Collaborating with Relational References

By Gerry Stahl, Drexel University

For presentation at AERA 04, San Diego, CA

A previous analysis of the data considered here used a simple concept of reference in which an utterance refers to an identifiable object in the world – a specific rocket description in the simulation list. In this paper, the analysis is deepened to reveal the learning by the group of students of a more sophisticated reference that involves pairs of objects compared in a subtle way. Mastering practices that define such reference is necessary for conducting collaborative scientific experiments involving controlled variables. This accomplishment is achieved by the group of students as a whole, working with computer-based artifacts under the guidance of an adult mentor. The group of students in the previous paper encountered confusion about which rockets they were referring to in their talk-in-interaction. In this paper, it becomes clear that their task of referring was complicated; it involved a new way of looking at the meanings embedded in the simulation artifact.

EMBEDDING MEANING IN SOFTWARE

Several years ago I met Tony Petrosino at a conference and was intrigued by his research on using model rockets to teach science to disaffected middle school students in Texas. He explained that the use of model rockets is quite widespread in middle school curriculum and that kits for building model rockets with a variety of rocket engines are readily available. Since we were at a computer-oriented conference, Tony and I started talking about developing a computer simulation of model rockets to supplement his curriculum.

When I returned to my office, I discussed the idea with Alex Repenning, my office mate at the time and the developer of Agentsheets, a software environment for end-user programming of simulations. We decided that this would be a good exercise for me to undertake in learning more about Agentsheets. So I got some data from Tony about the effects of different rocket options on the flight of model rockets and I programmed a simulation. Using the Agentsheets visual programming language (Repenning & Sumner, 1995), I defined the behavior of rockets to correspond roughly to Newton's laws, taking into account different air resistances due to rocket shape and texture (based on Tony's data), the thrust of the different rocket engines and gravity. I translated Newton's laws into difference equations for computing a rocket height at every time slice of the simulation. Then I added a random factor ("weather conditions") to make predictions more interesting. While middle school students do not know the equations of physics, they can find averages on their calculators to take into account the random noise.

At the time, I was working with two middle school classes, developing software for them to practice writing summaries. In the Spring, these classes broke into special science projects, for which parents and community members were encouraged to volunteer. The classroom teachers I was working with invited me to mentor a model rocket group, and I proposed to spend two hour-and-a-half sessions with them using my new simulation.

I was curious to see what kids in the space age really understand about rockets and scientific method. In particular, I wondered if they understood the basic principle of experimentation: varying only one attribute at a time while holding the others constant. So I equipped the simulation with 7 rockets whose configurations would allow one to measure the effects of each rocket variable and then predict the behavior of an 8th rocket.

But more than just being curious about what a certain group of students knew, I was interested in studying how middle school students would go about learning about a new software tool. I thought that having them work in a group would make their learning visible to me. So I decided to videotape them in order to capture a record of their learning.

Of course, students these days are adept at using software and at discovering its functionality based on hours of time spent with video games and similar devices. However, what I was asking them to learn was different. They had to learn the structure of the list of rockets and learn how to take advantage of that structure to complete certain computational tasks. In other words, I was embedding some meaning in the simulation and they would have to come to understand that meaning. One can conceptualize any software program as the embodiment of meaning that was programmed into its appearance and its behavior. For instance, the meaning of certain icons and menu items in a word processing program has to do with determining fonts for text. To understand that program, one must learn about fonts and their use, as well as about how to manipulate fonts using the interface icons.

One can say that a computer software program is an artifact that embodies "inferred," "referred," "derived" or "stored" intentionality. That is, the software designer programmed meanings or intentions into the software, and these allow the software to behave in a meaningful way. A clear example of this is given in artificial intelligence. An AI program is supposed to exhibit human-like intelligence in responding to inputs. Of course, that is only possible if the programmer reduced some limited domain of intelligent behavior to algorithmic rules (or heuristic rules that were close enough to mimic human decisions most of the time) and then programmed these into the software. The meaning of the software's behavior is derived from the human software designer's symbolic external representations (Keil-Slawik, 1992) in the programming language. The user notices traces of the designer's intention in the form of the operational software artifact. The meaning is referred from its source in the designer to its appearance in the interface, much as "referred pain" appears in a different part of the body from its causal source. The software embodies designer intelligence analogously to how commodities and machinery embody "stored" or "dead" human labor in a way that determines their exchange value according to Marx (1867/1976). In the case of the computer simulation, not only the temporal behavior of the rocket but also the useful arrangement of the rocket attributes in the list of rockets are intentional artifacts whose meaning was structured by the designer.

