Understanding Educational Computational Artifacts Across Community Boundaries

ABSTRACT

Viewed within its activity system, learning is a social process in which artifacts – whether physical, digital or linguistic – play central roles. Even individual learning is immersed in contexts of collaborative learning, in which communities define structures of meaning, goals of research, distribution of tasks and audiences for new knowledge. The field of Computer Supported Collaborative Learning (CSCL) is devoted to designing and evaluating artifacts such as communication media and digital simulations that foster learning by groups in schools. The artifacts in question must be understood by three communities: their designers, their users and their researchers. As meaningful physical objects, artifacts by definition both provide persistence across the three communities and require interpretation by each community. The first community designs into the artifact meaningful affordances that must be properly understood in practice by the second community. To evaluate the success of this undertaking, the third community must interpret the designed affordances and also interpret the users' practical understandings of these.

As researchers, we take a detailed look in this paper at how a group of middle school students understands a digital simulation as they collaboratively struggle to use it to solve a scientific task. We focus on a particular moment of collaboration lasting 17 seconds that was particularly hard to understand from the transcript. A micro discourse analysis of this moment demonstrates that the students were engaged in making visible to each other the structure of references within their discourse that

had become problematic for them as a group engaged in collaborative learning within a classroom activity structure. In making their learning visible to themselves, they made it visible to us as well. Furthermore, they made visible the central affordance of the artifact, that had until then eluded them and caused their group confusion.

The students constructed a shared understanding by making explicit the references from their discourse that had created confusion when different students had constructed divergent interpretations. To make their learning visible to us as researchers, we deconstruct the references within their discourse. The meaning that the participants constructed is analyzed as constituting a network of semantic references within the group interaction, rather than as mental representations of individuals. No assumptions about mental states or representations are required or relevant to the researcher's analysis. Collaborative learning is viewed as the interactive construction of this network. Shared understanding consists in the alignment of utterances, evidencing agreement concerning their referents.

The world, situation or activity structure in which the students operate consists of a shared network of references among words and artifacts. To design new artifacts for these worlds, designers must understand the nature of these referential networks, build artifacts that fit into and extend these networks in pedagogically desirable ways, and provide tasks and social practices that will lead students to incorporate the artifact's new references meaningfully into their shared understandings. Researchers who understand this process can analyze the artifact affordances and the situated student discourse to assess the effectiveness of CSCL technologies. The theory sketched here implies a methodology for CSCL design, practice and research that goes beyond the scope of this paper; here we will focus on the concrete, empirical discourse analysis to illustrate how students collaboratively constitute the referential networks in which they interact and comprehend collaboratively.

METHODOLOGICAL INTRODUCTION

Computational artifacts such as scientific simulations, productivity software, organizational knowledge repositories and educational systems are designed by one community (e.g., software developers, educators, domain experts or former employees) for use by another (end-users, students, novices or future employees). The two communities typically operate within contrasting cultures; their shared artifacts must cross cultural boundaries to be effective. Diversity among interacting communities of practice leads to many of the same issues and misunderstandings as cultural diversity among traditional communities.

A computational artifact embodies meaning in its design, its content and its modes of use. This meaning originates in the goals, theories, history, assumptions, tacit understandings, practices and technologies of the artifact's design community. A user community must activate an understanding of the artifact's meaning within their own community practices and cultural-historical contexts. Given the diversity between the design and user communities, the question arises: how can the meaning embodied in a computational artifact be activated with sufficient continuity that it fulfills its intended function? A further question for us as researchers is how we as members of a third community can assess the extent to which the designers' intentions were achieved in the students' accomplishments.

This paper investigates the process of meaning-activation of computational artifacts through an empirical approach: It conducts a micro-ethnographic analysis of an interaction among middle school students learning how to isolate variables in a computer simulation. The analytic affordances designed into the computational simulation of rocket launches were activated through the involvement of the students in a specific project activity. Their increasing understanding of the artifact's meaning structure was achieved in group discourse situated within their artifact-centered activity.

This micro-ethnographic analysis is a scientific enterprise, like viewing under a microscope the world within a drop of water, a world that is never seen while crossing the ocean by boat. We try to uncover general *structures* of the interaction that would be applicable to other cases and that thereby contribute to a theoretical understanding of collaboration. The conversational structures of small group collaboration are different from those of dialog commonly analyzed by discourse analysts, and this has implications for the theory of collaborative learning and of Computer Supported Collaborative Learning (CSCL) (Stahl, 2000, 2002b).

This approach to studying collaboration differs radically from both traditional educational research and from quantitative studies in CSCL, both of which can produce useful complementary findings. Experiments in the Thorndikian tradition focus on pre- and post-test behaviors, inferring from changes what kinds of learning took place in between. Such a methodology is the direct consequence of taking learning for an internal individual mental process that cannot directly be observed (Koschmann, 2002). However, if we postulate learning to be a social process, then the conditions are very different. In fact, it is not only necessary for the participants in a collaboration to make their evolving understandings *visible* to each other, this is the very essence of collaborative interaction. As we will see in a moment, when the evolving learning of the group is not displayed in a coherent manner everyone's efforts become directed to producing an evident and mutually understood presentation of shared knowledge. That is, in the breakdown case the structures that are normally invisible suddenly appear as matters of the utmost concern to the participants, who then make explicit and visible to one another the meaning that their utterances have for them. As researchers who share a cultural literacy with the participants, we can take advantage of such displays to formulate and support our analyses.

