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Reasoning about Structure and Function: Children's Conceptions of Gears

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Abstract: Twenty-three second graders and 20 fifth graders were interviewed about how gears move on a gearboard and work in commonplace machines. Questions focused on transmission of motion; direction, plane, and speed of turning; and mechanical advantage. Several children believed that meshed gears turn in the same direction and at the same speed. Many second graders provided very incomplete explanations of transmission of motion. Most children confused mechanical advantage with speed. Yet as the interview proceeded, several fifth graders generalized conceptions about transmission of motion into a rule about turning direction. They increasingly justified their ideas about gear speed by referring to ratio. Children's reasoning became more general, formal, and mathematical as problem complexity increased, suggesting that mathematical forms of reasoning may develop when they provide a clear advantage over simple causal generalizations. © 1998 John Wiley & Sons, Inc. J Res Sci Teach **35:** 3–25, 1998.

This study investigates the way that second- and fifth-grade students reason about gears, both in configurations on a gearboard, where no purposeful function is entailed, and in other familiar machines that have a known purpose, such as handheld eggbeaters and bicycles. Despite a growing interest in technology education, little research has been conducted to ascertain how elementary school children reason about the way that mechanical devices work (although for exceptions, see Brandes, 1992; Piaget, 1960). Such knowledge is important because it provides a window into children's reasoning about the relationship between structure and function, a fundamental concern in nearly every form of scientific reasoning.

Because of a concern within developmental psychology for exploring early competence in causal reasoning, there is a research literature exploring how very young children and infants understand the behavior of simple objects and mechanisms (Baillargeon, 1987; Bullock, Gelman, & Baillargeon, 1982; Spelke, 1991). Moreover, a growing literature exists on adults' mental models of more complex devices such as doorbells, thermostats, steamplants, and handheld calculators (e.g., Gentner & Stevens, 1982). However, relatively little is known about the kinds of transformations in device reasoning that typically occur during middle childhood. Such research has practical as well as scientific significance because much of children's learning during the elementary years, especially in science and technology, depends on their capability to

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inspect things and figure out how they work—that is, to make inferences about the function of a device from its structure. The importance of this kind of reasoning is emphasized in current science education reform objectives, such as those developed by the American Association for the Advancement of Science and the National Research Council. These objectives target the relation between structure and function as a central organizing theme for science instruction.

In this study, gears were the focus for studying children's understanding of structure and function because gears provide an easy entry point for learning, yet also incorporate some relatively deep scientific (e.g., torque, mechanical advantage) and mathematical (e.g., ratio, proportion) principles. Like other simple machines, some aspects of gears' operation seem deceptively straightforward, but others are not simple at all. On the one hand, unlike devices such as calculators or sewing machines, the operation of gears is directly inspectable and involves no hidden parts, and the transmission of motion is visible. Research on the development of causal reasoning suggests that even preschoolers are well equipped to understand the simple transmission of motion (Bullock et al., 1982). On the other hand, the literature on naive physics forewarns that developing a robust understanding of *how* motion is transmitted may require a considerable amount of inference which in some cases may be governed by misapplied intuitive understandings (diSessa, 1993). For example, as we will explain below, some children thought that turning force tends to die away as additional gears are added to a train. According to this interpretation, gears that are farthest from the driving gear will turn noticeably more slowly than gears that are close to the driving gear. Thus, even though gears are open, inspectable devices, reasoning about them can be challenging.

One source of the challenge is that gears are typically arranged in trains of two or more meshed gears. Understanding such a system can entail figuring out a rather complex set of constraints. For example, the turning direction of any gear in a configuration is constrained by the position of the others. Moreover, the turning speed of a gear depends on its size relative to the other gears. To make matters yet more complex, what one interprets as a gear's speed depends on the frame of reference that one adopts. For example, for all gears that mesh, the velocity of their gear teeth will be the same, yet in a given period of time, smaller gears will complete more revolutions than larger ones. Although it is possible through direct observation to learn about speed and direction of turn, some principles of gear functioning, such as mechanical advantage, are not directly observable.

In summary, although a superficial understanding of gears can be gained readily by direct observation, a deep understanding is unlikely to emerge without considerable reflection. Such reflection involves the application and coordination of two different but complementary perspectives, referred to as mathematical and mechanistic, respectively. In fact, when people observe regularities in the world, both these perspectives are usually engaged to some degree; here we consider them separately only for explanatory clarity. The perspective we are calling mathematical involves observing and symbolizing patterns and regularities. The perspective we are calling mechanistic involves imputing mechanisms that underlie and explain these observed patterns (the distinction is akin to the one made by Shultz [1982], who distinguished Humean and Kantian interpretations of causality).

To illustrate a mathematical perspective, after observing the turning speed of several pairs of meshed gears of different sizes, one might observe that across several such combinations the ratio of the circumferences of the gears equals the ratio of the turning speeds. This search for regularity or pattern in data is thus associated with mathematizing nature.

Alternatively, one can think about the same phenomenon mechanistically, noting that each tooth on the driving gear must push one tooth on the gear that it drives. Thus, the turning speeds of the two gears must depend on the number of pushing teeth and the number of teeth that get pushed. The mechanistic perspective is associated with identifying underlying mechanisms, and thus is associated with explanatory scientific models. Because gears and other simple machines readily lend themselves to thinking from either mathematical or mechanistic perspectives, they afford an opportunity for constructing links between mathematical and scientific thinking. These connections between mathematics and mechanics are important because they may be developmental precursors to the mathematization of science that occurs in more full-fledged model-based reasoning (Kline, 1980). The development of such connections is therefore an important focus for study.

The connections between mathematics and mechanics can be developed at different levels of generality and complexity. First, as described above, after considering pairs of gears of different sizes and in differing configurations, one can formulate local rules about speed and direction of turning of pairs of meshed gears. For example, one may develop the rule that pairs of meshed gears must turn in opposite directions, or that small gears turn faster than large ones. One may also develop higher-level generalizations about entire systems of gears: for instance, that every other gear in a train of meshed gears will move in the same direction. Finally, one might develop rules in which causality is mathematized by noting that the turning speed of meshed gears depends on the ratio of their circumferences. Fully understanding these ideas likely requires experience, instruction, and the development and use of forms of notation that permit children to fix, compose, and coordinate transformations (e.g., changes in position, rotations) that are observed. In this study we began investigation of these issues by studying the extent to which second- and fifth-grade children reason about them when questioned about simple toys and everyday devices.

This work is preceded by three related studies, each focusing on how children come to understand the transmission of movement on a gearboard (Metz, 1985, 1991; Perry, Graham, Freedman, & Woolley, 1992). However, in neither of these studies was the motivating interest children's understanding of gears per se or children's ability to reason about relationships between structure and function. Rather, gears were used as a context for exploring a more general psychological question, such as the development of children's explanations (Metz, 1991) or the effectiveness of principle-based instruction (Perry et al., 1992).

