AC 2009-1279: ANALYSIS OF CHILDREN’S MECHANISTIC REASONING ABOUT LINKAGES AND LEVERS IN THE CONTEXT OF ENGINEERING DESIGN

Molly Bolger, Vanderbilt University
Marta Kobiela, Vanderbilt University
Paul Weinberg, Vanderbilt University
Richard Lehrer, Vanderbilt University
Analysis of Children’ Mechanistic Reasoning about Linkages and Levers in the Context of Engineering Design

Abstract

Reasoning about mechanisms is one of the hallmarks of disciplined inquiry in science and engineering. Despite the central importance of mechanistic reasoning, its origins are not well understood. Numerous curricular efforts involve simple machines and related physical systems, but these do not yet build toward a systematic and longer-term vision for promoting the development of reasoning about mechanisms. The research we describe here was developed in partnership with a team of engineers and science educators who aim to support the early development of mechanistic reasoning through a curriculum that challenges children to design kinetic toys called MechAnimations. Our research aims to characterize the intellectual resources available to children as they engage in design challenges and to describe the process by which these design activities may promote development of mechanistic reasoning. This paper provides an in-depth look at children’s prior understandings of a key aspect of MechAnimation design – the mechanics of linkages and levers. In a flexible interview, 9 children at grades 2 and 5 were asked to predict and explain the motion of mechanical linkages. Children explored contrasting pairs of mechanisms, chosen to highlight components of the system important to its functioning (such as the location of the fulcrum in relation to the input). As one might expect, many student responses focused on aspects of the mechanical system that were not oriented toward its function. For example, “it looks like a plus sign.” However, children also exhibited more sophisticated thinking, such as describing the parts and structure of the mechanisms. The most sophisticated student responses included mechanistic descriptions of how the parts and structure worked to: constrain motion, affect the direction of rotation, coordinate the direction of motion for input and output levers, coordinate the movement of lever arms, and affect the magnitude of motion. Overall, children who more readily tended to relations between input and output seemed better able to predict mechanism motion. All children demonstrated at least some elements of mechanistic thinking, but many of their responses lacked coordination of multiple elements. When children coordinated multiple elements, they were also more likely to successfully predict the motion of one or more outputs, given an input. Children who predicted incorrectly tended to exhibit mechanistic reasoning only after observing the mechanisms move, if at all. Although designed to ascertain children’s’ naïve ideas about mechanisms, certain aspects of the interviews seemed to support the development of elements of mechanistic reasoning. For example, comparing the motion of contrasting mechanisms helped some children notice relevant variables not apparent before the contrast. These results suggest methods for characterizing mechanistic reasoning as well as potential resources for supporting its development. We anticipate that the latter may profitably be incorporated into design challenges.
Introduction

Casual reasoning about mechanism, *mechanistic reasoning*, underpins understanding the ways things work, and more broadly, the functioning of natural phenomena. Hence, mechanistic reasoning contributes significantly to understanding both the designed world and the natural world. Russ, Scherr, Hammer, and Mikeska (2008) clarify that mechanistic reasoning involves not only associating causes with effects but also includes a description of the process responsible for such association. Through focusing on the processes that underlie cause-effect relationships, mechanistic explanations take into account how the activities of various entities affect one another, thus building a causal scheme. “Complete descriptions of mechanisms exhibit productive continuity without gaps from the set up to terminal conditions” (Machamer, Darden & Carver, 2000, p. 3). Establishing complete mechanistic descriptions is often daunting, as witnessed by the historic challenge of the transition from literal, push-pull conceptions, ie one object pushing or pulling on another object, to those involving action at a distance (Hesse, 1962; Nersessian, 2008), and by the contemporary challenges posed by the emergence of inter-disciplinary fields (Machamer et al., 2000).

Because our interest is in the early origins of mechanistic reasoning, we focus on children’s understanding of the historically antecedent push-pull form of description. An emerging body of research suggests that some components of push-pull mechanistic reasoning emerge spontaneously in the course of everyday development. For example, Gopnick, Sobel, Schulz, and Glymour (2001) presented 3 and 4 year old children with a machine that turned on when a block of one color, but not a block of second color, was placed atop the machine, or if both blocks were placed on the machine. Children in the study quickly and reliably discriminated the relevant cause-effect relationships. These early forms of competence have their counterparts in early childhood. In her study of children’s reasoning about gears, Metz (1991) found that children as young as 5 years could explain the motion of a gear system by explaining that turning the first gear would make the other gears turn. In related research with 7- and 10-year old children, Lehrer and Schauble (1998) found that both age groups suggested contact between gears as determining output—the direction and speed of a terminal gear in a train of gears. However, older children were much more likely than younger children to invoke push and pull among teeth of the gears. The explanations of the older children were more mechanistically complete tracings of the relation between input and output, involving entities (gears), properties of entities (size, teeth), and activity (teeth push and pull). These native resources for developing accounts of mechanism were less available even for the older children when the gear mechanisms were either oriented differently in space (e.g., relating the input and output of a hand-cranked eggbeater) or when the mechanism of transmission was indirect (e.g., the chain connecting front and rear gears in a bicycle). Hence, although children often display surprising mechanistic competencies, the conditions for expression of these competencies, as well as their limitations, is still not well understood. Yet such knowledge would appear critical for the design of instruction and the conduct of teaching that could support children’s further development of mechanistic reasoning.

In the research reported here, we explored early manifestations of mechanistic reasoning by investigating how children (grades 2 and 5; ages 7, 10 years) reasoned about the operation of simple systems consisting of links and pivots, such as that displayed in Figure 1. Our choice of
links and pivots was motivated by our collaboration with Gary Benenson and Jim Neujahr, who propose to cultivate mechanistic reasoning by engaging children in the design of toys that move, *MechAnimations*

![Mechanical Toy Diagram](image)

Figure 1. *MechAnimation and pegboard model from Benenson and Neujahr.* Arrows indicate relative motions of input and output links, given a force applied at input. Fulcrums are designated as fixed pivots. Transmission occurs at points designated as floating pivots.

Our research is aimed at developing a description of children’s understandings of the entities and actions of entities in these systems before instruction, with an eye toward informing pedagogy based on how children typically reason about these mechanisms. We anticipate too that our efforts to characterize reasoning will also serve as the foundation for the development of a system of assessment. From the perspective of probing children’s reasoning about mechanisms, the link and pivot systems have the virtues of easily discriminated input and outputs, as well as visible workings of the components. Hence, in principle, these are mechanisms that afford relating causes to effects and to tracing the activity of the entities involved. Two questions guided our investigations:

1. Although all entities and activities of these simple mechanisms are visible in principle, how do children parse the system? Which entities and activities are typically noticed and how are they coordinated to develop an account of the output?
2. What forms of explanation are evident when children account for either predicted or observed motions in these mechanisms? Is mechanistic reasoning the dominant form of explanation?
Method

Participants

Participants (n=9, 5 male) attended an elementary or middle school serving primarily underrepresented youth in a city located in the southeastern region of the United States. The percent of children attending the schools that qualify for free or reduced lunch ranges between 60 to 90 from year to year. The five elementary school children (ages 7, 8, referred to as Sam, Katie, Brian, Don and Beth, all pseudonyms) came from one second grade classroom. The middle school children (all fifth grade, ages 10, 11, referred to as Kim, Chuck, Greg and Anne, all pseudonyms) came from one classroom and a school-wide after-school program. The children were ethnically diverse (6 African-American, 1 Middle Eastern, 2 Indian, 1 Samoan) and according to their teachers, represented a wide spectrum of achievement.

Materials

As illustrated in Figure 1, children worked with mechanisms made from two types of materials: wooden pegboard and paper. Wooden pegboard mechanisms consisted of strips of wooden pegboard, called links, affixed either to another link by a brad fastener (a floating pivot) or to a pegboard base (a fixed pivot). The resulting mechanisms ranged in the number of links and in the shape of links used (i.e. rectangular or circular), but all mechanisms contained one input and at least one output. Some mechanisms included a paper constraint, a holder, which facilitated linear motion of the link. The input on each mechanism was marked by a blue piece of paper. Mechanisms made from paper, called MechAnimations, were decorated to resemble an animated object.

Procedure

Children at each grade level responded to a flexible interview (Ginsburg, Jacobs & Lopez, 1998) conducted over the course of three or four days, approximately one hour each day. Interviews were recorded using two cameras, each with a flat table microphone. One camera was positioned directly four feet in front of the interview table. The second camera was positioned at the side of the student, only about one half foot away from the table, angled down to capture what the he or she was looking at. Interview sessions were digitally rendered for further analysis, with views from both cameras juxtaposed. Children first saw a completed MechAnimation and were informed that they would be participating in activities that would help them create their own MechAnimation during the last part of the interview. Children were provided with two links, a pegboard and brads, and then guided through the process of making a fixed and floating pivot. Hence, children were familiar with the materials before proceeding to the next phase of the interview.

Interview Design & Procedure

Children saw 8 different mechanisms. The order of presentation was the same for every student and was arranged in a presumed order of complexity ranging from simple to more
complex. We used contrasting pairs (with one exception) to draw children’s attention to functionally relevant features of the mechanisms. Here we describe each pair and its intended relevance for eliciting mechanistic reasoning. Figure 2 illustrates each of the mechanisms to which we refer in the sections that follow.

**Single input and output.** Each of three mechanisms, A1, A2, A3, was composed of a single input and a single output. A holder constrained the input to linear motion, a floating pivot connected the input and output, and a fixed pivot served as the fulcrum. Motion was generated when a directed force was applied to the input. The output motion generated varied with the location of the position of the fulcrum. Mechanism A1 was a third class lever (with the input located between the output and the fulcrum/fixed pivot). Mechanism A2 was a contrasting, first class lever (with the input and the output on either side of the fulcrum). The fixed pivots on mechanisms A1 and A2 were equally distant from the input link, but on opposite sides, affecting the direction of the output when the input was pushed “up.” The fixed pivot on A3 was on the same side as A1, but much farther from the input link, affecting the relation of the distance of input motion to output motion. This was the second contrasting case. Figure 2A illustrates the structure and movement of each mechanism. The order of presentation was the same for each student: A1, A2, A3.

**Single input, multiple outputs.** The second pair of mechanisms (B1, B2) were similar to those just described, but each contained two outputs instead of one (see Figure 2B). The two mechanisms differed in location of the fixed pivots. For mechanism B1, one fixed pivot was placed above the input link and the other below the input link. In contrast, for mechanism B2 both fixed pivots were positioned above the input link. These differences altered the direction of motion of the output links; when the input was pushed to the right, the outputs on Mechanism B1 moved in opposite directions, traveling inward in slight arcs. The outputs on Mechanism B2 moved in the same direction, traveling right and downward in a slight arc.
Figure 2. *Construction and Motion of Mechanisms Used During Interview Tasks*. Each Mechanism was presented to each student. Children were asked to make comparisons between the mechanisms within a group after working with the individual mechanisms in that group.

