Combining Analyses of Cognitive Processes, Meanings, and Social Participation: Understanding Symbolic Representations

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Abstract

We propose three analytic representations of collaborative problem solving. *Activity nests,* a generalization of goal-subgoal trees, represent functional decompositions of task activity into components, using nesting to indicate operations that satisfy task functions. *Semiotic networks,* an extension of semantic networks, represent meanings as refers-to relations between symbolic expressions and other signifiers, and relations in situations and situation types, along with general relations between these meanings. *Contribution diagrams,* an adaptation of contribution trees (Clark & Schaefer, 1989), represent how turn sequences collectively achieve task components. We developed these representations to analyze how pairs of middle-school students constructed tables to represent quantitative properties of a simple physical device that models linear functions. Variations between activity nests of different pairs support an explanation of activity in terms of attunement to constraints and to affordances and abilities, rather than following procedures. The semiotic networks support a hypothesis that task components are completed through accomplishing *alignments* of refers-to relations, which is a generalization of goal satisfaction. Similarities between the contribution diagrams support a general pattern that we call the *turn structure of collaborative operations,* in which task information is recognized and task operations are initiated, performed, and accepted. Interaction is organized into this structure in order to support mutually aligned intentions, understandings, actions, and agreements.

Introduction

We hope that this paper contributes to two growing bodies of research and conceptualization. One of these is the effort to combine analyses of cognitive processes and social participation to understand reasoning and conceptual understanding. The other is the study of how people construct and interpret symbolic representations like diagrams, graphs, equations and (in the case of this paper) tables. Along with current investigators such as Hutchins (in press) and Lave (1988), and following theorists such as Bartlett, Dewey, Gibson, and Mead, we consider cognitive processes such as reasoning, understanding, and representing to be accomplished by systems that include humans interacting with each other and with available material resources, rather than as processes that only occur inside individual human minds. Although we do not consider symbolic representations as a ubiquitous substrate for cognition, we consider constructing and interpreting symbolic representations as a distinctive aspect of human social/cognitive activity that is important to study and analyze, as do other investigators such as Hutchins (1995) and Ochs, Jacoby, and Gonzales (1994).

Task and Participants

We studied pairs of seventh- and eighth-grade students who were asked to construct tables to represent the quantitative properties of a simple physical apparatus, the *winch* (shown in Figure 1). Each of its two tracks held a block that was pulled along when the handle turned, winding a string around its spool. Spool sizes varied, determining distances per turn of 3, 4 or 6 inches. A conventional yard stick was fastened next to each track allowing the students to determine the position of each block after various numbers of turns.

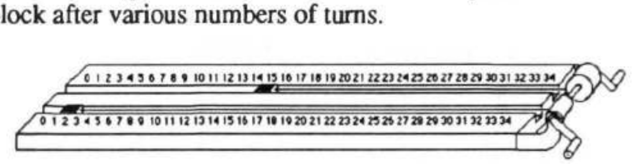

Figure 1. Winch apparatus.

We analyze students' work on the following item presented in a workbook:

> "Imagine that you had a 3-spool on one track and a 4-spool on the other track with both of the blocks starting at 0. Make a table that shows where the blocks would be after 0, 1, 2, 3, 4, 5, and 6 turns. Use the device if you want to."

This was the third item that the students worked on in the experiment. In the two previous items they had been asked to write what they thought would happen when they turned the handle with the winch set up in different ways, then to turn the handle, and then to write what did happen and whether it was what they predicted.

We have used this school-like task in these analyses because it is simple and well defined. Like cryptarithmetic, geometry proof exercises, and other tasks commonly used for cognitive analyses, the task of constructing a rows-by-columns table has a simple structure that was followed by most of our participants[1]. Because the task mainly involves constructing symbolic representations, it affords analysis of their semantics. The participants' active conversations as they worked on solving the workbook items provide useful information about patterns of social participation in cognitive activity.