In a study comparing 3-, 5-, 7-, and 9-year-olds, Metz (1991) described 11 successively more sophisticated kinds of explanations about transmission of movement and jamming of gears in patterns on a gearboard. Metz's subjects generated a range of explanations, including those focused on the function or reason for which gears and handles are intended, on the placement or connection of the gears, or on mechanisms accounting for the transmission of movement, such as gear teeth. The work of Perry et al. (1992) explored similar issues from an instructional rather than a developmental perspective. They compared third and fifth graders on tasks with gears, giving half the sample problem solving practice alone and the other half practice along with an explicit principle for identifying gear configurations that would jam. Perry et al. concluded that the principle-based instruction benefited the fifth graders but not the third graders, and recommended that instruction about simple machines be postponed until fifth grade. However, Metz's more finegrained studies and our previous pilot work suggest that primary grade children can generate rich and varying kinds of reasoning about gears.

This study extends the earlier work concerning transmission, mechanism, and direction of motion to additional concepts about gears, including speed of turning, changes in the plane of motion, and mechanical advantage. Following Metz (1985, 1991), we began by posing children with successively more complex patterns of meshed gears on a gearboard and asking them to predict how the gears would move and why. In addition to asking about transmission and direction of motion, as Metz (1991) did, we asked about relative speed and number of revolutions.

Along with these prediction/justification questions with the gearboard, we also asked students to reason about gears in the context of two familiar machines, a handheld eggbeater and a 10-speed bicycle. These devices afforded the opportunity to explore children's understanding of how gears can transmit motion through different planes and how they generate mechanical advantage.

In summary, the following research questions organized our inquiry: (a) How do elementary school children explain the following phenomena in different sizes and combinations of gears, some in stand-alone configurations and others embedded in working machines: how motion gets transmitted in a chain of gears, including how gears can change the plane of motion; direction of gear turning; and relative speed of meshed gears? (b) How do children conceptualize the tradeoff between speed and mechanical advantage in gears? (c) Do children apply concepts about transmission, direction, and speed consistently across differing patterns of gears and in familiar machines, or is their thinking more context dependent? (d) What characteristic differences in reasoning are observed between early elementary school (second grade) and late elementary school (fifth grade)?

Methods

Subjects

One intact class of second graders and one of fifth graders in the same elementary school participated in a study of "how people your age think about the way things work." The school is in a suburban neighborhood near a small midwestern city. With the exception of two students in the second grade and one in fifth whose parents withheld permission, all the students in both classes participated: a total of 43 children including 23 second graders (10 girls and 13 boys) and 20 fifth graders (8 girls and 12 boys). Mean age of the second graders was 8 years, 3 months (ranging from 7 years, 5 months, to 8 years, 9 months); mean age of the fifth graders was 11 years, 3 months (ranging from 10 years, 6 months to 12 years, 7 months).

Procedure

Each student participated in two individual interviews with one of the two authors. Interviews were conducted in rooms near students' classrooms. The first interview, which lasted approximately 35 min, presented children with patterns of meshed gears on a gearboard, coupled with a series of questions concerning how the gears would move if turned, and why. The second interview, which lasted approximately 20 min, included a series of questions about gears in the context of two familiar machines, a hand-held eggbeater and a 10-speed bicycle, which children operated during the course of the interview. Both interviews, described immediately below, focused upon children's understanding of transmission of force via gears, speed of turning of various combinations of gears, direction of turning (including plane of motion for the eggbeater), and mechanical advantage (the bicycle).

First Interview: Gearboard. The purpose of the first interview was to diagnose students' reasoning about gears. Six configurations were presented, each increasingly more complex, as illustrated in Figure 1. The patterns were based on hypotheses—some formulated from the work of previous investigators and some from our own previous pilot work—concerning concepts about gears that young children might plausibly hold. In each of the six configurations, the driving gear was a large blue gear placed in the middle of the gearboard with a small turning han-

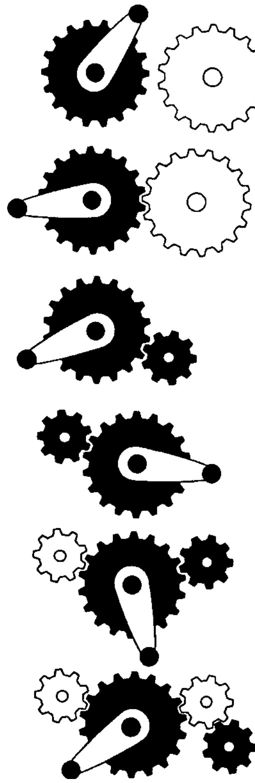

Figure 1. The configurations of gears shown to children in the gearboard interview, in order of their presentation (from top to bottom).

dle inserted into its center. Other gears were included on the board and meshed with the driving gear; they varied with respect to size and placement. All large gears were approximately 12.0 cm in diameter and had 18 teeth; small gears had diameters of approximately 6.0 cm and nine teeth. For each of the six configurations, children were asked questions about each target gear (gears propelled by the driving gear) on the board. Indicating a direction and speed for the driving gear, the interviewer asked children to predict the direction of turning, the speed of turning, and the number of full turns completed for each of the other gears, and to justify each response. Students received no feedback; the interviewer proceeded to the next problem without turning the gears and avoided commenting on the correctness of children's replies. Gestures that children made to indicate direction of turning were noted; these records were supplemented with audio recordings. The six gear configurations were used as the basis for five interview items described immediately below (mismatch between number of configurations and number of items is due to the fact that some configurations are used to explore related questions; these are grouped together).

Item 1: Two Large Gears, Unconnected (Referred to Below as L-L).

As Figure 1 shows, the first problem presented two large gears mounted on the gearboard so that they were not in contact. Gesturing in a circular fashion with pointed finger to indicate direction of turning, the interviewer asked, “If I spin the blue gear this way (clockwise direction), what will happen to the red gear? Why?” The purpose for this item and the one immediately following was to ascertain whether children were aware that gears need to be connected before motion can be transmitted from one to another. Metz (1991) suggested that young children may believe instead that gears turn primarily because that is the function for which they are constructed—with little or no regard for mechanism.

Item 2: Two Large Gears, Connected (LL—The Large Red Gear was Remounted So That It Meshed with the Blue Gear).

In addition to exploring children’s understanding of the need for contact, this item also assessed their beliefs about direction and turning speed of two same-sized meshed gears. Gesturing in a circular fashion, the interviewer asked, “If I spin the blue gear this way (clockwise), what will happen to the red gear? What direction will it turn? Why? Will the red gear go faster than the blue one, slower, or the same speed? Why? If the blue gear goes around one time, how many times will the red gear go around? Why do you think so?”

Item 3a: Large Blue Gear Connected to Small Green Gear (LS—a Small Green Gear Replaced the Red Gear in the Previous Configuration).

Gesturing as before, the interviewer asked, “If I spin the blue (large) gear this way (clockwise), what will happen to the green (small) gear? Which direction will it go? Why? Will the green gear go faster than the blue one, slower, or just the same speed? Why? If the blue gear goes around one time, how many times will the green gear go around? Why do you think so?” The intent was to discover if children knew or could infer by inspecting the gears that the smaller gear would turn faster than the larger driving gear and in the opposite direction. It also provided an opportunity to investigate children’s conceptions about speed. Children might apply at least two different conceptions of gear speed because if meshed gears are turned, the velocities of teeth on both gears are identical, but the numbers of revolutions made in a given period by the large and small gear differ.

Item 3b: Large Blue Gear Connected to Small Green Gear in Opposite Position (SL—the Green Gear from Item 3 was Removed and Remounted on the Opposite or Left Side of the Blue Gear).

