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Group Creativity in Interaction: Collaborative Referencing, Remembering, and Bridging

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Understanding collective creativity is crucial for advancing the general study of human creativity as well as for guiding the design of creativity support tools for small teams and larger collectivities. In this article, a qualitative case study of collective creativity online, derived from an analysis of collaborative interactions of virtual teams of students working in the field of mathematics, is presented. Group creative activity is examined broadly, ranging from the microlevel coconstruction of novel resources for team problem solving to the evolutionary reuse of ideas and solution strategies across teams. The analysis focuses on describing the relationship between the dynamics of creative work present in a single collaborative episode of an online group and their evolution across time and across collectivities. The analysis indicates that the synergy between these two types of interactions and the resulting creative engagement of the teams relies on three fundamental processes: (a) indexical referencing, (b) group remembering, and (c) bridging across discontinuities.

1. CREATIVITY AS A GROUP ACCOMPLISHMENT

Creativity has always been a social phenomenon. The creativity of an individual act is judged by the peer community based on established standards and shared histories. Creation is never ex nihilo but built on the shoulders of predecessors, extending the niveau of the prevalent culture and advancing social progress. A famous painting by Paul Klee may be an individual masterpiece, but it is also a commentary on art history, an interaction with the artist's contemporaries, and a product of the Bauhaus community. Philosophy from Plato onward, according to Hegel, has always been a "reflection of its times, grasped in concepts"—to say nothing of a 2,500-year-long dialog.

In the networked age, creative breakthroughs are increasingly team accomplishments: the Manhattan Project, the Apollo moon landings, the analysis of a nuclear accelerator experiment, the proof of Fermat's theorem, the consolidation

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of the European Union all involve coordinated efforts of many people. It is time to consider creativity as a group-cognitive achievement (Stahl, 2006a). If we are interested in promoting creativity, it may be important to understand, catalyze, and support the group aspects of creativity as well as the individual psychological.

Our current study of virtual math teams tries to explicate fundamental group phenomena that take place when a small group of students are challenged to work creatively in the domain of school mathematics. We do not expect to observe epoch-shattering acts of creativity here, but we hypothesize that we can see in the visible activities of interacting students some of the methods being awkwardly but explicitly worked out that experts use effortlessly and invisibly. By conducting the student discourses online, we can, moreover, easily capture for analysis a complete record of everything that is shared by the group in its collaborative work.

We assume that individual creativity involves mental efforts to pursue ideas about a problem. It may well also involve interaction with a variety of physical artifacts that are meaningful to the individual. In a setting of group creativity, this process must be extended, enunciated, and shared by the group members so they can understand the problem and proposed solutions with enough commonality to work together toward a group accomplishment. As a sense-making enterprise, group creativity must coconstruct group meaning that is appropriately individually interpreted by the group members (Stahl, 2006a, ch. 16). Because the effort must remain oriented to a shared task, it involves "a continued attempt to construct and maintain a shared conception of a problem" (Roschelle & Teasley, 1995, p. 70). The effort must be sustained; that is, it must overcome manifold potential discontinuities and disruptions. Group participants must be able to point to or index ideas and artifacts in the evolving problem space in ways that make sense to the others and are effective. New actions must be able to build on the past (of the group effort and of the larger culture) through group remembering situated in the present context.

If we want to support group creativity, then we have to support the building and maintaining of the shared problem space, the referencing of objects in that space, collective remembering of relevant histories, and bridging across related episodes of the group's activity. In this article, we explore the interactional character of referencing, remembering, and bridging in small-group creative efforts through analysis of our data on virtual math teams. We consider the effectiveness of our technological environment (text chat, shared whiteboard, persistent wiki, graphical referencing, social awareness) for supporting these aspects of group efforts at cognition and creativity.