Quantitative studies of collaboration are indispensable for uncovering, exploring and documenting communication structures. However, they cannot tell the whole story. Although measures of utterances and their sequences – such as frequency graphs of notes and thread lengths in discussion forums – do study the processes in which collaborative learning is constructed and displayed, they sacrifice the meaningful content of the discussion in favor of its objective form (Stahl, 2002a). This not only reifies and reduces the complex interactions to one or two of their simplest dimensions, it even eliminates most of the evidence for the studied structural relationships among the utterances. For instance, the content might indicate that two formally distinct threads are actually closely related in terms of their ideas, actors or approach. Coding utterances along these characteristics can help in a limited way, but is still reductive of the richness of the data. Similarly, social network analysis (Scott, 1991; Wasserman & Faust, 1992) can indicate who is talking to whom and who is interacting in a central or a peripheral way within a network of subgroups, but it also necessarily ignores much of the available data – namely the meaningful content – that may be relevant to the very issues that the analysis explores. We will look at a set of utterances that would be impossible to code or to analyze statistically; the structural roles of the individual utterances and even the way they create subgroup allegiances only become clear after considerable interpretive effort.

The other way in which both traditional experimental method and narrow discourse analysis tend to underestimate their subject matter is to exclude consideration of the social and material context. Some approaches methodically remove such factors by conducting controlled experiments in the laboratory (as though this were not itself a social setting) or basing their findings strictly on a delimited verbal transcript. Fortunately, countervailing trends are emphasizing the importance of *in situ* studies and the roles of physical factors, including both participant bodily gestures and mediating artifacts. Increasingly, the field is recognizing the importance of looking at knowledge distributed among people and artifacts, of studying the group or social unit of analysis and of taking into account historical and cultural influences. In our data it is impossible to separate the words from the artifact that they reference and interpret; we will see that artifacts are just as much in need of interpretation (by the participants and by the researchers) as are the utterances, which cannot be understood in isolation from physical and verbal artifacts.

The study of collaborative learning must be a highly interdisciplinary business. It involves issues of pedagogy, software design, technical implementation, cognitive theories, social theories, experimental method, working with teachers and students, and the practicalities of recording and analyzing classroom data. Methodologically, it at least needs its own unique intertwining of quantitative and qualitative methods. For instance, the results of a thread frequency study or a social network analysis might suggest a mini-analysis of the discourse during a certain interaction or among certain actors. Interpretive themes from this might in turn call for a controlled experiment with statistical analysis to explore alternative causal explanations. In this paper we present an attempt to uncover in empirical data the sort of meaning relationships that other methods ignore, but that might enrich their analysis.

WHAT'S IN A SENTENCE FRAGMENT?

We naively assume that to say something is to express a complete thought. However, if we look closely at what passes for normal speech we see that what is said is never the complete thing. Conversation analysts are well aware of this, and that is a major reason why they insist on carefully transcribing what is said, not forcing it into whole sentences that look like written language. The transcript of our moment is striking in that most of the utterances (or conversational turns) consist of only one to four words.

Utterances are radically situated. In our analysis we will characterize spoken utterances as indexical, elliptical and projective. As we will see, they rely for their meaning on the context in which they are said, for they make implicit reference to elements of the present situation. We will refer to this as *indexicality*. In addition, an individual utterance rarely stands on its own; it is part of an on-going history. The current utterance does not repeat references that were already expressed in the past, for that would be unnecessarily redundant and spoken language is highly efficient. We say that the utterance is *elliptical* because it seems to be missing pieces that are, however, given by its past. In addition, what is said is motivated by an orientation toward a desired future state. We say that it is *projective* because it projects the discussion in the direction of some future which it thereby projects for the participants in the discussion. Thus, an utterance is never complete in isolation. This is true in principle. To utter a single word is to imply a whole language – and a whole history of lived experience on which it is grounded (Merleau-Ponty, 1945/2002). The meaning of the word depends on its relationships to all the words (in the current context and in the lived language) with which it has co-occurred – including, recursively, the relationships of those words to all the words with which they co-occurred. We will see the importance of co-occurrences for determining meaning within a discourse.

In analyzing the episode that we refer to as "the collaborative moment" in this paper, we make no distinction between "conversation analysis," "discourse analysis" or "micro-ethnography" as distinct research traditions, but adopt what might best be called "human interaction analysis" (Jordan & Henderson, 1995). This methodology builds on a convergence of conversation analysis (Sacks, 1992), ethnomethodology (Garfinkel, 1967), nonverbal communication (Birdwhistell, 1970), and context analysis (Kendon, 1990). An integration of these methods has only recently become feasible with the availability of videotaping and digitization that records human interactions and facilitates their detailed analysis. It involves close attention to the role that various micro-behaviors – such as turn-taking, participation structures, gaze, posture, gestures, and manipulation of artifacts – play in the tacit organization of interpersonal interactions. Utterances made in interaction are analyzed as to how they shape and are shaped by the mutually intelligible encounter itself – rather than being taken as expressions of individuals' psychological intentions or of external social rules (Streeck, 1983). In particular, many of the utterances we analyze are little more than verbal gestures on their way to becoming symbolic action; they are understood as not only representing or expressing, but as constituting socially shared knowledge (LeBaron & Streeck, 2000).

We worked for over a year (2000/2001) to analyze a video tape of students learning to use a computer simulation (on March 10, 1988). I say "we" because I could never have interpreted this on my own even if I had already known all that I learned from my collaborators in this process. The effort involved faculty and graduate students in computer science, communication, education, philosophy and cognitive science as well as various audiences to which we presented our data and thoughts at the University of Colorado at Boulder. It included a collaborative seminar on digital cognitive artifacts; we hypothesized that this video might show a group learning the meaning of a computer-based artifact collaboratively and hence potentially visibly.[1]

We logged the three hours of video, digitized interesting passages, conducted several data sessions with diverse audiences and struggled to

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[1] The materials from this seminar are still available as of this writing at http://www.cis.drexel.edu/faculty/gerry/readings . This includes logs, digitized clips, transcripts, SimRocket, reading lists and related documents. In particular, the moment itself can be viewed at http://www.cis.drexel.edu/faculty/gerry/readings/simrocket/collab_short.mov .

understand what the participants were up to. Despite much progress with the rest of the learning session, one brief moment stubbornly resisted explanation. The closer we looked, the more questions loomed. In the following, we pursue a limited inquiry into the structure of that single moment. We try to understand what people meant by individual words and sentence fragments that they spoke.