The sequence of questions asked in Item 3a was repeated. This item follows up on earlier work by Metz (1985, 1991), who found that children sometimes reason about gears by attending to the shape of the overall configuration rather than focusing on connections between pairs of gears. If so, children might assume that changing the relative position of the gear with respect to the driving gear could result in a change in its speed or direction.

Item 4: Small Orange Gear Connected to Large Blue Gear (Driving Gear), Connected to Small Green Gear (SLS).

As in earlier items, children were asked to make judgments about direction of turning, turning speed, and number of turns for each of the gears in turn (first the orange gear, Item 4a, then green, Item 4b). Here children were shown a pattern of three rather than two gears. The item provided another opportunity to diagnose beliefs that direction of turning is determined by a gear's position in the train relative to the driving gear. It also permitted investigation of children's ideas about how motion is transmitted through a chain of gears.

Item 5: Small Orange Gear Connected to Large Blue Gear (Driving Gear), Connected to Small Red Gear, Connected to Small Green Gear (SLSS).

This problem included four meshed gears in a chain. In addition to eliciting conceptions about speed and mechanical transmission, it differentiated between children who reasoned about a gear's turning direction by computing the motion of each gear in turn and those who understood the general principle that contiguous meshed gears move in opposite directions.

Second Interview: Eggbeater and Bicycle. The second interview was conducted on a separate occasion within 1 week of the first. During it, participants inspected and operated a handheld eggbeater and a 10-speed bicycle and answered a series of questions about each machine. The questions, like those in the first interview, concerned direction and speed of turning of parts of the machine, as mediated through gears. In addition, children's concepts of mechanical advantage were probed. Whereas the gearboard questions asked for *predictions,* these questions focused upon children's *explanations* for phenomena that they observed while operating the machines. To preserve children's actions and gestures, these interviews were video recorded.

Eggbeater.

Students were handed a manual eggbeater and asked, "Do you know what this is? Can you show me how to hold it and make it go?" Since all the working parts of the eggbeater were exposed, the children could easily examine the gears as they turned the crank. Children were asked how the gears change speed of turn, direction of turn, plane of motion, and mechanical advantage.

Item 1: How Does It Work?

The interviewer first asked children to explain how the eggbeater works: "Suppose you were talking on the phone to somebody in a different country who had never seen one of these things before. What would you say to tell them how it works so that they could make one just like it?" As children explained, they occasionally referred to parts of the beater as "this" or "it," using gestures to indicate the referent. In this case, the interviewer prompted by asking, "Would your explanation help your friend understand how it works if he couldn't see it?"

Item 2: Plane of Motion and Direction of Turn.

Since the eggbeater crank turns through a vertical plane of motion while the beaters move in a horizontal plane, this device provided an opportunity to find out how children explain change in the plane of motion and whether they correctly implicate the gears. The interviewer used gestures (turning fingers in the appropriate plane of motion) to describe the turning referred to in this question: "Suppose I turn the crank this way [vertical plane]. What way do the beaters turn? If the crank goes this way [gesture—vertical plane], how come the beaters go this way [gesture—horizontal plane]?"

Item 3: Speed of Turn.

This item focused on the gears' role in stepping up the speed of turning from the crank to the beaters. "I'm going to turn the crank very slowly one time around, and I want you to watch the beaters. About how many times do the beaters turn? Do they go slower than the crank, faster than the crank, or just the same speed? Suppose I start turning the crank and I turn it faster and faster [actions accompany the description], and then as fast as I possibly can. Is there any way I could get the crank to catch up with the speed of the beaters? Why (why not)?"

Ten-Speed Bicycle.

The operation of gears on a 10-speed bicycle is challenging even for adults to explain. However, bicycles are perhaps the only familiar gear-driven machines that provide children with everyday experience of mechanical advantage. During the bicycle portion of the interview, children inspected and operated a 10-speed bicycle mounted on a stationary frame so that the pedals could be turned by hand.

Item 1: Function of Speeds on a Bicycle.

"Have you ever ridden a bicycle? Does your bicycle have speeds? How many? Why do we need different speeds?" If children said (as most did) that the purpose for speeds was to go faster or slower, the interviewer asked, "Couldn't we just pedal harder or easier with our feet to go faster and slower? Do we really need to have speeds? Why?"

Item 2: Purpose of Shifting Gears.

"I've been noticing that sometimes people shift gears when they come to a hill. Why do they do that?" If children said (as many did) that shifting gears helps you go faster, the interviewer asked, "Well, if shifting gears helps you go faster, how come people don't just keep their bikes in hill gear all the time?"

Item 3: Explaining Mechanical Advantage.

Each child was asked to pedal the bicycle by hand as the researcher shifted the gears. "I'd like you to turn the pedals with your hand, just as we turned the crank on the eggbeater. While you turn the pedal, I'm going to change the gears." As the gears switched, the interviewer asked, "What happened? Tell me when it gets harder to turn and when it gets easier to turn. Why is it easier to turn when the chain is up there [on the largest rear cog] and harder to turn when the chain is down there [on the smallest rear cog]?" Children were given several opportunities to observe and experience the results of the chain shifting from one gear to another. Only the rear gear, closest to the child's line of sight, was shifted.

Coding of Interviews. To score the gearboard interviews, the authors read 10 of the interviews (five at each grade level) and developed a coding scheme to characterize the responses that children gave to each question. Responses included both judgments (e.g., which way does the gear turn?) and justifications (why does it turn that way?). This draft scheme was then applied by one of the experimenters to the remaining interviews, with adjustments and revisions made as necessary to incorporate the distinctions that seemed important in the children's answers.

Then the revised coding scheme was applied independently by the other experimenter to 10 of the remaining second-grade interviews and to all 20 of the fifth-grade interviews. A reply was scored as an agreement if the raters agreed both on the child's judgment and on the accompanying justification for the judgment. Because each of the items in the gearboard interview involved multiple questions, the total number of judgments scored for each child was 20. Total percentage agreement was 89.1%, ranging from 78% (on two items) to 100%.

For the eggbeater and bicycle interview, the authors first developed coding categories for 10 of the interviews (5 at each grade level) and then independently applied the coding scheme to all interviews. The total number of judgments scored for each child was 13. Total percentage agreement was 83%, ranging from 75% (on one item) to 100%.

Gearboard Interview.

For each of the six patterns of gears, children were asked for their predictions concerning transmission of motion, direction of turning, and relative speed of turning for several of the gears in the configuration. Both responses and justifications were considered in developing and assigning coding categories. Examples taken from interview protocols of children's reasoning about these ideas are featured below in the Results section. Here we provide a brief overview of the coding categories.

Responses (with justifications) about transmission of motion were coded into four categories. At the least sophisticated level, children might not understand that gears must be connected to transmit motion. At the next level, some children talked about one gear following another without mentioning push, pull, or other mechanisms of transmission. Some children regarded one gear as the agent (pushing gear) and the other gears as passive recipients of push. At the most sophisticated level, children's responses acknowledged that the gears interact—that is, push on each other.

Responses about direction of motion also fell into four categories. Young children very often claimed that meshed gears turn in the same direction. At the next level, children claimed that the turning direction of a gear depends on the position of the target gear with respect to the overall configuration of gears. Some children believed that the direction in which a gear turns depends on the direction in which it is pushed. Finally, a few children cited a general rule about direction of turning, a rule encapsulating the idea that contiguous gears always turn in opposite directions.