2. STUDYING GROUP CREATIVITY IN ACTION Q1

The potential of collectivities to engage in and succeed with rich explorations, discovery, and innovation in various fields has motivated many researchers, leaders, and field practitioners to promote and study group creativity (e.g., Hewett, 2005; Shneiderman et al., 2006). Half a century of research on individual creativity has clearly documented the complexity of the psychological, cultural and social processes involved in the creation of original and useful products (Mayer, 1999). When turning our attention beyond the individual creative agent, new challenges and opportunities emerge. For example, studying groups engaged in creative interactions offers us an opportunity to observe the methods employed by coparticipants to conduct their explorative work together and allows us to see insight and innovation as social constructs. In fact, the emergence of digital environments that support collaborative work has opened up the opportunity for researchers to go beyond studies of "solo" action and investigate distributed systems of cognition and creativity that situate artifacts, tasks and knowing in the interactions of coparticipants and activity systems over time.

In contrast to the attention that the social dimension of individual creativity has received in creativity research (e.g., Amabile, 1983; Csikszentmihalyi, 1988, 1990; Paulus, 2003), the interactional aspects of group creativity—how groups do creative work together—have only recently begun to be explored. For example, a new conceptual model of group creativity in music and theater (Sawyer, 2003) proposes that collective creative work can be better understood as the synergy between *synchronic* interactions (i.e., in parallel and simultaneously) and *diachronic* exchanges (i.e., over long time spans and mediated indirectly through creative products). Building on this model, we attempt to explore the interdependency between synchronic and diachronic interactions and analyze its relationship with creative work, broadly defined. In our study of mathematics collaboration online, we observe collective creative work as manifested in a wide range of interactions extending from the microlevel coconstruction of novel resources for problem solving to the innovative reuse and expansion of ideas and solution strategies across multiple teams.

After describing the Virtual Math Teams (VMT) project—the context from which our observations originate—we turn our attention to describing, incrementally, three central interactional mechanisms engaged in by the online collectivities we studied, which directly relate to the creative dimension of their work. We theorize that such mechanisms are central to the synergy between single-episode collaboration and the creative work of multiple collectivities engaged together over time. In addition to describing the interactions that the virtual teams observed engage in, we also reflect on the particular aspects of the online environment used, which might promote, support, or hinder synchronic and diachronic interactions.

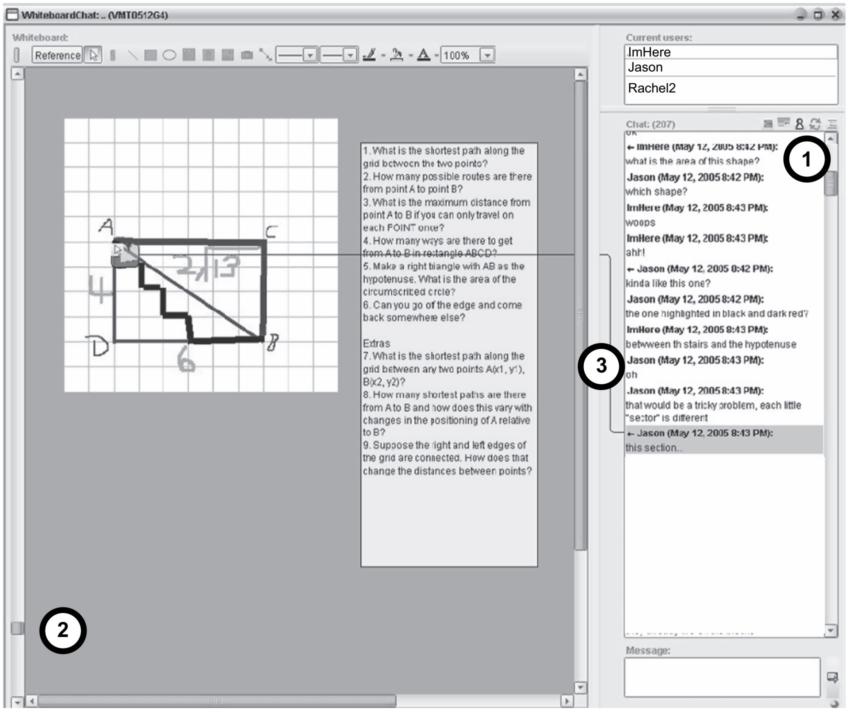
3. CREATIVE INTERACTIONS IN VIRTUAL MATH TEAMS