THE COMPLEXITY OF SMALL GROUP COLLABORATION

Conversation analysis has largely focused on dyads of people talking (Sacks, 1992). It has found that people tend to take turns speaking, although they overlap each other in significant ways. Turn-taking is a well-practiced art; it provides the major structure of a conversation. The talk is often best analyzed into conversation pairs, such as question/answer, where one person says the initial part of a pair and the other responds with the standard complement to that kind of speech act. These pairs can be interrupted (recursively) with other genres of speech, including other conversation pairs that play a role within the primary pair (Duranti, 1998).

In much of the three-hour SimRocket tape from which our moment is excerpted, talk takes place between the teacher posing questions and one of the students proposing a response. The teacher indicates satisfaction or dissatisfaction with the response and then proceeds to another conversation pair. This is, of course, a typical classroom pattern (Lemke, 1990). In the collaborative moment, something very different takes place. Collaboration is a many-to-many interaction in which meaning occurs at the group level; it departs from the teacher-centric dialog and teacher-interpreted meanings. It somehow overcomes the sequentiality of directed turn-taking – the promise of CSCL is to provide media that allow people to handle the increased complexity of collaborative interaction and temporality.

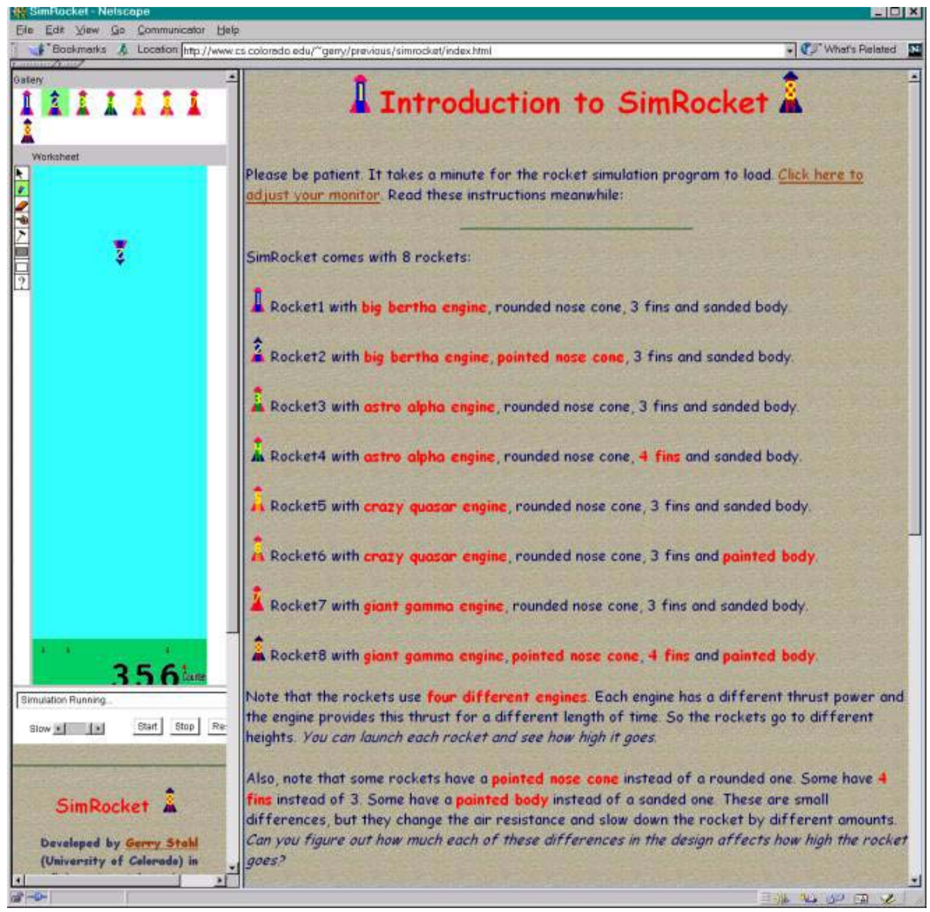

Figure 1. The SimRocket simulation and the list of rocket descriptions.

Let us take a first look at the episode of the transcribed moment.[2] The group of 11-year-old boys is discussing a list describing eight different rockets that can be used in a rocket launch simulation (see Figure 1). They are trying to come up with a pair of rockets that can be used experimentally to determine whether a rounded or a pointed nose cone will perform better. The moment is concerned with the students noticing that rockets 1 and 2 have the identical engine, fins and body,

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[2] Note on the transcription: Numbers in parentheses indicate length of pause in seconds. Brackets between lines indicate overlap. = between utterances indicate lack of pause between them. Underline indicates verbal emphasis.

but different nose cones, while rockets 3 and 4 differ only in number of fins.

About an hour and a half into the classroom session the teacher poses a question. For the past few minutes, the teacher has been dialoging primarily with Chuck, who has gone off describing some imaginary rockets he would like to design for the simulation to solve the problem of the nose cone. The teacher's question, accompanied by his emphatic gesture at the computer, succeeds in reorienting the group to the list on the screen. After a significant pause during which Chuck does not respond to this question that interrupted his train of thought, Steven and Jamie utter responses as though talking to themselves and then simultaneously repeat, as if to emphasize that they have taken the floor. But their response was to disagree with the teacher, something not so common in a classroom. So the teacher restates his question, clarifying what it would take to justify an answer. Chuck responds in a confusing way, not directly answering the question, but attempting to apply the criteria the teacher has put forward.