Analyses and Findings

For this task, the system we analyze includes the winch whose regularities are being represented, the workbook instructions which ask students to construct a table, space

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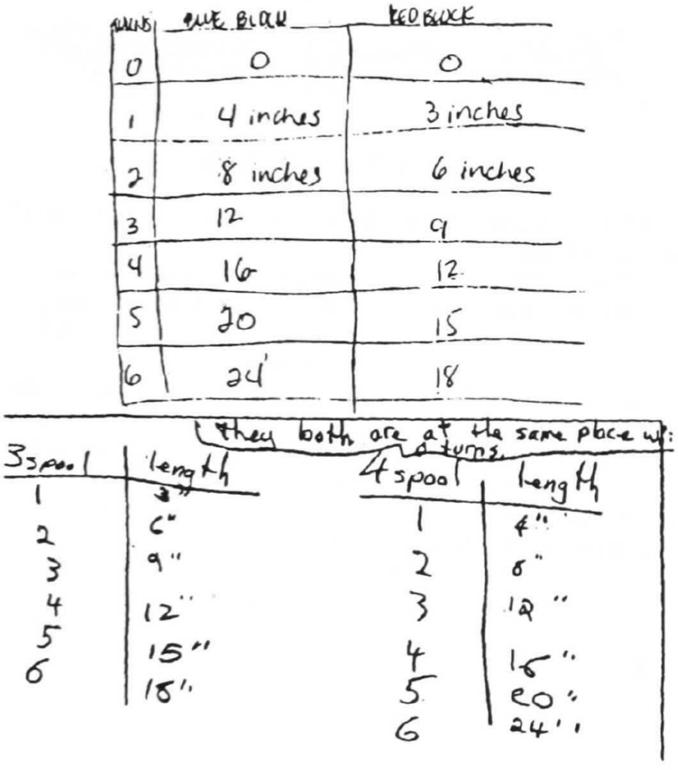
[1] Two of the six pairs constructed unconventional representations for this item, but presentation of these important exceptions requires a longer paper.

left in the workbook to do just that, and the students who are participating. Also in the system are key attunements to social practices like how to draw tables and represent quantities in them, how to use arithmetic operations to make inferences about numerical values, and ways of demarcating academic tasks to facilitate skilled performance.

Our theoretical goal is to arrive at hypotheses about what the participants knew in order to act the way they did in accomplishing the task. We consider knowing as being attuned to constraints (Barwise & Perry, 1983) and to affordances and abilities (Gibson, 1979) involved in activity. We use the concept of *schemata*, in Bartlett's (1932) sense, as a theoretical construct that describes ways in which activity is organized. A schema, in this view, is attunement to a collection of interrelated constraints and affordance/abilities.

We have constructed three analytical representations–activity nests, semiotic networks, and contribution trees–that allow us to analyze students' activity to include both traditionally "cognitive" and "social" aspects. We discuss each representation in turn, focussing on the performance of two pairs of participants. These two pairs, whose aliases are Julie and Paula, and Brad and Geoff, constructed the tables in standard form shown in Figure 2.



TURNS	BLUE BLOCK	RED BLOCK
0	0	0
1	4 inches	3 inches
2	8 inches	6 inches
3	12	9
4	16	12
5	20	15
6	24	18

they both are at the same place w/ 0 turns.

3spool	length
1	3"
2	6"
3	9"
4	12"
5	15"
6	18"

4spool	length
1	4"
2	8"
3	12"
4	16"
5	20"
6	24"

Figure 2. Tables by Julie and Paula (above) and by Brad and Geoff (below)

Activity Nests and Hypotheses about Attunements to Task-Content Schemata

Based on the videotaped records of the participants' performance and their transcriptions, we constructed representations of our hypotheses about how each pair structured this task, resulting in the activity nests shown in Figure 3.