The Math Forum (http://mathforum.org) is an online community, active since 1992. It promotes technology-mediated interactions among teachers of mathematics, students, mathematicians, staff members, and other interested parties committed to learning, teaching, and doing mathematics. As the Math Forum community evolves, the development of new interaction supports is essential for sustaining and enriching available mechanisms of community participation. As an example of these innovation endeavors, the VMT project at the Math Forum investigates the innovative use of online collaborative environments to support effective secondary mathematics learning in small groups. The VMT project researches sustained collaborative mathematical practices in computer-supported environments. Central to the VMT research program are the study of the nature and dynamics of group cognition (Stahl, 2006a) as well as the design of effective technological supports for quasi-synchronous and sustained, small-group interactions. Detailed descriptions of the project's goals, technology, methodology, and initial findings can be found in recent project publications (e.g., Sarmiento & Stahl, 2007; Stahl, 2006b, 2006c, 2007; Stahl et al., 2006; Wessner et al., 2006).

The VMT collaboration environment is based on ConcertChat (Mühlpfordt & Wessner, 2005; Wessner et al., 2006), a research collaboration environment combining persistent chat with a shared whiteboard and a referencing tool. By collaborating with the software developers, our educational researchers have been able to successively try out versions of the environment with different groups and to gradually modify the environment in response to our research. This process has allowed us to reflect on the design and development of support tools for group creativity, a topic to which we return at the end of the article. The primary interactional supports implemented in the basic ConcertChat environment are described in Figure 1.

In the spring of 2005 and 2006, we conducted a series of pilot studies using ConcertChat. In each study we formed five virtual math teams, each containing about four middle-school students selected by volunteer teachers at different schools across the United States or abroad. The teams engaged in online math discussions for four hour-long sessions over a 2-week period. They were given a brief description of a novel open-ended mathematical situation and were encouraged to explore this world, create their own questions about it, and work on those questions that they found interesting. For example, the teams participating in the 2005 study (and whose work we use to illustrate our observations about collective creativity) explored a non-Euclidian world where the concept of distance between two points in space had to be redefined. The initial task as presented to the students is displayed in Figure 2. We expected this kind of task to offer a propitious setting for the study of the dynamics of problem discovery and formulation, activities usually associated with creativity (Getzels & Csikszentmihalyi, 1976; Nickerson, 1999).

The analysis presented in the following sections uses the approach of ethnomethodology (Garfinkel, 1967) to examine recordings and artifacts from the team sessions to draw design implications for a full-scale online math discussion service. Ethnomethodology is a phenomenological approach to qualitative sociology that attempts to describe the methods that members of a culture use to accomplish what they do, such as carrying on conversations (Sacks, Schegloff, & Jefferson, 1974), using information systems (Button, 1993; Button & Dourish, 1996; Suchman, 1987) or doing mathematics (Livingston, 1986). Ethnomethodology is based on naturalistic inquiry to inductively and holistically understand human experience in context-specific settings (Patton, 1990). Our observations come from this type of qualitative analysis applied to our entire dataset of interaction logs. We will start at the microlevel of collaborative creative work and expand progressively toward more global interactional processes across collectivities and time spans.



(1) Chat conversations are persistent during and after each session. Latecomers can load all previous messages at will.

(2) The shared whiteboard allows chat participants to create drawings and share graphic information with each other. Every whiteboard action is recorded. Users can manipulate a slide bar to navigate through all changes made in the whiteboard since the creation of the chat room.