<table>
<thead>
<tr>
<th>A</th>
<th>Single Input &amp; Output (Group A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanism A1</td>
<td>Mechanism A2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B</th>
<th>Single Input, Multiple Outputs (Group B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanism B1</td>
<td>Mechanism B2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C</th>
<th>Circular Link (Group C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanism C</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>D</th>
<th>Constraining Motion in Different Ways (Group D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanism D1</td>
<td>Mechanism D2</td>
</tr>
</tbody>
</table>

**Key**

- Floating Pivot ○  Figurine used to indicate output
- Paper “holder” used as a constraint
- Fixed Pivot  ●
- Direction of motion of link  ↓  Blue Tab to indicate input

---

*Figure 2. Construction and Motion of Mechanisms Used During Interview Tasks*. Each Mechanism was presented to each student. Children were asked to make comparisons between the mechanisms within a group after working with the individual mechanisms in that group.
Circular link. Mechanism C (see Figure 2C) differed from all other mechanisms in that it contained a circular link placed between the input and output links. When the input link was pushed “up” on mechanism C, it caused the circle to turn counterclockwise. This counterclockwise turn would have moved the output link around in the same motion, but because of the constraint of a holder, the link moved to the left in approximately a straight line.

Constraining motion in different ways. The final pair of mechanisms, Mechanism D1 and D2 (Figure 2D) were designed to elicit student reasoning about constraint. In D1, the outputs traveled linearly due to the holders, but those in D2 did so because of an extra link placed horizontally across the output links. Although the two mechanisms looked somewhat different, they moved in the same way: when the input was pushed up, the left output link moved up and the right output link moved down.

Conduct of the Interview

For each mechanism, children described what they noticed, made a prediction about the output that would result from a given input, gave a rationale for that prediction, saw the result of a given input, and explained again, if necessary, the rationale for the observed motion. For paired mechanisms, children described how the mechanisms were the same and different and in some cases why that matter for the motion observed. Children built and inscribed one of the existing mechanisms, B1. Last, children responded to five assessment items and then designed and constructed a MechAnimation. These last activities are not included in the current analysis. A sample portion of the interview protocol is included in Appendix A.

Initial noticing. Children saw a pegboard mechanism and described what they noticed.

Predicting and explaining. Children predicted the motion of a stick figure (referred to as a “little man” by the interviewers) attached to one or more output links, given the direction of motion at an input. The interviewer gestured the motion of the input saying, “What if I push on it here on the blue part? What do you think will happen to the little man?” When the student described how the man would travel, the interviewer asked the child to show the path with his or her finger. Children explained the basis of their predictions.

Describing and explaining motion. After moving the mechanism, the Children again described what they noticed and provided an explanation for the movement.

Comparing. When working with mechanisms that were members of a paired contrast, Children compared what was “the same” or “different” about the two mechanisms. Though Children were presented with the mechanisms individually, the first mechanism in a pair remained on the table, available to the student, while the second was presented. The prediction task was somewhat different for mechanism B2. After mechanism B1 was presented, children saw only the motion of the outputs of mechanism B2 (the interior of the mechanism was screened with a piece of paper). Children then predicted the configuration of Mechanism B2. Specifically, they were asked to predict how they could make Mechanism B1 work like mechanism B2 and explain their prediction. Finally, children checked their prediction.
by removing the paper and were given the opportunity to explain how the mechanism worked and to compare it to Mechanism B1.

**Building and inscribing an existing mechanism.** After predicting the configuration of the mystery mechanism, B2, but before they predicted the motions of the remaining mechanisms (C, D1, D2), children attempted to build a replica of mechanism B1 with the pegboard materials. However, the pegboard used had its holes further apart, so that Children could not use a strategy of literally copying mechanism B1. Hence, the task focused on duplicating function. After building the mechanism, Children created a drawing that would help someone else build it.

**Analysis**

**Coding student predictions.** Children’ predictions were coded as “correct” or “incorrect” based upon whether the correct direction of the output link was specified relative to the given direction of the input link. Predictions about the structure of Mechanism B2 were coded similarly, but in regards to where the children expected the brads to be placed. For Mechanism C, the student was coded as correct if he or she correctly predicted the direction of rotation of the circle link. Additional attributes of predictions were also noted for different mechanisms. For Mechanisms in Groups A and B, the paths of children’ predictions were noted, that is, whether they predicted the man would move in an arc or a straight line. These paths were coded based on children’ gestures when they were asked to show with their finger how they thought the “little man” would move. On Mechanisms B1 and those in Group D, it was taken into account if children predicted the incorrect direction, but understood that the outputs should go in opposite directions. For Mechanism B2, it was similarly noted if children predicted that the brads should be placed on opposite sides of the input link even if they were not accurate. We considered predictions “partially correct” for Groups B and D if they took into account the opposite nature of the outputs (or the brads) but were not fully accurate.

**Coding student talk and gesture.** The remaining tasks (initial noticing, explaining and describing motion, and comparing) were all coded by developing an analytic framework to characterize children’s talk and gesture as they noticed, described and explained the mechanisms. All authors watched samples of video of children’s explanations and accompanying gestures for each task. Each author contributed what he or she noticed about interviewer-student interactions, student explanations, and student gestures. These video noticings (Jordan & Henderson, 1995) served as the starting point for development of a coding scheme to characterize children’s reasoning. The process followed was one of iterative refinement. A few children’s responses were coded independently by two coders and brought back to the group for further conversation. Disagreements often led to refinement of the scheme. When we judged that the process was stable, the coding scheme was applied to the entire sample. The analytic (coding) framework is described in the next section.

**Themes Guiding Analysis of Children’s Explanations of Motion**

We classified children’s responses into four thematic categories:
(a) **Noticing.** Talking about the appearance and components of the mechanism;

(b) **Structure.** Observing relationships between components, such as physical connections, but treating these relationships as if they contributed to a structure, not a mechanism;

(c) **Cause-Effect association.** Noting associations between the movement of two components or between the movement of a component and particular structural feature, without further explanation of the association. Associations included empirical regularities, such as noticing that the change in the location of a pivot was always associated with a change in link motion.

(d) **Elements of mechanistic reasoning.** Explaining how a component or relation among components contributed to a cause-effect association. Our focus on elements indicates that children often demonstrated pieces of this form of reasoning. More complete mechanistic explanations typically involved coordination among multiple elements.

**Analytic Framework for Coding Children’s Explanations**

The four thematic categories were further subdivided for purposes of closer description of student reasoning, as illustrated by Table 1 and described more completely in the sections that follow.

**Noticing.** These explanations referred to appearance, individual parts and unconnected movement. Appearance referred to perceptions of shape, form, and color. For example, “It looks like a plus sign.” And, [The stick figures on the outputs] “have different hair color.” Those student responses coded as individual parts demonstrated the student’s ability to describe individual components that are relevant to a mechanism’s function (e.g. brads, links, pegboard, and holders) but without reference to that function. For example, a student noticed that a mechanism had three links, when a previous mechanism had only two. Unconnected movement designated mention of the movement of an individual part of the mechanism without relation to other components. For example, one student explained an error in prediction as: “Because instead of going this way (gestures to the right), [the link] went this way (gestures to the left).”

**Structure.** This category referred to explanations that focused on the organization of parts without mention of the functional relation(s) among these parts. For example, “I see two of them [links] joined together.” And, “I notice that [Mechanism A2] has a peg on this side instead of being on this side.” In some cases children noticed difference in the distance from the fixed pivot to the input link, but did not ascribe anything else to the perception. For example, “I see that the brads are put farther apart.”
<table>
<thead>
<tr>
<th>Coding Categories &amp; Subcategories</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Appearance</strong></td>
<td>Focuses on visual aspects of the mechanism irrelevant to function.</td>
<td>“[Mechanism A1] looks like a cross.”</td>
</tr>
<tr>
<td><strong>Individual Parts</strong></td>
<td>Notes or describes specific parts of the mechanism (e.g. links, brads, holders) but without indication of how they contribute to the mechanism’s structure.</td>
<td>“They [Mechanisms A1 &amp; A2] both have two brads.”</td>
</tr>
<tr>
<td><strong>Un-connected Movement</strong></td>
<td>Describes how an individual part is moving (or will move), but does not connect this to the movement of other parts or to the mechanism’s structure.</td>
<td>“…[the output link] just went to the other side (points when output link ended up).”</td>
</tr>
<tr>
<td><strong>Structure</strong></td>
<td>Describes how parts of a mechanism are organized in ways that is relevant to the mechanism’s function.</td>
<td>“I see that the brads are put farther apart [on Mechanism A3 than on Mechanism A2].”</td>
</tr>
<tr>
<td><strong>Brad Covariance</strong></td>
<td>Notices that the direction or amount of motion of an output link covaries with the location of the fixed pivot.</td>
<td>“[The output links on Mechanism B2 both move in the same direction] ‘cause if you have the brads on the same side, they’ll go the same way and if you have them on a different side, they’ll go the opposite way.”</td>
</tr>
<tr>
<td><strong>Transmission of Motion</strong></td>
<td>Notices that the motion of one link covaries with the motion of another link, without necessarily attending to direction.</td>
<td>“[Mechanism A1 works the way it does because]…this [input] moving is going to make this part [near the little man] also move.”</td>
</tr>
<tr>
<td><strong>Linked Direction</strong></td>
<td>Correctly relates the direction of movement of the input to that of the output.</td>
<td>“When you move [the input link on Mechanism A1] up, [the little man] goes up. Whey you move [the input link] down, [the little man] goes down.”</td>
</tr>
<tr>
<td><strong>Incomplete Linked Direction</strong></td>
<td>Correctly relates the direction of the input OR output link’s movement to the direction of movement of a connected link (other than input or output).</td>
<td>In explaining the motion of Mechanism D1, a student relates the direction of input to that of the link connected to it, but stops before explaining the motion of the outputs: “If you push this [the input link] up, that [the left side of the short link] goes up.”</td>
</tr>
<tr>
<td><strong>Constraint</strong></td>
<td>Specifically references the fact that a fixed pivot is fixed/inmovable/stationary AND explains the motion of the link implied by this constraint.</td>
<td>In explaining the motion of Mechanism A1, a student notes: “this part is attached and that makes this one [the left side of the output link], this side to move up and down.”</td>
</tr>
<tr>
<td><strong>Fixed Pivot</strong></td>
<td>Describes the correct motion of a link resulting from the removal or addition of a holder constraint.</td>
<td>(In response to a question about taking away the holder on Mechanism C) “When it went down (pointing to the floating pivot on the circle), this (points to the little man) would have come this way (motions downward).”</td>
</tr>
<tr>
<td><strong>Holder</strong></td>
<td>Compares or contrasts the movement of the two lever arms OR talks about/gestures the coordinated motion of the two lever arms.</td>
<td>“…this one (points to right side of output link on Mechanism A2) goes up like that and this one (points to left side of output link) goes down.”</td>
</tr>
<tr>
<td><strong>Lever Arms</strong></td>
<td>Describes or gestures a rotary motion of a link.</td>
<td>“[The little man on Mechanism A1] only moves around (student gestures in a circle).”</td>
</tr>
</tbody>
</table>
Cause-Effect association. We distinguished two forms of talk that related effects to causes but that did not explain the basis for the association. The first, transmission of motion referred to instances relating how one link moved because another connected link moved. A student needed to specify transmission of force in some way, typically by using words like phrases like, “this link makes this link go up” or “this link controls this link”. However, if the student additionally specified direction of motion, their response was coded as Mechanistic Reasoning, as described in the next section. The second, brad covariance, referred to identification of empirical regularities resulting from location of a fixed pivot. That is, direction of motion for an output link covaried with the location of the fixed pivot. For example, when comparing Mechanisms B1 and B2, one student said, “(referring to Mechanism B1) Well it’s like one [brad] is on the bottom and one’s on the top, but they both like if you do it like that (moves input), [the links] go into each other because [the brads are] on the opposite. And this one (referring to Mechanism B2) if you do it, [the links] both go the same way...That one goes the same way because the [brads] are on the same place”

