Expert Scientific Reasoning Processes and Imagery: Case Studies of High School Science Classes[1]

Evidence is discussed for the spontaneous use of three types of scientific reasoning by high school students in whole class discussions. In two case studies, we identify multiple instances of students generating analogies, extreme cases, and Gedanken experiments and document their predominant association with spontaneous depictive gestures. Most were associated with gestures that appeared to depict motion or force, which are interpreted here as indicators of the use of animated mental imagery. We believe these issues warrant further study because it is possible that these processes, along with depictive gestures, allow students to share visual or kinesthetic meanings situated in exemplars in a way that allows the discussion to make sense to a greater number of students.

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Objectives

What types of reasoning occur within a student-centered whole class discussion in the science classroom? Does this reasoning involve situating meanings in imagery of concrete exemplars? If so, how do students attempt to convey such imagistic ideas to each other? The purpose of this study is to explore students' spontaneous use of several kinds of expert reasoning strategies and the association of these episodes with the spontaneous use of depictive gestures, which are interpreted here as providing some evidence for the use of mental imagery. Examining case study data, we seek to explore the roles these episodes played within student reasoning during two whole class discussions in high school science classes. The reasoning strategies investigated include Gedanken experimentation, analogical reasoning, and extreme case reasoning. Previous case studies of expert scientists have indicated that these processes can be central during scientific model construction. Of the numerous instances of these forms of reasoning observed in these classes, most were associated with depictive gestures that appeared to depict motion or force, which are interpreted as indicators of the use of animated mental imagery. Unpacking the basic reasoning "moves" students make facilitates our understanding of the nature of science classroom discussion.

Theoretical Perspective

The ability to generate and evaluate mental models appears to be a crucial aspect of science (Darden, 1991) and of student thinking (Gentner and Gentner, 1983); but Driver (1983) suggests that students often need to be helped to assimilate their prior experience (c.f. Smith, diSessa, and Roschelle, 1993) into scientifically accepted models. One powerful way to evaluate a mental

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model appears to be to run a *Gedanken experiment* (Nersessian, 1992; Gooding, 1992). (*Gedanken* is German for "thought." This term originally referred to the Einstein-Bohr experiments but, as with the other reasoning processes we discuss, has been given no consistent definition in the literature.) Previous philosophical analyses include the structure of Gedanken experiments (Brown, 1986) and their function in scientific thinking (Kuhn, 1977; Sorenson, 1992). More recently, Clement (2002) has investigated Gedanken experiments that were spontaneously generated and used by experts during problem solving, but Gedanken experiments also appear capable of playing an important role in teaching and learning (Gilbert and Reiner, 2000). According to Reiner (1998) and Reiner and Gilbert (2000), some students can and will use Gedanken experiments to find solutions to problems when the problems are formulated in a way to encourage this, especially in small-group collaborative settings. Very few of these studies, however, have investigated the role of Gedanken experiments in large class discussion. Exceptions are Hammer (1995), who identified thought experiments in use in large class discussions in high school physics, and Nunez-Oviedo, Rea-Ramirez, & Clement (2008), who identified them in middle school physical science classes.

The work of Gentner and others (Gentner and Gentner, 1983; Collins and Gentner, 1987; Clement, 1993) suggests that people use *analogies* to help construct mental models and that carefully constructed analogies can be used to address students' preconceptions in physics. These analogies can work by making use of "anchoring" conceptions that ground instruction on students' intuitions (Clement, Brown, and Zietsman, 1989). Recent work by Podolefsky and Finkelstein (2006) indicates that analogies can enable students to generate inferences during instruction. In addition to teacher-constructed analogies, student-generated analogies can be used as a tool for understanding (Wong, 1993). Experts also use *extreme case* reasoning (Clement, 2008; Stephens and Clement, 2008), another non-formal reasoning process that can play a role in instruction (Zietsman and Clement, 1997). Our documenting of these constructive reasoning processes should complement the discussion of argumentation processes by Duschl and Osborne (2002); Clark and Sampson (2005); Osborne, Erduran, and Simon (2004); McNeill and Krajcik (in review); and Walton (1996).

