More than the Sum of the Parts: Shared Representations in Collaborative Design Interaction

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Submitted to the Department of
Industrial Design Engineering
Royal College of Art

In partial fulfilment
of the requirements for the degree of
Doctor of Philosophy

January, 2007

ABSTRACT

More than the Sum of the Parts: Shared Representations in Collaborative Design Interaction

This dissertation presents an inquiry into the roles played by persistent, shared external representations in design collaboration. It advances an understanding of the active participation of these representations—including drawings, models and prototypes—in the collective reasoning of design teams. Interaction was analyzed using a novel network formalization to portray the accomplishment of essential work in this context. A synthesis of analyses over different time scales provides the basis for a comprehensive notion of representational support for design interaction, and a diagnostic for problems that may arise with inadequate support and/or disparities of access and participation.

Data were collected during working sessions of a leading, "real-time" concurrent design practice at NASA's Jet Propulsion Laboratory, notable for accelerated performance and the use of technologically-advanced, shared representations. Fine-grained analysis of this activity offers insights to complement those obtained from laboratory studies of individual designers, ad-hoc groups, and organizationally-situated ethnographic accounts. A micro-analytic technique was developed to assess dynamic interaction between participants and representations. The resulting, novel formalization of an actor-discourse network makes concepts derived from actor-network theory operational to understand the work accomplished through design interaction. Network visualization and structural metrics highlight patterns associated with productivity in the design process. On this basis, indicators for the quality of design conversation are proposed: these include the degree of participants' engagement, the development of design discourse, the integration of representations and the consolidation of commitment to action. Specific roles and situational attributes of representations are identified that foster and sustain advances in collective design reasoning.

The dissertation advances a view of design activity in terms of temporally-evolving constellations of issues and actors, in which representations act to stabilize and anchor expanding networks of commitment. Directions for further work include technical enhancement to network metrics and visualization, extension of the actor-discourse network formalization and further exploration of theoretical and practical issues pertaining to representational actors in social situations.

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ACKNOWLEDGEMENTS

This research could never have been completed successfully without the sustained interest and unwavering support, over many years, of my two principal advisors, Prue Bramwell-Davis and Helga Wild. Each contributed a wealth of knowledge of design and relevant social science disciplines, with a deep commitment to making this knowledge meaningful in the context of real work and design practice. To the extent I have achieved any useful synthesis in this regard, I am in their debt. Deficiencies in this work are entirely my own.

I wish to thank Syed Shariq, Prof. Clifford Nass, and the Kozmetsky Global Collaboratory at Stanford, as well as the RGK Foundation for their generous support of my research. In particular, I thank Dr. Shariq, for his conviction that real-time design environments have implications that extend far beyond the bounds of aerospace design, and without whom access to the JPL site would not have been possible.

Collaboration with Monique Lambert was invaluable during conduct of the fieldwork, both in making sense of the bewilderingly complex and rich data, and in addressing the many logistical and practical challenges associated with this research opportunity. Prof. Raymond Levitt of Stanford also provided valuable support and assistance, in particular, by making it possible for sensitive video data to be reviewed at Stanford (without which the analyses I report here would not have been possible).

I am also indebted to Prof. Larry Leifer and Ade Mabogunje of Stanford University, and to members of the Stanford Centre for Design Research, for the opportunity to take part in the collegial environment at the Centre, to participate in discussions of design research and methodology, and to benefit from years of inquiry into diverse aspects and dimensions of design thinking. I am further indebted to Prof. Daniel McFarland of Stanford and Skye Bender-deMoll for their support, encouragement, and advice regarding social network analysis, visualization and network metrics, and use of the SoNIA tool in particular.

I also wish to thank the team leader, cryobot study customer and members of the Next Generation Payload Development team at Jet Propulsion Laboratory (who were exceedingly generous with their time) for answering so many questions and opening their remarkable practice to study.[1] At JPL's Centre for Space Mission Architecture and Design, Paul DeFlorio, Terrence Moran and Andrew Geselbracht provided valuable assistance with data collection and with practical aspects of access to the site, for which I am grateful. I also

[1] I regret that, in keeping with my commitment to maintain confidentiality for research participants, I cannot thank these individuals by name.

wish to thank Rachel Claus of Stanford University, Ann Bussone of Caltech and Ronald Oliver of Jet Propulsion Laboratory, for their efforts to resolve difficult issues and review voluminous material to ensure compliance with export control restrictions on sensitive information pertaining to spacecraft design.

Along the way, I have benefited greatly from both casual and sustained interactions with members of the intellectual community around Stanford and at the former Institute for Research on Learning (where I undertook fieldwork in an earlier incarnation of this project, and first made the acquaintance of Dr. Wild). I was fortunate that such encounters kept me motivated and continually reinforced my conviction that the project was worth doing. Foremost among these individuals, I wish to thank Niklas Damiris, for the breadth of his thinking around issues of representation (and everything else), and Susan Stucky, for her nuanced understanding of knowledge and practice in organizations. Patrick Kelly was also a careful reader and patient interlocutor on many occasions.

