Draft of paper to be presented at the Annual Meeting of the American Educational Research Association (AERA), Chicago, April 9-13, 2007. Do not distribute to others: please contact the first author at suthers@hawaii.edu for updated version.

A Framework for Analyzing Interactional Processes in Online Learning

Daniel Suthers, Nathan Dwyer, Richard Medina, Ravi Vatrapu

Laboratory for Interactive Learning Technologies
Dept. of Information and Computer Sciences, University of Hawai`i at Manoa
1680 East West Road, POST 309, Honolulu, HI 96822, USA
collaborative-representations@hawaii.edu

Abstract: This work is based on the premise that the interactional construction of meaning is as important in online settings as it is face-to-face, especially in collaborative learning. Most studies of online learning use quantitative methods that assign meaning to contributions in isolation and aggregate over many sessions, obscuring the situated procedures by which participants accomplish learning through the affordances of online media. Methods for studying the interactional construction of meaning are available, but have largely been developed for brief episodes of face-to-face data, and need to be adapted to online learning where media resources, time scale, and synchronicity differ. In order to resolve this tradeoff, we have developed an abstract transcript notation to support sequential and interactional analysis of distributed and asynchronous interactions. Building on recent analytic work within our laboratory, we propose a framework for analysis that is founded on the concepts of *media coordinations* and *uptake,* and utilizes an abstract transcript representation, the *dependency graph*, that is suitable for use by multiple analytical traditions and supports examination of sequential structure at larger scales. Examples are provided using data derived from asynchronous interaction of dyads and small groups

Introduction

Online learning is becoming increasingly prevalent and important in both formal and informal science education (Allen & Seaman, 2005), being implemented under a variety of "blended" learning models (Orey, McClendon, & Branch, 2006) and K-12 settings (Parker, 2000) as well as strictly online models in university education (Mayadas, 1997). Online collaborative learning brings together social processes of learning and representational aids for this learning, providing a fertile area for research and development while serving an important application. Yet, although a collaborative inquiry learning approach is potentially equally valuable online as it is face-to-face, the reality of implementation falls short. Most online learning has been conducted with text-based discussion forums, but many fields need rich representations and the ability to manipulate and discuss those representations. Further work is needed to improve online media, both to provide the representations needed for the subject matter and the interactional resources to support co-construction of meaning online.

A survey of the research on online learning (a good compilation may be found at www.alnresearch.org, see also Moore, 2004) reveals that much of this research is mainly concerned with establishing and securing an institutional role for online learning. Research directed towards that pragmatic and instrumental end attempts to demonstrate the equivalency of traditional face-to-face classroom learning and blended or online learning, based largely on measures of learning outcomes and students and faculty perceptions of satisfaction (Ramage, 2002). These are important measures for those concerned with the implementation of ALN as a customer oriented business, but less satisfying from a learning sciences standpoint. A research agenda such as ours that seeks to understand how learning is accomplished within and influenced by the affordances of online media must consider process data in addition to outcomes and satisfaction. Examples in the online learning literature include Aviv, Erlich, Ravid, & Geva (2003) and Campos (2004).

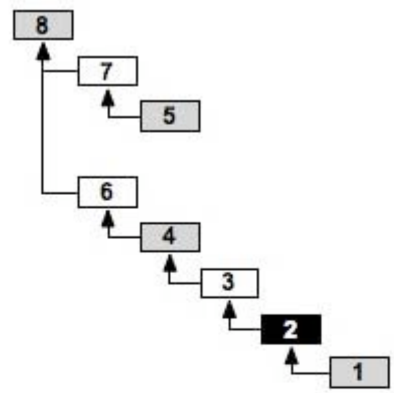

Figure 1. Reply structure of a threaded discussion

Most studies of online learning assign meaning to contributions in isolation, obscuring their indexical and interactionally constructed meanings. These methods also aggregate over many sessions, losing the actual procedures by which participants accomplish learning through the affordances of online media (Koschmann et al., 2005). Methods for studying the interactional construction of meaning are available (Goodwin & Heritage, 1990; Jordan & Henderson, 1995), but have largely been developed for brief episodes of face-to-face data, and require adaptation to online environments where media resources, time scale, and synchronicity all differ. Analyses that are too closely tied to media representations may fail to identify interactional sources of coherence. As a simple example, consider the reply structure from a threaded discussion shown in Figure 1. There appears to be two divergent lines of discussion, but an analysis to be presented in this paper shows that this is not the case. Additionally, since most research on online learning is currently conducted in text-based tools, we lack methods to study how richer representations might mediate online learning. The analytic tradeoff between scalability and fidelity must be resolved in order to inform the design of improved online learning environments and activities that engage participants more deeply in intersubjective meaning-making during collaborative inquiry (Suthers, 2006b). The immediate objective of the work reported in this paper is to resolve this tradeoff by scaling up sequential and interactional analysis to distributed and asynchronous interactions while remaining grounded in participants' use of media. The long-term objective is to obtain a deep understanding of how learning is accomplished in technology-mediated settings by analyzing computer-mediated interactions that span long durations of time and take place in different media among groups of various sizes. As a first step, we have developed an abstract transcript notation, the *dependency graph*, that provides a media-independent foundation for analyzing how participants build on each others' contributions. Dependency graphs are grounded in identification of *media coordinations* and are intended to support identification of *uptake* as a bridge towards further analysis. The remainder of this paper briefly introduces some theoretical assumptions behind the work; motivates and describes the dependency graph as the basis for analysis of meaning-making in online settings; and provides examples of this analysis to two sources of data (a laboratory study of asynchronously interacting dyads, and an online course discussion).

Motivations

Below we summarize the view of learning underlying our current work, assess prevalent analysis methodologies in relation to our needs, and then discuss additional requirements for eclectic methodologies.

Learning as an Interactive Process

Although we believe that the framework we offer in this paper can support analyses under a variety of views of learning, the framework is motivated by our own views of learning, particularly in social settings. Learning is conceived of not merely the transfer of information but rather as an interactional process of change. This conception of learning as interactional is compatible with theories of learning that identify individuals (Beck, 1997; Chi, Bassok, Lewis, Reimann, & Glaser, 1989), socially embedded individuals (Doise & Mugny, 1984; Vygotsky, 1978), social systems (Engestrom, 2001), or communities (Wenger, 1998) as the locus of change. Learning need not be deliberately sought: it is a result of participants' attempts to make sense of a situation (Dervin, 2003). *Meaning-making*, as we call it in this paper, takes place at multiple levels: solving a problem, maintaining interpersonal relationships, and/or affirming identity in a community (Bronckart, 1995). To study learning in social settings we must necessarily study individual trajectories of meaning-making and how they intertwine in practices of intersubjective meaning-making (Suthers, 2006b). Meaning is interactionally constructed and situated: the meaning of a given contribution is best understood as a function of its relationships to prior interactions and indexically with respect to the physical and social context (Koschmann, Zemel, & Stahl, 2004). (We use the term "contribution" in its colloquial sense of actions offered to advance a joint endeavor, specifically including actions in shared media that express attitudes and attentional orientation as well as information.) Meaning-making is mediated by the physical and social environment in diverse ways (Hutchins, 1995; Wenger, 1998; Wertsch, 1998). As designers of media for online learning, this mediation gives us an avenue for influencing meaning-making and possibly learning through the socio-technical affordances of the tools that we design (P. Resnick, 2002; Suthers, 2006b).

Methodology

Analytic methods can be roughly divided into two approaches: statistical aggregation and sequential analysis. An effective eclectic method must provide the same abilities as existing methods while also addressing the unique issues and needs of computer media.