Elements of Mechanistic Reasoning. When children attempted to explain the basis of a cause-effect relation, their explanations typically referred to one of six elements: (a) linked direction, (b) incomplete linked direction, (c) rotation, (d) lever arms, (e) constraint via fixed pivot, and (f) constraint via holders. Linked direction referred to explanations that related the direction of motion for an input link to the direction of motion for an output link. For example, as illustrated in Figure 3A, Brian related the input to the output motion of Mechanism A2 in the following manner, “When you push this one [input link] it [the little man] moves back and when you pull it [the input link] it [the little man] moves forward.” Instances in which the interviewer prompted the student to relate input and output direction of motion, such as when they asked the student to predict output motion, were not coded as linked direction. A related category, incomplete linked direction, again related the direction of motion of two links, but did not in turn coordinate these relative motions to inputs and outputs. This was only possible for Mechanisms C, D1, and D2, which contained a link separating the input and output links. For example, one student explained, “cause if you push it this way (gestures up, along the input link), it might push the circle (gestures counterclockwise around the circle).” Here the student did not mention direction for input and output but instead followed the motion from input to a separating link. Incomplete linked direction indicated explanations that related the direction of motion for either an input or an output to another link but that stopped short of relating the direction of motion for the input link to the direction of motion for the output link.

Rotation around a fixed pivot (see Figure 3B) contributes to the functioning of all 8 mechanisms. Any instance of talk and/or gesture designating rotation was coded. This included instances where children talked about rotation, mentioning “turns”, “spins”, and “goes around”, or gestured a rotary movement.

Lever arms indicated instances when children talked about, or their gestures indicated, the coordinated movement of the two lever arms (See Figure 3C).
A. Example of student reasoning about linked direction of the input and output links for Mechanism A2

When you push this one it moves back. and when you pull it it moves forward.

| ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) |

B. Example of student reasoning about the rotation of the output link for Mechanism A1

It only moves around both of them move around.

| ![Image](image5.png) | ![Image](image6.png) | ![Image](image7.png) | ![Image](image8.png) |

C. Student reasoning about the coordinated direction of the lever arms of the output link during her prediction for Mechanism A2

so this side will come up here with that one so this one will come down here.

| ![Image](image9.png) | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |

D. Student reasoning about constraint via fixed pivot during her prediction for Mechanism A2

this one [the fixed pivot] will stay in its place so it will make this side go over here

| ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) | ![Image](image16.png) |

Student reasoning about constraint via holder during her explanation for the movement of Mechanism C

When it went down, this would have come this way when it would have gone up it would have went that way.

| ![Image](image17.png) | ![Image](image18.png) | ![Image](image19.png) | ![Image](image20.png) |

NOTE: The arrows represent the path followed by the student’s finger.

**Figure 3. Examples of Elements of Mechanistic Reasoning**
Fixed pivots and holders constrained motion. Explanations recognizing the functional contribution of these constraints to the operation of system were represented by this category. For example, as shown in Figure 3D, on Mechanism A2, Kim explained, “this one [the fixed pivot] will stay in its place so it will make this side [of the output link] go over here.” Instances when children saw the paper holder on Mechanism C as constraining the motion of the output link to a linear motion, rather than a rotational motion, were also coded as representatives of this category. Instances where the student simply mentioned that the holder helped to keep the mechanism from “falling apart” or prevented a link from going “side-to-side” were coded as Structure.

Application of the Coding Scheme

The unit for coding was each student’s responses to each mechanism, which we termed a student performance. There were 72 performances coded (8 mechanisms x 9 children). Each performance was coded independently by two of the authors. Each coder designated “codeable episodes”, that is, segments of talk and gesture that represented categories in the coding scheme and marked these with time stamps to define their boundaries. There were 742 distinct episodes of explanation. When multiple codes applied to an episode, the highest possible coding was employed. In a few cases, more than one codeable episode was included within a single time stamp. This occurred when a student’s talk suggested more than one subcategory within a level.

Reliability. At least two of us independently coded each student performance. Because each coder independently decided first on what would constitute a codeable episode and then on how that episode should be coded, there were two potential sources of disagreement between coders. Substantive disagreements about the identity of episodes occurred 21% of the time (Substantive disagreement occurred when one coder failed to include an episode designated by the second coder or when the same period of time resulted in differences in the number of episodes.) Minor differences in the timing of onset and ending of an episode were ignored. These disagreements were resolved by consensus. The number of episodes coded for an individual performance (i.e., the response of a particular student to a particular mechanism) ranged from 4 to 18, with a mean of 10.3. Of the codeable episodes independently agreed upon by both coders (n = 586), mean inter-rater agreement at the level of theme was 89%. When raters did not agree about the identity of an episode, they jointly resolved disagreement about the episode and the appropriate code.

Results

The presentation of results is organized as follows: First, we compare the incidence of each of the four main types of student talk and gesture identified in the coding scheme: noticing, structure, cause-effect and mechanistic reasoning. Each of these four categories is further partitioned with an eye toward ascertaining student preferences for particular forms of explanation. Second, we relate the level of children’s explanations to their ability to predict the motion of an output given a specified input. Third, we exemplify how various forms of mechanistic reasoning were used in student explanations. Our examples include two in which a student seemed to employ a developed causal scheme and one in which such a scheme seemed to be absent. We conclude with an eye toward future classroom studies.
**General Thematic Trends**

Figure 4 displays the percent of \( n = 72 \) student performances (responses to each of 8 mechanisms) exhibiting one or more instances of each thematic category. Not surprisingly, perceptual features of the mechanisms were most readily apparent (noticing overall appearance, individual parts or motions), as were connections among components (structure). However, inspection of the figure also suggests comparatively high incidences of explanatory talk and gesture involving empirical regularities and elements of mechanistic reasoning. We additionally compared the overall frequency of the various forms of talk and gesture between second and fifth grade children and found no discernable differences. For this reason, all results are combined.

![Figure 4. Overall Frequency of Student Talk and Gesture in Each of the Four Coding Categories. Numbers represent the percentage of student performances that contained at least one codeable episode for each of the four top-level categories. A student performance was considered the entire time a student worked with a particular mechanism. There were a total of 72 student performances.](image)

**Initial noticing.** Figure 5A shows that children’s first impressions of each mechanism (before moving the mechanism) focused on the overall appearance of the mechanism or identified its individual parts. Occasionally, children mentioned the organization of parts, coded as “structure”.

---

*Page 14.*
Figure 5. Characteristics of Student Talk and Gesture and During Various Portions of Interview. Numbers represent the percentage of student performances that contained at least one codeable episode for each of the four top-level categories during the specified interview portion. A student performance was considered the time a student worked with a particular mechanism or pair of mechanisms during a particular task. In this figure, white bars represent the “noticing” category, which has been divided into three sub-categories, “appearance”, “individual parts” and “un-connected movement”. N=72 performances for Panels A, B; N=36 performances for Panel C.
Explaining and describing motion. Figure 5B shows a shift in student talk and gesture when they were asked to predict or observe motion. They were much more likely to talk about “unconnected movement,” describing either the prospective or actual motion of a single link without talking about the motion of other parts or implications of the mechanism’s structure. Interestingly, children were also much more likely to notice elements of structure during this task, compared to the first task, suggesting that moving the mechanism and explaining its function provided children with a context to look for these elements. Also, at this point, student talk and gesture shifted to include more reasoning about cause-effect relationships and elements of mechanistic reasoning.

Comparing mechanisms. Figure 5C shows the nature of student talk and gesture when they were asked to compare two mechanisms. Children tended to focus on individual parts of mechanisms while comparing, but unlike initial impressions, they appeared less likely to refer to the appearance of the mechanism. Children were more likely to refer to structure while comparing two mechanisms than while noticing an individual mechanism, suggesting the potential usefulness of such comparisons. Finally, when children were directed to compare two mechanisms they were less likely to include unconnected movement, cause-effect reasoning and elements of mechanistic reasoning than when they were directed to describe and explain mechanism movement. This finding was in keeping with our informal observation that children often seemed to focus on the mechanisms as static objects when asked to compare them.

Trends in Cause-Effect Association and Elements of Mechanistic Reasoning

Both noticing cause-effect associations and performing mechanistic reasoning require a child to make at least one causal connection between one motion or structural element and another motion or structural element. However, elements of mechanistic reasoning can be orchestrated, as we describe later in greater detail, to produce a form of reasoning that traces entities and their activities from input to output, thus constructing a causal scheme. In order to illustrate these distinctions, we focus on the sub-categories of these forms of reasoning.

Figure 6A shows the percentage of student performances containing at least one instance of each form of reasoning. For cause-effect association, inspection of Figure 6A suggests that transmission of motion was less frequently observed than brad covariance. Recall that brad covariance refers to noticing an empirical regularity: When the position of the fixed pivot changed, so too did the motion of the output.