I also gratefully acknowledge the support provided for this research by the Committee of Vice-Chancellors and Principles of the United Kingdom, in the form of an Overseas Research Student Award (ORS/97092004).

Last, but by no means least, I thank my wife Suzanne Thomas and my daughter Ruby. I am grateful to Suzanne for her infinite patience, confidence (or effective simulation thereof), encouragement and the sterling example she set (completing her own dissertation just two months before giving birth)—and to Ruby, for being the first person to call me "Dr. Papa" (at which point it was pretty much all worthwhile).

for

Marilyn Shaw and Stuart Shaw

1. INTRODUCTION

Creative collaboration is an engine for innovation. Developing novel products and services requires the synthesis of knowledge from disparate sources and perspectives. The ability to do so nimbly and efficiently, in an effective and sustained manner, is an important goal for many of today's firms. Yet, while creative collaboration conveys competitive advantage and can be deeply rewarding to participants, it is often difficult to achieve in organizations. This conundrum is a point of departure for the work I undertake in this dissertation.

Creativity is an essential aspect of work in many design fields, where collaboration is frequently accomplished with the aid of various shared representations—including drawings, models and prototypes. This dissertation is motivated by a keen interest in design collaboration, and a belief that the quality of many purposeful, small group interactions might be enhanced by expanding the repertoire of shared representational objects. In this dissertation, I will develop a perspective and an observational method for assessing design collaboration as it unfolds over shared external representations. This emphasizes the active participation of representations in human interaction, and their involvement in essential aspects of collective design reasoning. The vehicle for developing this understanding will be a close field study of an unusual, and exemplary concurrent design practice.

In this introduction, I discuss some of the reasons creative collaboration may be difficult to achieve in practice, and how a confluence of organizational research and management literature suggests the need for greater attention to the use of shared representations in support of group work. I introduce some of the challenges and opportunities presented by recent technological developments, underscoring the need to understand collaborative interaction in rich representational environments. I outline the foci of directly-related research and highlight the need for the particular contribution this dissertation aspires to make, finally describing how this may be effectively achieved through the field study I will present.

Creative Collaboration in Organizational Teams

Most commercially-significant design activity is carried out in groups. Over the last twenty years, cross-disciplinary, concurrent engineering and design teams have been recognized as best practices (cf. Ulrich & Eppinger 1995, Bowen et al. 1994, Clark & Fujimoto 1991, Takeuchi & Nonaka 1986). There has been a sustained enthusiasm for teams in the management literature, but the number of books offering practical advice for managers makes it clear that success remains problematic (Gundry & LaMantia 2001, Lipman-Blumen

& Leavitt 1999, Leonard & Swap 1999, Bennis & Biederman 1997, Schrage 1995, Katzenbach & Smith 1993). Evaluating the effectiveness of groups has proven to be a complex undertaking (Devine 2002, Cohen & Bailey 1997). Depending upon the type of group and the form of its work products, key attributes of performance may differ and may be impacted by a number of variables that are difficult to tease apart.

There are a number of reasons that creative collaboration may be difficult to achieve in organizational groups. Empirical organizational research and descriptions in the management literature highlight certain themes and identify a number of factors that appear to enable creative collaboration. These include the diversity of participants' backgrounds and experience, their commitment to a shared task, the creation of a supportive yet challenging environment and a focus on tangible outcomes. In the discussion that follows, I will touch upon these factors, and offer some discussion as to why each may be problematic.

Diversity

In creative collaborations, diversity is an essential source of strength. However, along with diversity comes the potential for both interpersonal and managerial difficulties. Leonard & Swap (1999) describe a constructive balance between conflicting points of view in terms of "creative abrasion." They discuss the management challenges associated with defusing interpersonal conflict and fostering the convergence necessary to realize coherent action from a multiplicity of perspectives. Cohen & Bailey (1997) aggregate empirical studies of team performance, indicating that compositional diversity—in and of itself—has complex and contradictory effects. Ancona & Caldwell (1992) find that unless properly managed, functional diversity of product development teams is likely to have a negative impact on performance.

John-Steiner (2000) emphasizes the value of diversity in successful collaborations, but underscores the importance of complementarity amongst participants' temperaments, knowledge, skills, techniques and modes of thought. When a significant degree of complementarity does exist, even talented individuals do not *necessarily* know how to collaborate. This may be traced, in part, to the fact that creative behaviour is often framed in individual terms. There are fewer concepts generally available to help participants distinguish between creative *collaboration* and individual behaviour that may be creative but that is not collaborative (John-Steiner 2000, Sawyer 2003b, Csikszentmihalyi & Sawyer 1995).

Even individuals sharing a collaborative orientation may encounter friction and difficulty working together for a variety of reasons. Some difficulties may result from interpretive barriers that stem from organizational specialization and participants' disparate thought worlds (Dougherty, 1992). In product development teams, frustrations can find their way into discipline-level stereotypes and other negative attributions that can obscure potentially generative differences between perspectives (Shaw 1997, Griffin & Hauser 1996). Bennis & Biederman (1997) emphasize the importance of resolving disagreements so that team members are at least able to articulate the positions of others, ensuring that enemies remain external rather than internal to the team.