Though some researchers have downplayed any potentially existing non-propositional aspects of reasoning processes (Forbus & Gentner, 1997; Kintsch, 1986, 1988), Hegarty (1992) hypothesizes that a mechanism involved in subjects' evaluation of their mental models is the use of mental animation to run the models. Hegarty and others have investigated the use of mental animation in problem solving by students and experts (c.f. Clement, 2006). Some of the mental imagery involved appears to be kinesthetic in nature, as when expert physicists imagine exerting a push or a pull (Gooding, 1992b; Clement, 2006). Kinesthetic imagery appears to be associated with physical intuition (Gooding, 1996) and has been targeted in instruction (Camp, et al., 1994). Kinesthetic thinking appears to have an effect in problem solving in domains other than the physical sciences, such as in geometry (Sellares and Toussaint, 2003), which suggests that the role of this form of thinking may be more fundamental than previously thought. We know of almost no one who has made an evidence-based argument for the involvement of imagery in Gedanken experiments, analogical reasoning, or extreme case reasoning.

We believe the results from the literature lend strong support to our own contention that subjects' gestures can provide information about their mental imagery. Type and amount of gesture appear to be closely associated with the nature of the subject's internal representation (Lozano and Tversky 2005, Iverson and Goldin-Meadow 1997, 1998). Representational gesture production, in particular, appears to be associated with visuo-spatial and other imagistic processes (Iverson and Goldin-Meadow 1997; Krauss 1998; Hostetter and Alibali 2004; Alibali 2005; Feyereisen and Havard 1999). Depictive gesture appears to be a natural way of expressing the results of mental animation and conveys information about the animation not revealed in subjects' words (McNeill 1992; Hegarty, Mayer, Kriz, & Keehner 2005). *Representational* gesture is a broad category that includes any gesture that conveys semantic content, as by using shape, placement, or motion of the hands (Alibali 2005; McNeill 1992). Representational gesture excludes gestures used merely for rhythmic emphasis. *Depictive* gesture, which is our focus, is a subset of representational gesture and depicts an object, force, or event; it excludes stylistic representational gestures such as the "thumbs up" sign (Clement 1994; Clement, Zietsman & Monaghan 2005).

Methodology

We have examined a number of transcripts of classroom activity where inquiry-based methods of teaching and learning were being employed. Coding was done jointly by consensus of two coders working in iterative cycles, partly to help us refine the definitions of categories in this generative phase of research. After we developed the explicit definitions given below, the transcripts were coded for the presence of *spontaneously generated* analogies, extreme cases, and Gedanken experiments. Although we also observed students evaluating and re-running each others' analogies, extreme cases, and Gedankens, we are particularly interested here in episodes in which students generated these processes.

Spontaneous reasoning processes

An Analogy has been generated when (1) a subject, in thinking about a target situation A, without provocation, refers to another situation B where one or more features ordinarily assumed fixed in the original problem situation A are different; that is, the analogous case B violates a "fixed feature" of A (to be defined below); (2) the subject indicates that certain structural or functional relationships (as opposed to surface attributes alone) may be equivalent in A and B; and (3) The related case B is described at approximately the same level of abstraction as A. As used here, fixed features are those features of the problem situation that are commonly assumed to be givens which are not subject to change; and problem variables are features that are assumed to be changeable or manipulable.

An Extreme Case has been generated when, in order to facilitate reasoning about a situation A (the target), a situation E (the extreme case) is suggested, in which some aspect of situation A has been maximized or minimized. This includes going almost to the end of a continuum for the aspect or well outside the normal range of the aspect.

Performing an evaluative Gedanken Experiment is the act of considering an untested, observable system designed to help evaluate a scientific concept, model, or theory—and attempting to predict aspects of its behavior. In these experiments, an element of a theory is evaluated as it is applied to the untested system. By untested, we mean that the subject has not observed that aspect of the system before nor been informed about its behavior (Clement, 2006).

Gestures

We also coded the videotapes for the presence of *depictive gestures***.** These gestures appear to depict an object or location (Clement, 1994), and are taken as one indication that internal, or mental, imagery is being used (Clement, 2008). These gestures exclude stylistic representational gestures such as the "thumbs up" sign. Visual inspection alone was sufficient to identify the presence of depictive gesture. We then categorized the gestural episodes. The purposes of this were (1) to identify indicators of the presence of mental imagery; then, where mental imagery appeared to be present, (2) to identify indicators of the presence of animated mental imagery; and finally, where possible, (3) to identify indicators of the presence of dynamic/kinesthetic mental imagery involving forces.