(3) When someone types a new chat message, they can select and point to an area in the whiteboard or to a previous message, displaying a connecting graphical line (as shown in the figure)

FIGURE 1 ConcertChat online collaboration environment.

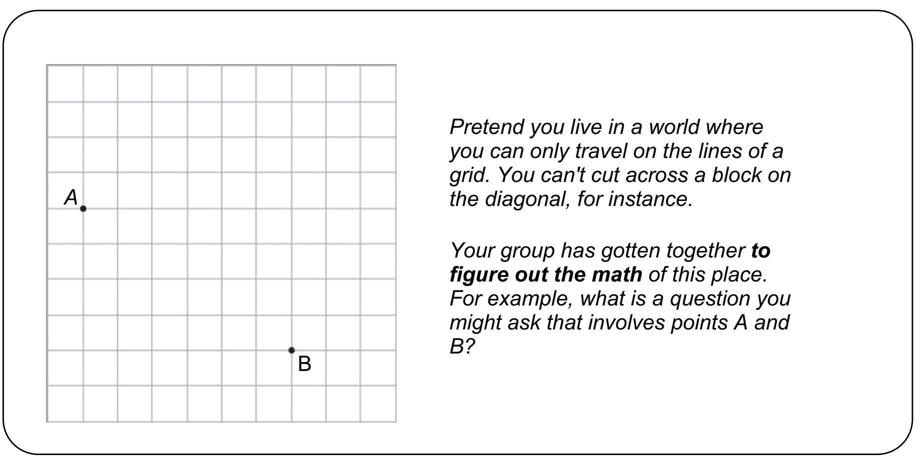


FIGURE 2 Grid-world task.

4. REFERENCING IN A JOINT INTERACTION SPACE

Our analysis of the collective interactions of virtual math teams suggests that these groups concern themselves repeatedly with the creation and development of a joint set of problem and solution proposals. In the VMT environment, participants use the textual and graphical resources at hand and a number of interactional methods to achieve this. These resources and the proposals for their use emerge from the collective activity of the groups themselves. References to them evolve through a complex web of indexicals, which join them through elaboration, contrast, reframing, and so on. The network of resources and utterances about them constitute the primary material of the groups' creative work. Similarly, *indexicality*, the referencing or symbolic pointing achieved through language and other means, is one of the unique aspects of group creativity that Sawyer (2003) described in his analysis of creative collaboration in music and theater groups.

Figure 3, contains a passage of interaction from the last session of one of the participating teams that illustrates the importance and complexity of collective referencing. As can be seen, the virtual chat room used by the teams in our pilot experiments provides a space of interaction where words, diagrams, labels, and sequences of manipulations can be used as resources for collective interaction. In this case we see on the shared whiteboard a series of textual notes with some questions that the team is investigating, a grid, and some other diagrams and