Other tensions arise when departmental or functional agendas from the organization seep into the collaborative relationship. To the extent they are engaged in something truly innovative, a group is likely to encounter active resistance from existing structures of the organization within which it is embedded (Lipman-Blumen & Leavitt 1999). Other organizational structures, management practices and individual personality traits may help to mitigate these effects, but it remains difficult to create the conditions for creative collaboration simply by decree[2]. Despite the benefits to organizations and to the individuals involved, it seems that many people are likely to experience frustration working together and trying to accomplish things in groups. There is hope, however, in looking more deeply at the factors that hold groups together and help them harness diversity for collaborative production.

Shared Task Commitment

Reconciling the tensions that arise from diversity is not simply a matter of communication and conflict resolution.[3] Accounts of creative collaboration in the management literature emphasize successful groups' near-total preoccupation with their shared task, above and beyond other personal and organizational demands. This is echoed in the empirical research in the construct of group cohesiveness, which has been positively associated with performance (Cohen & Bailey 1997). Carless & DePaola (2000) specifically find task cohesion to be a stronger predictor of performance than social cohesion. That is, members of high-performing groups are more likely to feel united by their shared task than by friendship or personal affinity for one another.

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[2] Bennis & Biederman (1997) describe "great groups" that flourish as "islands, but with a bridge to the mainland" (p. 196). They identify important roles including those of the visionary leader and the corporate liaison/champion/protector. Lipman-Blumen & Leavitt (1999) similarly underscore the importance of insulating "hot groups" from prevailing norms, structure and bureaucracy, so that they can better respond to change and take advantage of opportunity.

[3] Conflict resolution behaviour and internal communication have been associated with individual participants' satisfaction, but not necessarily with group performance as a whole. Conflict may be positively associated with performance in non-routine tasks (Cohen & Bailey, 1997) and beneficial to learning (Walz et al. 1993).

Lipman-Blumen & Leavitt (1999) emphasize the importance of a vision and a mission that participants believe to be both vital and personally ennobling. Bennis & Biederman (1997) describe participants' orientation toward accomplishing this shared task, in the "great" groups they studied, as one of "delusional" self-confidence.[4] Bennis & Biederman emphasize another aspect of the task orientation in these groups: "they ship." That is to say, the task focus is very much directed toward producing and mobilizing a tangible outcome. This is echoed in empirical research with regard to the performance benefits of purposeful engagement and substantive (vs. consultative) participation (Cohen & Bailey 1997).

A Supportive and Challenging Environment

Rather than using the metaphor of abrasion to describe collaborative encounters, John-Steiner (2000) describes creative collaboration in terms of mutual appropriation. This requires that participants remain open to adoption and adaptation, and make aspects of their knowledge and practice visible to their partners—in essence, they must display a willingness to teach as well as to learn. John-Steiner emphasizes the importance of having collaborators to provide close support in endeavours that seek to transform or overturn paradigms. "The weight of disciplinary and artistic socialization is hard to overcome without assistance." (p. 203) John-Steiner also highlights the individual growth experienced by participants in creative collaborations.[5] "There is a deep and interesting paradox in productive collaboration. Each participant's individual capacities are deepened at the same time that participants discover the benefits of reciprocity." (p. 204)

Lipman-Blumen & Leavitt, and Bennis & Biederman also emphasize the personal growth experienced by participants in groups that make major collaborative contributions to their fields. They highlight how careful selection of team members and the self-reinforcing character of excellence and high performance standards also contribute to individual growth. Rather than portraying the management challenge primarily as one of channelling internal friction (i.e. to produce light rather than heat, cf. Leonard & Swap 1999), these authors emphasize the need to create the conditions for growth and cultivation from the inside, while providing a necessary degree of protection from the outside.

Further developing this notion of team climate in organizational research, Bain et al. (2001) find that voiced and enacted support for innovation and a strong, shared task orientation are most likely to characterize more innovative research teams. Hoegl & Gemuenden (2001)

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[4] In the empirical research literature, this is probably most closely associated with group efficacy (cf. Pescosolido 2001) or collective self-efficacy (Cohen & Bailey 1997).

[5] In the Vygotskian developmental psychology employed by John-Steiner, this occurs through mutual appropriation and the expansion of individuals' zones of proximal development.

report that the balance of member contributions, mutual support, effort and cohesion are all significant factors predicting the performance of innovative software design teams. Edmondson et al. (2001) determine that a supportive group environment promotes more rapid and effective learning in medical teams adopting new surgical techniques.