Shape-indicating gestures [G-S] appear to depict a shape, as when a subject indicates the shape of a globe. These gestures are taken as an indication of the presence of mental imagery but are not sufficient to indicate animated or dynamic/kinesthetic imagery.

Motion-indicating gestures [G-M] appear to indicate the motion of an object (it may be a point-object; that is, it may be an object that occupies an arbitrarily small volume and for which no shape is defined, though its location and/or trajectory are specified) and are taken as an indication of the presence of animated mental imagery. They are not sufficient to indicate dynamic/kinesthetic imagery.

Force-indicating gestures [G-F] appear to indicate the action of a force and can be quite emphatic (see Figure 7). These gestures are taken as an indication of the presence of dynamic/kinesthetic imagery. At times, an educated guess can be made from the appearance of the gesture alone as to whether it is intended to convey a force; however, a subject's use of *force terms* such as "pulling" or "throwing" was used as additional evidence for the choice of this category.

We call these last two categories *action gestures* and consider them evidence for the presence of animated, as opposed to static, imagery. Even in the case of opposing forces where no motion would normally be involved, in our experience, the gestures used to describe the scenario often involved motion. In cases where it was not clear whether a gesture was intended to depict motion or to depict force (which might be causing the motion), it was coded a motion-indicating gesture as the more conservative choice.

Method of analysis

We organized our data by *case*, *variation* of a case, and *episode*. A *case* is a concrete example of a system. A case introduced during a discussion about the causes of gravity, the US/Australia case, comprised the Earth, two people standing on it, and the gravitational forces between the Earth and the people. A *variation of a case* involved the same concrete example of a system but with some variable changed in a significant way (such as to create an extreme case) or with an additional variable highlighted. For instance, when a student introduced the rotation of the Earth into the discussion as a possible factor causing gravity in the US/Australia case, we counted this as a variation of that case. An *episode* involved a single student either generating or running a case or variation.

Individual episodes were examined to determine whether they met the criteria above for spontaneous student generation of an *analogy, extreme case* or *Gedanken experiment*. We then noted which episodes were associated with depictive gestures or other imagery indicators. We also noted where a student evaluated or modified a case that had been proposed by the teacher or by another student, though in the present study, we are primarily interested in student-generated processes.

Data sources

The two case studies are of lengthy discussions triggered when a physics teacher presented target cases designed to elicit student misconceptions. The discussions occurred in two college-preparatory physics classes in a middle class suburban high school in the northeastern United States. The teacher was using an innovative curriculum (Camp, et al., 1994). The classes, which were videotaped, were from different years and the discussions were on different topics, though gravity was a factor in both. Because we were focused on developing coherent observation categories, transcripts were selected for analysis that appeared to contain exemplars of the phenomena to be analyzed and described; no claims for typicality of frequencies are made. Each of the discussions lasted about 45 minutes.

Classroom Evidence

Book on Table Transcript

In this lesson, the teacher wanted students to consider whether a table exerts an upward force on objects resting on its surface. A common conception prior to instruction is that inanimate objects cannot exert upward forces against gravity. The target model for the lesson was one in which objects exert normal forces that are equal and opposite to the weight of objects resting on them. The whole lesson was structured around a series of bridging analogies (see the curriculum, Camp et al. 1994; also Clement 1993), and the teacher repeatedly mentioned to the class that he was using analogies.

At the beginning of the lesson, the teacher placed a book on his desk and called students' attention to it, then drew two figures on the chalkboard. One was a simple line drawing of a book on a table and another of a hand pressing downward on a spring. He asked the students to compare the two cases. According to the teacher, he hoped that all of the students would believe that the spring pushed up on the hand and that he could use this case to anchor new concepts about normal forces within students' prior intuitive knowledge. It had become clear in previous years that, although many of his students had believed that the spring would exert a force on the hand, a large number had not believed that the table would exert a force on the book. Therefore, the teacher decided to introduce a number of *bridging analogies* designed to bridge the distance between the spring/hand case and the table/book case.