Statistical Aggregation

Many empirical studies of online learning follow a quantitative paradigm in which contributions (or elements of contributions) are annotated according to a well-specified coding scheme (e.g., De Wever, Schellens, Valcke, & Van Keer, 2006; Rourke, Anderson, Garrison, & Archer, 2000). Statistical methods are then used to characterize aggregate behaviors that may then be compared across experimental conditions. This approach has three significant strengths. First, a coding scheme is a concrete classification of behaviors that supports mathematical methods for estimating consistency (reliability) between multiple analysts. Second, the approach has well defined statistical methods for comparing results from multiple sources of data such as experimental conditions and replications of studies. Third, this approach can scale up analysis by quantifying data across large groups. The trade-off is that "coding and counting" obscures the sequential structure and situated methods of the interaction. "Coding" assigns the meaning of an act as an isolated unit, and therefore either does not take the indexicality of this meaning into account or fails to record the evidence on which the analyst relied in making a judgment. "Counting" or statistical aggregation loses the sequential methods by which media affordances are used in particular learning accomplishments, making it more difficult to identify important design elements at the same temporal and spatial grain as the actual interaction itself.

Sequential Analysis

A contrasting approach finds the significance of each act in the context of the unfolding interaction. This approach includes Conversation Analysis (Goodwin & Heritage, 1990; Sacks, Schegloff, & Jefferson, 1974), Interaction Analysis (Jordan & Henderson, 1995), Narrative Analysis (Hermann, 2003), and the family of analysis methods loosely classified as "sequential analysis" (Sanderson & Fisher, 1994).

Many of these approaches (especially the first two cited) draw upon the ethnomethodological assertion that order emerges from the participants' interaction (Garfinkel, 1967). Typically, short interaction segments are repeatedly examined to uncover the methods by which participants accomplish their objectives. For examples applied to the analysis of learning, see (Baker, 2003; Koschmann & LeBaron, 2003; Koschmann et al., 2005; Roschelle, 1996). This paradigm is becoming increasingly important in computer supported collaborative learning because an approach that focuses on accomplishment through action is necessary to truly understand the role of technology affordances (Stahl, Koschmann, & Suthers, 2006).

This approach is a complement to statistical aggregation and has the opposite strengths and weaknesses. These methods document the actual practices of learning by attending to the sequential structure of the interaction, producing detailed descriptions that are deeply situated in the medium of interaction. Yet, sequential analyses are often time consuming to produce and difficult to generalize to different media or groups. A micro-analysis can capture sequential properties because analysis is focused on short interactions that an analyst can view and review, but progressively larger structures escape its grasp. Exploratory sequential data analysis address some of these concerns with computational support for statistical and grammatical analysis (Olson, Herbsleb, & Rueter, 1994).

Other limitations are due to assumptions about the interactional properties of the media they study. Much of the foundational work in sequential analysis of interaction has focused on face-to-face interaction. Production blocking and the ephemerality of spoken interactions constrain communication in such a manner that turns (Sacks et al., 1974) and adjacency pairs (Schegloff & Sacks, 1973) are appropriate units of analysis for face-to-face data. These units of analysis are not as appropriate for CMC since most online media support simultaneous production and persistence of contributions. Contributions may become available to other participants in unpredictable orders, may not be immediately available, and may address earlier contributions at any time (Garcia & Jacobs, 1999; Herring, 1999). Because conceptual coherence can be decoupled from temporal or spatial adjacency, we cannot restrict analysis to the relationships between adjacent events. Nor is it appropriate to treat CMC as a degenerate form of face-to-face interaction (e.g., by seeking an analog to adjacency pairs) since people use attributes of new media to create new forms of interaction (Dwyer & Suthers, 2006; Herring, 1999).

Media Generality

Some methods tie their analytic notations closely to data representations that mirror the media within which interaction takes place. As a result, the different environments and media under examination have spawned multiple environment- and medium-specific analytic notations. For example, ethnography relies to a large extent on freeform notes taken by observers. Studies of conversation have used simple transcripts of utterances (Roschelle, 1992) and more detailed transcripts using Jeffersonian notation (Sacks et al., 1974). Video has become the standard recording medium for studies of practice (Jordan & Henderson, 1995; Koschmann et al., 2004), but methods tied to this medium are clearly not applicable to most studies of online learning. Online interaction simplifies the creation of transcriptions: software tools can record a detailed and comprehensive log of an interaction. However, online media introduce asynchronicity and hide the production of contributions (Clark & Brennan, 1991), introducing different demands on analytic notations. Analysis of the simultaneous use of many communication media and channels has relied on ad hoc, eclectic representations (see, for example, Hmelo-Silver, 2003; Suthers, 2006a).

Analysis methods based on annotation of units (e.g., categorizing utterances, or tagging video time points) will not support relational analysis; and methods that rely on fully linearized representations of data will not capture the asynchonicity of CMC. The spatial distribution of contributions across media or workspaces should also be considered. Because interaction relies on many different semiotic resources, analysis of interactional processes must be sensitive to the social affordances of the specific medium being analyzed, yet also be applicable across multiple media in order to facilitate dialog between researchers. This introduces a pair of related challenges to the creation of a generalizable method: it must be media agnostic but simultaneously media aware. A workable method needs to be independent of the form of the data under analysis. At the same time, the method needs to maintain a record of how people make use of the specific affordances of media. This is required to allow analysis to speak to design and empirically drive the creation of new, more effective media.

Based on considerations discussed in this section, we sought an analytic approach that (1) maintains the sequential and situational context of activity so that an account of the interactional construction of meaning is possible, (2) does not assume that the medium of interaction has any particular interactional properties (e.g., synchronicity, availability of contributions, or persistence), but (3) records these properties where they exist. Additionally, it should (4) be sufficiently formalized to enable computational support for analysis, including sequential and statistical analysis, and (5) capture aspects of interaction that are critical to learning. The analytic framework we developed draws on other interaction analysis methods, but it uses generalized concepts of interaction elements and structures that are independent of any particular medium. The next section describes the theoretical foundations for our analytic representation, and how it is constructed and used.

Theoretical Foundations

We need a unit of interaction that abstracts from media-specific concepts such as adjacency, is applicable to the wide variety of temporal, spatial and notational properties of media, and is capable of tracing the entwinement of individual and intersubjective trajectories of meaning-making. Since collaborative learning is only possible when something is shared and transformed between participants, we built this unit of analysis on the concept of *uptake* (Suthers, 2006a). Uptake is how we describe the act of a participant taking reifications of prior or ongoing participation (e.g., expressions of information, attitudes and attentional orientation; whether ephemeral or persistent) as having certain relevance for further participation. A participant can take up one's own prior reifications as well as those of others. Therefore uptake as a fundamental unit of analysis is applicable to both intrasubjective and intersubjective meaning-making. Uptake is a transitive act, in that it always is oriented towards the taken-up as its object, which is foregrounded by the act as being relevant. Uptake is interpretative: some particular aspect of the object is brought forth and given (further) meaning. The "thematic connections" of Resnick, Salmon, Zeitz, Wathen, & Holowchak (1993) are an example of uptake, although our conception allows for nonlinguistic forms of expression, and for other kinds of interpretative acts in addition to argumentative ones. An act of uptake is a form of participation: it is available as such only within a realm of participation in which it is visible. An individual working through ideas via mental processes and external notations has access to his or her uptake across as well as within these media, but in the social realm only visible acts can foreground and interpret prior reifications. [1]

Our framework for uptake analysis tries to be useful to multiple theoretical and analytic paradigms, but is based on two theoretical assumptions about the nature of artifact-mediated collaborative interaction.