The frequency with which children generated different elements of mechanistic reasoning varied. Linked direction was by far the most frequently coded element. Incomplete linked direction was the second most frequently occurring element. Constraint via holder was rarely coded; later we explore how this element requires fairly sophisticated reasoning. We should note that it was not possible to reason with every element on every mechanism. For example, Mechanisms B1 and B2 did not have holders. Figure 6 takes this into account by showing occurrences as a percentage of possible occurrences, taking into account the mechanisms for which that element was possible to achieve.
Panel A: Numbers represent the percentage of student performances that contained at least one codeable episode for each of the sub-categories for explanatory talk. A student performance was considered the entire time a student worked with a particular mechanism. Percentages were calculated taking into consideration for which mechanisms a particular code was possible to achieve. The total number of performances in which each element was possible is as follows: linked direction, 72; incomplete linked direction, 27; rotation 72; linked direction; lever arms, 63; constraint via fixed pivot, 72; constraint via holder, 54; brad covariance 63; transmission of motion 72.

Panel B: Table entries represent the number of Children that correctly predicted the motion for the stick figure on each mechanism. Note that in three instances we were unable to obtain a clear prediction, one each for Mechanisms A1, A3 and C.

Panel C: Student performances were divided into two groups – those in which Children correctly predicted mechanism movement and those in which they did not. There were a total of 28 “correct” performances and 41 “incorrect performances”.

Figure 6. Frequency of Various Forms of Reasoning and Correlation to Prediction.
Because a causal scheme for mechanisms should include more than one element of mechanistic reasoning, we looked at how the different elements did or did not co-occur within individual student performance. Sixty-three percent (n=45) of student performances included at least one element of mechanistic reasoning. Out of these performances, 56% contained a single mechanistic element. Linked direction occurred in isolation most frequently (n=18; 25%), followed by rotation (n=3; 4%). These data suggest that elements of mechanistic reasoning are often employed in the absence of a complete causal scheme. Among those performances which contained more than one element of mechanistic reasoning (n=19), we evaluated the complexity of children’s explanations. The most complicated and complete mechanistic explanations involved four mechanistic elements. For example, on Mechanism C1, one student, Kim, reasoned about rotation, linked direction, fixed-pivot constraint, and holder constraint. A total of five student performances contained four elements. For student performances containing more than one element of mechanistic reasoning, the modal number of elements was 3.

Prediction and Forms of Reasoning

For each mechanism, children predicted the motion of “little men” that were attached to output links. Figure 6B shows how many responses were coded as “correct” or “incorrect” for each mechanism. Out of 72 predictions there were 28 correct predictions (39% correct). Mechanisms A3 and D2 seemed the easiest for students to predict. 5 out of 8 predictions for Mechanism A3 were correct and 5 out of 9 for D2 were correct.

Figure 6C shows which forms of explanatory talk were associated with correct predictions. Correct predictions were associated most strongly with elements of mechanistic reasoning, especially linked direction and constraint via fixed pivot. Reasoning about rotation was also observed more often when the prediction was correct. Cause-effect associations, which we considered as precursors of mechanistic reasoning, were not strongly associated with correct prediction. Among performances when children noticed these associations, children who exhibited knowledge of the effects of a change in the position of the fixed pivot predicted correctly more often than those who referred to transmission of motion. “Constraint via holder” was very rarely coded, only during three student performances, but each of these episodes were associated with correct predictions.

Figure 7 shows a correlation between the number of elements of mechanistic reasoning in a performance and the child’s prediction during that performance. Children’s performances were divided into those associated with correct or incorrect predictions and the number of elements of mechanistic reasoning were examined. For purposes of this figure, “multiple elements” refers to at least two distinct elements within a performance, excluding performances in which the same element was coded multiple times. Children who did not use mechanistic reasoning or used only one element of mechanistic reasoning most often predicted incorrectly instead of correctly. However, children who used multiple elements of mechanistic reasoning during a single performance were more likely to correctly predict the motion of the mechanism in that performance. Later we exemplify how one student, Kim, used multiple elements of mechanistic reasoning in a coordinated way to explain the motion of mechanisms.
Inspection of Table 2 illustrates the propensity of individual children to employ particular elements of mechanistic reasoning as they constructed explanations of the eight mechanisms. Children were rank ordered (least to greatest) by the number of predictions coded as “correct” or “almost correct” (as defined in the figure legend). Inspection of this Table suggests that, in general, children who explained using more elements of mechanistic reasoning possessed a greater predictive accuracy about the behavior of the system.

Inspection of the relative frequencies of each element of mechanistic reasoning for each individual represented in Table 2 clearly indicates intra-individual differences as well. Only one child, Kim, reasoned mechanistically across all tasks. The other children seemed to provide mechanistic or partially mechanistic explanations for some mechanisms, but not for others.

Mechanistic Schemes

Although coding elements of explanation reveals the entities and activities that constitute children’s mechanistic reasoning, a look beyond the frequency of individual codes is needed to capture how children orchestrate these entities and activities to explain or predict the behavior of the system. We term this orchestration of elements a mechanistic scheme. In this section, we compare and contrast two children as they constructed an explanation about the functioning of mechanisms. The first student, Kim, was chosen because her explanations consistently employed multiple elements of mechanistic reasoning, and she coordinated these elements to create a mechanistic scheme. The second student, Sam, reasons about a fixed pivot, but his explanation does reveal a complete causal scheme.
For both mechanisms, despite their differences in complexity, Kim used the same elements of mechanistic reasoning: linked direction, rotation, lever arms and constraint via fixed pivot. We first briefly characterize how she coordinated these elements in talk and gesture and then go on to explore her protocol more fully.

Embodying motion by tracing. To navigate a mechanism’s system, Kim engaged in a practice we refer to as “tracing”, using her fingers to physically follow the motion of the mechanism from input to output. Tracing served to link the input and output directions by relating their motion to how the rotation of lever arms was affected by the constraint of the fixed pivot. When explaining a prediction, she could not yet move the mechanism, so the tracing resembled her vision of the mechanism’s movement.

<table>
<thead>
<tr>
<th></th>
<th>Linked Direction</th>
<th>Incomplete Linked Direction</th>
<th>Rotation*</th>
<th>Lever Arms</th>
<th>Constraint</th>
<th>Fixed Pivot</th>
<th>Constraint Holder</th>
<th>Cause-Effect Associations</th>
<th>Number of correct predictions (out of 8)</th>
<th>Number of partially correct predictions (out of 8)</th>
<th>Total Correct and Partially Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anat</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Greg</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 5 1 0 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beta</td>
<td>2 1</td>
<td></td>
<td>3</td>
<td>0</td>
<td>4</td>
<td>2  (out of 7)</td>
<td>1</td>
<td>3 (out of 7)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chuck</td>
<td>2 1</td>
<td></td>
<td>2 1</td>
<td>1</td>
<td>1 3 2 1 3</td>
<td>4 5 6 7</td>
<td>2</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brian</td>
<td>2 2 2</td>
<td></td>
<td>1</td>
<td></td>
<td>7</td>
<td>3 2 2 4</td>
<td>3</td>
<td>5 (out of 7)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Don</td>
<td>2 1</td>
<td></td>
<td>1</td>
<td></td>
<td>2 1 3 5</td>
<td>3 4 6 7 8</td>
<td>2</td>
<td>5 (out of 7)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Katie</td>
<td>4 6 1 1</td>
<td></td>
<td>1</td>
<td></td>
<td>1</td>
<td>4 4 2 6</td>
<td>4</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sam</td>
<td>9 1 1 3 4</td>
<td></td>
<td>1</td>
<td></td>
<td>2 8 6 0</td>
<td>6 7</td>
<td>8</td>
<td>8</td>
<td>0 6 (out of 7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kim</td>
<td>16 2 14 4 13 2</td>
<td></td>
<td></td>
<td></td>
<td>8 8 0 8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Predictions and explanatory talk of individual students. All performances for each student were coded for elements of mechanistic reasoning. A circle denotes only one occurrence of an element. Each triangle contains the frequency of a particular element of mechanistic reasoning across all performances for each individual. The total number of correct predictions for each student is also shown. Partially correct predictions included: for Mechanisms B1, D1 and D2 students who said the output links would move in opposite directions, but the specific directions were not correct; for mechanism B2, students who predicted a structure similar to the correct structure, but with the two fixed pivots on the incorrect side of the input link. TM is transmission of motion; BC is brad covariance.

Kim: Constructing a Mechanistic Scheme

For both mechanisms, despite their differences in complexity, Kim used the same elements of mechanistic reasoning: linked direction, rotation, lever arms and constraint via fixed pivot. We first briefly characterize how she coordinated these elements in talk and gesture and then go on to explore her protocol more fully.
The coordinated motion of the input and output links (linked direction) was an observable phenomenon and the other aspects of mechanistic reasoning, such as rotation or lever arms, were “the mechanism” or the explanation for that phenomenon. She began each explanation by describing the input motion followed by the resulting motion of a link, or a part of a link, and continued this trace until arriving at the output motion. Because each movement characterizes a particular aspect of mechanistic reasoning, her explanation entailed traveling among the aspects of mechanistic reasoning. She often supported transitions of movement between parts of the mechanism with connecting words such as “so”, “and” and “because”.

**Overlapping and embedding.** Kim further tightened the link between elements by overlapping and embedding descriptions of aspects of mechanistic reasoning. In these cases, the movement of a part of a mechanism was included in two elements that were being coordinated. For instance, in Mechanism A2, Kim described the motion constrained by the fixed pivot to be that of one of the lever arms. She then explained that the movement of this lever arm subsequently caused the motion of the other lever arm. The overlap of ideas in this example is illustrated in the first part of Figure 8.

When embedding ideas, one aspect of mechanistic reasoning was encompassed within another. For example, when describing the motion of a lever arm, Kim often illustrated that it followed a rotary path. On the other hand, when overlapping ideas, two aspects of mechanistic reasoning shared a common motion (such as the movement of a part of the mechanism).

**Kim’s reasoning about mechanism A2.**

In the following text, Kim explained her prediction of the motion of Mechanism A2. Because of the heavy reliance on gesture and connection of several ideas, the text alone is difficult to follow.

*If you pushed right there (points to handle of input link), and went up, this one (points to little person) will come here (traces path with finger in an arc, down and to the right), because this one will slide forward (gestures up along input link) and this one (points to fixed pivot) will stay in its place. So it will make this side (points to right side of the output link) go over here (gestures up and slightly left). So, umm, it'll move WITH this one (points to input link) up here (taps input link) and then (points near little man). So this side (points to right end of output link) will come up here (gestures with finger up and left in an arc) with that one. So this one (points to left side of output link) will come down here (gestures with finger down and to the right in an arc).*
And this one [the fixed pivot] will stay in its place. So it will make this side [the right lever arm] go over here (gestures up and slightly left). "…so this one [the left lever arm] will come down here (gestures with finger down and to the right in an arc)."