Before the teacher could introduce the planned bridging analogies, his students preempted him by producing their own bridging cases. They spontaneously invented a number of novel scenarios to support their positions, including a series of increasingly warpable tables. See Stephens and Clement (2008, in review) for discussions of extreme case and analogical reasoning, respectively, during the warped-table series. The following episode occurs after the warped table episode.

Extreme case reasoning

Some students believed that warpable tables could exert a force; however, S5 did not. He argued that, unlike the spring, the table cannot exert a normal force; the table does not have enough power to "exceed" the weight of an object to move it in the other direction, "and as soon as (*the weight*) gets too great then the table collapses." Another student, S15, then recast S5's statement as an extreme case in order to argue that even though the table is breakable, warping could be present (and therefore, presumably, a normal force could be present):

S15: (*S5's*) idea is compatible with the warped table theory. The idea is that the [*points to drawing of table on chalkboard*] elephant sitting on the table is too much [*hand extends toward chalkboard*] for the material that the table is made out of, and it [*sharp downward thrust:* G-F] **punctures** the thing; it [*hand sweeps through a deep curve:* G-S] warps it too much.

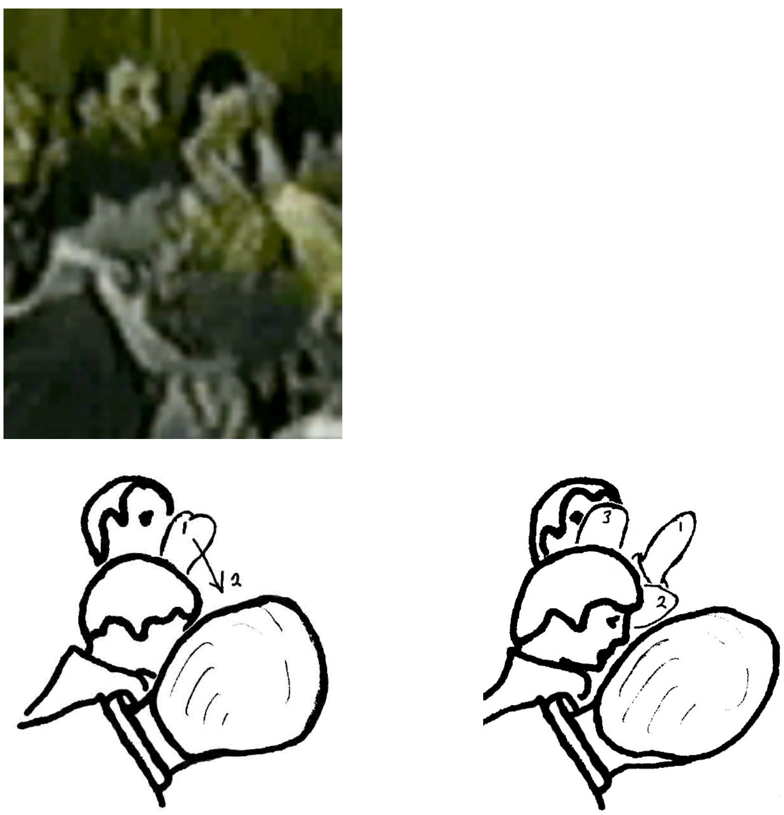

Figure 1. *"...it [G-F]* ***punctures*** *the thing; it [G-S]* ***warps*** *it too much."*

[G-S] and [G-F] refer to shape- and motion-indicating gestures, respectively, and are placed at the point in the transcript where the student began the depictive gesture. "Puncture" is in bold face to denote that it is a force term that supports our interpretation of the accompanying gesture as a force-indicating gesture. The shape depicted by the final gesture was a deep curve, concave from above, much deeper than a table could normally form without breaking (Figure 1). By pushing the warped table to an extreme, the student had transformed the warped table into the broken table, arguing that this was a different regime, and that the possibility of breakage was not evidence against the presence of warping. The gestures give evidence of the presence of visual imagery, and the sharp downward thrust accompanied by the force term *punctures* suggests the presence of kinesthetic imagery as the student appeared to embody the act of puncturing.