- *Coordination:* Efforts to coordinate between the personal and social realms are enacted through media (including expressions and perceptions).
- *Ongoing sequential structure:* The sequential structure of these coordinations at successively overlapping and expansive granularities is significant in understanding how meaning-making is accomplished.

All interaction is mediated by physical and cultural tools (Wertsch, 1998), whether in ephemeral media such as thought, speech and gesture, or persistent media such as writing, diagrams, or electronic representations. Distributed cognition (Hutchins, 1995) describes how information is transformed as it propagates via *coordinations* of representations through a distributed socio-technical system. According to Hutchins, the coordinated representations include individuals' internal conceptions in addition to external, perceptible representations. We draw on the idea of coordination, noting that coordination between personal and social realms can be accepted regardless of whether one accepts the existence of cognitive representations. A typical distributed cognition analysis starts by identifying a system's function (e.g., steering a ship) and involves tracing the propagation of information through the system and identifying transformations that take place at points of coordination between the participants and external representations. In settings fundamentally concerned with the creation of new knowledge, this focus on the enactment of functional relationships implies too static an interaction structure, and indeed takes as a starting point that which analysis seeks to uncover. An analysis based on

[1] Asynchronous media cause a problem both for Clark's distinction between "utterance" and "contribution" and for this visibility requirement. Does an utterance become a contribution only when a grounding exchange has completed? Is an act uptake only when a participant asynchronously accesses it? The requirement on uptake has the advantage that the act *is* uptake in the intrapersonal realm even before it becomes available to others. However, I am considering dropping this stipulation and treating the question of whether it is available to other participants as a separate question.

uptake, in contrast, starts with the identification of acts of coordination and the dependencies between them, and seeks to recognize what is accomplished through the interaction. In doing so, we draw on the ethnomethodological idea that the meanings of actions are indexical (deeply tied to the time and place of their enactment), and the consequence that the sequential structure of activity is of fundamental importance (Garfinkel, 1967; Koschmann et al., 2004).

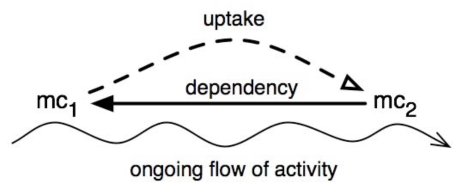

Figure 2. Schema for a dependency

Motivated by the need for a common transcript representation that exposes interactional structures in diverse forms of mediated interaction, and for a formal structure that is amenable to computation, we developed the *dependency graph*. A schema for the basic analytical elements is shown in Figure 2. Any empirical analysis must be built upon observable events. We assume that an analyst is interested in deliberate acts, not just any physical event. Therefore the analyst will examine the ongoing stream of events and identify those that appear to be coordinations between the personal and public realms. These *media coordinations* are exemplified by mc_1 and mc_2 in Figure 2. The existence of conceptions is implied by media coordinations, but we need not (yet) identify these conceptions. The analyst need only make a commitment that certain coordinations are of interest.

If a media coordination mc_2 is to be understood as taking up the contribution of a prior coordination mc_1, then there must be some observable relationship between the media coordinations. Therefore, we further ground the uptake analysis in empirical evidence by identifying *dependencies* between media coordinations that suggest that there is uptake. Dependencies can be found in media-level, representational, and semantic relationships between media coordinations: these will be discussed below. The dependency graph representation takes the form of a directed acyclic graph consisting of media coordinations and the dependencies between them (see Suthers, 2006a for a formal definition) on which we may layer analytic interpretations. Dependencies provide evidence that uptake may exist, but not all dependencies as defined at the media level need be uptake. The distinction between dependencies and uptake is made because dependencies reflect the myriad of ways in which human action is deeply embedded in and sensitive to the environment and immediate history of interaction, while only some of these relationships enter into the realm of meaning in which participants are demonstrably oriented towards reifications as having relevance for ongoing participation. Once these relationships have been identified, the graph defined by reversing the arcs may be properly called an *uptake graph,* as in (Suthers, 2006a).

Although we have described uptake as something that participants do, uptake is more accurately understood as an etic abstraction that we as analysts use to identify interactionally significant relationships between acts. From an emic perspective, participants don't engage in the abstract act of uptake; they engage in specific acts that they affirm (through subsequent activity) as the accomplishment of recognizable activity (Garfinkel, 1967). The analyst's identification of uptake is a bridge between empirical dependencies and further analysis. Uptake analysis is a proto-analytic method that must be completed by further analysis motivated by a given research program. The dependency graph provides resources for this further analysis by offering potential instances of uptake and grounding analysis in empirical media coordinations. This representation can support multiple methods of analysis, is amenable to computational support and visualization, and is meant as a boundary object for discussion and collaboration across different analytical traditions.

Uptake Analysis

This section describes the practical tasks involved in producing and interpreting a dependency graph, accompanied by a discussion of related issues and concrete examples from our analysis work. In practice, the process may iterate between identification of media coordinations, dependencies, and uptake; and may be driven by specific analytic goals or may be more exploratory in nature.

Identifying Media Coordinations

A dependency graph is built on observed media coordinations for which conceptual or interactional significance is claimed. Media coordinations are a more general form of elements from other analytical methods. Content analysis methods that work with text highlight and code elements in the text record. Conversation analysis and video-based micro-analysis identify points of interest in the media recording or transcript, and the media or transcript may be similarly coded or annotated. The analyst's identifications of media coordinations fulfill the same function as these annotations. Media coordinations are represented as vertices in the dependency graph. We call these vertices *fixed points* since they constitute the points of departure for analysis. Fixed points are anchored in media coordinations that can vary in granularity from a single instant to a period of time. The fixed point's anchor should be specific enough to allow the analyst to return to the media action as accounted in the data record. As in most interaction analysis methods, the source data is always the final authority.

Some media coordinations are easy to identify. When analyzing spoken conversation or CMC, utterances and messages are obvious candidates for media coordinations. The creation of an object in a shared workspace is similarly easy to identify as a media coordination. We use the general term *expressions* to refer to media coordinations of this nature. Other media coordinations are less obvious. For example, if two items are placed near each other in a workspace this may be an expression of relatedness (Dwyer & Suthers, 2006). This illustrates the more general issue of not confusing the representational vocabulary of a medium with the actions supported by the medium. For example, a medium that supports spatial positioning may be used to create groups even if no explicit grouping tool is provided.

Perceptions (e.g., hearing or reading another's expression) are another form of coordination between representation and conception. Explicit identification of perception is absent from many other analysis methods, which implicitly assume that each participant perceives every contribution, and does so at the time that it is produced or displayed. With asynchronous data this assumption is clearly untenable. The applicability of this assumption to synchronous interaction can also be questioned. For example, we cannot assume that a chat message was seen when it was produced. Even active participants may have scrolled back into the chat history. Therefore our abstract transcript representation allows for explicit specification of evidence for perceptions as another form of media coordination. It is difficult to identify the conception that results from a perception, but it is sufficient to assume that *some* conception results and mark the perception event as a media coordination. Researchers interested only in public behavior need not go further than to use the perceptual media coordination to narrow the temporal scope of uptake of the perceived contribution. Researchers interested in psychological (e.g., cognitive) claims about individual learning may subsequently attempt to infer the conception based on other evidence, including dependency relations. In either case, the observed evidence for perceptual coordinations has been made explicit.

A fixed point is incomplete without a description of the evidence on which the analyst based its identification. The practice of making evidence explicit addresses several issues. It limits the degree to which analysts can make assumptions about media coordinations. For example, maintaining the distinction between expression and perception has forced us to question our assumptions about which contributions are available to others. Specifying the evidence distinguishes the descriptive "what" of the interaction from the explanatory "why" of the analyst's interpretation, making clear the specific details that were seen as significant. This helps multiple analysts collaboratively review their observations and interpretations and facilitates trans-disciplinary discussions.