VARIETIES OF MEANINGFUL ARTIFACTS

We can distinguish different categories of meaningful artifacts:

- physical artifacts
- symbolic artifacts
- computational artifacts
- cognitive artifacts

By definition, an *artifact* is something man-made. We might think of an arrowhead, pot shard or figurine unearthed by an anthropologist. The physical artifact is made out of some material that has survived thousands of years. It has a form or outer appearance that displays some purpose or meaning and that shows that it was made by a person, by a designer who embedded that meaning in it. We may not be sure exactly how to interpret the meaning – whether a given figurine is religious, magical, fertility enhancing, artistic, a child's doll, a remembrance of an important individual or a decoration – but we know that we are in the presence of a meaning and we know that someone at some time in the distant past intended the artifact to have a meaning. We are tempted to attribute some interpretation to the meaning. With our interpretation comes a glimpse into a faint and distant world: a culture within which this artifact was once transparently integrated.

A *physical artifact* embodies meaning in the physical world. Our folk theories influenced by Descartes' conceptualizations think of the meanings as something purely mental, divorced from the physical world. According to this view, meanings are ideas we have in our heads about things in the world. But if we consider the nature of artifacts, we soon realize that the physical world is full of mental meanings, the world is meaning-full – not because I as an observer apply values and meanings to things I see, but because practically everything in our world has been made by people and has been designed to have specific meanings. Our shared culture makes these meanings available to us all. Even the rare glimpses we get of nature are imbued with historical or aesthetic dimensions; they are measured by what it would take for us to climb or touch or paint them; they are framed by the eye of an architect, landscaper or urban planner who purposely left them for us to glimpse. The very concept of nature is so socially-mediated that any sharp separation of meaning and the physical is misguided.

And *vice versa*. *Symbolic artifacts* are not completely ethereal. Words appear in sounds, ink or pixels. They could scarcely do their jobs as conveyors of meaning from one person to another if they did not appear in the physical world where they could be perceived and shared. Symbols do not come from nowhere; nor are we born with them inside us, like the neurons of our brains. We learn the meaning and use of symbolic artifacts — the words of our languages and of our language games — from our activities in the world, primarily from interacting verbally with our care-givers, our siblings, our childhood best friends, our various teachers and other people.

Artifacts have been around as long as humans, although the concept of artifact as a bridge across the mind/body distinction has only played a central role in philosophical ontologies since (Heidegger, 1927/1996), (Benjamin, 1936/1969) and (Vygotsky, 1930/1978). However, *computational artifacts* are a relatively new phenomenon. An artifact like the `SimRocket` simulation enlivens with computational power the meaning that is programmed into the software bits. The rocket icon moves with a behavior whose meaning was programmed in by the designer, although carefully designed random and interactive elements make the precise behavior unpredictable, as well as dependent upon the user's actions. The computational, interactive artifact has a different kind of complexity than the prehistoric arrowhead – although the crafting of some arrow heads may have been so skilled that they are impossible to duplicate today. While it may be hard to specify precisely how meaning and physicality are merged in the bits of software that can be limitlessly duplicated and reconfigured, it seems clear that effective usage presupposes that the user recover the meaning of the software that was designed in there to empower the user.

In educational contexts there is an expectation that the meaning will be taken a further step: that the lessons will be *learned*, that is that whatever meaning is unearthed with the artifacts will be internalized by the student. This expectation does not necessarily entail a return to the view that meanings exist in minds. Rather, the expectation is that the student will be able to make use of the meaning learned from an encounter with a physical, symbolic or computational artifact in one situation when the student is in a new situation in which that meaning might again be relevant. Without speculating about what might be involved in the student internalizing a meaning, we simply look at the student interpreting the meaning in the original situation and then using this experience as a resource for constructing some similar form of meaning in a new practical situation in the world.