1:21:53	Teacher	And (0.1) you don't have anything like that there?
1:21:54		(2.0)
1:21:56	Steven	I don't think so
1:21:57	Jamie	Not with the same engine
1:21:58	Steven	[No
	Jamie	[Not with the same
1:21:59	Teacher	With the same engine … but with a different (0.1) … nose cone?=
1:22:01	Chuck	[=the same=
	Jamie	[=Yeah,
1:22:02	Chuck	These are both (0.8) the same thing
1:22:03		(1.0)
1:22:04	Teacher	Aw [right
1:22:05	Brent	[This one's different

The teacher pauses at 1:22:03, encouraging student discussion, and Brent jumps in, cutting the teacher off, lurching forward and pointing at a specific part of the list artifact, while responding to the teacher's quest for something "different" (see Figure 2). For the next 16 turns, the teacher is silent and the students rapidly interact, interjecting very short, excited utterances in a complex pattern of agreements and disagreements. From the conversational structure, one sees that the standard, highly controlled and teacher-centric dialog has been momentarily broken and a more complex, collaborative interaction has sprung forth. Normally reticent, Brent has excitedly rocked forward off his chair, pushed through a line of students, filled a void left by the teacher and directed attention pointedly at the artifact.

Dramatically transforming the stage within which talk takes place, Brent has signaled an urgent need to resolve some disturbing confusion. We can see the importance of this move in the bodily behavior of Kelly, a student who says nothing during the entire episode. Kelly had been slouched back in his seat, with his head rolling around distractedly up to this point in the transcript. As Brent leaned forward, Kelly suddenly perked up and leaned forward to pay attention to what was transpiring.

At 1:21:53 the teacher opened a conversation pair with a question. It was taken as a rhetorical question, that is as one that expected the conversation partner to see that there was something "like that there" and to answer in the affirmative, signaling that he had seen what the teacher was pointing out. We can see that it was taken as a rhetorical question because the negative answers supplied by the students were not accepted. The three students who tried to answer in the negative – first Steven and Jamie simultaneously, and later Chuck – repeated their answers, as if to re-assert answers that were not called for. Rather than accepting these answers, the teacher rephrased the question and paused for an affirmative answer.

Fig 2. Teacher, Jamie, Chuck, Brent, Steven and Kelly. Brent has leaned forward to point at the list of rocket descriptions on the computer screen.

Brent responded to the conflict between the expectation given by the rhetorical question and the attempts by the other students to give a negative answer. The following can be seen as an attempt by the group to resolve this conflict and provide the sought affirmative answer to the teacher's question, finally completing the interrupted conversational pair.

THE PROBLEM

Brent interrupts the teacher with, "This one's **different**." The word "**different**" goes back to the teacher's last statement. The teacher's full question, elaborated in response to Steven and Jamie's disagreement was: "And (0.1) you don't have anything **like** that there? . . . With the **same** engine but with a **different** (0.1) nose cone?" In the meantime, Steven and Jamie had both picked up on the teacher's term "**same**," as had Jamie.

1:22:05	Brent	└ This one's different ((gestures with pen at computer 1 screen))

The teacher had used the terms, "same" and "different" to clarify what he meant by "like". In rhetorically asking, "Don't you have anything **like** that there?" The teacher was suggesting that the list of rockets ("there" where he was directing their attention) included a rocket whose description was "like" the rocket they needed, namely one that had the same engine but a different nose cone from the one that they would compare it with.

The teacher's original statement at 1:21:53 was *elliptical* in its use of the term "like". It assumed that the audience could infer from the context of the discussion in what ways something ("anything" "there") would have to be like the thing under discussion ("that"). After two students responded that they could not see anything like that there, the teacher tried to explicate what "like" meant here. He did this by picking up on Jamie's "Not with the same engine" and defining "like" to mean "with the same engine, but with a different nose cone." Scientific talk tries to avoid the elliptical ways of normal conversation. Throughout the session, the teacher models for the students this explicit way of talking, often taking what a student has stated elliptically and repeating it in a more fully stated way. Now the teacher is doing just that. Sometimes one of the students will pick up on this and start to talk more explicitly. Here Brent has picked up on the term "different" as a key criterion for determining likeness.

Of course, the problem for us as researchers is that Brent's exclamation, "This one's different," is itself elliptical. In what way is "this one" different?

THE CONFUSION

There is also the interpretive problem of reference or *indexicality*. Brent is pointing at the list of rocket descriptions, but it is impossible to tell from the video data which description he is pointing to. Even if we knew which one Brent was pointing to, his utterance does not make clear which other rocket he is comparing with the one to which he is pointing. We have to deduce the answers to both these questions from the ensuing discussion, to see how the participants themselves took the references.

Jamie's immediate follow-on utterance begins with "Yeah, but" indicating a response that is partially supportive. Since we know that Jamie is responding to Brent, we know that Jamie's use of "it" refers to Brent's "this one." Chuck in turn builds on Jamie, reclaiming the floor by interrupting and completing Jamie's incomplete utterance of the term "nose cone." So Chuck's subsequent utterance – which he ties to the preceding with "but" uses "it's" to refer to Brent's "this one" as well.

1:22:06	Jamie	Yeah, but it has same no…
1:22:07		(1.0)
1:22:08	Chuck	Pointy nose cone=
1:22:09	Steven	=Oh, yeah=
1:22:10	Chuck	=But it's not the same engine

Here we see the conflict begin to be stated. Chuck's "but" suggests a disagreement with Brent and possibly with Jamie also. In the next second both Jamie and Brent come back with "yes it is," showing that they took Chuck's comment to be a clear disagreement with what they were saying.

Kelly's non-verbal behavior again indicates that something unusual is going on. Now he rocks forward onto his elbows to follow events more closely. He stays in this position for the rest of the moment.

At this point in our interpretation, we have several shifting factions of opinion. At first, all the students seemed to be disagreeing with the teacher. Following Brent's bold gesture, some of the students seem to be disagreeing with others. We have not yet worked out the basis of this disagreement because of the elliptical and indexical nature of the utterances that form our data.