The final major issue that we investigated with the gearboard concerned children's conceptions about speed of turning. Here five categories emerged, four of which again fell into an order that could be considered roughly hierarchical. Some children argued that gears connected into a chain always turn at the identical speed. Others believed that speed of a gear varies with the number of additional gears included in the configuration. A few believed that as gears are placed farther from the driving gear, momentum dissipates, so that these more distal gears turn more slowly. Finally, at the most sophisticated level, children cited relative gear size as predictive of gear speed. In addition to these categories, some children reasoned by analogy, especially analogies involving anthropomorphism (e.g., big people are fast; so too, are big gears.)

Eggbeater and Bicycle Interviews.

The same coding categories for transmission of motion, direction of motion, and speed of turning were applied to children's explanations in the eggbeater and bicycle interviews. In addition, the eggbeater interview responses were coded to ascertain how children explained changes in the plane of motion (e.g., from vertical rotation of the handle to horizontal turning of the beaters). This and other issues were coded in a summary mechanism score that captured the number and kinds of mechanisms that children mentioned to explain how force is transmitted through the eggbeater. One point was awarded for each explicit mention of the following: gear beveling, push-pull of gear teeth, fixed ratio of gear speed, differences in number of gear teeth, and fixed ratio of gear size.

Finally, children's grasp of mechanical advantage was coded in their responses to questions concerning changing gears on a bicycle. A few children could not venture a response about why one would change gears on a hill. The next category contained responses that equated the function of gears as being an increase or decrease in speed. The final category concerned replies that indicated some recognition of the fact that changing gears affects relationships between two or more of the following: speed, effort, and distance covered per stroke.

Results

The first subsection describes the major kinds of thinking displayed during the gearboard interviews; the second describes the eggbeater and bicycle interviews. We report results at the group level for both interviews. Where significant differences were found between second and fifth graders, they are described.

Gearboard Interview

The three major issues investigated in the gearboard interviews were children's understanding of (a) transmission of motion, (b) direction of turning, and (c) relative speed of turning. We briefly describe the range of thinking that children generated with respect to each of these issues and, where applicable, report the regular co-occurrence between certain forms of reasoning and particular kinds of gear configurations.

Transmission of Motion. First considered are children's explanations about how motion gets transmitted from a driving gear to the driven gears in a train of meshed gears. These explanations were usually stated in reply to the first interview question, "If I turn the blue gear [driving gear] in this direction [clockwise gesture], what happens to the other gear?" First we explore whether children focused on the intended function of gears, rather than on the gear configuration, to explain their movement. Next, children's explanations for transmission are described. These ranged from explanations that did not mention mechanism at all to those that posited gears interacting by pushing against each other.

Connection as a Prerequisite for Transmission of Motion.

Some of the younger children in Metz's (1991) sample explained the motion of gears by referring to their intended function rather than their structure. That is, they said gears turn because that is what they are made for. To decide whether configurations would move or jam, the children in Metz's study apparently did not consider connections among gear pairs; instead, they talked about the purpose of gears. In the current study, the item designed to probe these conceptions was Item 1, the two large, unconnected gears (L-L). Recall that subjects were asked what would happen to the large red gear if the (unconnected) blue driving gear were turned in a clockwise direction. All 43 children replied that the red gear would fail to move. Four children, all second graders (17% of the younger children), briefly entertained the possibility that there might be some hidden connection behind the gearboard that could make the unconnected gear move, but once allowed to inspect the back of the gearboard, no child concluded that the red gear would turn.

Nineteen of the 43 children (44%) emphasized that for the red gear to move, the gears need to be touching or in contact. However, these children did not specify why or how the contact would effect movement. An additional 23 children (54%) focused more directly on mechanism, mentioning the need for the gears to be connected, hooked together, or attached. The older children (40%, or 8 of 20) were more likely than the younger children (9%, or 2 of 23) specifically to mention the role of gear teeth (Fisher exact text, $p < .03$).

Explanations for Transmission of Motion That Do Not Cite Mechanism.

Table 1 shows that for the remainder of the items, in which the gears *were* connected, the younger children were especially likely to generate explanations for the transmission of motion that failed to mention mechanism. The fifth graders' explanations became increasingly likely to mention mechanism as the interview progressed and the problems became more complex. In contrast, if anything, the second graders became less likely to suggest mechanism with later items in the interview. (Although problem complexity and order were confounded because we chose to give the simpler problems first, nevertheless the difference in responses by the second and fifth graders suggests that order alone would not be sufficient to account for changes in reasoning.) For example, the simplest of the connected gear chains appears in Item 2 (LL), the two same-sized large gears. While reasoning about this problem, 9 (40%) of the second graders' and 6 (30%) of the fifth graders' explanations failed to mention mechanism. In Item 5, the most complex problem, which included a chain of four gears (SLSS), nearly half of the second graders

Table 1
Percentage of children[a] giving each justification for transmission of motion

Gear Problem	No Mechanism	Agent/Patient	Interaction	Rule
Item 2 (large–large)				
Grade 2	39.1	52.2	8.7	0.0
Grade 5	30.0	45.0	25.0	0.0
Item 3[b] (large–small)				
Grade 2	39.1	52.2	8.7	0.0
Grade 5	20.0	65.0	15.0	0.0
Item 4[c] (small–large–small green)				
Grade 2	47.8	34.8	4.3	13.0
Grade 5	20.0	70.0	5.0	5.0
Item 5 (small–large–small orange)				
Grade 2	52.2	34.8	4.3	8.7
Grade 5	15.0	75.0	5.0	5.0
Item 5 (small–large–small–small)				
Grade 2	43.5	30.4	0.0	26.1
Grade 5	5.0	40.0	0.0	55.0

[a]$n = 23$ second graders and 20 fifth graders.
[b]Items 3a and 3b are presented together because justifications were not affected by change in configuration.
[c]Items 4a and 4b are presented together because justifications were not affected by change in driven gear.

but only one child in Grade 5 explained transmission of motion without reference to mechanism. Second graders often responded to the items only with statements about simple contingency: for example, “If the blue gear goes around this way, the red one will, too.” Sometimes these second-grade children described the driven gears as “copying” or “following” the driving gear. An example is the following discussion taken from the protocol of a second grader.

> I: “Okay, so the blue one will go this way and the red one will go in the same direction?”
> S: “Yes.”
> I: “Why will it go that way?”
> S: “Because . . . the . . . if the blue gear went that way the red gear would probably go that way because . . . it . . . it . . . it’s kind of like a copycat.”

The Driving Gear Conceived of as Agent and Others as Passive.

Although substantial numbers of younger children did not discuss mechanism, the modal response to questions about transmission of motion portrayed the driving gear as an active agent responsible for pushing other gears in the train (Metz, 1985). Other gears were described as playing no central role in the transmission of motion; instead, children apparently conceived of them as passive recipients of motion. In reply to Item 2 (LL), the two large connected gears, 12 (52%) of the second graders and 9 (45%) of the fifth graders justified the motion of the driven gear by explaining that the teeth on the blue gear push the teeth on the red (similar patterns of response were observed on the remaining problems as well). Most of these children talked about the driving gear as the agent and the other as the patient, as illustrated by the following explanation from a second grader.