Vygotsky recognized that we do have an inner mental life and he succeeded in relating our mental life to our social life in the world by arguing that our private mental world was an internalization of the primary shared social world. We learn to speak, act and be in the world by interacting with other people and by sharing a culture and a meaningful world with them. As we begin to master these as a young child, we start to talk to ourselves — first out loud and then silently. We follow a similar sequence with reading — and then with debate and other social skills. In each case, when we internalize a skill it undergoes a complex sequence of transformations, eventually becoming a *cognitive artifact*, a mental tool. For instance, an arrowhead might allow us to kill our prey in the world, the language of hunting allows us to discuss group plans for an expedition, a computer lets us simulate hunting scenarios and the internalized language lets us imagine a glorious hunt. The nature of the hunt is different depending on whether it is mediated by a physical, symbolic, computational or cognitive artifact. The silent self-talk that Vygotsky analyzed is the start of the stream of consciousness that forms our private mental life. Various skills like the ability to construct narratives (Bruner, 1990) and to give an account of our actions (Garfinkel, 1967) enrich that life.

In this paper we want to observe how a new cognitive artifact can evolve out of social interaction involving a computational artifact. How do the students develop the cognitive skill of comparing experimental cases with various attributes?

THE STRUCTURE OF THE ROCKET LIST

The `SimRocket` applet is a *computational artifact.* It includes the simulation panel of the rocket flight and the rocket list describing the available rockets. Based on Tony’s model rocket kits, I designed the simulation rockets to have four variable attributes:

- Nose cone shape (rounded or pointed)
- Number of fins (3 or 4)
- Surface texture of body (painted or sanded)
- Rocket engine (Big Bertha, Astro Alpha, Crazy Quasar, Giant Gamma)

The rockets are paired in the list of available rockets (see Figure 1 in the previous paper (Stahl 2002) for a view of the actual screen). There are two rockets with each kind of engine. The first three pairs have identical attributes, except for one difference:

- Rockets 1 and 2 differ in nose cone shape
- Rockets 3 and 4 differ in number of fins
- Rockets 5 and 6 differ in body texture
- Rockets 7 and 8 differ in nose cone, fins and body

The computer simulation was carefully designed with this particular set of rockets. This set of rockets allows the user to determine the effect of the different attributes on the flight of the rocket by, in effect, holding all variables but one at a time constant. Thus, one can determine the effect of nose cone shape by comparing flights of rockets 1 and 2; of number of fins with rockets 3 and 4; of body texture with rockets 5 and 6. These effects can then be combined to predict how rocket 8 will fly, given the flight of rocket 7, which differs from rocket 8 by these three attributes.

There are other sets of configured rockets that would allow similar calculations and predictions. Rather than varying attributes in pairs of rockets (call this "paired configurations"), one could compare a set of different rockets to one common standard (call this "standard configurations"). For instance, rockets 2, 3, and 4 could each differ from rocket 1 by a different individual attribute. Then, rockets 5, 6 and 7 could be like rocket 1, but have the different engines. This would also allow one to compute the effects of each attribute singly and combine them to predict any configuration of rocket 8. Either this standard configurations combination of 7 rockets or the paired configurations combination above allows one to compute the dynamics of all 32 possible rocket configurations using a set of just 7 different rockets.

Using the contrast just made of paired configurations to standard configurations, we can better understand the breakdown analyzed in the previous paper. The students discovered that rockets 3 and 4 could be compared to determine the best fin configuration because 4 was a variation of 3. They then sought a variation of rocket 3 that could be analogously compared for nose cone shape. The students were assuming a standard configurations model in which everything is compared to one standard rocket (rocket 3).

However, the rocket list is, in fact, structured with paired configurations. Brent's gesture first draws attention to a pair with the needed difference, using a paired configurations model. The result of the subsequent collaborative interaction is to reach a consensus in which the whole group takes the pair (rocket 1 and 2) as the focus of comparison, rather than insisting on looking for a variation of the standard rocket 4 engine.

UNCOVERING EMBEDDED MEANING

At this point it may seem obvious to the adult reader how one should compare rockets in the `SimRocket` list to find out the effects of the different attributes. However, it clearly was not obvious to the young students. We saw in the last paper how their references to rockets to be compared became quite confused. It presented the occasion for an exceptional interaction among the students to sort out this breakdown in the references. They accomplished this efficiently, with the use of brief, productive utterances that are hard for an observer to interpret but proved to be incredibly effective within the discourse. Once the references were resolved and accepted as shared by the group, the students were able to quickly draw the scientific conclusions about rocket characteristics. They then displayed in their talk their mastery of how to compare rockets. They accomplished this not by talking about "controlling variables" – such adult (schooled, professional) terminology was never used – but by making the proper use of their data. They learned the principle of scientific comparison in the practical, situated sense that they could actually carry out the appropriate operations on their data.