Constraint via Fixed Pivot

Left Output

Um, so this one [points to left output] will go forward (gestures up along output link)

Right Output

And then this one (points to right output link) will go down

Rotation

because (points to upper horizontal bar) this link will be going this way (gestures up and in an arc)

cause it’ll be twisting around the brad. (rotates hand in circle)

cause this side (points to right side of upper horizontal link) will be going this way

Lever Arms

when you push it, these (points to fixed pivots) will stay

and then his link right here…and this one over here (points to horizontal lower link) they’ll kind of twist a little bit

Um, so this one [points to left output] will go forward (gestures up along output link)

Figure 8. Diagram of Kim’s mechanistic explanations. of Mechanisms. A) Mechanism A2. The left oval captures her talk that illustrates reasoning about the constraint that the fixed pivot provides and the resulting movement. The right oval captures her reasoning about the differing directions of the two lever arms. The intersecting part of the two ovals illustrates the shared component of the two aspects of mechanistic reasoning. Note that because Kim repeated herself, some of her dialogue is omitted. B) Mechanism D2. Each oval captures a particular type of mechanistic reasoning (either constraint via fixed pivot, rotation or lever arms). The circles highlight input and output movements. The arrows indicate the direction of her talk. The figure illustrates how ideas overlap and are embedded. First of all, the input motion is embedded as part of Kim’s reasoning about constraint via fixed pivot. Also, she mentioned the rotation ("twisting") around the fixed pivot twice, once when talking about the constraint offered by the fixed pivot and the second when discussing the lever arms. Thus, this iteration of the motion served as a link between the two aspects of mechanistic reasoning. Note that because Kim repeated herself, some of her dialogue is omitted.
We now provide a tour of this explanation, highlighting the components of mechanistic reasoning and how she orchestrated among those aspects.

To begin, Kim predicted that when the input link was pushed up, the output (the stick figurine) would move down and right in an arc. She illustrated the motion of both the input and output links by moving her finger along their predicted paths.

Kim’s explanation for this prediction began with an enactment of the input motion, tracing her finger up along the input link and saying “because this one will slide forward” (emphasis added). She immediately pointed to the fixed pivot and added, “and this one will stay in its place.” Her word choice of “because” positioned the input’s movement and the immobility of the fixed pivot as significant for the upcoming motion of the right lever arm.

Kim recognized that because the fixed pivot was unable to move, an upward push of the input would cause the output link’s right lever arm to move counterclockwise: “so it will make this side [the right lever arm] go over here” (emphasis added). She illustrated this motion by tracing its path with her finger. This relation between the lever arm’s motion and the fixed pivot’s inability to move is an example of how the fixed pivot serves as a constraint. Additionally, embedded in her gesture of the lever arm’s path is a recognition of the rotary nature of its movement.
Before continuing along the “path” of the mechanism’s movement, Kim revisited the motions she had just finished tracing. Instead of simply restating her argument, she again followed her finger along the mechanism’s input. She emphasized that the motion of the lever arm that she had just described was contingent to the motion of the input, highlighting their simultaneous occurrence: “so. um it’ll move WITH this one [the input link]” (capitalization indicates stress added by the student). She then began to move her finger towards the output (the stick figurine), as if to describe its motion.

Before reaching the output, she instead broke the motion and returned to the right lever arm. She retraced the right lever arm’s motion, again emphasizing its movement “with” the input link.

She then linked the motion of the right lever arm to that of the left lever arm: “so this one [the left lever arm] will come down here” (emphasis added). Her reasoning about the coordinated directions of the mechanism’s lever arms directly linked to her previous prediction of how the
output would movement. In this sense, Kim overlapped aspects of mechanistic reasoning in two ways: 1) the motion of the right lever arm served as an overlap of her reasoning about the constraint via fixed pivot and about the coordinate motion of the lever arms and 2) the motion of the left lever arm was simultaneously that of the output, serving as an overlap in reasoning of lever arms and linked direction. The significance of the right lever arm in linking Kim’s use of constraint via fixed pivot and the coordinated motion of the lever arms is illustrated in Figure 8(A). This figure shows how the two forms of reasoning are inseparable due to this shared component.

When explaining her prediction for the movement of Mechanism A2, Kim’s ideas appeared to be situated within her interactions with the pegboard. Each separate idea was accompanied either by touching the mechanism or motioning along its parts. Some significant aspects about the mechanism’s movement (such as the rotation of the lever arms) were only apparent in Kim’s reasoning through her use of gesture. Even when re-describing the input movement, she brought her hand back to the link to physically act out the motion each time. Kim’s language facilitated her travel within and between the various parts of the pegboard. Almost every transition was verbally accompanied by a conjunction linking the ideas (e.g. “so”, “and”, “because”). The word “with” also served to describe the connection between the input’s movement and that of the right lever arm.

**Kim’s reasoning about mechanism D2.** For mechanism D2, Kim predicted that when the input was pushed up, the left output link would move up and the right output link would move down. She initiated her explanation for this prediction by drawing attention to the structure of the mechanism, pointing to the fixed pivots (“Because there’s two fixed brads this time”).

Kim noted that the two fixed pivots would “stay” and then described how this aspect would affect the motion of the mechanism’s two horizontally oriented links. After first gliding her
finger over the top horizontal link and then holding the bottom horizontal link, Kim demonstrated with her hand how they would both “twist” around the fixed pivot in a clockwise direction. Her use of linking words signaled that she recognized that the combination of the push of the input and the stableness of the fixed pivot would jointly result in a rotary motion, attending not only to the constraint of the fixed pivot but also rotation of the intermediary link: “Because there’s two fixed brads this time, and so when you push it, these [the fixed pivots] will stay and…they’ll [the two horizontal links] kind of twist” (emphasis added). However, these transitions were not completely smooth. In between talking about the fixed pivots and the resulting movement, Kim paused momentarily and her hand touched the left output link. It appeared when doing so, Kim considered shifting to the output’s movement but instead opted not to skip the intermediary movement of the mechanism. Additionally, Kim’s talk about the push of the input was embedded in her reasoning about the constraint of the fixed pivot. This is illustrated in the oval for “constraint via fixed pivot” in Figure 8B.

<table>
<thead>
<tr>
<th>And</th>
<th>and then so, this, this</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>This link right here, the bottom one.</th>
<th>And this one over here</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>They’ll kind of twist</th>
<th>A little bit. um</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Kim then linked the rotation of the horizontal links to the direction of motion of the left output link, explaining that it would move “forward”, tracing her finger up along the link. Like before, she almost moved to the other output link but changed her mind and then replayed the motion of the left output link.
Kim proceeded to further explain the cause for the movement of the left output. She gestured over the top horizontal link and then traced with her finger the path it would follow, motioning up and down in an arc.

To explain the motion of this left lever arm, she referred back to the “twisting” she had spoken of earlier: “cause it’ll be twisting around the brad.” As she talked about this circular movement, she yet again rotated her hand in the same manner she had earlier. This parallelism of the talk and gesture positioned rotation as a common entity connecting the ideas of the constraint of the fixed pivot and the coordinated motion of the lever arms. This overlapping quality of rotation is
illustrated in Figure 8B by the oval crossing into her reasoning about fixed pivot constraint and lever arms. This common element among the two mechanistic ideas creates a tie between the otherwise separate forms of reasoning.

Kim ended her explanation by tying the downward motion of the right output link to the motion of the right lever arm. She explained that “this one [the right output link] will go down because this side [right lever arm] will be going this way,” gesturing with her finger down and left in an arc.

Although Mechanism D2 was much more complex than Mechanism A2, Kim employed similar methods to facilitate tying together ideas in her explanation. Minus a few pauses and detours, Kim for the most part traveled from the input of the mechanism to the outputs, making sure to include the intermediary links. Moreover, Kim tied aspects of mechanistic reasoning together through embedding and overlapping. For instance, when discussing the motion resulting from the fixed pivot, she illustrated with her finger how it would cause the link to “twist”. When she repeated this idea of rotation later, when discussing the lever arms, it further created an overlap between the role the fixed pivot played and how that eventually led to the motions of the lever
arms. Figure 8B illustrates Kim’s reasoning sequence and how she tied together aspects of mechanistic reasoning on Mechanism D2 through embedding and overlapping.

Sam: Elements of Mechanism

Children often mentioned fewer elements of mechanistic reasoning and often did not coordinate these elements. We illustrate by considering how Sam explained the motion of mechanisms A1 and A2.

I: I was just curious because you said...you noticed that these (touches fixed pivot) were on different sides
Sam: mmm hmm
I: and that changed the direction
Sam: yeah
I: Why do you think that is important?
Sam: umm because I noticed that when you pull this part down (pulls input down on Mechanism A1) this part stays (-touches fixed pivot) that this part is attached and that only makes this one, this side to move up and down (moves output up and down with left hand while keeping right hand on the fixed pivot)
I: ok
Sam: ( touches fixed pivot on Mechanism A2) and this part is attached, it moves, but because on this side [right lever arm] it doesn’t have one of these [fixed pivots]...since it doesn’t have a peg this side moves any way it wants, but this part, but this part stays (touching fixed pivot while moving input up and down)

In this instance, Sam was able to express the beginnings of an understanding of how a brad connecting a link to the board can serve as a fixed pivot, allowing that link to rotate around the pivot. We should note, however, that the interviewer made reference to the explanation Sam made earlier in his work with this mechanism when she said, “...you said...you noticed that these (touches fixed pivots) were on different sides”. Sam’s initial explanation, before and after moving the mechanism, was that the location of the brad [fixed pivot] was different for Mechanisms A1 and A2 and that was why the outputs moved differently. These portions of Sam’s talk were coded as “brad covariance”. Because our coding scheme focused on elements of talk and gesture, rather than applying a single category to each performance or task, we were able to capture such mixed and emerging explanations, which were not uncommon, particularly among children who gave partial mechanistic explanations.
Visualization of Mechanism Motion

When children reasoned mechanistically, they often described movement or detailed aspects of movement that were not immediately visible to children reasoning in less mechanistic terms. We identified two features that seemed to indicate the ability of children to “visualize” the motion of a mechanism: the ease with which children tended to reason in dynamic rather than static terms, and the tendency of children to notice non-surface details of the paths traveled by outputs. Each of these aspects of visualization and their relation to mechanistic explanations is further discussed in the next section.

Examples of dynamic and static reasoning about mechanisms. We first took note of a number of instances in which a child provided mechanistic justifications for her predictions. Though the mechanism was not actually moving, children in these instances used dynamic language and gesture to describe the mechanism. This ability to describe non-existent motion contrasted sharply to those children whose explanations, given while the mechanism was in motion, seemed to rely heavily on observing the motion as they explained. Further, some children seemed to see the mechanisms as static objects even as they were allowed to move the objects. Next we provide examples of Children who demonstrate varied abilities to visualize the motion of mechanism parts.