Gedanken experiment involving an analogy

Later in the class, S14 drew an analogy between the book on the table and a situation the class had studied earlier, that of a boat powering upstream against a current. If the current were to stop suddenly, the boat would move upstream in response; likewise, if the table were not there pushing against the book, the book would fall down. S15 replied to S14 by using the same analogy between the book situation and the boat situation. However, rather than imagining the current stopping, he imagined the boat engine disappearing and predicted what would happen to the boat due to the current; he then made an analogy between the force of the engine and the force of gravity and predicted what would happen to the book if gravity disappeared:

S15: But by the same analogy, then, if gravity disappeared, right, the **force** of the [*sudden thrust downward:* G-F] engine on the boat, even the book would just [*flings arms upward and outward:* G-M] fly off into space.

Figure 2. "...the book would just [G-M] fly off into space."

We take these gestures to be indications of the student's use of animated mental imagery that had kinesthetic as well as visual components. (See Figure 2.)

The student appears to be saying that if the engine disappeared, the current would move the boat, and by analogy, if gravity disappeared, the normal force would send the book off into space.

(The table would suddenly unwarp.) We consider this to be a Gedanken experiment. The case of gravity disappearing is an untested system and the student attempted to predict an aspect of its behavior—what would happen to a book on a table in such a situation. And the case appears to have been constructed to evaluate an aspect of the theory of the existence of normal forces.

Later in the class, students were presented with a model of solid matter as being made of atoms with spring-like bonds between them. The class ended with a demonstration that optically magnified the effect of warping in an apparently solid table, and most students appeared convinced that, if the table could warp, it could push back against objects resting upon it.

Results

Nine episodes of spontaneous student introductions of Gedanken experiments, extreme case reasoning, and analogies were identified in the 45 minutes of transcript (Stephens and Clement, in review). Of these nine, seven were accompanied by action gestures, indicating the presence of imagery involving force or motion.

Gravity Class

In the second transcript, the class had finished a unit on density and was just beginning a unit on gravity. Common conceptions of students prior to instruction are that causes of gravity include the rotation of the Earth and/or the "downward" pressure of the atmosphere. The target model of the lesson was one in which every particle of matter pulls on every other particle. The teacher planned to introduce three cases during the course of the lesson; however, his students pre-empted him and came up with the third case on their own before the teacher could introduce it.

The first case was designed to elicit misconceptions such as those just mentioned and to stimulate discussion. The teacher drew a figure on the board (see Fig. 3) and asked the class to vote on the following: "Compared to the United States, gravity in Australia is: a little less, equal, a little bit more."

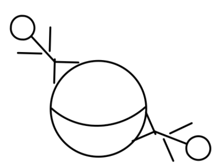

Figure 3. US/Australia Case

After the students had recorded their votes on voting sheets, the teacher opened the discussion by asking, "Just what is it that causes gravity, anyway?" What followed was a very lively discussion in which the teacher played a role that was almost neutral, restating student positions, asking for clarification, and occasionally recasting a student utterance into a slightly altered form.

Early in the class, some students suggested that the rotation of the Earth either causes gravity or contributes to it. Although several students countered this idea, the proponents of the spinning model of gravity appeared not to be convinced. (The number to the left of each utterance is the transcript line number.)

17 S4: I might be all messed up from reading too many science fiction novels but I thought that gravity [G-M]– when the Earth spins on its [G-S] axis the– I don't know [G-M] how but [G-M] somehow the fact that it spins causes a lot of the [G-F] **main force** of gravity. I agree with [another student] in that everything is [G-F] **pulling** on each other, but I think that that's not enough gravity. For instance, when you go to other planets that aren't spinning as fast, or that are smaller masses, there's not as much of a [G-F] **pull**.

Figure 4. "…there's not as much of a [G-F] ***pull****."*

This student appears to include the rotation of the Earth as an important causal factor in his model of gravity. His gestures accompanying the term "pull" are brief and are somewhat ambiguous as far as specifying the orientation of the pull. As we shall see, this student will increasingly distinguish between possible causes of gravity and directions of forces over the course of the discussion.

Gedanken experiment involving an extreme case

Apparently in response to S4, S7 suggested the following Gedanken experiment.