The learning that we 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 collaborative moment is also expressed – following the hermeneutic principle that interpretation must go back and forth between part and whole.

During the ten minutes surrounding the thirty-second 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 from the longer transcript that illustrate this development, by presenting significant statements that expressed the evolving group understanding. They are given here in ten stages:

- *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

- *Stage b*, after some discussion of statistical analysis, Steven still articulates the same group position as Chuck had, 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?

- *Stage c*, Jamie suggests to see whether the set of rockets with pointed noses does better overall than those 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

- *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 (made out of soda pop bottles) 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.

- *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.

- *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.

- *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 collaborative moment analyzed in the previous paper. 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.

- *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 [the structured list] is good how it is,” fully appreciating that the necessary pairs 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.

- *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 ten 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.

ARTICULATING MEANING

How was the meaning of the rocket list as a set of paired configurations constructed by the group of students? In reviewing ten stages of understanding that evolved in the group during the ten minutes surrounding the half-minute moment of collaboration, we have seen that the group went from simply wanting to identify the "best" rocket "overall" to proposing various methods of comparing rockets and then – after the intensive collaborative moment – to understanding the paired configuration and using it to complete their task.

Let us return to the transcript in the previous paper to see in some detail how the pivotal insight developed. Consider the significant pauses of a second or two in the interaction at 1:21:54, 1:22:03 and 1:22:07.

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
1:22:06	Jamie	Yeah, but it has same no…
1:22:07		(1.0)

The teacher starts with a question that points to the rocket list in order to reorient the group to the computational artifact that Chuck's speculations about an alternative software have forgotten. The students do not respond immediately, but the teacher uses "wait time," waiting out the long silence and thereby encouraging the students to take the floor. Steven begins hesitantly to reject the implication of the teacher's question, hedging his "No" as "I don't think so" at first, but then confirming it when backed up by Jamie. Jamie justifies or clarifies the negative response with, "Not with the same engine." He then repeats this utterance up to the word "same," making that term focal.

The teacher picks up on Jamie's term "same" to explicate his term "like." In asking, "And you don't have anything like that here?" the teacher was asking if there was a pair of rockets in the list on the computer monitor that could be used for determining the effect of the nose come shape the way that Chuck's proposed software variation of rocket 3 or 4 would. Jamie's response points out that there is no rocket in the list that could be paired with rocket 3 or 4 for this purpose because none of the other rockets have the same engine as rockets 3 and 4. So the teacher adds the clarification: "With the same engine, but with a different nose cone," repeating Jamie's "same" as applied to the engine, and introducing the term "different" applied to the nose cone.

Of course, this expanded version of the question is still ambiguous: it could be applied to either a list of paired configurations or one of standard configurations. After Chuck and Jamie make unsuccessful attempts to respond to the issue of "the same," the group falls silent. This is the point of *aporia* that Plato (350 BC/1961) considered the catalyst of insight: silent wonder in the presence of a question that one finally understands to be a captivating mystery.

As if suddenly aroused from his intellectual slumber by a muse of scientific thought, Brent dramatically breaks the silence with "This one's different." Jamie does not see what is different and repeats what is the same. Another pause.

Then Steven and Jamie – but not yet Chuck – demonstrate a change of interpretive perspective:

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
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

At first, they simply register a change of view and alignment with Brent. Then Janie and Brent make the new comparison explicit: “Compare two and one,” “Number two.” They continue to explicate: “Are the same,” “It’s the same engine,” “So if you compare two and one,” until Chuck sees things their way: “Oh yeah, I see, I see, I see.” The crucial move is to look at rockets 1 and 2 as a paired configuration. Then one can see that they both have the same engine (and the same other attributes, except nose cone), so they can be compared for different nose cones.