We have actually overcome the problem of the elliptical – but not the indexical – character of the utterances by looking closely at how the individual utterances build off of each other, repeating the use of the same words or using conjunctions like "but" or "yeah" to signal continuity of topic. However, it is harder to know, for instance, which rockets are indexed by pronouns like "it". It seems likely that Jamie and Chuck are, in fact, indexing different rocket descriptions with their use of the pronoun "it." This would certainly cause confusion in the discussion because the repeated use of the same word should signify commonality of reference. To determine which rockets they are each indexing in their utterances, we will have to continue our interpretive effort.

THE REPAIR

In the next couple of seconds, Jamie and Brent state virtually the same thing simultaneously. This indicates that the state of the group discourse – from the perspective in which Jamie and Brent are viewing it – must be very clear. That is to say, the network of indexical references as interpreted in Jamie and Brent's utterances is univocal. Within this set of references, Chuck's claim that "it's not the same engine" is clearly wrong. Jamie and Brent insist that "it" is the same engine.

1:22:11	Jamie	Yeah, it is, =
1:22:12	Brent	=Yes it is,
1:22:13	Jamie	┌ Compare two n one
	Brent	└ Number two

Here Jamie and Brent support their counter-claim precisely by clarifying the references: they are talking about similarities and differences between rocket number two and rocket number one on the list in the simulation artifact.

Jamie's imperative, "compare two and one," is first of all an instruction to Chuck to look at the descriptions of rockets two and one on the list. At the same time, it is a reminder that the purpose of the whole discourse is to conduct a comparison of rockets in order to determine the best nose cone shape. Jamie's utterance serves both to propose an explicit set of indexical references for the problematic discussion and to re-orient the discussion to the larger goal of solving a specific scientific task. His utterance thus serves to state both the indexical and the *projective* basis of the discourse. He is saying that the group should be indexing rockets one and two in the list comparison so that they can then conduct a comparison of one and two in the datasheet artifact as their projected future task.

Jamie and Brent have now solved our task of interpreting the indexical references. Of course, we might still want to try to reconstruct the networks of references that different participants had at different points in the discourse. We would thereby be retrospectively reconstructing the process of construction that the discourse originally went through to reach this point. We would be "deconstructing" the discourse.

If we go back to the minute of discussion between the teacher and Chuck that preceded our transcript, we indeed find the source of the confusing references. Chuck had switched the discussion from nose cones to fins and had in fact solved the problem of how to determine the best rocket fin configuration. He said to compare rockets 3 and 4, which are identical except that rocket 3 has 3 fins and rocket 4 has 4 fins. Then Chuck wanted to return to the problem of nose cones. He proposed making the simulation software modifiable by users so that he could either change the nose cone of rocket 3 or 4, or else change the engine of rocket 2 to match the engine of 3 and 4 so he would have a pair with the same engine as his baseline rocket (3 or 4) but different nose cones. So Chuck was actually following the right theoretical principle already. However, his description of the changes he would make got quite confusing – plus it made unrealistic assumptions about the software.

So the teacher's opening remark, directing Chuck and the others back to the list on the screen can now be seen as a *projective* attempt to have Chuck recognize that rockets 1 and 2 could be compared as is without changing one of them to be comparable to 3 or 4. In other words, the list had this built-in structure – that Chuck was not seeing and taking advantage of – that it had been organized to solve the problem of rocket comparisons. Unfortunately, because the discussion had been focused on rockets 3 and 4 as the basis for comparison, none of the students could see at first that 1 and 2 met the criteria. As Jamie said, there was no rocket with a pointed nose cone, “not with the same engine,” where we can see that “same” referred to same as the engine in rockets 3 and 4.

When Brent points to what must be rocket 2 and says, “This one’s different,” his utterance refers to the fact that rocket 2 has a pointy nose cone, which is different from all the other rockets. At this point, Brent’s and Jamie’s utterances must be taken as comparing 2 to rocket 1. Because when Chuck keeps insisting that “it’s not the same engine” (meaning 2’s engine is not the same as 3 and 4’s), Brent and Jamie retort “yes it is” and explicitly refer then to 1 and 2. As they repeat that they are looking at descriptions of rocket 2 and another rocket with the “same” engine, even Chuck gradually aligns with the reference to rockets 1 and 2. With this look back at the situation prior to our moment, we can reconstruct how our moment developed out of its past and we can determine a consistent and meaningful interpretation of the references of the utterances, as understood from the perspectives of the different participants’ utterances.

THE RESOLUTION

In the final segment of our transcript, Chuck responds to Jamie’s clarification. When Jamie says “compare two and one,” Chuck actually turns to the computer screen and studies it. With gradually increasing alignment to what Jamie is saying, Chuck says tentatively, “I know.” This is the first time during this episode that his utterances are agreements. Jamie goes on to instruct on how to make the comparison of rockets one and two: note how they “are the same.” Chuck’s “Oh” response indicates a change in interpretation of things. Brent makes even more explicit how Jamie’s “are the same” is to be taken, namely that both rockets have the same kind of engine.

1:22:14	Chuck	(0.2) I know.
1:22:15	Jamie	(0.2) Are the same=
1:22:16	Chuck	=Oh
1:22:17	Brent	It’s the same engine.
1:22:18	Jamie	So if you [compare two n one,
1:22:19	Chuck	[Oh yeah, I see, I see, I see

1:22:21	Jamie	(0.8) Yeah. Compare two n one. So that the rounded n- (0.1) no the rounded one is better. Number one.

Jamie now repeats his double-edged imperative, "compare two and one." But he precedes it with "so if you." Now he is not only telling Chuck to look at these two descriptions and to compare them, but also saying that if you do this then you can go on and do something in the future, namely compare the data that the students had collected in the previous hour for these two rockets and determine the best nose cone design. While Chuck is conceding that the descriptions of these two rockets meet the criteria that the teacher spelled out at the start of the moment, Jamie has started to look over the data sheet that he had been holding ready at hand during the whole conversation and had brought up to his line of sight at 1:22:13. (Steven had also gone to retrieve his data sheet at 1:22:15, after hearing Jamie's first "compare two and one" and then checking the list on the screen for a moment.) Now Jamie announces the findings from the data. In the final utterance at 1:22:21, Jamie compares two and one – but now their data, not their descriptions. He announces that the rounded nose cone is better based on its performance data. He stops himself in the middle of this announcement to check his analysis, which requires combining information from the list and the datasheet. Finally, he links the conclusion about the rounded nose cone to the rocket description ("number one"). This not only resolves any possible conflict about the references of the discussion, but shows how they worked to solve the larger task that had been projected for the discourse.