Supportive environments appear to involve a combination of participative safety as well as a collective sense of identity as innovators—overlaying whatever diverse individual backgrounds and experiences exist in the group. These are not simply the results of naming acts or of formal organization; they arise organically through shared practices and an auspicious, self-reinforcing confluence of incentives, norms and behaviours—maintained both formally and informally.[6]

Improving Collaborative Performance

Reviews of empirical research on team performance highlight certain constructs that suggest ways in which the collaborative performance of teams might be improved. For example, substantive participation and task cohesion appear to be positively associated with performance in many settings. Cohen & Bailey (1997) specifically identify group cognition, shared mental models and group affect as phenomena that impact performance, requiring further theoretical refinement and empirical study. Mohammed & Dumville (2001) also discuss shared mental models and the need to understand the dynamics of cognitive consensus formation and the optimal relationship between diversity and consensus. It may be that the complex and contradictory empirical findings regarding the performance benefits of diversity can be resolved by delving more deeply into the nature of supportive environments and task cohesion. In the management literature, two practices that have drawn significant attention in promoting the productivity of project teams and improving cross-functional team work are co-location and prototyping. These practices recall issues raised by the empirical research literature in that they may be understood as ways of enhancing shared task focus and building a supportive environment.

Co-location

Since Allen (1977) first documented the effect of spatial proximity on information-sharing, physical co-location has become one of the most widely-used approaches to improve cross-functional teamwork in product development (Griffin & Hauser 1996, Ulrich & Eppinger 1995). The built environment impacts patterns of movement in ways that have powerful

[6] Sutton & Hargadon (1996) find such a system at work in their situated study of brainstorming practice in a successful design firm.

effects on social relationships and workplace interaction (Hillier 1996, Hillier & Hanson 1984). Casual contact and informal interaction between non-routine co-workers may be important stimuli for creativity and innovation; these can be promoted or hindered by features of the physical work space (Penn et al. 1999, Becker & Steele 1995, Backhouse & Drew 1992). Transformation of the work environment can be used to reinforce innovation in work practice—particularly when a participatory design approach is employed (Horgen et al. 1999).

In addition to speeding routine information sharing, close proximity is likely to increase individuals' familiarity with each other and their awareness of less-obvious aspects of the work of others. These factors are probably conducive to the formation of a supportive environment, but there are limitations to the extent co-location can be relied upon. Some difficulties relate to the practicality of moving people as frequently as is required by the dynamic nature of modern projects; other tensions relate to the prevalence of electronic communication and the increasingly global distribution of people who must work together. There are also potentially adverse learning impacts on functional excellence, as well as problems associated with engendering a "skunk works mentality" that inhibits information flow beyond the group (Griffin & Hauser 1996, Rafii & Perkins 1995, Leonard-Barton 1995).

Close contact and interaction within a community of practitioners is essential to develop knowledge and to maintain expertise within a particular discipline (Boland & Tenkasi 1995, Brown & Duguid 1991). The use of physical space in general—and co-location in particular—has great potential to enhance teamwork, but should not be seen as the sole solution. Impacts on learning, knowledge, skill and expertise in the larger organization may be complex and must be taken into account. Effective use of co-location requires a strategy for learning and using project interaction to develop integrative knowledge and leadership capacity (Leonard-Barton et al. 1994, Bowen et al. 1994).

Prototyping

A number of authors have drawn attention to prototyping as a prominent behaviour in successful collaborative environments. Prototypes provide a focal point for communication and purposeful interaction amongst individuals with differing expertise and perspectives (Leonard & Swap 1999, Leonard-Barton 1995, 1991). They emphasize concrete and tangible outcomes, and help attract and organize people around innovative ideas (Schrage 2000, 1996, 1995, 1993). Prototypes can be vehicles for learning about users, testing assumptions and engaging in experiential learning (Bødker 1998, Bødker & Grønboek 1996, Bowen et al. 1994).

Schrage (2000) describes prototyping in innovative organizations as revolving around the use of models and representations to envision alternatives and test interventions in imagined futures. According to Schrage, physical prototypes are particularly effective ways of enlisting allies and supporters, as well as flushing out critics and enemies. Besides facilitating communication and opening assumptions to challenge, models and prototypes draw participants into interactive conversations that clarify priorities and reveal biases. Good models and prototypes also have the capacity to surprise; by provoking responses, prototypes can say as much about their creators as they do about the futures they are constructed to represent.

Prototyping is one aspect of a broad range of phenomena that relate to the use of shared representations in design, and its benefits suggest some of the effects representations may have in socially-situated design activity. As I elaborate in the following section, we live at a time of rapidly-developing opportunity and unprecedented challenge in this regard. There is a need for a better understanding of the ways in which complex representations operate in collective design processes and similar situations. Through this work I hope to contribute to this understanding in a way that transcends any particular representational medium or the designation of a particular object as a model or a prototype.

External Representations in Design Interaction

Broadly construed, design activity involves envisioning preferred possible futures and charting courses of action to bring them about (Simon 1996). In practice, the creation of shared representations both scaffolds and propels this process. Small groups engaged in design make conspicuous use of shared artefacts like drawings, models and prototypes as they work. The ability to invoke and incorporate such external artefacts and representations in individual thinking and collective action is a defining human characteristic. In evolutionary terms, it has extended our cognitive capabilities, enabled the cultural transmission of knowledge and fostered the development of forms of living that exceed our individual limitations (Donald 1991, Hutchins & Hazlehurst 1991).