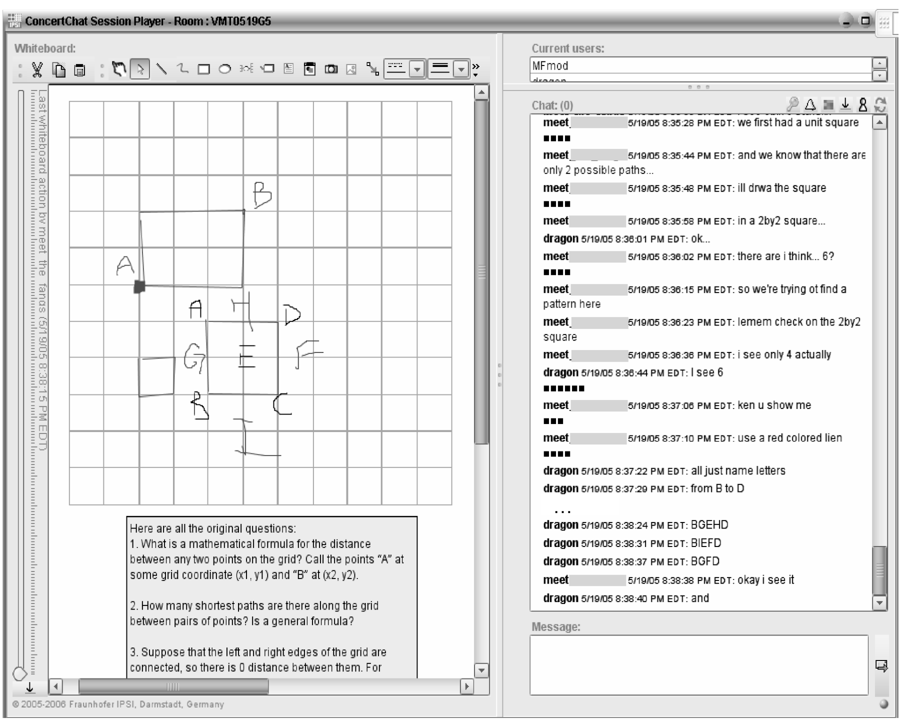


FIGURE 3 Excerpt of interaction from team five, session four.

labels created by the participants. Following the chat dialog we can see how the team members use a set of objects (e.g., a unit square, paths, 2×2 square, etc.) and, through interaction, construct a collective web of references (e.g., "ill draw the square," "there are only two possible paths," "from B to D," etc.) that are determinative of how the group's joint action flows. This type of referential activity was widespread across all teams and sessions, although with different levels of intensity. This leads us to conjecture that the use of *indexicality* in combination with textual and graphical resources allowed teams: to create visualizations of strategies and ideas, to contrast multiple representations of a problem situation, to coordinate different problem-solving paths among different team members, and to reconstruct collectively past work so that it can be continued in the present moment. Indexicality seems to play a unique role in collective exploratory work when teams are engaged in active problem formulation and in the early stages of problem solving; at least this is a hypothesis that requires further analysis.

Although the VMT collaboration environment provides some explicit supports for referencing (i.e., pointing with arrows from the chat area to the whiteboard or from one chat posting to another), the observed referencing practices extend well beyond the explicit supports provided. Our analysis points to the importance of these referential practices in creating a tightly interwoven sets of resources that represent the joint interaction space. Elsewhere we have described instances of such referencing work embedded in the collaborative mathematical work of the teams (Sarmiento & Stahl, 2007; Stahl et al., 2006). These analyses have motivated us to reconsider, as designers, the affordances in the online environment that support indexicality. Our particular interest in long-term collective engagement has resulted in a series of modifications of the VMT collaboration environment to explore and support the construction and maintenance of a sustained joint problem space. Before introducing them, we first expand our initial characterization of the role of referencing and indexicals to consider the relationship between single-episode interactions (synchronic) and longer (diachronic) sequences of interaction.

5. GROUP REMEMBERING WITH SHARED ARTIFACTS

The virtual teams involved in our studies demonstrated across their sessions a variety of methods for producing and managing relevant resources for their mathematical work. Because this work was spread over multiple sessions, they also engaged in activities related to managing their trajectory as a team. In fact, the excerpt of interaction captured in Figure 3 represents a case in which the team is collectively engaged in trying to reconstruct parts of their previous session in order to initiate their current problem-solving activity. Of interest, in this unique sequence of interaction, remembering of past activity unfolds as a collective engagement in which different team members participate dynamically. Some of the current team members were not present in the previous session, yet they are instrumental in the reconstruction of that past and in shaping its current relevance. In the case captured in Figure 3, for instance, *Meet* is engaged in remembering the work conducted in the previous session. Although he remembers that there were six shortest paths in a 2×2 square grid, he is only able to "see" four paths. *Drago*, who was not part of the previous session, is able to see all six possible paths. Up to this point we could see this interaction just as a case of memory failure. However, the work in which these two participants engage in subsequently is a unique form of memory work that establishes a new method to "see" the six paths that were discovered in the last session—and to allow for that method to be more accessible and persistent so it can be shared effectively. The team creates a labeling mechanism that allows them to trace and name each path in the 2×2 grid (i.e., "from B to D," "BGEHD," "BIEFD"). This method is then reused for the rest of the session to explore other grid arrangements and, more important, to produce artifacts that can work as records of procedures, discoveries, and arguments that others can inspect, challenge, or extend. In this work, we see how indexicality also plays a central role, but we have labeled this kind of activity *group remembering* because of its particular importance to reconstructing past achievements that are relevant to present tasks.