At the end of our collaborative moment, a quiet consensus has been reached. Jamie and Steven have moved on to the data sheets and everyone else is looking intently at the list, having acknowledged the teacher's rhetorical question, "And you don't have anything like that (rocket one and two descriptions, with the same engine and different nose cones) there (in the list) ?" Now all the references are aligned with those of the teacher's original question, bringing an end to the breakdown of references and allowing the group to affirm the question and move on to solve their task using the newly comprehended list artifact.

MAKING LEARNING VISIBLE

The teacher provides efficient guidance by: (1:21:53) directing attention to the list artifact, (1:22:00) defining criteria of sameness and difference, and (1:22:04) allowing the students to solve the task collaboratively. Brent points the way with a bold gesture at what already exists in the list artifact (the descriptions of rockets 1 and 2) as the solution. Jamie clarifies how to take this as the solution. Through a sequence of brief, highly interactive turns, the students collaboratively move from treating the list as inadequate, irrelevant and uninteresting to seeing it as holding the key to solving the group task. The sequence ends with a sense of consensus and collaborative accomplishment. In addition to a solution to the nose cone problem, the group has articulated, accepted and put into conversational practice a terminology for discussing sameness, difference, comparison, etc.

By making explicit the references that grant meaning to the discourse, the students made visible to each other the understanding that was being expressed in the interactions. In particular, they made visible the elliptical, indexical and projective references that had become confused. As researchers, we can take advantage of what the participants made visible to each other to also see what was meant and learned as long as we stand within a shared interpretive horizon with them (Gadamer, 1960/1988). Methodologically, our access to these displays is ensured to the extent that we share membership in the culture of understanding that the participants themselves share. For instance, the people who interpreted the transcript and video clip are native speakers of English, have experienced middle school classroom culture in America, have a lay understanding of rockets, but may not be privy to the latest teen pop culture or the local lore of the particular classroom so we can legitimately interpret much but perhaps not all of what goes on. The equivalent of inter-rater reliability is established by our developing interpretations of the data in group data sessions and presenting those interpretations in seminars and conferences of peers, where our interpretations must be accepted as plausible.

It is considerably harder to interpret what learning took place in the collaborative moment than in the rest of the three hour session. When the dialog format between a teacher and one student dominates, one can assume – unless there is evidence to the contrary – that learning has taken place for the student (if not necessarily for the whole class) if the student's response to the teacher's question has been evaluated as appropriate by the teacher. One basically follows the teacher's displayed interpretation of what is unfolding, assigning learning to students who he indicates have responded appropriately to his questions. In a collaborative moment, there is no authority guiding, structuring and evaluating the interaction. Deeper interpretation is required to determine what takes place at all, let alone who learns what when where and how. In a CSCL setting, for instance, where many students may be interacting autonomously within a threaded discussion system on the Internet, one must rely on an analysis of student discourse that has a many-to-many structure rather than a teacher-centric one. The potential here is great because learning can overcome the teacher bottleneck and allow much higher levels of student participation in knowledge building discourse. The problem is how to assess what learning is taking place.

In our preceding analysis, we have seen that the factors that have in cases of individual learning been taken to be hidden in occult mental representations can in cases of collaborative learning be taken to be visible in the discourse. The meaning of utterances – even in elliptical, indexical and projective utterances – can be rigorously interpreted on the basis of interaction data such as digital video or discussion forum logs. Learning – now viewed at the group unit of analysis – can be taken to be a characteristic of the discourse itself. In addition to the group's shared understanding, however, one can also determine the interpretive perspectives of the individual participants, particularly in cases where there are breakdowns of the shared understanding and the participants must make things explicit.

STEPS TO A SCIENTIFIC UNDERSTANDING

The learning that we have uncovered in the collaborative moment transcript played a key role in the larger classroom session. It is now possible to review the larger transcript and find statements in which learning associated with the issue addressed in the moment is also expressed. (This is an instance of the hermeneutic principle that interpretation must go back and forth between part and whole.) During the ten minute interaction surrounding the moment (from about 1:17 to 1:27), where the teacher and students discussed how to analyze their rocket data, the group understanding went from a rather naïve and vague sense of how to use the list artifact to a very clear and explicit appreciation of the meaning of that artifact and a practical knowledge of how to use it to achieve useful and meaningful results. Following are a series of excerpts that illustrate this development through 10 stages, by presenting significant statements that expressed the evolving group understanding.

In *stage a*, Chuck expressed the group's assumption that one could simply adopt all the features of the rocket that flew the highest. When the teacher suggested that a particularly strong engine could mask the differences caused by the other features, the students were at a loss on how to proceed without strong guidance from the teacher, leading up to the collaborative moment with its breakthrough insight.

1:17:01	Chuck	We'll just go with number one uh (.) an that did the best, (.) or something, out of all ours compa:red

In *stage b*, after some discussion of statistical analysis, Steven still adopts the same position as Chuck, to go with all the features of the best rocket.

1:17:44	Steven	Well we'd look at- (.) we'd look at the graph that we do an see which has (uh) the ↑best. An whichever has the ↑best like rocket one two n three or- so on, (.) .h n whichever has the best we'd look to see if it has a rounded, or a pointed, which (.) which ours shows so far, that a ↑rounded, (.) that a ↑rounded is better?

In *stage c*, Jamie suggests to see whether the group with pointed noses does better overall than the group with rounded noses, assuming that this kind of averaging will cancel the effects of the other features.