Opportunities and Challenges

Developments in technology now enable rapid communication and novel forms of representation.[7] These developments directly impinge upon design, imparting the ability to gather and disseminate high-fidelity models and images, coordinate more distributed teams and involve broader ranges of stakeholders and collaborators. Computer-aided design enables increasingly realistic and immersive representations to be rapidly deployed and coupled with advanced analyses and rapid prototyping technologies (cf. Ragusa & Bochenek 2001). As a general-purpose representational tool, the computer also enables truly new kinds of representation in the form of system dynamics and agent-based models and simulations. On the one hand, these allow us to see how complex forms and life-like behaviours may arise from simple rules, recursively enacted by large numbers of agents (cf. Epstein & Axtell 1996). On the other hand they potentially allow the simulated behaviour of complex physical and social systems to enter dynamically into design processes (Bonabeau 2003, 2002; Kunz et al. 1998).

As our collective capabilities have grown, so has our potential to adversely impact the natural and social systems upon which we depend. We face increasing challenges to anticipate the impacts of our actions on complex systems over longer time frames and across more diverse communities of stakeholders. The difficulty of individual and organizational decision making is compounded by a continual pressure to accelerate our activities that allows less time for deliberation. The dynamics of purposeful interaction and social cognition in rich representational environments is therefore an important, and timely area for study.

Research directly relevant to this project comes from two directions: first, from studies of design activity that encompass (to a greater or lesser extent) the use of external representations; second, from workplace studies in the traditions of human-computer interaction, situated action and distributed cognition. Among the former, relatively few studies have been conducted on authentic, organizationally-situated design groups that attend in close detail to the simultaneous dynamics of social interaction and representational activity. The latter offer methodological models for fine-grained analysis of interaction over artefacts, but by and large, do not take into account the particular nature of design activity or design representations.

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[7] Some examples for the sake of breadth include: the virtual worlds of multiplayer on-line gaming (Herz 1997); "smart mobs" using cell phone messaging to coordinate movement in urban protests (Rheingold 2002); responsive rich media spaces (Sha Xin Wei 2002); collaborative virtual storytelling in learning (Ryokai et al. 2003).

Studies of Representation in Design

A variety of studies of designers' use of external representations have been undertaken at different levels of analysis. These range from ethnographic studies of situated design activity (e.g. Henderson 1999, Carlile 2002, Bucciarelli 1994) to psychological studies of individual designers engaged in sketching and drawing (e.g. Oxman 2002, Scrivener et al. 2000b), and observational studies of small groups engaged in brainstorming and hypothetical design tasks (e.g. Cross et al. 1996, Reid & Reed 2000, Brereton 1999, Goldschmidt 1995, Tang 1991).

These studies shed light on the details of designers' communicative practices and the implication of objects and media in design thinking. However, a number of gaps remain. Ethnographic studies highlight various roles played by representations in organizational design and coordination processes; however, while the descriptions are rich and certain theoretical constructs are invoked (e.g. actor-networks, boundary objects), the outcomes are embodied in narrative more than a readily-transportable micro-analytic approach.

Psychological studies shed light on the relationship between design thinking and individual activities of sketching and drawing; however these constitute only a fraction of the representational forms involved, and say little about collective aspects of real-world design activity. As Reed & Reid (2000) observe, by attending primarily to cognitive aspects of sketching, "little is yet known about how designers combine visible workspace actions with speech in the collaborative process of building on, and developing shared design ideas." (p. 339)

Finally, laboratory studies of ad-hoc groups and student teams are based upon observations under controlled—but ultimately contrived conditions. Without invoking professional identities, established relationships and external organizational context, participants' motivations and analysts' judgments of performance remain proxies for "the real world." As a result, the connection between individual behaviour, collective representational activity, and organizationally-relevant innovation remains speculative. There is a gap, therefore, in understanding small group design interaction with complex representations at a fine-grained level in a real-world setting.

Studies of Technologically Mediated Interaction

The potential of technology to mediate interaction across distance has spawned a great deal of research on collaborative work between remote participants (cf. Olson, Malone & Smith 2001). However, the face-to-face situation still provides the richest opportunities for participants to perceive each other, to convey nuanced information, to draw upon context and to control their shared environment. Research focusing on interaction that is *entirely* mediated by technology risks overlooking important factors in these areas, because the relevant phenomena are never present to be observed.

Tightly-coupled tasks that require intense and continuous interaction are likely to be carried out most effectively when participants are co-located. Physical co-presence may be essential to build trust and to enable subsequent remote collaboration to be more effective (Olson & Olson 2001b, Driskell et al. 2003). Design often involves both synchronous and asynchronous activity, carried out in small group meetings and by individuals working independently. The emergence of new and extraordinarily productive practices that emphasize co-present collaboration requires renewed attention to face-to-face interaction that takes place *in the presence* of technology, not entirely *through* technology.