The use of the whiteboard represents an interesting way of making visible the procedural reasoning behind a concept (e.g., shortest path). The fact that a newcomer can use the persistent history of the whiteboard to retrace the team's reasoning seems to suggest a strategy for preserving complex results of problem-solving activities. However, the actual meaning of these artifacts is highly situated in the doings of the coparticipants, a fact that challenges the ease of their reuse despite the availability of detailed records such as those provided by the whiteboard history. Despite these interpretational limitations, we could view the persistent artifacts created by this team as "memory" objects which, in addition to being representations of the teams' moment-to-moment joint reasoning, could also serve for their own future work and for other members of the VMT online community. These particular objects are constructed in situ as a complex mix of resources that document, represent and recall different points in their own problem solving and, potentially, in those of others. As can be seen in Figure 4, the two team members depicted a complex network of interrelated resources: the cases being considered, the labeling and procedural reasoning involved in identifying each path, a summary of results for each case (i.e., the list of paths expressed with letter sequences), and a general summary table of the combined results of both cases. The structure of these artifacts represents the creative work of the team but also documents the procedural aspects of such interactions in a way that can be read retrospectively to document the past, or "projectively" to open up new possible next activities. In Figure 4 there are multiple representations of mathematical relationships that are displayed on the shared whiteboard.

Despite the fact that the problem-solving artifacts and conversations are the result of the moment-by-moment interactions of a set of participants and, as such, require a significant effort for others to reconstruct their situated meaning, they can serve as resources used to "bridge" problem-solving episodes, collectivities, or even conceptual perspectives. Here, we use the term *bridging* to characterize interactional phenomena that cross over the boundaries of time, activities, collectivities, or perspectives as relevant to the participants themselves. Bridging thereby might tie events at the local small-group unit of analysis to interactions at

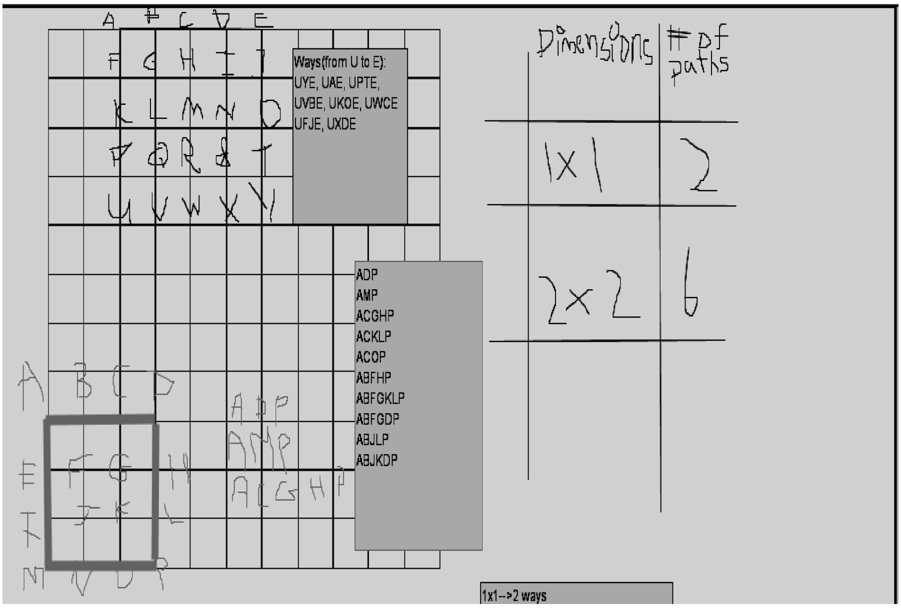


FIGURE 4 Multiple representations of mathematical relationships are displayed on the shared whiteboard.