> I: “Now, if I turn the blue one this way, what would happen to the red one?”
> S: “It would just turn around, too, and I think it turns the opposite way.”
> I: “Why does it go that way?”
> S: “Because this one is pushing on it, so it turns.”

Interaction: Gears Moving around or Pushing on Each Other.

Relatively few children described both gears in a yet more sophisticated way—as pushing against each other or moving around each other. In the protocols of these children, there was evidence that they perceived the driven gears as also pushing back against or constraining the driving gear and other meshed gears in the train. In response to Item 2 (LL), the two large connected gears, 9% of the second graders and 25% of the fifth graders gave explanations of this kind. For example, the interviewer asked one second grader, “If I move the blue gear this way, what’s going to happen to the red gear?” The child responded by explaining that the red gear cannot turn in the same direction because of the way that the gear tooth on the red gear (the “spiky thing”) pushes against teeth on the blue gear.

> S: “It’s going to go around that way.”
> I: “Okay, why will it go that direction?”
> S: “Because this one . . .”
> I: “The blue one?”
> S: “The blue one is going up and it won’t go up because the spiky thing is in it, so then it [red gear] will go that way [opposite direction], but they’re [the gear teeth] going

> against each other. When they [gear teeth] come back in [revolve and meet], they come together [e.g., mesh]."

Over the course of the interview, these justifications based on simple push-pull mechanisms gradually were replaced by use of a general rule to explain the direction of turning gears. The percentage of children using this rule is recorded in the final column in Table 1. These results illustrate that children cited such a rule more frequently as the interview progressed (the top-to-bottom arrangement of the items reflects their sequence in the interview). This rule is discussed in the following section on children's conceptions about direction of turning. As noted previously, the order of items was the same for every participant; hence, it cannot be determined whether these changes over the course of the interview were due primarily to increasing time devoted to thinking about gears or whether they were cued in some way by the increasing complexity of problems in the latter parts of the interview. Because no feedback was given to students' responses, we favor the latter interpretation, but it is not possible to know definitively whether one of these interpretations is correct or whether both contributed to children's apparent increasing understanding of directional pattern.

A few children who otherwise reasoned mechanistically appeared to expect an observable delay in transmission of motion from the driving gear to other gears in the train. This kind of reasoning, illustrated below by a second grader, especially tended to appear in response to gear chains that included several gears. For example, Item 5 (SLSS) featured four gears, and 9% (two) of the second graders and 30% (six) of the fifth graders suggested that there would be a delay in transmission of motion to the small green gear, the gear most distant from the driving gear.

> I: "Now, if I spin the blue one in this direction, in what direction does the green one go?"
>
> S: "Since this is going to be going around this way [clockwise], this [red intermediate gear] is probably going to be spinning that way [counterclockwise], while this [red gear] is going to be hitting that [green gear], and then it's going to be coming around this way. It has to . . . it's going to have to wait until that hits there, and then probably by then it's going to be halfway to where it was before. . . . The red's probably going to be spinning the same way, but then the green is going to have to wait until that has to hit him."

In summary, approximately half of the second- and fifth-grade children held conceptions about the transmission of motion that depended upon simple ideas of push. Children understood that gears needed to be touching for this push to be effected, although few of the young children specifically mentioned the role of gear teeth. Moreover, with more complex arrangements (those that varied number and size of gears), the younger children were less likely to rely on explanations that featured mechanism. On these problems, some of the younger children resorted to justifications that mentioned transmission but did not suggest a mechanism for it. The other second graders and most of the fifth graders eventually began to cite a rule that summarized their observations about the way that transmission of motion determines the direction of turning of gears in a train.

Direction of Turning. The second major issue addressed in the gearboard interview was children's conceptions about the turning direction of meshed gears. Some children apparently believed that all meshed gears turn in the same direction. At the other end of the continuum of replies, some children cited a general rule that every other gear in a chain turns in the opposite direction.

Meshed Gears Turn in the Same Direction.

As Table 2 shows, the younger children, especially, tended to predict that all meshed gears would turn in the same direction. For example, when reasoning about Item 2 (LL), 30% of the second graders but only one fifth grader stated incorrectly that both of the large connected gears would turn in the same direction, Fisher exact test, $p < .05$. A similar pattern was observed in response to the remaining items (Fisher exact test, $p < .05$ for Items 3a, 4a, and 5, respectively), except for Items 3b and 4b. In these cases, children were being queried about a gear placed to the left of the driving gear. Since some of the children believed that the turning direction of a target gear would change if its position were switched from one side of the driving gear to the other, it is difficult to be confident that these responses indicate better understanding.

These incorrect judgments about direction were often associated reliably with explanations about transmission of motion that did not cite mechanism. That is, a child who said that gears move "because they are connected" or "because they touch" was also liable to say that "If the blue gear goes one way, so do the others." For example, in reply to Item 2 (LL), a total of eight children said that both gears would go in the same direction; of these, seven said that was because the red gear "follows" or "copies" the driving gear. These children frequently failed to inspect the gears closely and often seemed confused by the very question about direction of turning. It is difficult to tell for sure, but they may have been relying on a general heuristic such as, "Things generally go in the direction that they are pushed." In contrast, 27 of the 35 children who correctly said the two gears would turn in opposite directions justified those responses by referring to pushing or pulling between gears (Fisher exact test, $p < .001$). Hence, as one might expect, whether children reason correctly about direction of turn may depend upon whether they tend to focus on mechanisms that might account for direction.

Direction of Turning Depends on Spatial Configuration.

Small proportions of children believed that the direction of a gear's turn depends primarily not on pushes exchanged between contiguous gears, but on the position of the target gear with respect to the overall spatial configuration of gears. Especially suggestive of this belief are the children's replies about the direction of the small gear in Items 3a (LS) and 3b (SL), because as Figure 1 illustrates, the only difference between these two items was that the identical gear was

Table 2
Percentage of children[a] making incorrect judgments about the turning direction of the target gear relative to the driving gear[b]

Gear Problem	Grade 2	Grade 5
Item 2 (*large*–large)	30.4	5.0
Item 3a (*large*–small)	26.1	0.0
Item 3b (small–*large*)	13.0	15.0
Item 4a (small–*large*–small green)	39.1	10.0
Item 4b (small orange–*large*–small orange)	17.4	5.0
Item 5 (small–*large*–small–small)[c]	30.4	5.0

[a]$n = 23$ second graders and 20 fifth graders.
[b]In all cases, the italicized gear is the driving gear.
[c]For Items 2–4b, the correct answer is "opposite direction," whereas for this problem, "same direction" is the correct answer.

meshed to the right of the driving gear in Item 3a and to its left in Item 3b. Three second-graders and two fifth-graders explicitly said that the small gear in Item 3b would turn the opposite way as in the previous problem because of its change in position. Also of interest is children's reasoning about Items 4a and 4b, in which the large driving gear is sandwiched by two small gears. Although the turning directions of the green gear and the orange gear in this problem are identical, Table 2 shows that children did not give the same answers to Questions 4a and 4b, but rather judged that the two gears would turn in opposite directions. These children, mostly second graders but a few fifth graders as well, gave replies on the basis of the target gear's position on the left or right of the driving gear. This may be due to the second graders' tendency to favor the belief that the driven gear turns in the same direction as the driving gear because it follows the driving gear. If one gear is perceived as following, a gear on the opposite side of the driving gear may not be perceived as following.