40 S7: Well, in reference to rotation and gravitational force, I think of them as being two opposite forces because if you stand on-- let's just [G-S] imagine a ball floating in space you tape your feet to. And you start spinning the ball around, you're gonna [G-M] **feel like you're gonna be** [G-F] **thrown** off. But if it's a small ball, then the attraction between you and that little small mass is negligible so that you're just gonna [G-F] **feel the forces being spun around** in a centrifugal force.

Figure 5. "[G-S] Imagine a ball floating in space . . ."

*Figure 6. "You're just gonna [G-F] **feel the forces** being spun around.... " (moves finger tip in circular motion in horizontal plane)*

This is an imaginary case that appears designed to evaluate the gravity-from-spinning theory by pitting it against a strong conflicting intuition. When weighing oneself, the spinning of the Earth does, in fact, reduce the reading on the scale slightly, but many students have trouble imagining and understanding this effect, and instead guess that spinning may be one of the causes of gravity. S7 employed *extreme case reasoning*, taking two variables to unusual values, one low and one high. The rotation of the spherical mass, which in the initial case produced one complete revolution every 24 hours, was taken to a rapid spinning (to judge by the student's gesturing). Meanwhile, the pull of gravity was taken to a "negligible" amount. The result was a situation where the contrast between the effects of the gravitational force and the effects of the rotation was maximized (although the student's terminology was imprecise).

The student suggests to his classmates that they imagine their feet taped to the ball. He generates a prediction from this situation (untested—unless he has previously taped himself to a ball in space): "you're gonna feel like you're gonna be thrown off." The prediction of a force opposite to that of gravity is a result (observable, at least in principle) that would tend strongly to discount spinning as a casual factor in the pull of gravity. Thus, the student has *considered an untested, observable system that appears to have been designed to help evaluate* a theory about the cause of gravity *and he has predicted an aspect of the behavior of this system.* This episode therefore meets our definition of an evaluative Gedanken experiment. We hypothesize that this episode can be viewed as a student's effort to design a case that maximizes the potential of the rotatingglobe scenario to evoke comprehension via kinesthetic imagery. It appears designed to help him and his classmates convincingly distinguish between the (felt) effects of rotation and the (felt) effects of the downward pull of gravity. His depictive gestures provide evidence for his own use of both animated and kinesthetic imagery throughout this episode. The phrases in bold are also regarded as evidence for kinesthetic imagery as he talks of feeling the forces; thus, there is considerable evidence for imagery in this episode.

Student Gedanken Incorporates Teacher's Extreme Case

In response to a question about whether gravity would change if one climbed a mountain, S4 replied,

143 S4: I think how far you are from the poles has more to do with it.

Although a semi-quantitative relationship is implied here, it is doubtful whether the student would have taken it further had the teacher not recast the comment:

144 T: Now the other issue that you're bringing up that was kicked around some and not resolved last time was that the gravity has to do with the Earth spinning, also is another issue that was mentioned. If that's the case, let's give it a little bit of thought about what (S4) is saying. If I were to stand at the North Pole, say the pole is here and I hold on hand on the pole, how long does it take me to spin around that pole?

Once the class reached agreement that it would take one day and that the movement around the pole would be slow, the teacher continued,

163 T: …Let me point out, if I stand on the equator, however—

And a student replied,

164 S7: You're going real fast.

The teacher had converted S4's vague phrase: "how far you are from the poles" into the extreme comparison of a person at the North Pole and a person at the equator, and the students promptly began to reason about the comparison.

Soon after, S4's reasoning about the effects of rotation undergoes a change. First, he makes a statement that appears to modify the emphasis he had placed in Line 17 on the importance of the effects of spinning as a cause of gravity.

173 S4: But I'm saying I think that almost all of gravity is done by the relation between mass and the [garbled]. There's an incredibly huge mass below us. All I've been saying from the beginning is that rotation has something to do with it too.

A little later, he appears ready to consider a further modification to his model of rotational effects. In contrast to an earlier statement he had made that rotation is "somehow helping to hold," in Lines 182-186, he begins evaluating the implications of a "throwing" model of rotational forces; he takes the extreme case comparison of a person at the Pole and a person at the equator and runs the extreme case as a Gedanken. We suggest that his depiction of the direction of the forces has also become clearer, as revealed through both words and gesture. (Comparing Figure 7 with Figure 4 may give some idea.)