In this analysis, we see that the terms *same*, *different* and *compare* have become focal to the discourse. These are terms that relate two objects. So references using these terms refer to pairs of objects. The discourse broke down until the reference of the teacher’s question could be interpreted by all the students as being directed to the pair of rockets 1 and 2 instead of to a pair based on rocket 3 as a standard.

All the participants in the discourse understood that the teacher’s rhetorical question was referencing a set of related rockets. It took several interactions to shift everyone’s understanding from a model of standard configurations to one of paired configurations. Because the reference was to a relationship rather than to a single object, the breakdown in shared understanding could not be repaired by simply pointing, as Brent tried. It was necessary for Jamie and Stephen to take this further and explicitly name both of the objects and the relationship (*compare*) itself.

DISCOURSE AND UNDERSTANDING

The unfolding of the collaborative moment reveals a subtle interplay between the group discourse and the understandings of the individual participants. This interplay becomes visible during a breakdown in the discourse – caused by a non-alignment of the individual interpretations. The character of this interplay does not lend itself to description using traditional conceptualizations of meaning and minds. In particular, we are tempted to say that the students had various ideas in their heads; that they expressed these ideas in their utterances; and that they changed their ideas in the course of the interaction. However, we have no evidence about ideas in their heads beyond the utterances (and other interaction behaviors) themselves. Nor did the participants have any evidence about mental states of their co-collaborators, other than the same utterances that we have as observers. The only meanings that we (or they) have access to are those embodied in the utterances of the discourse themselves.

Nevertheless, the question arises as to how some of the participants could (according to our analysis above) understand the shared discourse in different ways, resulting in the breakdown as well as its gradual repair. It seems clear that there are two different levels of meaning-making taking place: a group level on which meaning is built up through discourse in which everyone participates, and an individual level on which each participant constructs his own evolving understanding of the references and other features of the discourse. In particular, the pauses in the collaborative interaction and the arguments in the group discourse seem to stimulate – whether by applying some kind of social pressure or simply by opening up a creative space – reinterpretations by the individuals.

We already observed in the previous paper that most of the individual utterances had little meaning on their own if viewed in isolation. The meaning was constructed at the level of (in the context of) the group discourse, through the references of words, phrases, gestures and glances to elements in the discourse, the social interaction, the associated artifacts and the physical space. A word like *same* derives its lexical meaning from its contrast to *different*, its use in *compare*, etc. It also builds up its socially-shared meaning from repeated uses of it and related terms. It is common in discourse for one speaker to repeat a term that someone else recently used, as a way of referencing the previous occurrence. In this way, the term takes on a role in the discourse that cannot be attributed to an individual as the expression of a mental idea. The word is better analyzed as a resource for interaction that is shared by the group. While we may not know quite what a certain student meant when uttering a term, we can see how it was interactionally picked up by others and how it came to play a role in the group discourse. The terms used in the discourse gradually form a web of meaning, which specifies and deepens the meaning of the various terms within this context. One can say that the students, as individual speakers in the interaction, learn over time to understand these terms more deeply (as quasi-technical terms) and to use them more skillfully (as fledgling scientists). Alternatively, one can say that the group discourse progressively refines the shared group meaning of the terms.

The terms *same*, *different* and *compare* are everyday words used to describe a relational reference that might be discussed in terms of "holding variables constant" in scientific jargon. At different points during the collaborative moment, each student shifted his understanding of this relational reference from a model of standard configurations to one of paired configurations. This shift during the collaborative moment was an important feature of the interplay between the group discourse and the individual understandings.

This analysis suggests that collaboration may often take place with the following structure:

a. A group is engaged in building meaning in its discourse.
b. Each participant develops an individual understanding of the meaning of the discourse in parallel to the group interaction.
c. Participation in the group interaction is affected by the individual understandings; the individual contributions to the discourse reflect the distinctive understandings, but simultaneously merge into the creation of the discourse's group-level meaning.
d. Individual understandings are visible (to other participants and to observers) in the interactions of the participants in the group – as nuances in how their contributions are integrated into the discourse. The trajectory of an individual's contributions can be seen as a personal narrative within the history of the group interaction.