Identifying Dependencies

The second task in constructing a dependency graph is to identify and document the dependencies between media coordinations. A dependency represents a grounded assertion that the media coordination identified by one fixed point enables the media coordination identified by another fixed point. Dependencies map out the sequential unfolding of the interaction. They are defined in terms of a set of participating media coordinations and grounded evidence for their interdependencies.

Two or more media coordinations can participate in a dependency relationship. Dependencies are directional and point backwards in time. A dependency expresses how a single media coordination depends on *one or more* prior media coordinations. If multiple coordinations are dependent on a single coordination, then multiple dependencies are specified. If mc_2 depends on mc_1 then we are claiming that mc_1 enabled mc_2, but there is no assertion that mc_1 caused mc_2. We might be tempted to say that mc_1 is necessary but not sufficient for mc_2, but the reality of identifying dependencies is that we as analysts are not always able to determine the level of necessity. In our work we have frequently had to work with the ambiguity of "potential dependencies". Dependencies are a generalization of relationship types from other sequential data analysis methods, such as "adjacency pairs," "reply," "thematic connections," etc., and are candidate uptakes. Specifying the evidence for the dependencies serves the same purpose as for the fixed points. In particular, explicit examination of the evidence makes it easier to distinguish the assertion of the dependency from its interpretation. In contrast, in many coding methods the analyst simply asserts an interpretation, e.g., that a contribution is an "elaboration" on or "objection" to another (L. B. Resnick et al., 1993). The validity of this interpretation is established through computations of inter-rater reliability based on agreement that do not make the evidence explicit. With dependencies, the evidence must support the assertion that one or more media coordinations played a role in enabling or shaping another media coordination. Some types of evidence are more easily identified than others. We have used three types of evidence for dependencies in our work. Starting with the most concrete they are media dependencies, representational association, and semantic dependency. These are discussed below along with examples.

The most concrete evidence is in the form of *media dependencies*—one action on the representation could not have taken place in the absence of a previous action. A reply in a threaded discussion depends on the prior existence of the message being replied to, and modifying an element of a shared workspace depends on the previous act of creating the element. However, care must be taken not to fall into the trap of conflating the representational vocabulary with the steps in the interaction. Consider a reply in a threaded discussion. The reply message is dependent on the message being replied to, but in terms of dependencies between coordinations it is more accurate to say that the creation of the reply message is dependent on the author's perception of the message being replied to. The importance of this will be exemplified later, in the example associated with Figure 6, where the inclusion of dependencies involving read events give a dramatically different impression of the coherence of a discussion.

The second type of dependency evidence is *representational association*. The use of similar representational attributes is often used to indicate relatedness (Dwyer & Suthers, 2006). The representations can have similar visual attributes (e.g., color or type face) or they can be grouped together or aligned spatially. Temporal proximity can also indicate relatedness—expressions that follow each other closely are often part of the same exchange. Each of these indications of relatedness can imply a dependency. (Previewing forthcoming examples, in Figure 5, spatial connectivity is our evidence for the dependency of perception 20a on 19; and in Figure 6, temporal proximity is part of our evidence for the dependency of 2 on 7b, 5b, 6b, 4b, and 3a.) Representational association can also consist of repeated words and phrases indicating a dependency on the media coordination in which they were introduced. This can sometimes be easy to identify, for example when copy and paste is observed, or a phrase is typed soon after reading it. However, in general it may be more difficult to identify the original source of any content or to determine whether or not its re-use is actually dependent on the prior use.

The final type of evidence is *semantic relatedness*: the semantic content of a media coordination can be traced to the semantic content of another media coordination. (See for example the dependency of 7 on 20a in Figure 5.) Semantic dependency can be difficult to identify and is often open to debate. For example, in one case we looked at, one participant added three related nodes to an evidence map. The other participant, after reading them, added a fourth node that seemed to summarize the first three. In general, representational and semantic dependencies are more convincing if convergent evidence exists (e.g., temporal proximity *and* semantic relatedness).

Documenting other media elements

A dependency graph is a partial transcription of an interaction. It may be necessary to record additional information to contextualize the interaction. This additional information can annotate or augment the dependency graph formalism. For example, in (Suthers, Vatrapu, Medina, Joseph, & Dwyer, 2007), we used an asynchronous protocol. In order to identify which representational elements each participant had available at any point in time, we incorporated indications of workspace updates by which participants received new data from their partner, visualized as vertical bars in Figures 3 through 5. The reply structure of a threaded discussion is an important resource for understanding the participants' view of the medium, and so is included in visualizations of dependency graphs such as Figure 6.

Interpreting the Dependency Graph

A dependency graph is not a complete analysis, but rather is an intermediate structure that can be thought of as an abstract transcript that indexes to the original data. The analysis itself identifies sequences of dependencies between fixed points as (inverted) sequences of uptakes, and interprets the significance of the sequence and the nature of the uptake based on the theoretical phenomena of interest, such as argumentation, knowledge construction, or intersubjective meaning-making. Because the construction of evidence and the analytic interpretation are separated, the dependency graph can serve as a basis for comparison and integration of multiple theoretical interpretations, i.e., serve as a boundary object (Star, 1990) for the study of collaboration.

Iteration and Densification

Production of the dependency graph is an iterative process of densification: multiple passes through the data identify additional elements and provide new insights into the interaction. The formalism of the dependency graph provides support for this process. New fixed points and dependencies can be continually added to the graph. We used using open coding from Grounded Theory (Glaser & Strauss, 1967) to document our opportunistic observations of the data by assigning codes to media coordinations and dependencies. This made it easier to search the uptake graphs for particular interactional practices or the use of particular information. The coded uptake graphs are amenable to theoretical sorting as well as various statistical methods.

Iteration has the following ramifications. The graph can grow in complexity to reflect a deepening knowledge of the data, but the graph can never be considered “complete,” except with regard to particular representational elements (e.g., it is possible to claim that every discussion posting has been recorded as a fixed point). Therefore, one must be cautious about asserting that a practice or pattern never occurs. The quality of the analysis is proportional to the richness of the data. In our work with threaded discussions for online courses we only have log entries for when a message was created and when a user opened a message. Other media coordinations such as scrolling are not logged. On the other hand, our experimental configuration provides a complete record of every mouse and keyboard event, every action on the shared representation, and a video capture of the computer screen from each client. The richness of the latter data has allowed us to examine interaction at a much finer grain. Nonetheless, the threaded discussion data is sufficient for coarser grained analysis. Finally, repeated iterations may identify new *types* of representational elements, media coordinations, and dependencies. Our work has suggested two other constructions: interactionally defined representational elements that do not correspond to any explicit representational notation, and composite media coordinations in which two or more media events seem to share a conception.

Examples: Dyads in a Laboratory Section

In this and the next section we provide three examples from exploratory analyses conducted over the past year. The first two examples are based on data from dyads interacting in a laboratory setting. This example illustrates analysis of intersubjective meaning-making in an asynchronous context where detailed data is available. The third example is based on server logs of asynchronous threaded discussions in an online course. This example illustrates how our method can be adopted to conventional online learning settings, and the advantage of an analysis that is not tied too closely to media structure.