Direction of Turning Depends on the Direction of Push.

As reported above under Transmission of Motion, most children judged the turning direction of a gear by thinking about how it would be pushed by other contiguous gears in the train. These children carefully inspected the gears, and if the target gear was not immediately contiguous to the driving gear, they appeared to be recomputing the direction of each intervening gear. As other investigators have found (Perry et al., 1992), there was widespread use of circularly turning fingers to model turning direction down the train of gears. Reference to pushing was the modal response (about half the children) even by the very first problem posed in the interview, and children continued to reason in this way as the interview progressed.

Rule-Based Reasoning about Direction.

As mentioned above, especially during later problems in the interview, a few children began to cite what appeared to be a general rule about direction of gear turning. This rule encapsulates the children's emerging understanding that contiguous gears turn in opposite directions. As Table 1 shows, in response to the fifth and final problem, SLSS (the chain of four gears), one quarter of the second graders and over half the fifth graders used this form of reasoning. It may be that this rule was evoked for the more complex cases because it circumvents the need to figure out the direction of each gear independently, and thus helps manage working memory demands. The following protocol from a fifth grader illustrates rule-based reasoning in response to Item 5.

> I: "Now, if the blue goes around this way, what way does the green one [final gear in the chain] go around?"
> S: "The same way."
> I: "Why does it go the same way?"
> S: "Because there is one gear in between. This gear [blue] goes this way [clockwise], which makes this gear [red] go the opposite way, so the green gear goes the opposite way of the red gear. It's opposite of the one before it. So if there is one in between them, it just goes the same."

Relative Speed of Turning. The final major issue investigated with the gearboard was children's conceptions about gear speed. As with transmission of motion and direction of turning, children generated a variety of kinds of reasoning when asked about the relative speed of gears. These are described next.

Meshed Gears Go the Same Speed.

As Table 3 shows, several children argued that all gears turn at the same speed regardless of their position or size. For example, although half the children in both age groups correctly predicted that the small gear in Item 3 (LS) would turn faster than the large gear, approximately one third of the children believed that both gears would turn at the same speed. These children referred to the driving gear as being "in charge" and the smaller gear as "holding on," or talked about the fact that the gears were connected, as if this provided *prima facie* evidence that they must therefore turn at the same speed. Similar responses were given in response to the remaining items in the interview. It is interesting that these incorrect responses about speed did not differ with age. In contrast to their ideas about mechanism and direction, the fifth graders were about as likely as the second graders to hold these incorrect conceptions about speed.

There is other evidence in the children's protocols that they found gear speed particularly difficult to grasp. For example, Table 4 illustrates the relationship between children's judgments about the relative speed of the two gears in Problem 3 (LS) and their predictions about the number of revolutions that the smaller gear would make for each full revolution of the large driving gear (this item is the one presented because it is the first item in which unequal-sized gears are presented). Of interest is the diagonal in Table 4, which shows that there is a fair amount of consistency in children's replies about speed and number of turns—those children who thought the small gear would turn faster also tended to believe that it would complete more turns; those who thought it would turn slower believed it would make fewer turns. However, the cell defined by the intersection of "same speed" and "more revolutions" indicates that seven of the children held the view that even though the gears turn at the same speed, the smaller gear nevertheless makes a greater number of turns.

These inconsistencies in reply are not necessarily all motivated by the same conception. Some of the children appeared to be concerned with an undifferentiated notion of impetus and

Table 3
Percentage of children[a] judging that the target gear would turn slower than, at the same speed as, or faster than the driving gear

Gear Problem	Slower	Same Speed	Faster
Item 2 (large–large)			
Grade 2	17.4%	(65.2%)	17.4%
Grade 5	0.0	(100.0)	0.0
Item 3 (large–small)			
Grade 2	17.3	30.4	(52.1)
Grade 5	10.0	35.0	(55.0)
Item 4a (small–large–small green)			
Grade 2	8.7	43.5	(47.8)
Grade 5	5.0	50.0	(45.0)
Item 4b (small–large–small orange)			
Grade 2	8.7	43.5	(47.8)
Grade 5	10.0	45.0	(45.0)
Item 5 (small–large–small–small)			
Grade 2	21.7	30.4	(47.8)
Grade 5	5.0	50.0	(50.0)

Note. Parentheses indicate the correct answer for this problem.
[a]$n = 23$ second graders and 20 fifth graders.

Table 4
Children's responses to Item 3: Relation between conceptions about speed and conceptions about number of turns

No. of Children Expecting Small Gear to Make:	No of Children Expecting Small Gear to Turn Slower than Large Gear	Same Speed	Faster	Total
Fewer turns than large gear	3	1	0	4
Same no. of turns	2	6	1	9
More turns than large gear	1	7	22	30
Total	6	14	23	43

its conservation, and argued that a certain amount of "oomph" put into the system by turning the handle would have to result in an equal amount of "oomph" in other parts of the gear train. Other children may have been answering these questions by relying upon different frames of reference. For example, some seemed to be claiming that the speed of a tooth on the circumference of the large gear moves at the same speed as a tooth on the smaller meshed gear. This observation is correct and is not inconsistent with the judgment that in a given unit of time, the smaller gear will complete more turns than the larger one. However, without more systematic investigation, it is not possible to be confident about the basis for these judgments.

Speed Depends on Number of Gears.

Some children argued that the speed of a gear depends on the number, not the size of gears connected to it. One version of this position held that the more gears, the more power; hence, each gear in the chain goes faster when another gear is added. In another version, the result of adding more gears was perceived to be that the driving gear has more "stuff" to push; under this construal, the more gears included, the slower any particular gear moves.

These conceptions were particularly likely to surface in reply to Item 4a (SLS), which is identical to Item 3 (LS) and immediately follows it, except that one additional small gear is added to the train. As Table 3 shows, although half the children correctly judged that the small green gear would turn faster than the large driving gear, the other half insisted that it would go the same speed. Of these, six children explained that although a smaller gear would normally go faster than a larger one, in this case, the extra orange gear added to the train would make the driving gear work harder—hence, the smaller gears would turn no faster than the driving gear.

Dissipation of Momentum.

Conceptions about delay of transmission were addressed above, under Transmission of Motion. A related conception appeared to be influencing a few children's ideas about gear speed. These children believed that dissipation of momentum results in gears turning more and more slowly as they are positioned farther from the driving gear. For example, when reasoning about Item 5 (SLSS), 22 of the students (about half in each age group) expected that the small gear farthest to the right would turn either the same speed as or more slowly than the driving gear, which is larger. A few (six) of these children explicitly said that the slower speed of the target gear was due to delay or dissipation of momentum as it travels from gear to gear. The others cited justifications related to constant amount of power transmitted through the system—the "oomph" idea explained above.

Speed Depends on the Relative Sizes of Gears.