1:18:29	Jamie	Well what you do is you take every one that has a rounded nose an every one with a (.) pointed nose. (0.4) an you see which (0.2) one did better overall

In *stage d*, Chuck has the idea of manipulating one feature at a time while holding the others constant, but he wants to do this on physical model rockets rather than applying it to the data he just collected from the simulation.

1:18:36	Chuck	Yeah if you could bring in one that (.) like two two liter pop bottles you know that's (.) make one with a ↑pointed nosecone n one with a ↑rounded nosecone. an see which one did better .hh so then we c'd go with that one an then add the feature that was on that one to the other one .hh an whatever features you put on here, (.) you leave off of (1.0) that- uh off of the other one .hh that way you c'n j's see which one will fly. (.) 'F the features on this one didn' work then we take th'm off and then go from there.

In *stage e*, Jamie is ready to use the data from the simulation, but returns to the idea of finding which did "better overall."

1:19:05	Jamie	You can use the simulation by .h finding out (.) j'st which one has a rounded nose and which one has a pointed nose? (.) and which one did better overall. (0.8) Like w- (.) which (.) rockets like (.) if (.) only one rocket with a rounded nose .h did good, then (.) a rounded nose (.) isn't very good, (.) but like if. yeah but like if all the rounded noses are good, (.) compared to the pointed nose, then the rounded nose- noses are good.

In *stage f*, Chuck solves the problem for fins using the simulation and identifying rockets 3 and 4 on the list as having the necessary characteristics for valid comparison.

1:20:30	Teacher	So how would you find out which is better four fins or three fins. (1.0)
	Chuck	By launching ( ) with two different things on it–
	Teacher	–Which one – which two.
	Chuck	one with fou::r (.) n one with three: like (0.6) rocket four an rocket one. (0.8) Err no – (.) Ro:cke:ts, (.) fou:r, n rocket three. Cuz they both have the same engine. (0.8) An they both have the same nosecones.

In *stage g*, Chuck wants to change the simulation to create a comparable pair of rockets. He is willing to use the simulation, but has not looked carefully through the list to find what he needs.

1:20:03	Chuck	see 'f you guys c'd make one .h wha– with an astro (.) alpha engine four fins and pointed nosecone, (1.6) w'll see if you c'd do, (.) uh cha:nge all this around n stuff so that .hh you might get ( ) you also – .hh have an option of a pointed nosecone like – ((swallow)) .hh you could (.) kinda

		like in HyperStudio .hh if you were tuh (.) like (.) click on this .h it would give you (.) all kinds of things th't you (.) ought – like (.) on the (.) pointy nosecone (.) .h you c'd switch it to a rounded nosecone .h and the fins,

Stage h is the moment we have analyzed. At 1:22:21 Jamie turns to his data sheet and compares the data for rockets one and two, concluding that because rocket one went higher than rocket two and the only difference between them is that rocket one has a rounded nose cone, then a rounded nose cone is preferable.

In *stage i*, Steven explicitly describes the structure of the list for doing the task for all features of the simulation rockets. He says, "I think it is good how it is," fully appreciating that the necessary cases have been built into the list.

1:24:46	Steven	What we would do is test (.) test (.) uh- rocket three and rocket four, (.) cuz they both have a rounded nose they both (.) have that astro alpha engine n they- (.) n one has three one has four fins. I think it's good how it is because .hh every rocket has somep'n different. Like if you tested (.) five and six, then it- (.) they have the crazy uh- (.) quasar engine, .h they both have the crazy quasar engine, they both have the rounded .h nose they both have three fins, except th't if- if we uh- if we tested those two, we'd be - testing for thuh- uh painted body or uh -- a sanded body, (.) so I like it how it is.

In *stage j*, the whole group is in agreement about how to use the list and they are able to collaboratively draw scientific conclusions with its help.

1:26:46	Brent	I would say that ⌈three is better than four
	Jamie	⌊three is better than four ( )=
	Chuck	Yeah, three is better than four so=
	Teacher	=So ⌈your rocket⌉
	Chuck	⌊(we want) ⌋ three fins n a rounded nose⌈cone
	Teacher	⌊Your rocket three goes up higher 'n rocket four=
	students	Yeah ((multiple voices))
	Teacher	So that means that three fins is better 'n four.

By solving a sequence of problems that the teacher guided them through, the students developed an increasingly robust working knowledge of the fundamental principle of scientific experimentation, that only one variable should be varied while the others are held constant. Although this principle was built into the simulation's list of rocket descriptions and although the students started the classroom session by reading this list aloud and discussing it, they were not able to use this feature of the list in analyzing the data they collected until they worked through the preceding stages. Even as bright, motivated middle-school students, they were not developmentally able to grasp the principle on their own. However, this ability did lie within their zone of proximal development (Vygotsky, 1930/1978), and they succeeded in attaining it through a scaffolded collaborative process.

THE INTERTWINING OF GROUP AND INDIVIDUAL PERSPECTIVES

The preceding analysis gives us a new insight into the nature of the *group perspective*. It is true that only individuals can interpret meaning[3]. But this does not imply that the group meaning is just some kind of statistical average of individual mental meanings. A group meaning is constructed by the individual members as they interact. We have now seen an example of how this works. The discourse is elliptical, indexical and projective; that means that it implies and requires a (perhaps open-ended) set of references to complete its meaning. These are supplied by the individuals' interpretive perspectives. The on-going assumption is that everyone supplies roughly the same references. From time to time there is a breakdown and it becomes clear to the members of the group that different people are supplying different references. In the case we have observed, the group members repair the problem by clarifying what the references should be. This continues until – for all practical purposes – it seems that the utterances of all the members imply a common interpretation of

[3] The methodological recognition of interpretive perspectives avoids the reduction to behaviorism in bracketing out inferred mental states and focusing on observable interaction.

the references. Now the conversation can go on, which means that the group has decided that the group understanding is repaired.