We developed the approach during several years of our own analytic work, initiated to expose the practices of mediated collaborative learning in data from our prior experimental studies (designed to test hypotheses not directly relevant to the present paper). In an analysis undertaken in order to understand how knowledge building was accomplished via synchronous chat and evidence mapping tools, we used the concept of *uptake* to track interaction distributed across these tools (Suthers, 2006a). Subsequently, we began analyzing asynchronous interaction involving threaded discussion and evidence mapping tools (Suthers, Dwyer, Vatrapu, & Medina, 2007; Suthers, Vatrapu, Medina, Joseph, & Dwyer, in press). The uptake analytic framework was further developed to handle the asynchronicity and multiple workspaces of these data, from which the first two examples below are derived. Participants interacted via computers using evidence mapping and threaded discussion tools in a shared workspace to identify the cause of a disease on Guam. Information was distributed across participants in a hidden profile (Stasser & Stewart, 1992)such that information sharing was necessary to refute weak hypotheses and construct a more complex hypothesis. The protocol for propagating updates between workspaces was asynchronous. Rich data including server logs and video capture of the screens are available to us, so we are able to examine the interaction in great detail. Other data includes individual essays that participants wrote at the end of the session.

Detailed Explanation of the Dependency Graph Representation

Our analysis treated the essay writing as continuing participation rather than as a single point of measurement. We sought to identify whether and how the construction of the essays was accountable to the prior session, and especially whether interaction between participants influenced the essays. For each session analyzed, we began with the particiapnts' essays and traced dependencies back into the session to identify uptake trajectories that may have influenced the essays. Some sessions were chosen for analysis because there was convergence in the content of the essays and we wanted to identify how this convergence was achieved interactionally. Other sessions were chosen to examine a failure to converge or to share vital information. In both cases we want to relate significant instances of intersubjective uptake or failure thereof to practices of media appropriation. The first example presented below is of the former type: both participants (referred to as P1 and P2) mentioned "duration of exposure" as a factor in their essays, and the analysis sought to identify how this convergence was accomplished.

Relationship of the dependency graph to the data

In this section we describe the relationship of the elements of a dependency graph to data, drawing on an analysis we conducted for one session. We constructed the dependency graph in Microsoft Visio™ based on inspection of software log files and of video of participants' screens. The dependency graph we constructed is large (see Figure 3 for an impression). A relevant subgraph is shown in Figure 4: many fixed points and dependencies are omitted for simplicity. P1's media actions and fixed points for P1's conceptions are on the top and P2's actions and fixed points are on the bottom. In general, time flows left to right, but this being an asynchronous setting we cannot assume that a contribution is available as soon as it is created, nor can we assume that the clocks on each client were synchronized (they were not). The vertical lines in

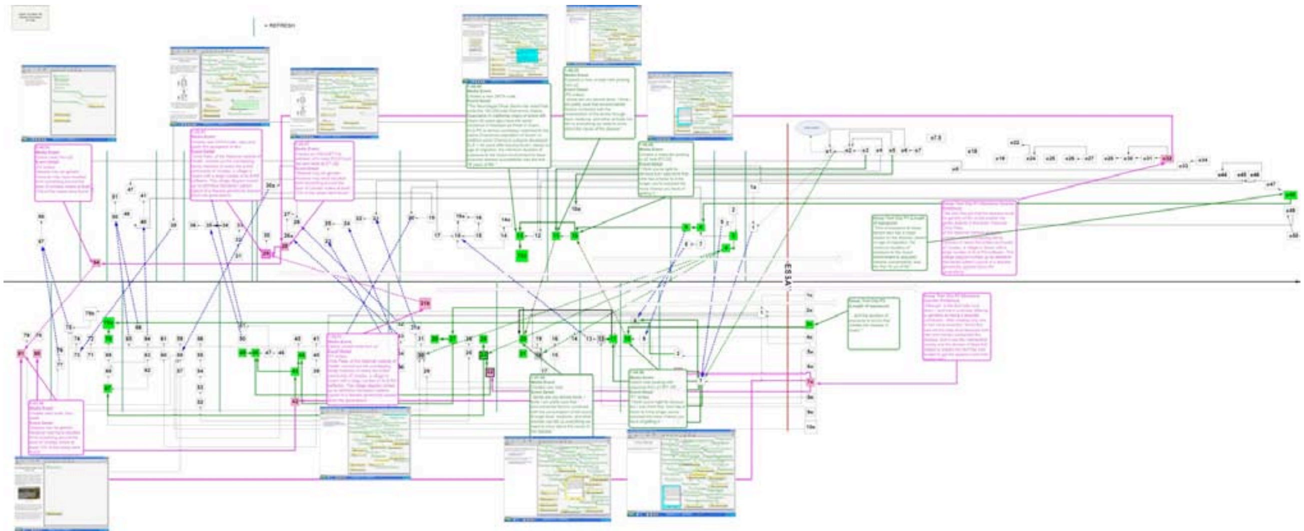

Figure 3. Full analysis for the first example

each participant's half demarcate when the local client updated that participant's workspace to display new work by the partner.

In Figure 4, the rounded boxes with text in them summarize data on which the presented portion of the graph is based, including media manipulation during the session and text written in the essay. The small square boxes represent fixed points, each of which claims the existence of a conception evidenced by media manipulations (such as editing the evidence map) or access to the partner's contribution (evidence map objects must be opened to be read). The links between media events and fixed points may be read as evidential links, showing how observed coordinations of representations provide evidence for the existence of conceptions, following (Hutchins, 1995).

Each fixed point is assigned a numerical identifier. Since the fixed point represents coordination between the representation and a conception, it is most accurate to discriminate between the *fixed point*, the *media coordination*, and the *conception* implied by the coordination. We will use these specific terms where they are warranted, but generally we will use the numeric identifier as shorthand to refer to the media event and the conception as well as the fixed point that binds them together.

Arrows between the fixed points represent dependencies (potential uptake relations). Dotted arrows represent intrasubjective and solid arrows represent intersubjective dependencies. An intersubjective dependency is always evidenced by perception of some media entity. The conception evidenced by the perception is dependent on but not necessarily identical to the conception evidenced by the creation of the media entity. For example, the conception claimed by fixed-point 20a is evidenced by access to the same media object the creation of which evidenced the existence of the conception claimed by fixed point 20. P1's conception (20a) upon reading this note at 1:50:23 is dependent on but not necessarily identical to P2's conception (20) when creating this note at 1:41:40.