Most of the children correctly stated—at least for some problems—that there is a relation between the relative sizes of meshed gears and the speed with which they turn. Some children justified this idea by referring to the number of revolutions completed; that is, they stated that the speed of meshed gears depends on the number of turns completed in a given unit of time. Since the number of revolutions depends on the relative size of the gears' circumferences, relative gear size determines speed. In reply to Item 3 (LS), 22% (five) of the second graders and 20% (four) of the fifth graders offered this explanation concerning why the smaller gear would turn faster than the larger gear. Some children (three fifth-graders) went even further to quantify that relation, stating that relative speed could be found by determining the ratio of the number of teeth on the target gear and the driving gear. In the more complex train of gears displayed in Item 5 (SLSS), one third (seven) of the second graders and one fourth (five) of the fifth graders talked about relative gear size; an additional second grader and 20% of the fifth graders counted and calculated the ratio of gear teeth. Hence, as the interview progressed and more challenging problems were posed, children became increasingly likely to reason mathematically, using ratio as a way of justifying their judgments about gear speed. It is interesting that these forms of mathematization appeared to take root even though children were not permitted to turn the gears on the gearboard and thus ascertain whether their predictions were correct.

Reasoning by Analogy

Some children who talked about size and speed developed explanations that relied upon neither mechanism nor observed regularities, but upon anthropomorphic analogy. Although only a few did so for any problem, these responses are interesting because they are neither primarily mathematical (based on pattern) or causal (organized around mechanism). Anthropomorphic analogies popped up regularly, even though they were used only by a few children at any one time. Some children proposed these analogies as justifications for predictions that small gears would turn more slowly than large gears (because they are smaller and hence less powerful). Others claimed that large gears move more slowly, like clumsy, large, or heavy people. Some children developed these analogies into elaborate stories about gears:

I: Why will the green one [in Problem 3] go faster?
S: Because it's smaller.
I: What does that have to do with it?
S: Smaller things weigh less, and . . . there's a little kid. His name is Jake. And when he's outside at recess, he's smaller than everybody, so he can go a lot faster.
I: If the blue gear goes around one time, how many times do you think the green gear goes around?
S: Twice.
I: Why do you think twice?
S: Because, as I was saying, the green gear is faster because it's smaller . . . like Jake. If you were doing laps with Jake, and if you run around twice, he could probably go around three times. If you went around once, he would go around two times.

In summary, children's ideas about transmission of motion, direction of motion, and relative speed of turning were variable. Although there was considerable overlap in the performance of second and fifth graders, there were also developmental trends. In one sense, these findings provide a reasonably optimistic view of children's conceptions about gears—in many cases, the correct response was the modal response. On the other hand, correct responses were not necessarily given on a consistent basis. Instead, there was a tendency for different items reliably to cue different kinds of responses. For example, switching a gear from one position on the board to another might cue the expectation that its speed of turning would change. Adding another gear to a train could cue the expectation that the entire train would slow down or speed up. However, it is at least possible that these variable responses were due to repeated questioning about gears in the relatively sparse, context-free frame of the gearboard, which did not evoke schemas about purpose or function that might support more consistent reasoning. Of interest was to what extent children might apply similar kinds of conceptions to explaining the workings of gears in machines designed with an obvious purpose. The interview involving the eggbeater and bicycle was intended to investigate the same general ideas—transmission of motion, direction of turning, and speed of turning—in a functional context, and also to provide an opportunity to probe children's understanding of gears' role in changing the plane of motion and achieving mechanical advantage.

Eggbeater and Bicycle Interview

When asked how eggbeaters work, most children spontaneously volunteered the information that the large gear attached to the handle is connected to the smaller gears on the beaters. However, fifth-grade students (85%) were more likely than the second graders (52%) to construct causal chains that involved relationships among three or more components of the tool, $\chi^2(1) = 5.21$, $p < .05$. For example, one fifth-grade child noted: "When you turn the handle, it turns this big gear, which turns these [little] gears, which turn the beaters." Second-grade students, in contrast, often simply enumerated the parts of the eggbeater without saying anything about their connections or explaining how motion gets transmitted from one part to another. Neither younger nor older children tended to include in their justifications notions of speed, direction, push-pull of teeth, or changes in the plane of motion. "How it works" appeared centered on point-to-point transmission: "This turns that, which turns . . ."

When asked how it is that the crank turns in a vertical plane while the beaters turn horizontally, 83% of the second graders and 95% of the fifth graders explicitly mentioned that contact among the gears was responsible for changing the plane of motion. Although most children did not discuss the shape of the beveled gears as an important factor in making transmission possible, 48% of the second graders and 65% of the fifth graders mentioned the importance of gear teeth in effecting change in the direction of motion. Recall that, in contrast, only 9% of the second graders mentioned the role of gear teeth in the function-free context of the gearboard (fifth graders performed equivalently in both contexts).

With respect to speed, only one fifth-grade student, but 35% of the second-grade students, thought that turning the crank handle very quickly might enable the speed of the handle to catch up with the speed of the beaters. Some of these children suggested that small gears usually go faster than large ones, but that the small gear speed would approach a limit, after which the extra energy provided at the point of contact (the crank) might enable the large gear attached to the crank to catch up. Interestingly, 5 of these 9 second graders reasoned about gear speed on the basis of anthropomorphic analogy, as described above. It is possible that considering whether large or small people can run faster leads children to think about intention and trying harder, and hence to entertain the possibility that good effort might make up for lack of speed.

Of those children who stated that the crank could *not* catch up with the beaters, over half in both age groups mentioned the relative size of the gears as a reason. However, the fifth graders were more likely than the younger children to cite the number of teeth on the gears (45% of fifth graders, 13% of second graders) or the fixed ratio of teeth on the large and small gears (35% of fifth graders, 13% of second graders).

Finally, we wondered whether the younger and older children would be equally likely to propose specific mechanisms that could account for differences in the speed and direction of turning of gears. Recall that the findings about the gearboard combinations reported above suggest that they would not. To explore this question, we developed a summary mechanism score to index children's propensity to propose mechanism as an explanation for the transmission of force through different planes of motion and the differences in the speed of the cranks and beaters. One point was awarded for each explicit mention of the mechanisms noted above: (a) beveling, (b) push-pull of gear teeth, (c) fixed ratio of gear speed, (d) differences in number of gear teeth and (e) fixed ratio of gear size. The mechanism score was calculated by summing these points, resulting in a potential range from 0 to 5. The mean for the younger children was 1.8 and for the older children, 3.0; in general, younger children were less likely than older children to emphasize mechanism in their explanations, $t(41) = 3.65$, $p < .01$.

We next turn to the bicycle portion of the interview. Here it was evident that children understand that gears have something to do with speed, but do not understand the relationship between speed and mechanical advantage. The general notion, one particularly compelling to the second-grade children, was that one changes gears for the purpose of changing speed (an idea mentioned by half of the second graders and one quarter of the fifth graders). Consistent with this idea, 58% of second graders explained that one would not use the gears for climbing hills all the time because it would not be safe: "You might go too fast and fall off on the street."

In addition, approximately three quarters of the older children and one quarter of the younger ones recalled that gears have something to do with difficulty of pedaling, but only 20% of the fifth graders and 13% of the second graders gave any evidence, even under the most lenient criteria, that they realized that there is a tradeoff between ease of pedaling and distance that the bicycle travels per pedal stroke.