Purposeful work interaction between multiple individuals revolving around technological artefacts has been the focus of fine-grained study in a variety of settings (cf. workplace studies: Heath & Luff 2000, Engeström & Middleton 1996; distributed cognition: Hutchins 1995, 2000[8]). However, these studies frequently focus on command centres, control rooms, and similar environments with relatively well-defined roles and structured tasks. Fine-grained studies of such patterned workplace interactions are instructive with regard to methods and the types of phenomena involved, but do not yield immediately useful conclusions for design collaboration or the use of design representations.

Emerging Practices: Radical Co-location and Real-time Design

Conventional meetings often primarily involve participants updating each other on past activities, making decisions and talking about work to be performed. Design meetings depart from the conventional paradigm of decision-making presumed by some instrumental research[9] in that the development of insight and the *discovery* of options is at least as important as the actual process of selection and decision (Olson et al. 1995, 1992). Recently, there has been interest in highly productive, co-present design environments in which participants carry out intense collaboration—doing the work *together, in real time* rather than talking about what they intend to do later independently. Related practices have been described in the literature as "radical co-location" (Teasley et al. 2000), "extreme collaboration" (Mark 2002), pair programming or "extreme programming" (Jeffries 2001) and "deep dives" (Kelley & Littman 2001).

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[8] These and other perspectives will be reviewed in greater detail in the following chapter.
[9] For example, as in decision analysis or group decision support systems.

The environments in which these activities take place have been referred to as "team rooms" or "warrooms." Unlike conventional co-location (in which individuals may simply have private offices in the same area of a building) these settings are characterized by high visibility with little if any private workspace. A degree of temporal bounding is frequently introduced, perhaps in the form of a deadline, to instil decisiveness and a focus on simplicity and outcome—if not a sense of urgency. Teasley et al. (2000) describe a doubling of productivity for software development teams working together in warrooms over the course of their projects. The benefits of these environments appear to derive from continual awareness, rapid communication, spontaneous meetings and serendipitous interactions. Participants' initial reservations about the lack of privacy often to subside as they adapt to the shared environment, though some concerns remain.[10]

Along these lines, Mark (2002) reports on the Advanced Projects Design Team (also known as Team-X) at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California. In response to a broad NASA imperative to increase scientific productivity and reduce program costs, this team was formed in 1995 to accelerate the development and improve the quality of advanced concept proposals for exploratory space missions. To develop a mission proposal, a standing team of aerospace design experts works intensively with scientists, technologists and program managers (who are in effect "customers") in a series of highly focused, interactive design sessions in an electronic warroom environment. This practice has dramatically reduced the time required to complete such proposals from several months to a few weeks (or even days); within JPL it is widely seen to have increased the quality of proposals and the effective re-use of technology (and technical knowledge), while reducing wasted time, energy and redundant effort.[11]

Mark makes a number of observations about the flexible, dynamic nature of the interaction between human participants in this setting, and how this is enabled and supported by a custom network of data-sharing spreadsheets. She describes how team members modulate their attention between their own task and the shared environment to focus selectively on

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[10] Interestingly, participants' concern over how management would evaluate them as individual contributors increased, suggesting the need for new incentive structures and evaluation procedures to accompany this new way of working.

[11] Numbers of completed mission proposals and development costs using JPL's concurrent design practice vs. traditional methods can be found in Rosenberg 1998 and Kwan et al. 2005. Discussion of the productivity of JPL's concurrent design practice can be found in Mark 2002 and Chachere et al. 2004. While it was not an objective of this research to quantify or validate specific performance claims, interviews with JPL project and program managers with experience of JPL's proposal process substantiated advantages in terms of time savings, early-stage design maturity and design knowledge reuse.

items of importance[12] Mark notes the essential role of the team leader to highlight potential problems and provide direction for the group as a whole. She also discusses the implications this way of working has for individual temperaments and work styles—not all of which are well-suited to the intense demands and high visibility inherent in the Team-X environment.

Mark's description of communicative behaviour and the intertwining of human and technological networks in Team-X is intriguing; it is not, however, explicitly formalized in terms that apply more generally to design activity. The description emphasizes awareness, task inter-dependence and information movement, from a standpoint of human-computer interaction, that is more appropriate to characterize patterned tasks than open-ended aspects of design activity. Mark notes the various types of display and the information structures employed by Team-X, but these do not include other conventional forms of design representation or a notion of representation appropriate for other design contexts.