larger units of analysis (e.g., the community). Bridging may reveal linkages among group meaning-making efforts by different groups or diachronically across events in time. Bridging might play a special role in contexts where creative work and knowledge building are being pursued by collectivities.

6. BRIDGING THE PAST, PROJECTING TO OTHERS

So far, we have explored two aspects of the creative dimension of the work that virtual teams engaged in as part of our studies. We have seen that the use of referencing and the configuration of indexicals are necessary elements of the "synchronic" interactions of these teams but that they can also play a central role in processes such as those that we have labeled "group remembering." As a matter of fact, we can see the central role of referencing as that of overcoming boundaries in joint activity. Deictic expressions (such as "the one highlighted in black and dark red") are sometimes used to overcome gaps in perception, whereas temporal deictic terms (e.g., "last time") can be used as part of the process of doing memory work and engaging with prior activities. In fact, in the contexts of extended sequences of collaborative knowledge work, where the membership of a team might change over time and where the trajectory of problem solving needs to be sustained over time, overcoming such boundaries might be especially challenging. We define this type of purposeful overcoming of boundaries through interaction as "bridging" work and turn our attention now to interactional strategies that virtual teams utilized to engage in these kinds of activities.

To investigate the dynamics of bridging we designed our studies in 2005 so that a number of teams worked on the same task for a series of four sequential sessions. In our study, teams used a different virtual room for each session and had no direct access to archives of their previous interactions. Despite this apparent limitation, they demonstrated several strategies to reconstruct their sense of history and to establish the continuity of their interactions.

Analyzing several interactional episodes, we noted that teams purposefully engage in attempts to establish continuity in collaborative problem solving as it relates to multiple sequences of work and also to the relevant work that other teams might be conducting. This type of activity involves the following:

1. The recognition and use of discontinuities or boundaries as resources for interaction.
2. Changes in the participants' relative alignment toward each other as members of a collectivity.
3. The use of particular orientations toward specific knowledge resources (e.g., the problem statement, prior findings, what someone professes to know or remember, etc.).

Bridging activity defines the interactional phenomena that cross over the boundaries of time, activities, collectivities, or perspectives. It defines a set of methods through which participants deal with the discontinuities, roles, and artifacts relevant to their joint activity.

As a result of our initial findings from our 2005 study, we designed in our 2006 study a setting in which "bridging" could be investigated more conspicuously. We arranged for the teams to reuse the same persistent chat rooms so that they had direct access to the entire history of their conversations and their manipulations on the whiteboard across the four sessions. In addition, mentors provided explicit feedback by leaving a note on the whiteboard of each team's room in between sessions. Finally, we also provided a wiki space to allow the teams to share their explorations (e.g., formulae found, new problems suggested by their work, etc.) with other teams. The comparative analysis of these interactions provides us with more detailed confirmation of the important interrelationship between synchronic and diachronic interactions.

The reuse of the same room by teams that were much more stable in their membership over time proved effective in stimulating the constructive establishment of continuity in the creative and problem-solving activity of the teams. The feedback provided by the external mentors, however, was in several cases problematic because it reframed past experiences in ways that seemed unfamiliar or curious to the participants themselves. In addition, the use of the wiki space provided us with a set of interesting examples of new "bridging" activity being conducted by the teams.