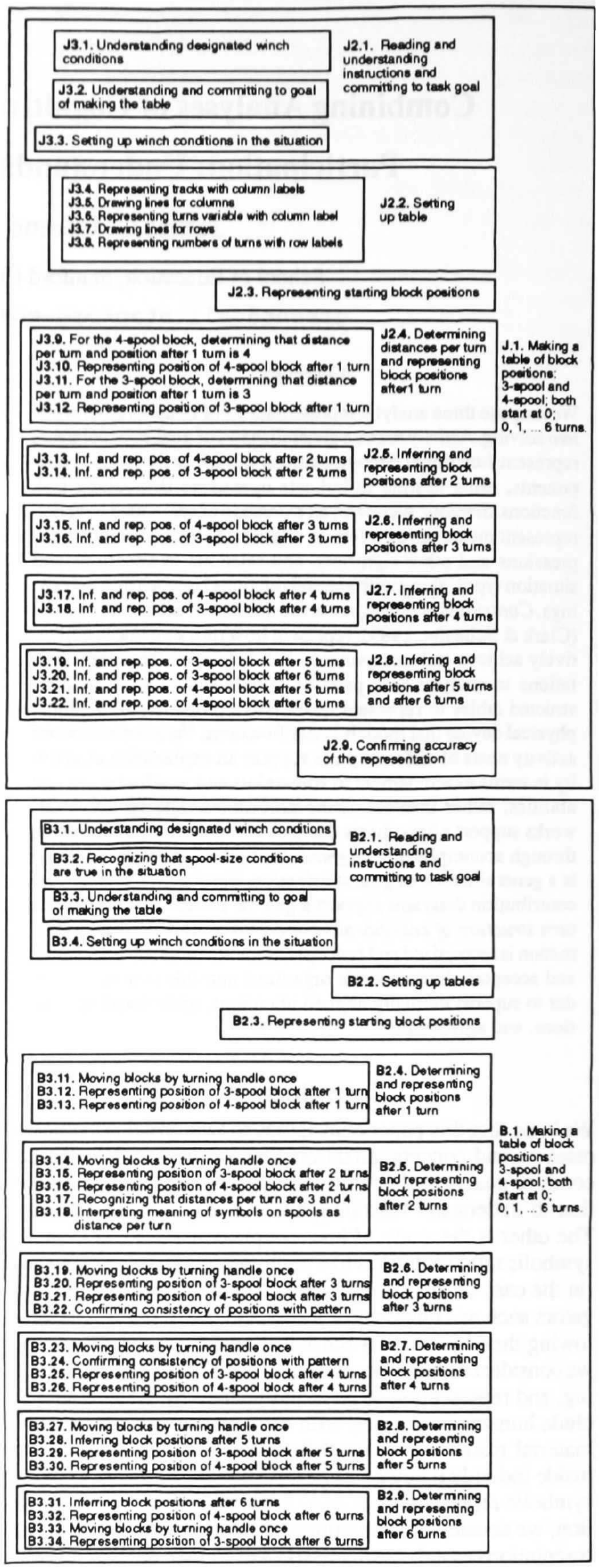


Figure 3. Activity nests for Julie and Paula (above) and Brad and Geoff (below)

In these diagrams, functional relations are shown using containment. Each rectangle labels a function which can be achieved by performing the operations contained in the rectangle within it. For example, if the four operations labeled J3.9 - J3.12 are performed, the function labeled J2.4 is achieved. In terms of constraints, in a situation where the contained operations are performed, the containing function is satisfied. We hypothesize that participants were attuned to those constraints of function-satisfaction that correspond to the containment relations of their activity nests. However, unlike standard goal-subgoal decompositions we do not assume that participants necessarily set explicit goals unless there is evidence of this in the data.

Based on the structure of the activity nests, we hypothesize that the students' task activity was organized partly by their attunement to a practice of completing school assignments, which includes reading instructions, understanding the kind of information that is to be represented, obtaining that information, and constructing a representation of it in a conventional form. In addition, to understand the instructions, they had become attuned to constraints and affordance/abilities of operating the winches so they could interpret references to spool sizes, starting positions, and numbers of turns. They also were attuned to constraints and affordance/abilities of the representational form of tables.

Our account of activity in terms of attunements to constraints and affordance/abilities, rather than procedures, is supported by the activity nests, which show differences between pairs of students. One kind of difference was in the ordering of components; most pairs worked row by row, as did Julie and Paula and Brad and Geoff; another pair completed the table column by column. In this example, the pairs differed in the ways they obtained the information they needed about positions of the blocks. Julie and Paula began by determining the distances per turn of the two spools by measuring their circumferences, and then inferred the positions of the blocks throughout, apparently using arithmetic addition. Brad and Geoff, on the other hand, began by turning the handles to determine the block positions empirically, then included arithmetic inference along with empirical observation when they recognized the pattern of constant numerical additions. Although procedural descriptions of these performances could be constructed, the variety of specific procedures needed would be very large. Therefore, it is more plausible to hypothesize that all the students were attuned to the general requirement of determining the block positions of a type of event in which the handles were turned with the specified spool sizes and starting positions, and were differentially attuned to the constraint of equal additions of the positions, and to the affordances of determining distances per turn by measurement and of performing handle turns to determine block positions.

