behave differently Pat brings in experience with terra cotta bun warmers, saying, ".....you put them in your bread basket to keep the rolls warm....I think those are pottery and not metal because I think once you take the metal out the heat will just go....It wouldn't feel as hot as the metal but it would hold the heat longer, it wouldn't dissipate as fast."

Models help Pat synthesize material and keep track of complex information but they also direct attention to ideas and topics that might be peripheral or idiosyncratic. For example, the holes in materials model motivates Pat to focus on holes to the exclusion of the material that creates the holes. Pat makes both productive combinations and unproductive linkages.

Lifelong learning

Do Pat's models help or hinder later learning? Pat adopts the heat flow model to explain most situations by the end of eighth grade and finds many connections to the model in high school biology and chemistry as well as in everyday examples. For example, after studying biology Pat integrates the concept of diffusion with heat flow, connecting two macroscopic views that have useful similarities. After chemistry Pat attempts to integrate a microscopic model of heat transfer with the heat flow model and makes some productive connections. For example, Pat says to explain thermal equilibrium, "...these are like heat energy waves transferring and so even so you want an equilibrium and energy, but its different from saying you want your carbon atoms to be balanced." There remain limits to integration, however. Distinguishing mechanisms for insulation and conduction poses problems for the heat flow model. In 10th grade Pat entertains a substance model of heat, saying "I want heat energy to be a particle" but cannot find a way to connect this idea. In 12th grade Pat makes more connections between a microscopic and macroscopic model but eventually concludes, "I guess they are the same but they just seem different." Eventually Pat distinguishes substance of material from constraints on flow.

Conclusions

This case study demonstrates how students integrate and differentiate thermal ideas and illustrates how a qualitative and macroscopic model like heat flow can form a firm foundation for subsequent instruction. Pat takes seriously the challenge to integrate scientific ideas across contexts, attempting to reconcile multiple models and diverse interpretations of everyday events. Pat connects ideas to the heat flow model in middle school and continues to refine these ideas and develop a microscopic model in high school.

This case study of knowledge integration and differentiation is consistent with a view of the learner as constructing understanding by building on and refining existing ideas as suggested by diSessa (1993) , White (1990) , and others. Siegler's (1976) study of student understanding of balance beam problems illustrates the process of differentiation and integration elaborated in this case study. Whereas Siegler postulated that students "muddled through" complex integrations of ideas, this case suggests that integrations usually make sense from the perspective of the learner. The case illustrates the value of asking students to explain their ideas both in class and in interviews compatible with research on self explanations (Chi & Bassok, 1989; Bielaczyc, Pirolli, & Brown, 1995). By attempting to explain complex events Pat often comes up with more powerful models or connects diverse ideas. And, Pat gains insight into science learning, remarking in twelth grade, "memorize *if* you understand science."

This study suggests the benefit of instruction that provides a supportive learning environment as well as opportunities for personal autonomy as suggested by Collins, Brown, and Holum (1991). Students who struggle to make sense of their class and personal experiences develop valuable skills as well as a perspective on the nature of scientific reasoning. Instruction that includes metacognitive information about ways that scientific ideas develop and methods for matching scientific ideas to new problems will help students continue to learn after they finish their classes. Developing the propensity for reflection and self-explanation seems productive given that students are likely to follow idiosyncratic paths. And, selecting models for science courses such as the heat flow model that students can connect to their experiences also will help students become lifelong learners.