Through the wiki postings, teams working on the same or similar task were made aware of the parallel work being conducted by their counterparts. In several cases, the wiki acted as an effective third workspace from which materials generated by one team could be used, validated, and advanced by other teams. The authors of the postings also used them to sustain their own problem solving across the four sessions. Postings and trajectories of use in the wiki showed a structure that was very different from the conversational and interactional style of the chat room artifacts. Some postings were purposively vague and others resembled highly elaborate summaries of the teams' findings. In a few cases, postings included a narrative structure abstracted from the chat sessions (e.g., "So in Session 3, our team tried to understand Team C's formula …").

In one instance, the wiki presented evidence of cross-team asynchronous interactions: Team B found a new problem generated by another team in addition to a possible solution. Team B proceeded to work on the problem, found a mistake in the solution formula originally reported, and proceeded to rework the original solution and post the corrected result back to the wiki.

These preliminary findings seem to suggest the potential of explicit bridging spaces to promote continuity and to sustain creativity in problem-solving work, particularly in the context of an online community formed of multiple virtual teams with overlapping interests and activities. Naturally, the availability of bridging resources like the wiki does not by itself determine the ways participants interact over time. In addition, the fact that certain social practices were promoted (e.g., reporting to others, imitating, reflecting, etc.) influenced the way such resources were used.

7. INTERACTIONAL DIMENSIONS OF GROUP CREATIVITY

When one looks closely at the interactional activity that goes into the formulation and communication of creative ideas, one sees limitations of traditional, ahistorical views of creativity. Creativity involves extended efforts to articulate, critically consider, and communicate notions that are not already part of the taken-for-granted life-world. Even when accomplished largely by an individual person, this generally involves sequences of trials with physical and/or textual artifacts (Schön, 1983). Such internal monologue generally incorporates skills learned from dialogues in dyads or small groups (Vygotsky, 1930/1978). The study of creative accomplishments in groups, where their interactions can be made visible for analysis, may provide insights about individual as well as group creativity.

Several models have been proposed to characterize features of individual creativity, such as the ability to concentrate efforts for long periods, to use "productive forgetting" when warranted, and to break "cognitive set" (Amabile, 1983). We expected that these individual skills could also play a role that is distinctively productive in the context of long-term collective knowledge building. In our analysis, we have seen that, in fact, some of these individual accomplishments can be characterized as fundamentally social and interactional. The virtual math teams we have studied rely for their creative work on basic interactional mechanisms such as referencing, group remembering, and the bridging of discontinuities.

Recent models of group creativity (Sawyer, 2003) argue that collective creative work has to be understood as the synergy between synchronic interactions (i.e., parallel and simultaneous) and diachronic exchanges (i.e., interaction over long time spans and mediated by ostensible products). Our analysis validates this model in the context of the creative and problem-solving work of virtual math teams and starts to provide an interactional description of some of the processes underlying these two types of interaction. This interactional description also applies to other published findings on social or collective creativity (e.g., Fischer, Giaccardi, Eden, Sugimoto, & Ye, 2005; Paulus, 2003).

Because continuity in itself is important to the success of virtual teams, we have observed how participants develop a series of interactional methods to coconstruct mathematical knowledge within single collaborative episodes as well as over time. The coconfiguration of indexicals and the use of referencing methods allowed a collectivity to create new mathematical objects that gained their meaning through interaction and opened up new possibilities for next possible steps within a synchronous episode. Group remembering and the bridging of interactional discontinuities allowed the teams to expand the referential horizon so that the objects created by themselves or by other teams could be expanded, reconsidered, or challenged. These methods allowed the teams to evolve a sense of collectivity engaged in building new knowledge and made it possible for them to interlink their collaborative interactions with those of other teams.

Just as we have argued that cognition should not be conceptualized solely or even predominantly as a fundamentally individual phenomenon (Stahl, 2006a), so we claim that creativity is often rooted in social interaction and that innovative creations should often be attributed to collectivities as a feature of their group cognition. Group creativity can be fostered by supporting interactional mechanisms like referencing, remembering, and bridging.

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