Such a structure would have important implications for how individual learning can result from group collaboration. If group learning and individual learning proceed in parallel as different interpretive facets of a single, complexly interacting process, then we can look for both group and individual learning taking place in all collaborative settings, not just those in which an individual division of labor is explicitly introduced. For instance, in the previous paper's moment of collaboration, the task of isolating the nose cone effect was accomplished by the group as a whole. Individuals were not assigned sub-tasks or roles. However, an essential, though unstated feature of the collaboration was that each individual had to understand the accomplishment of the group task. Each individual took responsibility for making sure that the others shared a common understanding. This responsibility can be seen to be at work in motivating the various contributions to the discourse. In fact, the intense collaboration was precisely an attempt to re-establish shared understanding during a breakdown of it. As individuals started to understand the relational reference that was the key to accomplishing the task, they focused on bringing the other participants around to sharing that understanding. Only when all participants acknowledged that their individual understanding of the group meaning was aligned with the others', did the group proceed to look at the data sheet in accordance with the relational reference to rockets 1 and 2 and solve the nose cone task.

The parallel working of group and individual learning is often overlooked when investigating collaboration. Either one focuses on the individual learning and misses the group-level phenomena, failing to identify the process as collaborative, or one focuses on the group interaction and assumes that special interventions – role definitions, task divisions, jig-sawing, reflection, reporting – are necessary to stimulate individual effects. In our case study, however, we see that the participants have spontaneously organized their interaction to ensure that each individual understanding of the meaning of the group discourse was aligned in agreement with each other. This was necessary for the discourse and the problem-solving to proceed, Of course, such agreement is not absolute in any sense, but adheres to practical criteria having to do with permitting the collaboration to continue. The result of this natural structuring of the collaborative process is that the individuals learn in parallel with the group learning. Our view of the discourse and the interaction generally made visible the learning at both levels.

The point is not that explicitly introducing individual roles into a group process is necessarily a bad idea; such pedagogical techniques have indeed proved useful in certain settings. Rather, the point is that individual learning may automatically take place within collaborative interactions. This suggests a response to the argument that group learning is irrelevant because the group will eventually break up and that we therefore need to focus on individual learning. On the contrary, it may be that group learning often supplies an essential basis for individual learning, providing not only the cultural background, the motivational support and the interactional occasion, but also an effective mechanism for ensuring individual learning.

ACKNOWLEDGMENTS

Rogers Hall made two suggestive observations related to the `SimRocket` data at a workshop on video analysis at the International Conference of the Learning Sciences (ICLS 2002): (1) that divergent interpretations of a group discourse might open a space for group creativity and (2) that the deictic relation of "This one's different" is not to a simple rocket object, but to a more complex relationship among objects, and that such a complexity caused problems for both the students and the analysts. I have attempted to explore these suggestions (1) by trying in other writings to understand the interaction of group meaning and individual interpretation and (2) by looking in this paper at the relational character of the reference.

REFERENCES

Benjamin, W. (1936/1969). The work of art in the age of mechanical reproduction (H. Zohn, Trans.). In H. Arendt (Ed.), *Illuminations* (pp. 217-251). New York, NY: Schocken Books.

Bruner, J. (1990). *Acts of meaning*. Cambridge, MA: Harvard University Press.

Garfinkel, H. (1967). *Studies in ethnomethodology*. Englewood Cliffs, NJ: Prentice-Hall.

Heidegger, M. (1927/1996). *Being and time: A translation of Sein und Zeit* (J. Stambaugh, Trans.). Albany, NY: SUNY Press.

Keil-Slawik, R. (1992). Artifacts in software design. In C. Floyd, H. Züllighoven, R. Budde & R. Keil-Slawik (Eds.), *Software development and reality construction* (pp. 168-188). Berlin, Germany: Springer Verlag.

Marx, K. (1867/1976). *Capital* (B. Fowkes, Trans. Vol. I). New York, NY: Vintage.

Plato. (350 BC/1961). Meno. In E. Hamilton & H. Cairns (Eds.), *The collected dialogues of Plato* (pp. 353-384). Princeton, NJ: Princeton University Press.

Repenning, A., & Sumner, T. (1995). Agentsheets: A medium for creating domain-oriented visual programming languages. *IEEE Computer. Special issue on visual programming, March*.

Vygotsky, L. (1930/1978). *Mind in society*. Cambridge, MA: Harvard University Press.

Stahl, G. (2002). The complexity of a collaborative interaction [poster]. International Conference of the Learning Sciences (ICLS '02), Seattle, WA.