This does not mean that we must assume that everyone in a group always has the same understanding. In our analysis we saw that different interpretive perspectives can and do arise. Chuck and the teacher had different and at times incompatible perspectives on the discourse. The other students intervened to repair this breakdown in group understanding. They did this by using the simulation screen as a shared artifact and tying the discourse to it. The problem revealed itself to be a matter of Chuck and the teacher interpreting the references of the elliptical, indexical and projective utterances that took place in the group discourse as referring to different items. Note that in our analysis it is not a matter of Chuck and the teacher advocating for different thoughts hidden in their heads but of their utterances implying different interpretations of the references in the publicly available group discourse.

It makes no sense to ask if "everyone is really thinking the same thing." Only evidence later in the conversation can question the shared understanding. To give everyone a secret test would be to pose a completely different task from the collaborative one. To survey the individuals about what they were thinking at the time would be to raise insurmountable problems of interpreting their responses as *post hoc* rationalizations for situated communicative actions that were not explicitly planned in advance (Suchman, 1987). Shared understanding cannot consist in some kind of formal agreement about inferred mental contents of the individuals, but only in the practical application and interactive handling of references that complete what is explicitly stated in the group discourse.

MEANING AS REFERENCE: RELATED AND FUTURE WORK

This paper has discovered through micro analysis of a moment of collaborative learning that meaning is constituted by references among elliptical, indexical, projective utterances and physical artifacts. This discovery raises many questions that cannot here be addressed. The fact that meanings must be interpreted and understood by minds of individual human beings does not imply that meanings exist in people's heads: the individuals bring their interpretive powers, but not necessarily the ideas or meanings. An indication of this is the fact that the utterances we observed are rather meaningless when taken just in the context of the person who uttered them, but get their meaning from the group context of other people's utterances, the activities of the group, the shared culture and the constituents of the physical setting. The roles of interpretation (Gadamer, 1960/1988), perspectives (Stahl, 1993) and common ground (Baker *et al.*, 1999) must still be worked out. Of course, the distinction we have made here between the meaning of language or artifacts (as intersubjective) and the interpretation of this meaning (as subjective) is somewhat arbitrary. The terms "meaning" and "interpretation" are borrowed from theories that did not adequately describe the relation between the social and individual phenomena we are trying to capture; we will have to see how well our use of these terms helps us to understand how these phenomena work together and influence each other.

We have also seen an example of how a group learns the meaning embodied in a physical or digital artifact. Little has been written to date about how this process takes place, although it is clearly essential for an adequate theory of collaborative learning. Other than a vague usage of the term "affordance" (Gibson, 1979; Norman, 1993), we have not explored how artifacts can act as boundary objects (Starr) between communities of designers, learners and researchers. We have claimed that because meanings exist intersubjectively as sets of references they can equally be interpreted by designers, learners and researchers. But we have not shown how these meanings can be designed into artifacts and have only given one example of how learners can become aware of the embedded meanings.

Meaning as reference among words is closely related to Lemke's use of "semantic relations" (Lemke, 1990), which is founded in functional grammar theory (Halliday, 1985). Research on latent semantic analysis (LSA) provides empirical evidence that human understanding of word meanings has the computational complexity that derives from taking into account the latent (or secondary) relationships of words in the corpus of experienced text from which the words are learned. That is, the similarity structures that one obtains from a statistically thorough analysis of a large corpus of text are functionally equivalent to a striking extent to what are commonly taken to be human meanings. Although discussions of LSA (Kintsch *et al.*, 2000;

Landauer & Dumais, 1997; Landauer, Foltz, & Laham, 1998) generally take it as a model of human mental processes, this argument could be turned around into a demonstration that "meanings" are inherent in the relationships within the discourse itself for many domains of words and texts. Of course, meanings are also grounded in the human condition, such as our bodily orientation and action structures. Further, our analysis finds the meaning references among spoken utterances and artifacts in the concrete interaction situation, not among individual words in an abstract large corpus of written text.

The term "reference" is in particular need of analysis. If meaning consists of "references" among words, utterances and artifacts, than this is an important and mysterious term. It is tied in with the view that meaning is not some kind of mental stuff divorced from the physical world – as so many theories since Descartes have taken it to be. If artifacts are defined as meaningful physical objects and collaborative knowledge is to be found in written and spoken texts, then we need to understand how meaning can exist and persist in the world. The phenomenological tradition has perhaps thought this through the most carefully: Building on Husserl, Heidegger developed a philosophy in which meaning inheres in the network of references among artifacts in the world. This network underlies our shared social life (Nancy, 2000), although Heidegger tragically failed to develop this aspect of his theory.

The references of indexical, elliptical, projective utterances tie together the present, past and future. In the conducting of discourses like the one we analyzed, we can see the participants interactively constructing a shared temporality. Again, this fits in with Husserl's (Husserl, 1917/1991) and Heidegger's (Heidegger, 1927/1996) analyses of human temporality. These were extended in Schutz's (Schutz, 1967) philosophy of social being and Garfinkle's (Garfinkel, 1967) methodology of social analysis. Thus, the discovery of reference leads quickly to core issues of a general theory of meaning, temporality and social being that could form a framework for work in CSCL once they are explicated.

The implication for designers of CSCL artifacts is that they must attempt to understand the shared understandings that are likely to arise from interventions that insert their artifacts into targeted learning communities. These artifacts should not be designed as isolated software applications, but as integral components of activity systems that support learning as collaborative knowledge building. Participatory design with teachers and students should be used to ground the artifact design in the culture of the potential user communities. Trial of the artifacts in realistic school settings is also essential in order to see what actually transpires. Cycles of prototyping and empirical trial are of course necessary, but the point is to make these trials under normal school conditions, with the usual social practices and reward systems – and then to analyze carefully the discourse and interactions that ensue. Perhaps most importantly, community discourse processes should be intentionally guided to help groups of users to re-activate and interpret the meaning of the artifact in their own terms and from their own perspectives. Without such carefully thought-out scaffolding measures, computational artifacts will continue to fail to effectively cross the boundaries between diverse design and usage communities.

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