182 S4 *(off camera)*: "Ok, say that it's [the rotation of the Earth] **throwing** you. Then that still means that the top is still gonna be **throwing you less** than at the side [at the equator]. So your weight's gonna be different."

183 S5: "Yeah, but that has nothing to do with gravity."

184 S4 *(now on camera)*: "Why not? What if— the [G-F] Earth is **trying to throw you around** at the equator.

Figure 7. S4: "The Earth has more pull *on you." Compare with Fig. 4.*

185 S5: "It's sort of like [turning] friction into a normal force and …."

S4 refines his statement:

186 S4: "How could that not have anything to do with it? If the Earth is **trying to throw you off,** in effect, at the equator, then it will kind of [G-F] counteract the [G-F] **pull of the Earth on you**. And at the [*points*] North Pole it wasn't **trying to throw you off** and the Earth has [G-F] **more pull on you**. Which means you'd weigh more. So it would change your weight."

This student appears to be putting considerable effort into both his words and his gestures. We suggest that one result of this is to make his imagined scenario easier for others to visualize; not only is the direction of the rotational effects in the opposite direction from Line 17, but the placement and nature of the forces in this scenario are much clearer/less ambiguous than they were in his articulations (in Line 143, for example) immediately before the extreme case was introduced. Thus, there is evidence that he has gone though some conceptual change since the beginning of the discussion.

We hypothesize that one mechanism that made this possible was enhancement of the precision and clarity of the student's imagery. It appears probable that this is due to the scaffolding of the teacher's extreme case—considering effects at the pole and the equator—an apparently minor modification of S4's own case. Though S4's phrase "how far you are from the poles" does not differ from the North Pole/Equator variation in terms of which variables are involved, we suggest that taking the value of the variable to contrasting extrema provides clarity when visualizing the directions of the rotational effects and the gravitational forces.

Comparing the gestures of Figs. 4 and 7, it is interesting to note that in the interim between the two gestures, S4 has increased his emphasis on the role of masses pulling on each other and downplayed the role of rotational effects as causes of gravity.

The discussion continued for several more minutes and included yet another Gedanken experiment and more analogical reasoning. The teacher ended the class by saying that he wished to defer the question of what causes gravity until the following day. This resulted in howls of protests and laughter from the students, with one student dramatically collapsing over his desk in a show of frustration.

Gravity Class Results

Eleven episodes of spontaneous student introductions of Gedanken experiments, extreme case reasoning, and analogies were identified in the 43 minutes of transcript (Stephens and Clement, in review). Of these eleven, ten were accompanied by action gestures, indicating the presence of imagery involving force or motion.

Overall Findings

Of the 20 episodes of spontaneously generated analogies, extreme cases, and Gedanken experiments identified in the transcripts, a total of 17 were accompanied by one or more depictive gestures. Furthermore, each of these 17 episodes was accompanied by one or more action gestures (indicating force or motion). We view this as evidence for student use of animated, rather than static, imagery in conjunction with these processes.

In some of the instances presented, there is evidence that students could use these processes when a test case or question was initiated by the instructor. More importantly, there is evidence that these students frequently initiated these reasoning processes themselves, that they generated creative test cases amenable for use within these processes, and that they then used the processes to reason aloud about important conceptual issues. For instructors interested in science process goals, this constitutes an initial "existence proof" that students can engage in creative scientific reasoning.

The student arguments converged on reasons in favor of the accepted scientific views of gravity and of normal forces, suggesting that these processes can also contribute to content goals.

Implications

Even in cases where this paper is preaching to the converted (readers who agree that students make use of animated mental imagery during their reasoning), it is a different matter to provide evidence to support this hypothesis. We need more research that provides an evidence-based argument for the involvement of imagery in these processes.

The ability to document the occurrence of these non-formal reasoning processes and to associate them with imagery opens the door to further investigation of whether such reasoning processes are central or peripheral when students are constructing and revising their mental models. It should permit the investigation of the role of mental imagery in these processes in a way that has not before been possible. Such imagery situates the class discussion in grounded examples. We believe these issues warrant further study because it is possible that the processes, along with depictive gestures, allow students to share visual or kinesthetic meanings in a way that allows the discussion to make sense to a greater number of students.

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