We compare two children, Kim and Brian, as they performed the same task, predicting the structure of Mechanism B2. The task followed an exploration of Mechanism B1. Whereas Kim had readily given a mechanistic explanation of Mechanism B1, Brain’s explanation lacked any components of mechanistic reasoning. When presented with Mechanism B2, the workings were concealed by a piece of paper so that only ends of the moving input and output links were visible. Both children were asked to observe this movement and predict how they might change Mechanism B1 so that it would move like Mechanism B2. Although both arrived at similar answers (that one fixed pivot be moved to the other side of the input link), their explanations differed in the degree to which they were able to visualize motion. In the examples that follow both Kim and Brian appear to be reasoning in dynamic terms. Kim, however, never actually moves the mechanisms, whereas Brian does so frequently. We look first at Kim’s explanation.
I: [Mechanism B2] operates like this (demonstrates). See that? What would you change... just telling me... What would you change on this one (Mechanism B1) to make it work like this one (Mechanism B2)?

Kim: You would move this one up here (gestures moving the right fixed pivot to the opposite side of the input link).

I: Why is that? Why do you say that?

Kim: Umm, because, when you push this over here (gestures moving input link on Mechanism B1), this little man comes this way (gestures right output’s movement) and these over here when you push it they come this way (gestures pushing input link on Mechanism B2 and direction of motion for output links).

Kim: So umm, and the reason why they're going this way (simultaneously gestures movement of two output links on Mechanism B1) is because they're on different, different sides (simultaneously touches two fixed pivots on Mechanism B1).

Kim: So you'd have to move this one (gestures moving left fixed pivot up) where this one over here is (touches right fixed pivot).

Next we look at Brian’s response. When first asked to predict, he suggested moving some of the brads to the middle of the input link. Subsequently, he suggested moving the right fixed pivot down to the opposite side of the input link. The text that follows is his explanation of why he would change Mechanism B1 in that way.

I: Why do you think that way will make it move like this one?

Brian: Because, like when you pull this (pulls input link on Mechanism B2) it will go...[the output links] both go the same way, and when you push it (pushes input link on Mechanism B2) they both go the same way. If you pull it (pulls input link on Mechanism
Whereas Kim readily described and gestured the movement of the various mechanism components while never actually moving the mechanisms, Brian seemed to rely heavily upon actually moving the mechanism as he reasoned. He also used these movements as demonstrations or descriptions during his explanation.

In contrast, in some instances, children focused on static descriptions of mechanism parts, even in the context of moving the mechanism. In the following example, Beth had just tested her prediction of the motion of Mechanism B1 and discovered that both links move inward when the input link is pushed, rather than outward, as she had predicted.

I: What do you notice about it now?
Beth: It’s... (continues moving input back and forth), it’s doing the same thing that I predict, but it’s a different way by... (pushes input link until movement of two output links is stopped as they collide) by coming (touches point where two links collided) doing the same... (pulls input link)
I: Yeah, so you predicted, something about when you move that way (gestures a push of input link), I think you predicted they would each go like that (uses the gesture that student made during her prediction for motion of output links), and what are you noticing that they do?
Beth: When we push it inside (pushes input link) they’re going like...this (emphasis as the two input links collide)
I: I see...
Beth: And then these three parts, this one is going that way (gestures along the static left input) and that one that (gestures along the static right input). It turns into an “A” (gestures along the static input link)

Though Beth was asked to reflect on how the direction of motion of the two output links was different from what she had predicted, she gravitated towards describing the final static state of the moving mechanism. We also suspect that her gesture of moving her finger along the static parts and her description of the overall shape of the mechanism (an “A”) are indicative of a student who is reasoning in static rather than dynamic terms. Greg used similar gestures and talk while predicting the motion of Mechanism D2. In his talk before moving the mechanism, Greg included a reference to how the mechanism resembled “a box”. The image below shows how Greg traced along the parts of the mechanism (white arrows) and his predictions of motion (red arrows). Greg’s prediction preserves the static orientation of the links; his prediction of the motion of the horizontal link is impossible. Similarly, Brian first noticed that Mechanism A1 looked like “a bird” and then made the prediction shown below, again preserving the orientation of the static parts.
We conjecture that visualizing or observing the motion of a mechanism’s parts supports the construction of mechanistic explanations. We suspect that children who correctly predict the motion of a static mechanism are able to visualize, or observe, how the various parts of the mechanism should move and that they tend to use at least some aspects of mechanistic reasoning to make their prediction. To examine this idea, we compared the types of explanatory talk employed by children before moving the mechanism to that after they began moving the mechanism. Additionally, we divided student performances into those in which children predicted correctly and those in which children predicted incorrectly.

Inspection of Figure 9 suggests a relationship between predicting correctly or incorrectly and the frequency of the forms of explanatory talk employed before and after moving the mechanism. In those instances when children predicted correctly, we saw no significant difference in the frequency of mechanistic reasoning before or after moving the mechanism. Likewise, there was no notable change in the frequency of children’s “transmission of motion” and “brad covariance” explanations for this group. By contrast, in those instances where children predicted incorrectly, we saw a significant increase in “elements of mechanistic reasoning” and “brad covariance” explanations after children were allowed to move the mechanisms. Interestingly, this group did not increase their frequency of “transmission of motion” explanations, suggesting that actually seeing a mechanism in motion can help children move towards more sophisticated and even mechanistic explanations. We suspect that viewing the motion of the mechanisms helped these children to reason in dynamic terms. By contrast, the group who predicted correctly may have been able to reason in dynamic terms about the static mechanisms.
Figure 9. *Frequency of Forms of Explanatory Talk and Gesture For Static and Moving Mechanisms.* Numbers represent the total frequency of codeable episodes of forms of explanatory talk present within the performances of students before they were allowed to move the mechanisms and after they were allowed to move the mechanisms. Student performances were divided into two groups: those in which student predicted correctly (first graph) and those in which students predicted incorrectly (second graph).
Visualizing rotation. Children traced the paths of output motions with their fingers. Because levers are essentially a line rotating around a fixed point, the path traced by any point on that line is an arc rather than a straight line. Interestingly, children often ignored the arc, visualizing the path as a straight line. While coding student interview responses, if a student clearly drew out a path for the output during his prediction, we noted whether he drew a straight line or an arc. Among those mechanisms for which the output links do move in noticeable arcs (A1, A2, A3, and B1), 17 of children’s finger drawn paths were straight lines and only 5 were arcs. Three of the five arc paths were drawn by Kim, the student with the highest level of mechanistic reasoning in the group.

To illustrate the difference in how children reasoned about path, we compare the responses of two children, Katie and Anne. Both reasoned about the path traveled by the output link on Mechanism C and the role the paper holder might play in determining that path (“What do you think would happen to the little man [the output] if I removed this holder?”) For this mechanism, the output link is connected to a rotating circle; a paper holder helps to maintain a nearly linear path for the output. Katie had earlier noticed how the path the link traveled was not strictly linear, that it went “in a crooked line”. The interviewer then asked her why the “little man” went in a straight line but the circle link turned in a circle. When responding to this question, she explained that the holder served as a constraint, that it “is making it [the output link] stay right here.” When the interviewer proceeded to ask Katie what would happen if the holder were removed, she showed with her finger the arced path that the output link would travel. Her description of this movement is illustrated.

By contrast, Anne had earlier accepted that the path was linear and proceeded to reason about the holder in less sophisticated terms. She explained that if the holder were removed, the output link “wouldn’t go in a straight line that it would pretty much go everywhere.”

Opportunities for Learning

Our purpose in performing these interviews and analysis was to understand how children reason about mechanisms containing levers and pivots in order to inform our research of the MechAnimations curriculum. The tasks in this interview were not designed to resemble the
curriculum, but rather to draw out information about children’s naïve understandings of how these mechanisms worked. However, the materials in the interview were similar to those in the curriculum. We were curious then what learning opportunities, provided minimal scaffolding, might be inherent in such child-material interactions. In this section, we illustrate how the materials and the task structure were possible supports for student learning.

Mechanisms and elements of mechanistic reasoning. We found that mechanisms varied somewhat in the kinds of explanations they tended to elicit. Table 3A shows the number of student performances that contained the various aspects of explanation for each mechanism. Compared to other mechanisms, D1 seemed to encourage children to reason about lever arms. Because this mechanism has output links attached to each of the two lever arms, it might help draw children’s attention to their coordination. In general, the simpler Mechanisms A1, A2 and A3 supported more elements of mechanistic reasoning than the similar, but more complex Mechanisms B1 and B2. Although Mechanism B1 was presented to children in the same way as the earlier mechanisms, children were less likely to keep track of input/output relationships (encompassed in the linked direction code). We suspect that the change in focus from one output link to the relative motion of two output links may have shifted attention away from the input. Mechanism C was relatively useful for supporting a variety of elements of mechanistic reasoning, all except for lever arms, since the mechanism contains none.

When making comparisons between the mechanisms, it is important to note that all children were presented with the mechanisms in the same order. It is therefore not possible to separate effects due to this order of presentation from inherent features of individual mechanisms. The order effect is probable when children tended to explain using “transmission of motion”. It seems that children were most likely to use this type of explanation when the mechanism they were presented with was novel (Mechanisms A1, B1, C and to a lesser extent D1 and D2).
Table 3. Inherent Features of the Mechanisms that Support Learning.

A) Frequency of Various Forms of Explanatory Talk and Gesture by Mechanism.
Each “x” represents the performance of an individual student which contained at least one codeable episode for each of categories listed. A student performance was considered the time a student worked with a particular mechanism. There were a total of 72 student performances. *For Mechanism C, we did not include instances in which the student mentioned the rotation of the circle.

B) Change in the Number of Children who Noticed Brad Position within the Context of a Paired Contrast For the first table, the horizontal rows represent the number of Children who did and did not notice the brad position on Mechanism A1. The vertical columns represent the number of Children who did and did not notice the brad position on Mechanism A2. The box on the top right of the table shows the number of Children who changed from not noticing to noticing when they saw or moved the second mechanism in the pair. Table B is organized in the same way for Mechanisms B1 and B2.
The effects of contrasting cases. Contrasting cases appeared to help children “see” relevant entities in the systems presented. As mentioned previously, mechanisms in each group (A, B, etc.) were presented to children in contrasting pairs in order to draw their attention to specific features of the mechanisms relevant to their function. Children at this age have been shown to struggle with creating tests that isolate variables in order to make valid comparisons (Schauble, 1990), an issue that will most likely arise in the MechAnimations curriculum. We therefore wanted to see how children would reason in the context of valid comparisons and determine which of these comparisons might lend themselves to fruitful classroom supports.