When children were asked specifically to hand pedal the bicycle and explain how the gears made it easier or more difficult to pedal, they gave a diverse array of replies. One third of the fifth graders and 29% of the second graders invented explanations that concerned the position of the chain around the rear gear, e.g., that it was becoming tighter or looser when it moved closer to the wheel, or that it could turn more easily when it "traveled downhill" (slanted downward) to curve around a smaller gear. Although 35% of the fifth graders and 25% of the second graders mentioned gear size, they talked about the relative size of the different rear gears, not of front-and-rear gear combinations. A characteristic explanation in this class was the straightforward claim that "It pedals easier on this gear because this is an easy gear." Only three fifth-graders proposed an explanation based on size ratio of the front to back gears, and two of these explanations were incorrect. Only one fifth-grade boy noted that a gear *combination* involving the smaller crank gear and the largest rear gear would mean that the "bigger gear in the back will go around fewer times but with more power." Indeed, during the interview, we noticed that many children did not seem to know where to look when watching the gears change as they pedaled with their hands, and had to be prompted to look at the gears themselves, not at the gear-shifting levers on the handlebars or at the cogwheel.

Discussion

An important lesson from the variability of children's reasoning is just how much there is to understanding open, inspectable devices such as gears that work by the simple transmission of motion. When reasoning about gears, seeing may or may not be believing. Yet much instruction in science and technology slides past these distinctions and instead emphasizes the mere recognition of gears, inclined planes, and levers in everyday environments. How and why machines work are rarely addressed, and even when they are, instruction does not appear to be informed by the kinds of conceptions that children bring to the table.

Developmental research on children's understanding of directly inspectable causal systems (such as the gear trains studied here) suggests that even preschoolers interpret situations by applying a small set of assumptions that are identical to those used by adults in making causal attributions. These principles include determinism, or the belief that events are always caused; mechanism, the expectation that causes bring about effects by direct or mediate transfer of causal impetus; and priority, the assumption that causes always precede or are coincidental with their effects. These three principles make up the "causal theory" shared by adults and children (Bullock et al., 1982). Yet research suggests, and the results of this study confirm, that although children and adults employ the same causal rules, this does not necessarily mean they will perform equally competently on all causal reasoning tasks. A general assumption of the causal model developed by Shultz and Kestenbaum (1984) is that causal errors are usually due to selecting a reasonable rule that is nonetheless inappropriate for the situation, and in general, children are less knowledgeable than adults are about which rule to apply in a given context, especially when they have no specific prior knowledge about mechanism.

Consistent with this analysis, many of the conceptions that children apply to understanding gears are reasonable rules about the way the world usually works, but do not apply in the context of gear trains. For example, younger children especially tended to predict that meshed gears would all turn in the same direction, presumably because things usually go in the direction they are pushed. Similarly, some children stated that all meshed gears turn at the same speed, perhaps relying on the general observation that things usually go at the same speed as things that push them. Children's reasoning about gears varied readily with superficial adjustments to the gear configurations. For example, moving a gear from one side of a driving gear to its opposite side might cue expectations that the gear would now turn in the opposite direction, because children perceived driven gears on one side as following the driving gear. The variability of children's reasoning, its sensitivity to cueing, and its relatively piecemeal nature are in general very consistent with diSessa's (1993) characterization of novice knowledge as characterized by relatively unconnected "phenomenological primitives." Those familiar with diSessa's work will also recognize that several of these responses reported as characteristic show good correspondence with specific "p-prisms" that he has proposed as being part of the knowledge system of most novices.

Yet over the course of a 40-min interview, the older children especially began to generalize their reasoning about mechanisms for transmission of motion into a general rule about direction of turning. Moreover, they also began to develop arguments about quantity and ratio (of gear teeth) to justify their judgments about the relative speed of gears in a chain. It is possible that these forms of reasoning appeared because children were learning over the course of the interview. Although they received no feedback, their close and repeated inspection of the gearboard may have led them to develop more confident generalizations about the way that the structure of the gears constrained their motion. Moreover, the problems became more complex as the interview progressed—later problems included more and more varied combinations of gears. We conjecture that the increase in complexity and challenge also played a role in eliciting these more sophisticated forms of reasoning. Children's reasoning became more general, formal, and mathematical as it became more costly to recompute anew and hold in mind the turning direction and turning speed of several different-sized gears in a train. This finding is intriguing, because it suggests that model-based forms of reasoning may be especially likely to develop when they provide a clear advantage over the application of simple causal generalizations.

When asked to explain how an eggbeater works, most children spontaneously mentioned that gears are important, and many of them explained how the gears in an eggbeater can transmit motion from the crank to the beaters, change the plane of motion, and change speed of turning. However, we noted that children seldom initially or spontaneously looked carefully at the devices they were explaining. For almost every child, a careful inspection of the machine did not occur until after we had asked a question for which the child had no ready answer. Children, and perhaps people in general, may have a tendency to overlook how machines work and attend instead to what they are made to accomplish (e.g., Brandes, 1992). Not until they began to think about the questions we were asking did the children seem to understand that there was anything at all that required explanation. Given an orientation to purpose rather than structure, people may spend little time inspecting devices and reasoning about how they work or why they work that way—mental models of everyday devices may remain relatively sketchy unless and until people encounter a compelling need for a more elaborate model.

If we are right, instruction emphasizing the mere recognition of gears or other simple machines is liable to leave these conceptions unaltered. Moreover, because there is such wide variability in what children see in a train of gears, direct instruction about how gears work may also be ineffective for those whose expectations and perceptions do not match those that the teacher assumes. As suggested in the introduction to this article, the instructional challenge is to identify a means to encourage children to go beyond merely noticing empirical regularities or patterns, to search for explanations that would account for those observed regularities. Similarly, it is also important to encourage them to look beyond their existing favored conceptions about mechanism to consider patterns of data that may or may not be consistent with those theories. Coordinating these two forms of information—empirically observed patterns of regularity and ideas about mechanism grounded in theory—is cognitively more challenging than working only within either. Yet doing so is foundational for model-based reasoning, which emphasizes *relationships*—such as those between mathematics and mechanics, or more generally, between a model and the phenomenon being modeled in the world.

In work subsequent to the current study, we explored the possibility that a context based on technology and design may be a fruitful way of bringing these relationships to children's attention (Lehrer, Schauble, Carpenter, & Penner, in press; Penner, Giles, Lehrer, & Schauble, 1997; Schauble & Lehrer, 1995). Using gears and other machines to invent solutions to design problems may help focus children's attention on developing, testing, and revising hypotheses about the relationships between structure and function. The need to achieve a clearly specified outcome invites both the generation and test of promising means. Design problems often elicit diverse solutions, and therefore tend to result in opportunities to be surprised by outcomes that are not initially expected. Moreover, disconfirming results are less likely to be dismissed out of hand, because the need for a design solution remains even when a first solution fails. If it is compelling, the need for a solution inspires continued reasoning and testing. The search for better design solutions may, in turn, yield information relevant to alternative explanations. In classrooms where effective design standards and criteria are in place, reflection about successful and unsuccessful solutions is a standard part of the design cycle (Lehrer, 1993). Beyond their instructional promise, such contexts are also important for further study of children's reasoning about the relations between structure and function, because extended problem solving contexts that support feedback and knowledge revision can provide a stage for moving beyond the study of children's beginning conceptions about gears—or, for that matter, other domains—to study processes of learning and conceptual change.

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