Semiotic Networks and Hypotheses About Attunements to Representational Schemata

Semiotic networks are an extension of semantic networks. They represent how participants construct and use symbolic, indexical, and iconic signifiers (following Peirce) to refer to states of affairs of situations and to properties and relations of situation types. Like semantic networks, our semiotic networks also include relations between meanings.

A simple example of a semiotic network is shown in Figure 4. The notation is adapted from situation theory (Devlin, 1991). Each expression between double angle brackets is an infon, a basic unit of information. An infon includes the name of a property or a relation, followed by symbols that indicate arguments. Nonitalicized arguments indicate specific entities in the situation; italicized arguments are parameters. States of affairs involving signifiers are in ellipses. Infons those signifiers refer to are in rectangles. The lines between ellipses and rectangles indicate refers-to relations.

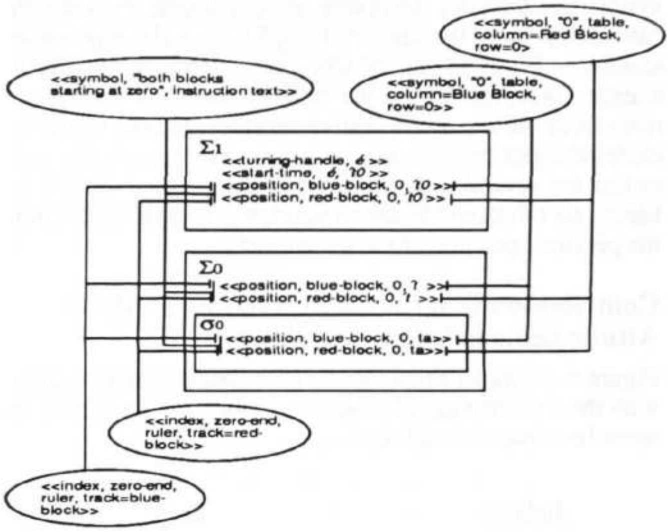


Figure 4. Refers-to relations constructed or used by Julie and Paula in Turns 35-38.

Figure 4 represents meanings of signifiers concerned with the starting positions of the blocks. The referent infons in Figure 4 include states of affairs that held in the specific situation, σo, as well as properties of situation types, Σ0 and Σ1. The instruction text included the phrase, "both blocks starting at zero." Julie and Paula adjusted the positions of the blocks to agree with that description, so that the positions that "zero" referred to were indicated by the ends of the rulers beside the tracks. Figure 4 shows that this printed phrase and the ends of the rulers were interpreted as referring to states of affairs in σo, the positions of the blocks at the time of Julie and Paula's interaction, the time called "ta." The tokens of "0" that Julie and Paula wrote in the top row of their table also referred to these same states of affairs.

The students interpreted their tables as referring to properties of the general type of situation in which the handle was turned with the specified conditions. The situation type Σ1 has an event of turning the handle, with starting positions of zero, and the symbols were interpreted as referring to the type infons of those starting positions. We include Σ0 for completeness. Affordances are relations between situation types, so the actual situation, σo, was related to the situation type, Σ1, by an affordance between Σ0, the type of σo, and Σ1.

From creating these semiotic networks, and seeing the correspondence of referents of the various signifiers, we hypothesize that *semiotic alignment* plays a crucial role in reasoning, especially in the construction of symbolic representations. In this example the alignment, which included a phrase in the instructions, indices in the situation, and symbols that the students constructed, provided the basis for their symbols being correct in the interpretation that we and they adopted. The other numerical symbols provided more complex examples. For some participants, including Julie and Paula, the situation when they wrote numerical symbols did not include turning the handle. We hypothesize that the situation type Σ1 was represented by the students with mental simulations that provided some of the needed information, such as the direction and continuity of motion. The symbols referred both to the quantitative positions of blocks and to numbers within the arithmetic system that includes the operations of addition and multiplication. Aspects of the situation type, Σ1, were also represented iconically. For example, the temporal ordering of turns in the situation is represented in the table by the spatial ordering of rows from the top to the bottom. Further analysis would include relations between the meanings of these symbols, such as that the several turns are parts of the event of turning the handle six times, and that each position is a displacement from the previous position of the same block.