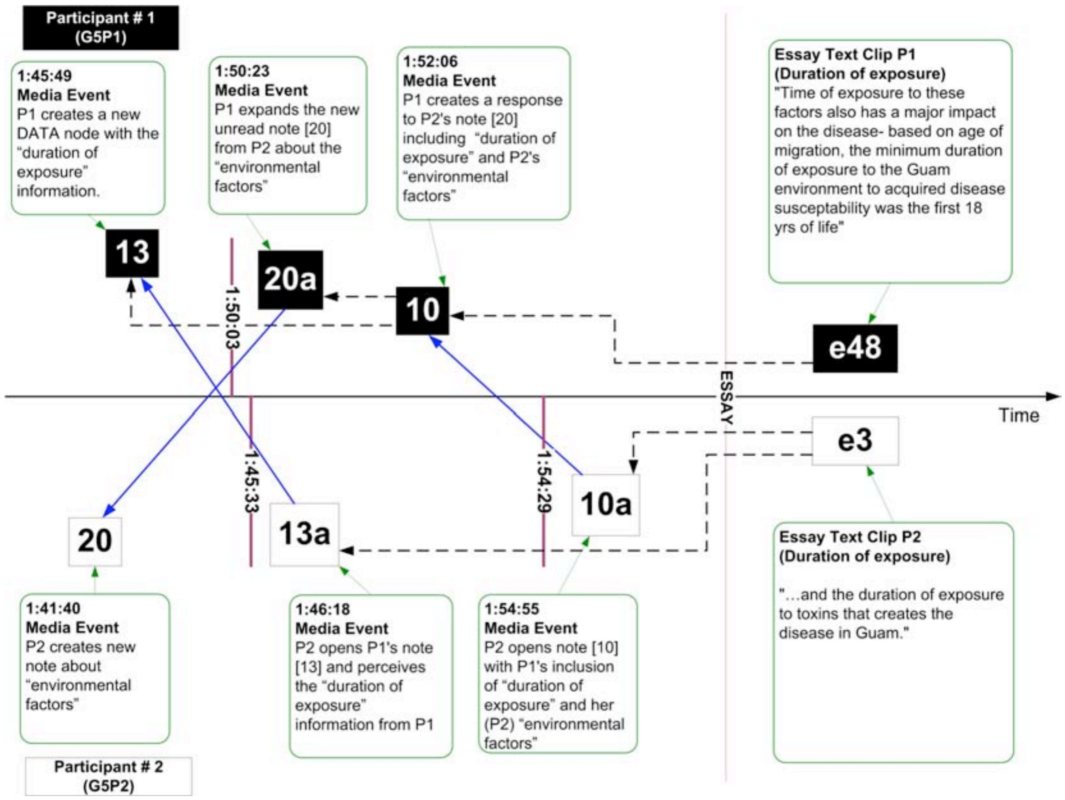

Figure 4: Fragment of a dependency graph for asynchronous dyads. Participant 1's coordinations are above and Participant 2's coordinations are below the timeline. Vertical bars represent workspace synchronizations in which the partner's recent work became available.

Dependencies can also be evidenced by editing media objects or by lexical similarity, and can be further evidenced by temporal and spatial proximity. For example, at 1:52:06, P1 added a comment (expressing conception 10) to the same note object that she had just read at 1:50:23. (A note object can contain a sequence of comments from both participants.) Since the expression of the conception 10 could not have taken place unless this media object existed, we have evidence that conception 10 depends on (and therefore takes up) conception 20a. The same example illustrates lexical and temporal evidence for a dependency. The media coordination that evidences 10 uses the phrase "environmental factors," which is present in the note that was accessed at 1:50:23, providing further evidence that 10 is dependent on 20a. Finally, the media coordination event that evidences conception 10 takes place 103 seconds after the media coordination event that evidences conception 20a, providing circumstantial evidence by temporal proximity that 10 depends on 20a.

Interpretation of the dependency graph

In this section we walk through the graph of Figure 4 to trace out a simple example of the interactional construction of meaning while highlighting further features of the graph. At 1:41:40, P2 creates a note summarizing environmental factors as disease causes (fixed-point 20). This note is not yet visible to P1. Around then in clock time but asynchronously from the participants' perspectives, P1 creates a data object (13) concerning the minimum exposure to the

Guam environment needed to acquire the disease. Subsequently, a workspace refresh (1:50:03) makes the note expressing conception 20 available to P1. Fixed-point 20a represents the conception that results from P1's access to this note at 1:50:23, and the corresponding arrow to 20 represents evidence for intersubjective uptake. Later at 1:52:06, P1 adds a comment to the note object (10). We interpret this as an uptake of the conceptions of 20a and 13, as evidenced by the media-level facts for 20a discussed in the previous section and the incorporation of the concept of "duration of exposure" from 13. Clearly, 10 is the crucial contribution that integrated two lines of evidence about this disease. (Claims that something is the only instance of a given kind of event should be taken with caution, as dependency graphs are never complete. We feel we can make this claim because we were careful to include all media coordinations addressing this topic in the full graph of Figure 3.)

Awareness of representational elements is not symmetrical in asynchronous media. At one point in the interaction just described, both 13 and 20 existed but neither was available to the other participant. Analysis must account for the contents of both workspaces to address these kinds of issues. The vertical line notation indicates when the media manipulations of other participants become available to a given participant, but analysis cannot simply rely on the appearance of a media object in a workspace. The analysis must find evidence that a contribution was actually accessed, which is why we need the "perceptual" fixed points such as 20a. Notations developed for face-to-face and synchronous communication often assume a single context and immediate availability of contributions. These are reasonable assumptions for those media but significantly limit those notations' applicability to asynchronous media.

Let us now examine how information originally available only to P1 (13) and P1's integration of it (10) become available to P2. Sometime after 13 was expressed, a refresh (1:45:33) makes the corresponding data object available to P2, who accesses it as 13a. Subsequently (after P2 does other work not shown), another refresh (1:54:29) makes 10 available to P2, soon accessed at 1:54:55 (10a). Since P2 has considered both 13a ("duration of exposure") and P1's endorsement of the relevance of duration of exposure for environmental factors (10a), we view P2's inclusion of these concepts as "the duration of exposure to toxins" in her essay (e3) to be an uptake of both of these conceptions. P1's essay portion (e48) also evidences uptake of the environmental factors (20a via 10). The "round trip" from 20 through 20a, 10 and back to 10a and e3 represents intersubjective meaning-making on the smallest possible scale beyond one-way information sharing (Suthers, Medina, Vatrapu, & Dwyer, 2007). We cannot rule out that e3 is uptake of only 13-13a and hence a one-way transfer of information, but nor can we rule out that P1's endorsement of the importance of the idea in 10, taken up in 10a, also influenced P2's inclusion of this idea in the essay. It is plausible that both were a factor.

Interactionally Defined Representational Elements

In working with the evidence map data, we often realized that the participants were creating groups of graph elements on the screen by moving graph elements with similar content into the same workspace area, although these groups were never mentioned explicitly in the text of the interaction. We identified fixed points anchored on the media coordinations of spatially positioning of the graph elements. Moving a graph element into a group is dependent on the prior existence of the group, but there was no explicit representational element defining the group. The "group" only existed because the participants added elements to it—its existence was defined in terms of the pair's interaction.

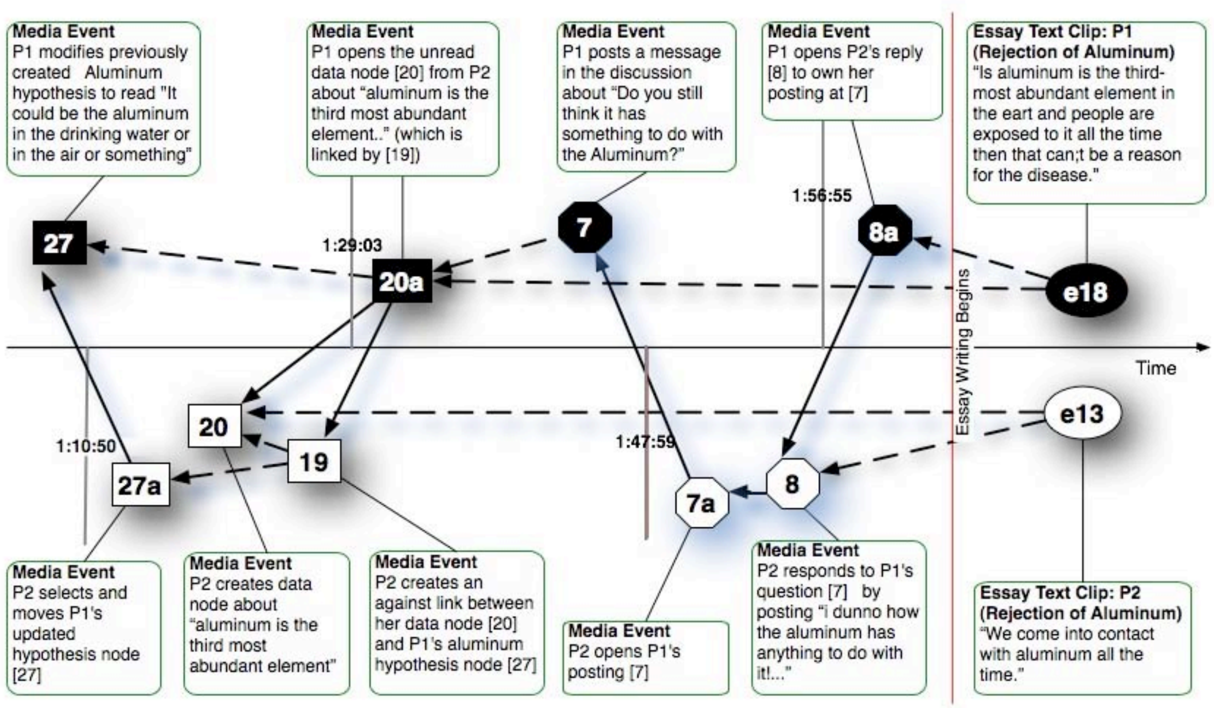

Figure 5. Dependency graph of a dyad collaborating asynchronously with multiple media. Rectangles, octagons, and ellipses represent coordinations with an evidence map, a threaded discussion, and a word processing tool, respectively. The graph is partial and was constructed by identifying dependencies backwards from the portions of the essays shown.