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Interview Session	Context	Description*	Explanation/Model	Integration/Differentiation
Eighth Grade— Prior to Instruction	Objects in a room	*All objects come to room temperature* *Temperature of the room stays the same unless an object is large*	Go into the air and the temperature would make it room temperature	
	Objects in an oven	*Temperature of the wood would be lower than temperature of the oven* *Metal would be about oven temperature*	Wood is not a conductor; metal is a conductor	
Eighth Grade— Following Probing Your Surroundings	Cold cabin and hot car trunk	All objects come to room temperature *Car trunk is like a room*	Go to the temperature of the room or the surroundings	*Integration* of thermal equilibrium for any environment
Eighth Grade— Following Rate of Heating and Cooling	Drying oven and air conditioned hotel	All objects come to room temperature *Conductors reach equilibrium faster than insulators*	Heat energy goes into conductors faster Metals attract heat	*Differentiation* of rate of change from thermal equilibrium *Integration* of rate of change with conduction and insulation Uses attraction model as mechanism
Eighth Grade— Following Insulation and Conduction	Warming Oven	All objects come to room temperature Conductors reach equilibrium faster than insulators	Heat energy goes into conductors faster	Persistence of ideas
Eighth Grade— Following Instruction	Objects in a room and objects in an oven	All objects come to room temperature	Heat energy goes into them all the time Flows in for colder, flows out for hotter so they all get to room temperature "Like another room in the oven"	*Integration* of rate of change, heat energy, direction of heat flow and thermal equilibrium using heat flow mechanism
Tenth Grade— Following Biology	Cold ski cabin and hot car trunk	All objects come to room temperature *Larger objects reach thermal equilibrium more slowly*	Diffusion longer for large objects If heat energy had a brain would want to make everything isotonic Heat particles would diffuse	*Integration* of heat flow and diffusion *Differentiation* of insulation and mass Use of anthropomorphic mechanism
Twelfth Grade— Following Chemistry	Objects in chemistry drying oven and objects in a room	All objects come to room temperature *Larger objects reach thermal equilibrium more slowly; Conductors reach thermal equilibrium faster*	Would take heat energy longer to reach the center of a large object Atoms that lack heat energy would *want* to take heat energy away from warmer object	Attempt to *integrate* microscopic model and heat flow

* New ideas in *italics*

Figure 1: One student's integration and differentiation of thermal equilibrium from eighth to twelfth grade

Interview Session	Context	Description*	Explanation/Model	Integration/Differentiation
Eighth Grade— Prior to Instruction	Objects in oven and objects in room	*Conductors and insulators feel different temperatures*	Conductors feel colder than insulators; I don't know if they are different temperatures	
Eighth Grade— Following Probing Your Surroundings	Objects in unheated ski cabin and objects in room	*Hand is warmer than the object* *Metal heats up when touched* *Wood remains the same temperature when touched*	Conductor takes heat energy from hand to object I don't know why wood remains the same Mentions holes model for wood in another context	*Differentiates* conductor in room from conductor wrapped around an object
Eighth Grade— Following Rate of Heating and Cooling	Warm and cold objects	Hand is warmer/colder than the object Metal heats up or heats hand when touched *Heat from hand flows through the wood when cold; flows from wood to hand when hot*	Holes from the wood let heat flow through the wood so there is no change in the temperature of the wood	Confusion about heat leaving the hand and change in temperature *Differentiates* flow of heat from hand (has own temperature) with flow of heat in thermal equilibrium *Integrates* insulator as wrap for object with feel of insulators using the holes model
Eighth Grade— Following Insulation and Conduction	Warm and cold objects	Hand is different temperature than object *Hand heats up metal faster than insulator or metal warms hand faster than insulator* *Wood becomes warmer or colder*	Metals attract heat Object gets hotter or colder depending on which is warmer	*Integrates* rate of heating from hand for both insulators and conductors *Integrates* metal as conductor when touched and when wrapped around warmer or colder object Indicates that these integrations aided by instruction
Eighth Grade— Following Instruction	Warm and cold objects	Hand is different temperature than object Hand heats up metal faster than insulator or metal warms hand faster than insulator *Wood feels warm and stays warm*	Wood traps heat in the air holes and makes heat energy not go	*Integrates* feel of object with insulation and conduction, direction of heat flow, and flow model
Tenth Grade— Following Biology	Warm and cold objects	Metal feels colder than wood	Metal is a conductor Wood is porous and has air pockets	*Integrates* porousness with air pockets view. Relies on poor recall; does not construct
Twelfth Grade— Following Chemistry	Warm and cold objects and objects that produce own heat energy	Metal feels colder or warmer than wood	Heat energy flows from the metal to hand faster than it flows from wood Metal is a conductor so flow is more noticeable Child is a source of energy in a room	*Integrates* insulation and conduction with feel of object for self and child *Integrates* instruction about energy sources Reconstructs ideas rather than relying on recall

* New ideas in italics

Figure 2: One student's integration and differentiation of ideas about why objects feel warm or cold from eighth to twelfth grade