Early in 2002, an opportunity arose to undertake a study of another of JPL's concurrent design teams, the Next-Generation Payload Development Team (or NPDT, Oxnevad 2000). Also convening customers and a standing expert team in intense, co-located design sessions, the NPDT differs from Team-X in certain respects, focusing more on the design of surface vehicles and scientific payloads than overall missions. Because of the greater emphasis on hardware design, rather than the networked spreadsheets of Team-X, NPDT uses sophisticated computer-aided design, modelling and analysis packages for mechanical, thermal, electrical and optical systems. NPDT is also somewhat smaller and, while electronic data sharing of CAD and other information takes place, key information exchange occurs verbally and is more amenable to non-invasive observation. These differences make NPDT a promising setting in which to address the focal issues of this research.[13]

The Contribution of this Study

In this study, I will explore the ways in which purposeful human interaction and external representation are interwoven in design collaboration. As we face unprecedented opportunities and challenges, there is a great need to understand the dynamics of collaboration and the formation of collective commitment in rich representational

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[12] Mark cites Cherry (1953) regarding the "cocktail-party phenomenon," which is the ability to detect mention of one's name within the background murmur of cocktail party conversation.

[13] In interviews, respondents indicated that, compared to Team-X, NPDT is more appropriate for missions with less precisely-formulated objectives and a greater requirement for novel hardware design. Conversely, Team-X is most appropriate, "when you already know what you want to do and are ready to optimize a mission around it." This difference accords with my special interest in innovation over patterned performance and operational efficiency.

environments. By creating a shared task focus and providing a vehicle for the substantive participation of team members, shared representations have the potential of positively impacting the performance of organizational teams involved in innovation more generally.

A situated study of an authentic, collective design practice will provide a useful complement to laboratory observations of individuals and ad-hoc groups. The concurrent design practice at JPL offers an advantageously-bounded setting for the study of real-time design interaction, one which prominently features advanced shared representations. This will enable the development of a more formalized, micro-analytic approach to understand representational activity in design—compared to previous ethnographic studies—while encompassing collective processes to a greater extent than psychological studies of sketching and drawing.

The standing teams at JPL rapidly convene diverse expertise to effectively meet project requirements for focused periods without burdening early-stage projects with large headcounts.[14] This setting represents an emerging form of concurrent design practice with the potential to offer general insights on design and innovation. The objective of this research will be to develop an understanding of the dynamic engagement between human participants and representations in this type of environment, particularly in conjunction with the emergence of novelty and the consolidation of commitment to action. The outcome should provide a way of looking at these situations that can do justice to the potential of new forms of representations, and an analytic approach that can inform their more effective use.

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[14] As an organizational form, this represents a hybrid of conventional work and project teams (Devine 2002, Driskell 2003), and potentially, a novel solution to the exploration/exploitation problem organizations typically face in allocating resources (March 1994, 1991).

2. LITERATURE REVIEW

To better understand the use of shared representations in design collaboration, in this study I propose to observe an exemplary concurrent design practice—one which features highly interactive design sessions and extensive use of technologically-advanced representations. These sessions differ from traditional meetings by emphasizing the conduct of actual design work in real-time, as opposed to more conventional discussion and static presentations. Exemplifying an emerging practice known as "extreme collaboration" or "real-time design," this way of working has been developed over a number of years at Jet Propulsion Laboratory (JPL) and presents several features useful for study.

The design activity at JPL takes place in a highly focused small group setting that is clearly bounded, yet also organically situated within an authentic practice and a larger organizational context. This distinguishes the setting from that of laboratory studies of individuals working under controlled, but ultimately contrived conditions. Using prior studies of situated, group design activity as points of departure, I will review relevant literature for the purpose of identifying theoretical frameworks and other resources that may be useful. First, I elaborate the general nature of design activity and design interaction through a comparison of two of the principal metaphors used by prominent design theorists. I then highlight certain aspects of design as a *collective or group* activity (as opposed to an abstract process or individual activity), taking into account unique aspects of the JPL context and my particular focus on interaction with representations.

Based on this characterization, I review several theoretical frameworks most relevant for understanding purposeful work interaction that involves artefacts and representations. The issues raised are brought into sharper focus with the aid of several ethnographic accounts of organizationally-situated design that have been informed by these perspectives. Finally, in light of the gaps identified, and because of the potential vastness of the subject of representation, I will more precisely bound what I mean by a design representation in this context.

Design Activity and Design Interaction

Design is a particular type of purposeful human activity. While its general outlines and methods may be known in advance, the precise goals of any particular effort and the manner in which it unfolds are unpredictable—contingent upon interaction between the individuals involved and the particulars of each situation. Design is manifest in a variety of forms and involves a number of distinct practices. Descriptions of designing inevitably rely upon metaphors that highlight different aspects as problematic, ranging from individual creativity and cultural expression, to problem solving and grappling with complex systems (Coyne & Snodgrass 1995, Snodgrass & Coyne 1992). Attention to metaphor is also analytically important, as this has an impact on the phenomena we are prepared to see and the interpretations we are likely to make (Schön 1993, 1987, 1983). Because any metaphorical framing conveys only a partial understanding, this section begins by presenting two of the dominant metaphors employed by influential design theorists.[15] I discuss relevant aspects of each with regard to the real-time design situation I intend to study and draw upon them to frame aspects of the use of external representations in collaborative design.