Contrasting pairs A1/A2 and B1/B2 were designed to isolate the variable of fixed pivot location and allow children to reason about its effect on the direction of motion of the output link(s). Table 3B shows the number of children who noticed where the fixed pivot was located on the first and second mechanism in each contrasting pair. In the A1/A2 contrast, seven out of nine students noticed fixed pivot location only for Mechanism A2, suggesting that the contrast drew most children’s attention to this feature. In the B1/B2 contrast, five out of nine children noticed brad location on both mechanisms, whereas three did so only on mechanism B2, suggesting that the contrast drew the attention of a few children to this feature. It is impossible for us to know if the five children who noticed the fixed pivot location on Mechanism B1 did so because they had learned the importance of this feature from the previous contrast or whether the feature was more obvious when two fixed pivots were on the same mechanism.

Not only did children notice the fixed pivot in the A1/A2 and B1/B2 contrasts, they took note of the cause-effect association between brad location and direction of output motion. Table 2 shows that the performances of six out of nine children on Mechanism A2 and five out of nine on Mechanism B2 contained at least one instance of "brad covariance" reasoning. Interestingly, only 2 children talked about "constraint via fixed pivot" for Mechanism A2 and no children did so for Mechanism B2. This suggests that while the comparison was successful at allowing children to connect surface structural features to mechanism movement, it did not instigate most children to investigate why this brad's location was important.

The other paired contrasts were less effective in drawing children’s attention to relevant details. Mechanisms A1 and A3 were designed to draw attention to the relationship between relative input/fixed pivot location and the relative distance traveled by the input and output. Three children did notice some aspect of how far the outputs moved on A3 who had not done so on A1, suggests the possibility that although a rare noticing, a compared contrast may highlight this feature. However we found no clear evidence of children reasoning about a cause-effect relationship between the relevant structural features and relative amount of input and output motion. The final paired contrasted elicited, D1 and D2, although intended to elicit talk about the constraint of the holder, led to no notable changes.

Examples of Individual Student Learning when Interacting with the System

In addition to the learning opportunities that were inherent in the structure of the materials, we observed several individual cases of student learning related to how children interacted with the materials. Here we provide two examples of student learning.
Learning through building. We suspect that, for some children, building a mechanism supported their noticing of a structural quality, the connection of brads to the pegboard. After moving and comparing Mechanisms B1 and B2, children were asked to build a mechanism that functioned like Mechanism B1. Interestingly, almost every student struggled with this task, primarily because they did not fully understand the mechanistic importance of fixed and floating pivots. Most children initially made all pivots fixed pivots, thus creating a structure that could not move at all. The children’s eventual success in building Mechanism B1 relied on differentiating fixed from floating pivots in practice—a differentiation that appeared to trail their recognition of the difference when merely observing the systems.

In some cases, children seemed to display what they learned from the building experience as they worked with subsequent mechanisms. Each of the four children who did not note that fixed brads were connected to the pegboard as they worked with the first five mechanisms did so for mechanisms they worked with after the building experience. Brian was one such student. When asked to explain how Mechanism C moved, he spontaneously investigated the back of the mechanism and determined which pivots were fixed.

Interviewer: So what do you think makes [the mechanism] work like that?

Brian: (lifts the board and examines the back) Well it’s a little bit from yesterday (when Brian performed building task). One, two, three, four, five, six, seven (counts brads on the back, looks on the front of mechanism, then the back again) There’s seven of them, but I don’t see the other one. Ohhh it was just like yesterday. You have to fold it under here for that part (gestures creating a floating pivot)....

Although Brian identified fixed and floating pivots on Mechanism C, he only did so after moving the mechanism and being asked about its function. Furthermore, when the interviewer probed Brian, he did not use this structural information for mechanistic reasoning but instead described the motion of the mechanism.

Interviewer: So why do you think [the floating pivot you have discovered] is important in helping the little man move that way?

Brian: Well it looked just like an elevator it goes up (pushes the input link) and it goes (pause) first it goes this way, then it can move backwards (gestures movement of output link with hand), but the back part doesn’t go up.

Five children talked about fixed and/or floating pivots, at least as structural elements, both before and after the building task. Of these five, two, Kim and Sam, talked about fixed pivots as mechanistic elements before and after building, 1 student, Beth, was able to talk about a fixed pivot as a mechanistic element only after building and 2 children, Don and Katie, never addressed fixed pivots as mechanistic elements.

Learning about rotation. In this example, Chuck seems to learn about the rotation of links in the earlier simpler mechanism, but seems to struggle to apply this reasoning to the more complex mechanisms. Chuck incorrectly predicted the motion of Mechanism A1 and did not mention rotation before moving the mechanism. Here, after moving the mechanism Chuck talked about the rotation of a link:
Int: Okay, why does he [the little person] go up?
Chuck: Cause like, when you move this piece (points to the input link) then this brad (points to floating pivot and rotates hand above it) turns this piece up (motions up and right).

Subsequently, Chuck was able to correctly predict the motion of Mechanism A2. Here he talked about rotation as he explained his prediction, possibly using information he learned by moving Mechanism A1.

Chuck: The green guy is gonna (gestures down and to the right in an arc) start coming down here...It’s kind of like, like when this (points to right side of the output link) spins up (gestures up and to the left), this (points to the left side of the output link) is going to come down cause like when you turn something, let’s say when I have something like this (enacts rotating), when you turn it

However, Chuck’s ability to employ rotation as an element of mechanistic reasoning seemed to depend on the context of the mechanism. When Chuck was asked to explain the motion of Mechanism C, he did not include rotation in his explanation. This could be surprising, since the majority of children at least mentioned the rotation of the circle link for this mechanism. However, we suspect that the increased complexity of Mechanism C may have prevented Chuck from employing what he had learned about rotation. As we have described above, only those children with the highest level of mechanistic reasoning were able to consistently “trace” the motion of mechanisms, especially more complex mechanisms. Interestingly, when the interviewer guided Chuck to trace through the motion of Mechanism C, he was able to talk mechanistically about the rotation of the floating pivot on the circle and rotation around the fixed pivot on the circle.

Interviewer: What does this link (points to input link) do with the circle and then this link (points to output link)...so if you could just tell us, when you push, walk us through all the way what happens...

Chuck: This link is going up and then the brad (points to floating pivot) that is under this link is going around...

Interviewer: and then?

Chuck: It’s revolving around this brad (touches the fixed pivot)

Although we have only illustrated a couple of examples of possible venues for student learning, working with these mechanisms, in particular the paired contrasts, apparently helped some children learn about mechanism structure, cause-effect relationships and even elements of mechanistic reasoning. The tasks did not help all children learn in a uniform way and learning seemed to depend on knowledge barriers that individual children had, which may include lack of understanding about mechanism structure, difficulty in applying observed patterns to new
situations, and difficulty with tracing the motion of more complex mechanisms. Understanding student’s barriers to mechanistic thinking as well as which aspects of mechanistic thinking are most difficult for children will likely play an important role in further studies of teacher support of these ideas in a classroom setting.

Discussion

Reasoning about mechanism is an important milestone in the development of explanations of systems, both those designed and those that occur naturally. Although the literature is replete with evidence about early competencies and resources for constructing mechanistic explanations of systems, the results of this study indicate that for even simple systems such as those investigated here, reasoning about mechanism is challenging. As indicated by Russ et al. (2008), to describe a system mechanistically, children must identify the entities, activities of entities and their relations. The findings of this study suggest that identification of relevant entities, even in systems whose workings are entirely visible, is not trivial. Both younger and older children often incorporated overall appearance and lists of parts as they explained function, suggesting a predominant focus on structure, not mechanism (diSessa, 1993). Moreover, elements of the functioning of the system that would provide clear clues about some of the relevant entities, such as the arc path generated by rotating around a fixed pivot, were largely invisible to children. That is, although children could literally see that the motion of an output did not travel in a straight path, qualities of the path were often subsumed by its direction.

However, children’s explanations often included cause-effect seeds of mechanistic reasoning, such as transmission of motion and brad covariance. The former echoes findings in previous research conducted with systems of gears (Lehrer & Schauble, 1998; Metz, 1991). Children reasoning about transmission often referenced the connection between links created by the floating pivot, a readily visible aspect of mechanism structure. Though transmission of motion often seemed to be an in-the-moment form of reasoning about a single mechanism, children reasoning about brad covariance often made comparisons between the movement and structure of two different mechanisms. This form of reasoning also required children to notice a less obvious structural feature – the location of the fixed pivot. This type of cause-effect relationship is analogous to the empirical regularities that children sometimes noticed about the movement of gears, such as the fact that alternating gears move in opposite directions (Lehrer & Schauble, 1998). Somewhat surprisingly, though children in our study often recognized the cause-effect relationship between direction of link motion and fixed pivot location, they almost never noticed the relationship between relative pivot location and the amount of motion of the links.

In addition to these seeds of mechanistic reasoning, all children’s explanations included at least one element of a more comprehensive mechanistic account. Elements of mechanistic reasoning, especially reasoning about linked direction, rotation and fixed pivots was more common in the talk and gesture of children who correctly predicted mechanism motion. By examining children’s protocols in more depth, we were able too to suggest how students could orchestrate these and related elements to develop a more systematic account, which we termed a
mechanistic scheme. Kim’s protocol suggested the prospective importance of embodiment for developing mechanistic explanations. For example, she literally enacted in gesture the flow of motion resulting from application of a force at the input through the system to its output. We termed this gestural simulation, tracing. Tracing, in turn, was supported by overlapping, during which a component of the system participated in two (or more) elements of mechanistic reasoning, and by embedding, during which an element applied to reason about a component of the system now serves as an input to another element of mechanistic reasoning. For example, when reasoning about Mechanism A2, Kim’s use of rotation was embedded within her talk about the lever arms, contained within her description of their movement. Moreover, she positioned the motion of the right lever arm as a common element of her descriptions of two mechanistic aspects: the constraint of its motion due to the fixed pivot and its coordinated motion with the left lever arm. These are all ways in which the material circumstances of the system mediate reasoning about it.

As children worked with these mechanical systems, we noticed several ways in which the arrangement of material and task might support learning. First, by posing mechanisms as contrasting pairs, children were often assisted in noticing which components of the system were most relevant to its functioning. In particular, contrasting cases helped children reason about the cause-effect relationship between fixed pivot location and direction of link motion. Second, the visibility of these systems, compared to many others in which mechanisms are invisible (for example microscopic and molecular mechanisms underlying biological phenomena), appeared to support the ability of some children to visualize the dynamic motion of the system. Others have pointed to the importance of dynamic reasoning when children attempt to explain and predict a natural or physical phenomenon (diSessa, 1993). However, as we noted previously, despite such clear view, many children did not readily notice the rotary nature of the links and the relative distances they traveled. Even though the building activity did seem to help some children notice the connection of fixed pivots to the pegboard in subsequent mechanisms, it did not necessarily help these children relate this to the fixed pivot’s function. Lack of reasoning about constraint via fixed pivots was common in incomplete mechanistic explanations. Clearly, ways of highlighting these features are good targets for instruction.