Discovery of an Interactional Pattern

Figure 5 presents a dependency graph from derived from a different dyad in the same a study of collaborative argumentation with evidence maps and threaded discussions. This analysis was done to understand how two participants used media resources to converge on the conclusion that aluminum is probably not the cause of a disease under consideration. The relevant evidence had been distributed across participants in the hidden profile. See (Suthers, Medina et al., 2007) for discussion of the question of whether convergence is achieved by information sharing alone or whether interactional "round trips" are required. Construction of the dependency graph allowed us to discover an interesting interactional pattern that goes beyond simple round trips. The information that "aluminum is the third most abundant element" and that this contradicts aluminum as a causal agent has been successfully shared in an evidence map (media coordinations 27, 27a, 20, 19 and 20a). From an information sharing perspective, this sequence is sufficient to explain the fact that both the participants mentioned the abundance of aluminum (the successfully shared information) in rejecting aluminum as a disease factor. However, participants did another round trip for confirmation over 20 minutes later in the session (7-7a-8-8a). By exposing this dual round trip structure, the uptake analysis enabled us to hypothesize an interactional pattern in which information is first shared in one exchange, and then agreement on a joint interpretation of this information is accomplished in a second exchange. The analysis also helped us discover that participants accomplished the second confirmation round trip by moving to a different interactional medium, the threaded discussion (coordinations with which are represented by octagons in the figure). See (Suthers, 2006a) for related results in the choice of more flexible media for meta-discussion.

Example: Asynchronous Online Discussion

The laboratory setting provided far richer instrumentation than is typical in online learning applications. In order to explore how our method can be adopted to conventional online learning settings, we analyzed server logs of asynchronous threaded discussions in an online graduate course on collaborative technologies. The collaborative learning software (discourse.ics.hawaii.edu, developed in our laboratory) records message-opening events as well as message postings, but there is no other record of participants' manipulations of the screen.

Figure 6 provides a fragment of the dependency graph we constructed in one analysis. After reading a paper on socio-constructivist, socio-cultural, and shared cognition theories of collaborative learning, a student facilitator suggested that students write "grant proposals" to evaluate learning in the course itself, and discuss how their choice of theory would affect how they approach the evaluation. The episode took place over 5 days, indicated in Figure 6 by vertical lines for midnight of each day. The actual reply structure is shown as thick grey arrows between the postings (rounded boxes). This reply structure is also summarized in Figure 1, replicated in the lower left of Figure 6. The episode of Figure 6 was chosen because it illustrates conceptual integration across two subthreads, and hence the independence of conceptual dependencies from media structure. The small graph lower left is sufficient for analysis of the threading structure, but the main graph situates the threading structure in a richer network of uptake derived from dependencies.

Stepping through the graph, at 8 the instructor (P2) has posted a comment concerning a prior contribution that used the phrase "socio-cultural" but seemed to express a socio-cognitive approach. Unfortunately, the assignment mentioned "socio-constructivist" rather than "socio-cognitive" and the student (P1) reading this message (8a) is confused by the different name. She raises questions about the distinction in two separate replies, 7 and 6. (Not shown in this simplified graph is a sequence of message reads between 7 and 6: P1 appeared to be searching for more information on the topic.) The next day, P2 returns, sees 7 (7a), replies with an explanation of "socio-cultural" in 5, and then starts down the other subthread. Seeing 6 (6a) the source of the confusion becomes apparent and P2 replies with a terminological clarification (4). Later that day, P1 reads both threads (5a, 4a) but replies only to the second with a "thank you" (3). On the third day, P3 reads messages in another discussion (not shown), and then enters this discussion, reads both threads (7b, 5b, 6b, 4b, 3a), and replies to the last "thank you" message with a meta-comment about the confusion that related back to the other discussion: an integrative move that was consistent with her assigned role as student facilitator for this assignment.

Participants' reading and posting strategies as well as the default display state and no-edit policy of the medium affect whether conversations are split up or reintegrated. By posting two separate replies (rather than editing her first reply—not allowed—or responding to that reply), P1 opens up the possibility of a divergent discussion. By following a strategy of reading and replying to each message one at a time, P2 continues the split that P1 has started. The discussion tool also allows one to scroll through a single display of all messages that one has opened in a single discussion. By following a strategy of reading all messages before replying, P3 brings these separate subthreads together. However, the reply structure of the discussion tool does not allow this convergence to be expressed in the medium: P3 must reply to one of the messages, so replies to the last one she read. Her message seems odd as a reply to the "thank you," as it is referring to "several of our grant proposals." In a sequence of reads not shown, P3 had read through the grant proposals about an hour before posting 2.

The dependency graph captures aspects of the coherence of the mediated interaction that are not apparent in the interface itself (e.g., the threaded reply structure in this example). Although some of this coherence can be recovered through analysis of quoting practices (Barcellini, Détienne, Burkhardt, & Sack, 2005), our analysis goes further to include (for example) lexical and temporal evidence for coherence, evidence that can also be partially automated. This ability to identify trajectories that are independent of yet influenced by media structures is an important strength of the method.

Composite Media Coordinations

In the threaded discussion, the reply structure implies two threads with a common root. However, the semantic content of the messages indicates that the first two replies (6 and 7) seem to represent a single question split across two postings. In our analysis it became useful to consider the sequence of creating these two messages as a single, composite media coordination. Similar practices were observed in e-mail threads—a single individual might send a message and then quickly send a follow up message with a further thought or postscript. It has been useful to consider the discrepancy between multiple media coordinations that are conceptually unified. The contrast has provided some useful insight into the constraints of the medium.