Contribution Diagrams and Hypotheses About Attunements to Interactional Schemata

Figure 5 shows an example of a contribution diagram, along with the transcription of Julie and Paula's activity during the same four interactional turns.

Julie	Paula
J2.3	
35. Starting at zero	
	36. Ok, started, they're both at zero, is that what they're saying?
37. Yeah, so this would be zero [*wrote "0" in first row of both columns*]	
	38. Ok, zero
	J2.3

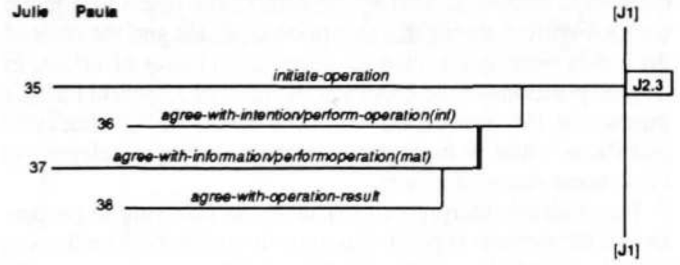


Figure 5. Julie and Paula, Turns 35-38, dialogue and contributions.

The transcription and contribution diagram are cross-referenced with that pair's activity nest. In the transcription, bold symbols indicate the beginnings and ends of activities that accomplished the designated task components. A symbol on the left marks the beginning, and a symbol on the right marks the end. In this case, the activity accomplished the component of representing starting block positions, labelled J2.3 in Figure 3. The contribution diagram presents our analysis of the way that these turns were interrelated in order to accomplish task components. We have adapted a method developed by Clark and Schaefer (1989) for this. In our use of the method, turns are grouped according to the activity components they achieved. Julie and Paula's Turns 35-38 accomplished the operation of determining that the starting positions were zero and entering symbols representing that in the table, Operation J2.3. Julie's Turn 35 initiated this operation. Paula's Turn 36 registered the information that was to be represented. Julie's Turn 37 completed the action of representing the starting positions by writing the symbols. Paula's Turn 38 expressed agreement and completed the contribution. The students' statements provide evidence for some of the refers-to relations in Figure 4. Paula's "They're both at zero" apparently referred to the positions of the blocks in the situation, and Julie's "So this would be zero" apparently referred to the values to be written in the table, which referred to the situation type involving turning the handle.

A more extensive and complicated example, by Brad and Geoff, is the transcription shown in Figure 6 and the contribution diagram of Figure 7. As the diagram indicates, Brad and Geoff were working on the component we labelled B2.4, determining and representing block positions after one turn. They had moved the blocks by turning the handle once and recorded the symbol" 3" in the table for the position of the 3-spool block.

In Turns 43-48, Brad and Geoff identified the position of the 4-spool block after one turn as 4 1/8, and Brad recorded that, corresponding to Operation B3.13. They began Operation B2.5, determining and representing the positions after two turns, with Brad's initiating Turn 49. Geoff turned the handles and Brad adjusted one of the handles so it had made one complete revolution, finishing Operation B3.14.

In Turn 52, Brad recognized the positions as 6 and 8 and recorded them. Geoff's Turn 53 was apparently interpreted by Brad as agreeing with his statement and representation of the position of the 3-spool block. In the light of Turn 60, we interpret this as the beginning of a presentation of the inference that the positions increased by constant increments of three and four inches, Operation B3.17. However, that operation was not established in their common ground, so we indicate it in parentheses. Brad's Turn 55 was a signal to proceed to the third handle-turn, B2.6, but Geoff hesitated, saying,"So--." We believe this was a continuation by Geoff of considering the pattern of constant additions. It seems likely that it also involved a question or disagreement with the symbol " 4 1/8"," which had been written in Brad's Turn 48. Geoff apparently interpreted it as a question of the more recent operation of writing " 6" " and " 8"," and reiterated those states of affairs. Geoff's Turn 58 agreed with that, completing their activity on Operations B3.15 and B3.16. Brad's response in Turn 59 was to emphasize that they had finished the second handle-turn, and he repeated his initiation of the third handle-turn activity in his Turn 60. Then in his Turn 61, Geoff stated the pattern of increases of the symbols in the table,which we consider as performance of an operation of stating an infon—the pattern—as well as presenting disagreement with the symbol " 4 1/8"," thus reopening Operation B3.13. Brad agreed with the pattern in his Turn 62,which established the pattern in their common ground, completing Operation B3.17. Brad then stated the change of the 1-turn position to "a regular four," and erased the "1/8" symbol from the table, in Turn 63. Geoff agreed