A mechanistic explanation identifies entities and their properties, describes the activities of the entities made possible by their properties, and specifies relations among entities and activity that enable tracing from inputs to outputs of the system so defined (Machamer et al., 2000). In this paper, we explored the early origins of this form of reasoning. Such exploration requires spadework, and accordingly, we set out to systematically describe components of children’s explanations of how these particular systems functioned. Our coding system puts forth a set of elements of mechanistic reasoning, which we believe to be important for three reasons. First, it allows us to easily recognize signature ideas that indicate that a student may be reasoning mechanistically. As others have pointed out (Russ et al., 2008) defining an explanation as “mechanistic” is not transparent and making such distinction depends on the particular entities and relations in a system. Second, the coding framework helps to support an in-depth examination of the causal schemes of individual children. As made clear in our example of a student tracing through her reasoning about the mechanism, children’s causal schemes for explaining even these simple mechanisms are complex. The coding scheme provides a framework for representing how children connect and relate the various elements of
mechanistic reasoning as they construct such schemes. Third, the coding framework allowed us to identify not only instances in which children displayed complete causal schemes to explain mechanisms, but also instances in which mechanistic explanations seemed to be incomplete or emerging. Because these particular systems are widespread in everyday life and in curricular units, we hope that our efforts may be useful to others in the field who share our interests.

We conclude with a now commonplace observation but one worth repetition. The predominant feature of children’s reasoning was its variability. Children were diverse in their native resources for mechanistic reasoning and in their ability to apply reasoning learned in the context of one mechanism to another mechanism. Individual differences were evident in children’s ability to predict and reason mechanistically, but children’s intra-individual differences were also pronounced. Elements of mechanistic reasoning evoked in one context were not the same as those evoked in another, despite similarities from a conventional point of view. This suggests, as we might suspect, that learning to reason mechanistically does not proceed in a routine or linear fashion, and that it will take careful design of classroom environments to support reliable development of mechanistic schemes.

References


APPENDIX A: Sample of Interview Protocol

VIDEO EQUIPMENT SET-UP:

Two cameras should be used for videoing, each with a flat table microphone.

One camera should be positioned directly in front of the table, about 4 feet in front. This camera can be at eye level.

The second camera should be positioned at the side of the student, only about $\frac{1}{2}$ foot away from the table. It should be raised as high as possible and angled down to focus on what she is looking at.

This diagram shows the positioning of the cameras from a top view and side view:
NOTES TO THE INTERVIEWER:

At the beginning of each day, the interviewer should start the recording by saying and spelling the child’s name.

Throughout interview, researcher and student should sit side by side. When introducing a new mechanism, the researcher should place the mechanism before the child in the proper orientation. Each Mechanism should be presented as shown in the pictures, with the input neither pushed in or pulled out. When comparisons are to be made, the first mechanism should remain on the table before the child as he looks at the new mechanism.

After the student says something, the researcher should avoid using evaluative language such as “that’s interesting,” “great,” “good.” Rather, the researcher should use phrases such as “okay” or “thank you.”

General Probes to Use (throughout entire interview):
- When the student uses a vague term: “Can you explain to me what [unknown word] is?”
  - It is important to avoid rephrasing student’s words and then asking for confirmation. For example: “So, do you mean _______?” If the researcher changes the meaning of what the student had said, we risk putting words into the student’s mouth that he/she wasn’t initially thinking.
- When the student is having difficulty articulating something or his/her explanation is unclear, the researcher should ask the student to draw what they are trying to explain: “Can you draw for me to help me understand what you’re talking about?”

Interview Packet Contents:
After interviewing, the researcher should place the following contents into the student’s labeled interview envelope:
- Interview Protocol (with notes taken)
- Any inscriptions the student used for explanation
- The student’s drawing of Mechanism C

To be added to the packet later:
- Copy of interview transcript
- Photos of front and back of the student’s designed MechAnimation
INTRODUCTION:

Hi. We are going to spend some time together looking at some things like this [show dog MechAnimation].

Introduction to MechAnimations:

We call this a MechAnimation. See how this moves? [Demonstrate] Try making the MechAnimation move. [Allow the child to try it] Later, we’re going to work with other MechAnimations and you’ll even get a chance to build your own.

Introduction to Pegboard Mechanisms:

The first thing that we will do is look at some mechanisms like this one and I will ask you to tell me about what you notice. [Don’t allow student to hold mechanism yet.] We hope that working with these wooden tools first will help get you ready to make your own MechAnimation.

As you are working with us you should know that there are no “right” or “wrong” answers. We are just interested in how you think about these things.

Okay? [Wait for confirmation from student]

Great! Before we get started, I’d like to read this form together and ask you to fill it out. I can help you if you need. It tells you a little bit about what you’re doing and asks you if you would like to participate. [Read form to student and allow student to read along.]

[Help student with form.]
Introduction to Pegboard Materials:

[Bring out 2 pegboards, 4 links, and brads. Give student one set.]

Here are the things we are going to be working with.
We call this a pegboard [Point to pegboard-both on A and on the parts].
We call these sticks [Point to links-both on A and on the parts] links. What are these? [Point to other links]
We call these brads [Point to brads-both on A and on the parts].
And, we call this a holder [Point to constraint-both on A and on the parts].

There are two kinds of things we can do with these materials.
First, we can attach two links together.

[Demonstrate]

Now you can try. [Allow student to attach links together]

We can also attach links to the pegboard. [Attach one of the links to the pegboard].

Now you can try.

When we have the link attached to the pegboard like this, we call this a fixed pivot.

When the links are attached to each other, but not to the pegboard like this, we call this a floating pivot. See how it floats over the pegboard?
NOTICING/PREDICTING/EXPLAINING/COMPARING:

Now I am going to bring out several things made with wooden links, pegboard and brads. I want you to tell me what you notice about each thing.

Group A Comparison (Single input & Output):

[Bring out Mechanism A1. Hold it flat on table—DO NOT GIVE TO CHILD.]

1. Here’s the first mechanism. I want you to just look at it. Can you tell me what you see?

2. I’m going to now put a little man right here. [Put little man on output]

What if I push on it here on the blue part [motion to the right]? What do you think will happen to the little man? Why do you think that?

3. [Give student the mechanism]. Why don’t you try moving it now? Was that what you expected? Why/Why not?

4. What do you think makes it work like that? [Use the student’s words and gestures.] [Put Mechanism 1A in front of child]

[Bring out Mechanism A2. Hold it flat on table—DO NOT GIVE TO CHILD.]

5. Here’s another mechanism. Just like with the other one, I want you to just look at it. Can you tell me what you see?

6. I’m going to now put the little man right here. [Put little man on output]

What if I push on it here on the blue part [motion to the right]? What do you think will happen to the little man? Why do you think that?
Possible probe – Why don’t you think it will move this way (point opposite to what student suggests).

7. [Give student the mechanism]. Why don’t you try moving it now? Was that what you expected? Why/Why not?

8. What do you think makes it work like that?

9. What is the same between the two of these?

10. What is different between the two of these?

   [Put Mechanism A2 to the side. Mechanism A1 should remain before the child.]

[Bring out Mechanism A3. Hold it flat on table—DO NOT GIVE TO CHILD.]

11. Here’s another mechanism. Just like before, I want you to just look at it. Can you tell me what you see?

12. I’m going to now put the little man right here.

   [Put little man on output]

Remember this one moved like this [operate Mechanism A1] and this one moved like this [operate Mechanism A2]. Looking at this new one, how do you think it will move?

- Possible probe – do you think it will move like this one or like that one?

Why do you think that?

13. [Give student the mechanism]. Why don’t you try moving it now? Was that what you expected? Why/Why not?

14. Let’s compare this mechanism to the first one you looked at [Put A3 and A1 in front of the child].

   a. PROBE: How are they the same?
   b. PROBE: How are they different?

[Put A1, A2, and A3 to the side as a group]
Group B Comparison (Single Input, Multiple Outputs):

[Bring out Mechanism B1. Hold it flat on table—DO NOT GIVE TO CHILD.]

1. IF TIME IS AN ISSUE, PUT LITTLE MEN ON IN ADVANCE. Here’s another mechanism. Just like before, I want you to just look at it. Can you tell me what you see?

2. I’m going to now put the little men right here.

   [Put little man on output]

   What if I push on it here on the blue part [motion to the right]? What do you think will happen to the little men? Why do you think that?

3. [Give student the mechanism]. Why don’t you try moving it now? Was that what you expected? Why/Why not?

4. What do you think makes it work like that? [Use the student’s words and gestures.]

   [Put Mechanism B1 in front of child]

[Bring out Mechanism B2 COVERED UP. Give it to the child.]

5. I now have a challenge for you. Here is another mechanism; it operates like this [Operate the mechanism for the child]. What would you change about this mechanism [Point to B1] to make it work like this one [Point to B2]? [DO NOT LET CHILD TINKER YET]

   a. Why did you decide to change that part?

   b. Did your idea work the way you expected? Why or why not?
6. Let’s look underneath the paper. Is this what you were describing? How is it the same/different from what you were describing?

7. What do you notice about this one?

[Put little men on outputs]

a. PROBE: Can you try moving it? What do you notice about how the little red man and little green man move? Anything else?

8. What is the same between the two?

9. What is different between the two?

[Give child pegboard with holes spread out more, brads and sticks]

10. Now I’d like you to build this mechanism [Point to B1] using this pegboard, links and brads. When you are building it it is o.k. of the mechanism does not look exactly like this one, but it should work the same way.

a. [When the child is finished] Tell me about how you went about building the mechanism.

11. I now have an even bigger challenge. Can you change the mechanism you built into one that works like this? [Point to Mechanism B1].

a. [As the child builds] What are you noticing?

b. What did you change to make it work like this mechanism?

[Get out paper and pencils]

12. Now I’d like you to use this paper to draw a picture of the first mechanism [Point to B1]. I want you to draw it so that anybody could look at your drawings and build what you built. The person looking at your picture should know that it works like this [Point to B1] and not this [Point to B2]. Just know that your drawing does not have to look exactly like the mechanism. The important thing is that someone would know that it works like the mechanism.
a. [When the child is finished] Tell me about what you drew.

b. How would someone know that this is a drawing of this mechanism [Point to B1]? Possible probe – How would someone known it is not this mechanism [Point to B2]?

c. How would someone know that the mechanism you drew here works exactly like this mechanism? [Point to B1]

d. Now I am going to use this pegboard to build what you drew. [Researcher builds the mechanism, following the plan. If student does not specify fixed or floating pivots, researcher will do the “wrong” thing.] Is this what you meant? Oh, what’s wrong with it? Is there a way you can think of to change your drawing so that I would know how to build it correctly?

[Put B1 and B2 to the side as a group.]