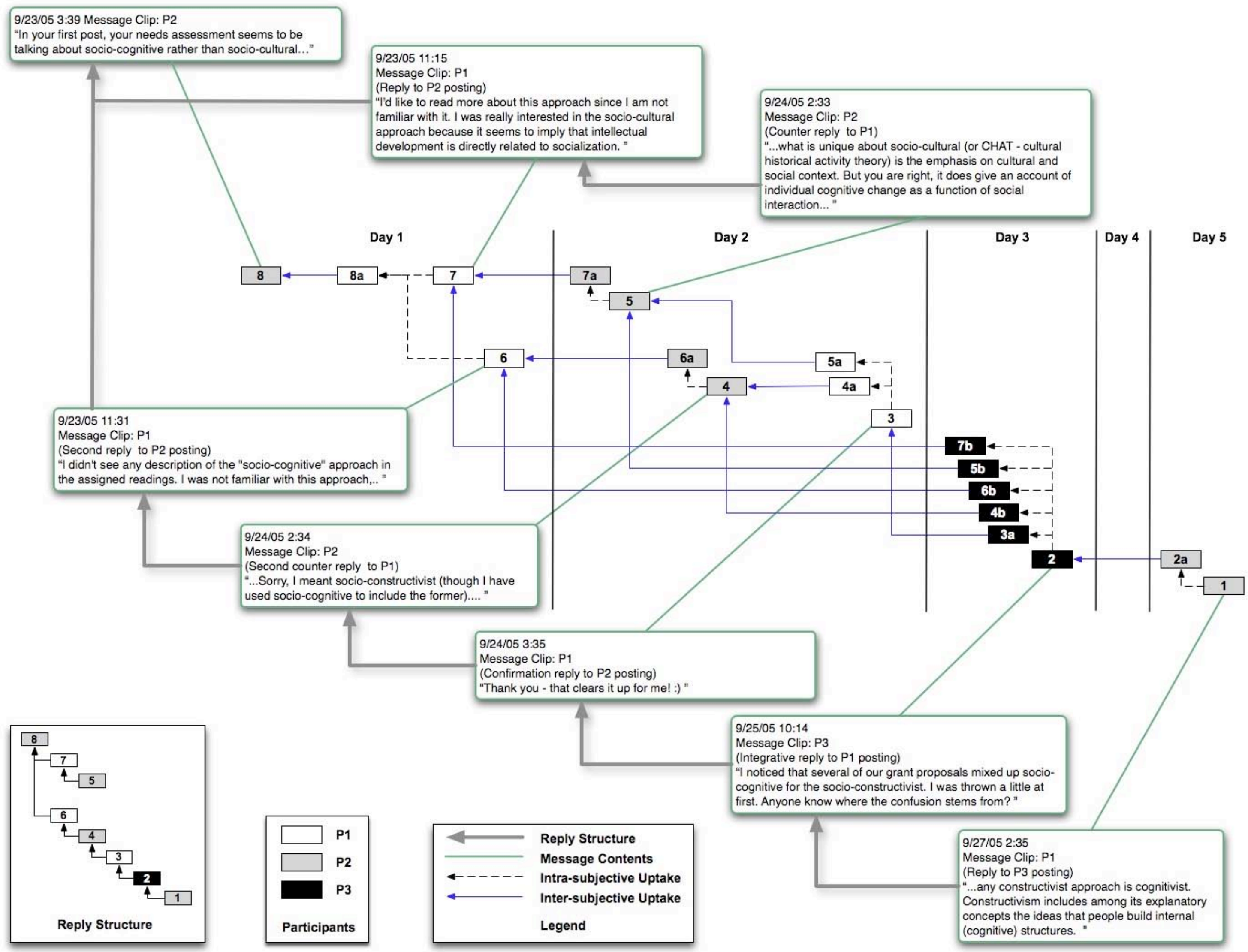

Figure 6. Fragment of dependency graph for an online discussion. The small graph lower left shows the graph that would result from considering only reply structure: this structure is also replicated in the thick grey arrows between media events. Fixed points without letters are evidenced by message postings and with letters are evidenced by message reads. Dashed lines represent dependencies for intrasubjective uptake.

Summary and Discussion

This paper presents an analytic framework that is based on the concepts of media coordinations and uptake, and includes an abstract transcript notation, the dependency graph, that provides the foundation for scaling up the advantages of sequential and interactional analysis to longer term distributed and asynchronous interactions. The dependency graph can also support quantitative analyses: see for example (Suthers, Medina et al., 2007). The approach has been prototyped on data derived from synchronous and asynchronous interaction of dyads and small groups. In each of the analyses we conducted, we were able to identify an interaction episode showing the potential of the method for producing a feature-rich analytical artifact supporting multilayered interpretation.

The dependency graph is media-agnostic. It is a record of the multiple coordinations that took place in an interaction and maps out their interdependencies. However, it is not media ignorant; it can bring in medium-specific information. Meaning-making can be identified independently of the media but is linked to media by the fixed points, so the relationship between meaning-making and the media can be examined.

The dependency graph enables one to separate out individual trajectories and identify when contributions are available to and accessed by each individual; to examine how these trajectories affect each other; and to step back and analyze the composite web of interpretations. “Group cognition” (Stahl, 2006a) is observable as the result of multiple individuals allowing their individual actions to be influenced by the perception and interpretation of other's behavior.

A delimitation of the framework is that, in focusing on observed interaction, it does not explicitly acknowledge the cultural or historical situatedness of the participants, or address identity and community, except where these constructs might be recorded in terms of prior interaction. Many theoretical and practical issues remain to be worked out. A pressing task is to extend the dependency graph formalism to better incorporate composite media coordinations and the possible ambiguity of dependencies. A complete explication of these two items is necessary to extend the potential algorithmic support provided by the dependency graph structure.

In interpreting our graphs we have encountered two issues related to the intrinsic incompleteness of the graph as a data representation. One must be careful not to make inferences based on the absence of fixed points and dependencies in the graph: any graph is partial and can be extended indefinitely due to the continuous nature of human action. One must not conduct an analysis entirely by using the dependency graph. In addition to being a structure of interest in its own right, the graph should be used as an index to the original media records. Visualization software can help address this problem by overlaying or simultaneously displaying the graph with the source media.

The greatest practical need is to develop software tools to help construct and use the dependency graph. Presently, it is time consuming to construct a dependency graph. Visualizations of dependency graphs were constructed using standard tools such as Excel™, Visio™, and Omnigraffle™. Time estimates that are predictive of future work are not yet possible, because the analyses reported in this paper took place concurrently with extensive discussions in which we developed the theoretical and practical basis for the framework. These discussions took place over many months with multiple revisions of the analyses. For example, the full graph of Figure 3 (180 fixed points and 220 dependencies) was developed and revised repeatedly over a period of about 8 months during which we also engaged in weekly discussions to refine the methodology and associated theory. More recently, we have conducted similar analyses of other sessions in several days. Customized software support can help address this problem by partially automating data collection and the construction of the graph through media-level, representational and semantic dependencies. The present work develops the representational specifications for such a tool. Once we are sure that these specifications are correct we will develop the tool. The need for improved analysis tools is a recurring theme (Sanderson & Fisher, 1994), and the size and density of the potential data sets exacerbates this need.

A related problem is the difficulty of retrieving information from and obtaining selective views of the dependency graph. Software support will also address this problem by displaying the dependency graph at multiple granularities and through filters, compressing it in time and/or scanning for patterns. An analyst need not even use a graph representation at all: visualization tools can convert the underlying graph model into whatever visualization is useful. Elaborations on the visual representation should be explored, including embedding dependency graphs in a CORDTRA-style representation (Hmelo-Silver, 2003) to relate interaction to both media and episodes of activity.

In ongoing work, we continue to apply the methodology to a diversity of data in preparation for development of software support tools. Our objective is to speed up the analysis of intersubjective meaning-making to the point where it need not be considered only a tedious variation on micro-analysis, but can also be efficiently applied on a larger scale. An important aspect of evaluating this framework will be to determine how well it scales to the types of interactions and media that are of most interest, including larger groups across longer time scales. With improved automation it might be possible to generate dependency graphs for larger online communities over the course of months or even years. It remains to be seen whether the constructs of media coordinations, dependencies and uptake remain useful as the foundation for further analysis at these scales. Finally, the value of this framework in supporting multiple analytic traditions and producing "boundary objects" for CSCL research can only be realized in collaboration with other laboratories undertaking analysis of collaborative interaction. Conversations are underway with others using similar techniques (Stahl, 2006b; Wee & Looi, submitted).

Acknowledgments

This work was supported by the National Science Foundation under award 0093505. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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