Brad	**Geoff**
B3.13	
43. And this one {*leaned over to see block positions*} is at --	
	44.Four and an eighth.
45. Four and, wait, no.	
	46. Yeah, four and an eighth.
47. {*pointing, counting division marks on yard stick*} One, two, three, four -- that's right. That's <--> about <-->	
48. {*wrote"4 1/8"" in the 4-spool table*}	
B2.5, B3.14	
49. Ok, do it again.	
	50. Another turn. {*sat down; turned handles*}
51. This one {*adjusted position of one handle*} good enough	
	B3.14
B3.15, B3.16	
52. Six and eight. {*wrote "6"," and "8"."*}	
(B3.17)	
	53. Six {*pointed to red block*}
54. Yeah.	
(B2.6)	
55. Ok, do it again.	
(B3.17)	
	56. So --
57. {*pointing to blocks*} That one's at six, this one's at eight.	
59.[I] already did it.	58. Ok, you did it [already].
	B3.15, B3.16
(B2.6)	
60. Do it again.	
B3.17	
	61. {*looking at tables*} Three, six. The four-spool would make this one {*pointed to 4-spool column*} [go up by four inches.]
62. [I know, nnh]	
63. This one should just be a regular four. Or else it doesn't make any sense. {*erased "1/8" in previous entry*}	
	B3.17
	64. Right
	B3.13, B2.3
B3.18	
65. We read it wrong. Ok, so the spool is the amount of inches it goes up.	
	B3.18, B2.5

Figure 6. Transcription of Brad and Geoff's Turns 43-65.

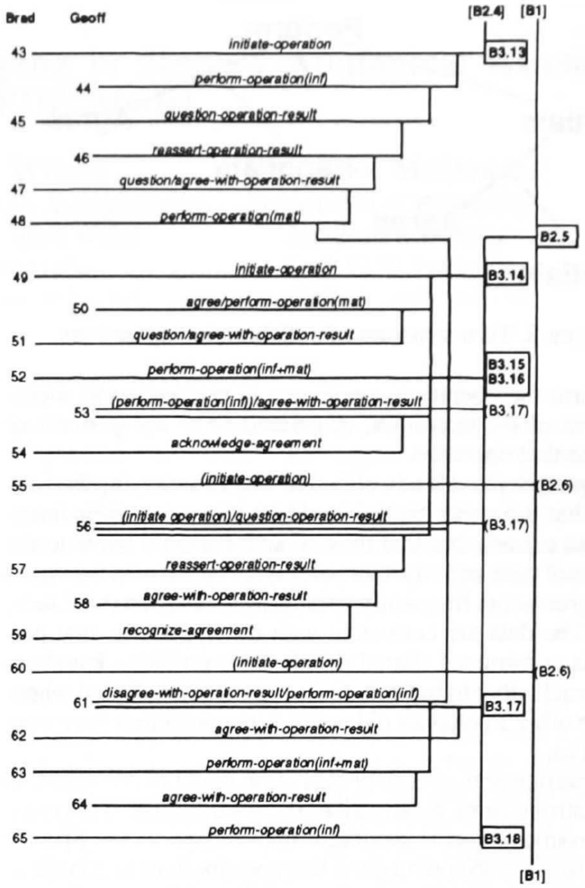


Figure 7. Contributions by Brad and Geoff in Turns 43-65.

with Brad's action in Turn 64, completing their activity Operations B3.13 and B2.3. In Turn 65, Brad recognized that the numerals stamped on the spools referred to their distances per turn.

Based on the contribution diagrams for all the pairs, a general interactional pattern, shown in Figure 8, emerged. As its title indicates, we view this pattern as a sequential structure that organizes interactional turns whenever a collaborative group is performing a joint operation. To interpret this schematic structure, consider right-branching links as obligatory and left-branching links as optional. A contribution that fit this pattern always included performance of an operation, which could be material or merely informational. When an operation was performed, the participants needed to agree on its performance and result for it to be included in their task solution. If one of the participants questioned or disagreed with the performance or result, there was a negotiation about it. As a result of the negotiation, the initial performance and result of the operation could be agreed to, there could be agreement to some modification of the operation or its result, or there could be agreement to not perform that operation, at least at that time.

Before an operation was performed, it could be initiated by one of the participants, which could be done by proposing the operation or by indicating in some less direct way that the operation would be appropriate. If the initiation of an operation was agreed to, the participants established a shared intention for that operation to be performed. If a participant questioned or disagreed with an initiation, they negotiated before the operation was performed, which could lead to agreement

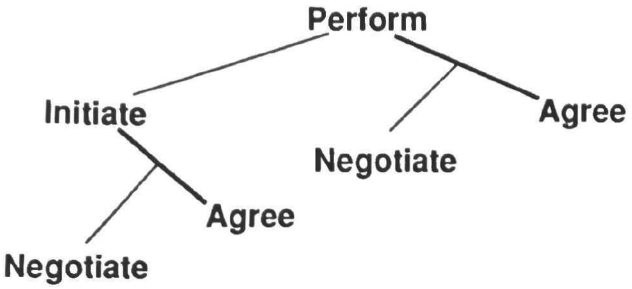


Figure 8. Turn structure of collaborative operations.

to perform the operation, agreement to perform some modified form of the operation, or agreement to not perform or postpone that operation.

This pattern provides an effective way of satisfying the constraint that the participants should be aligned in their intentions and actions and that they should mutually agree to the products of their activity. Our participants presented questions or disagreements frequently, with little mitigation (cf. Linde, 1988). The data are consistent with the hypothesis that participants constructed shared perspectives on the task and expected each other to indicate that they were not aligned whenever the other's behavior did not fit with constraints they were attuned to.

The participants also respected a constraint of relevance, in quite a strong form. Nearly all of the contributions were organized around performance of task-relevant operations. Sperber and Wilson (1986) pointed out that contributions to conversation are relevant in a general sense of applying to a context that the participants share. In this activity, apparently, the participants' shared context included a commitment to limit their conversations mainly to the assigned tasks. We expect that this constraint resulted from—or at least was reinforced by—the presence of an adult researcher and a videocamera, which created a situation of closely observed and supervised school activity. Whatever its cause, the participants' close adherence to a constraint of task relevance produced patterns of interaction in which nearly all the activity was functionally related to operations for making progress on the task.We do not believe that this relation between cognitive tasks and social interaction is general. Indeed, in other studies (Engle & Greeno, 1994) interpersonal relations also crucially shaped how the task was carried out, and we expect to find that as well when we apply these analyses to performance by these participants on less well-defined problems where they wrote equations for the first time.

Conclusions

The representations of activity nests, semiotic networks, and contribution trees provide evidence about the details of both the cognitive processes of accomplishing the table-construction task and the social participation through which the task was carried out. Because of explicit linkages between these analytic representations, we can begin to examine how cognitive and social aspects of collaboration are related.

Our analysis resulted in three main findings. First, students' activity can best be explained in terms of attunements to constraints and to affordances and abilities that form schemata of school assignments, forms and meanings of symbolic representations, causal and quantitative properties of the physical device, and patterns of collaborative activity. Second, students completed components of the table construction task through accomplishing alignments of refers-to relations involving signifiers in the instructions, on the winch, and in their table, which referred to properties and relations of the material system of the winches and the conceptual system of numbers and arithmetic. Third, the participants' structure of turn taking was organized to support mutually aligned intentions intentions, understandings, actions, and agreements relevant to task components.

We believe that the methods of analysis and representation that we have developed here will be applicable in more complex situations, but significant extensions may well be needed.

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