Design-as-Search

Herbert A. Simon (1996) frames design as essentially concerned with devising courses of action to change existing situations into preferred ones—an activity at the core of a range of professions including architecture, business, education, law, and medicine. Simon characterizes design activity as a search among alternatives, coupled with rational choice on the basis of optimal utility. Since he is concerned with human action in complex systems, Simon recognizes that the identification of alternatives and assessment of optimality may exceed the practical limits of knowledge, time, and resources in any given situation. His emphasis therefore shifts to heuristic search strategies, which include discerning decomposability (or factorization) within the search space, and a notion of bounded rationality and "satisficing".[16]

Simon's conception of design-as-search is relevant to the JPL context, not least because these are some of the terms JPL uses to describe its own practice.[17] The presence of the various experts (and the domains of expertise they represent) in design sessions can be seen as an institutional manifestation—developed through decades of experience—of the factorization strategy Simon describes. However, certain critiques of Simon's conception of design have been made and are also relevant. Agre (1997) objects to the overly-orderly notion of search that portrays planning as a detached, purely cognitive activity and accords

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[15] Metaphor is a fundamental cognitive process, essential to our understanding of abstract concepts (Lakoff 1987, Lakoff & Johnson 1980). Because any particular metaphor highlights only certain aspects of the thing being understood, use of a single or a highly coherent set of metaphors may lead to an understanding which systematically overlooks some aspects of the thing in question.

[16] The idea of factorizing a large search space to discern sub-problems that can be solved relatively independently is also contained in Alexander (1968). "Satisficing" is based on the observation that search in real-world situations usually stops with the identification of a satisfactory solution, rather than an optimal one.

[17] An information pamphlet prominently displayed to visitors in the concurrent design facility (Smith & Baker, n.d.) describes the primary benefits in terms of "shortened design cycle times and a more thorough investigation of the design trade space."

privileged status to certain mental processes (anticipation, reasoning and reflection) at the expense of situational awareness and contingency.[18] These latter arise, Agre argues, not from internal cognitive activity but from complex interactions between humans and aspects of their environment. Agre asserts that behaviour in situations of real-world complexity always involves improvisation, "the continual dependence of action upon its circumstances" (p.156).

> … individuals continually choose among options presented by the world around them. Action is not realized fantasy but engagement with reality. In particular, thought and action are not alternated in great dollops as on the planning view but are bound into a single, continuous phenomenon. Further, I propose to understand improvisation as a *running argument* in which an agent decides what to do by conducting a continually updated argument among various alternatives. (Agre 1997, p.161)

Ehn (1988) also calls attention to ways in which Simon's conception of search falls short. He points out that the notion of optimization—even when softened to satisficing and bounded rationality—obscures the diverse agendas and nearly-incommensurable goals that stakeholders may hold.

> Furthermore, in design many groups with different and often conflicting interests participate. They will typically neither agree on constraints nor a relevant utility function. Besides, if we accept that there is more to design knowledge than detached reflection over what can be formally described ... then a great deal of knowledge relevant to design is excluded by this way of representing a design situation. (Ehn 1998, p.177)[19]

A second aspect Simon's account fails to grasp, according to Ehn, is the contradiction between tradition and transcendence. Here, Ehn uses "tradition" to refer to established practices of production, use, and value assessment, and "transcendence" to refer to innovation in any or all those areas. Ehn asserts that the decomposition of complex systems, if employed as the sole guide to design, is inimical and actually *destructive* to the creative competence of skilled designers.[20]

Agre's criticism regarding the situated and improvisational nature of action may pertain to the way Simon's view is routinely implemented in artificial intelligence; however Agre's description does not seem entirely incompatible with Simon's view of design activity in complex systems. Simon sees design search as driven by action sequences called "productions," each comprising instances of perception and action that rely upon

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[18] Agre, 1997. pp.155-159

[19] Parallels to this situation can be seen in accounts of different "thought worlds" created by organizational departments in multi-disciplinary product development (Dougherty 1992; also Pelled & Adler, 1994; Fiol, 1994).

[20] Ehn 1998, pp.128-9; p.161; p.180. Ehn's contradiction parallels the "innovator's dilemma" explored in detail by Christiansen (1997).

engagement and inquiry.[21] It may be that "situatedness" can be preserved, in Simon's view, through sufficiently fine-grained productions.

In response to Ehn's criticism of satisficing, bounded rationality and decomposition, it should be noted that Simon's conception of search heuristics is in fact quite broad, encompassing "style", variety, novelty, and "interestingness" as legitimate criteria. Simon allows that design search can take place in the absence of known or fully agreed-upon "final" goals, and that indeed the real function of a design goal may be simply to motivate search—whereby new goals are discovered and new understanding is generated.[22]

Simon's conception of design has clear relevance to the practice I propose to observe. However, these critiques suggest some of the ways in which the metaphor of search may need to be tempered or augmented to avoid doing violence to important phenomena in real-world, collective design activity. For example, what orientation or competence on the part of the searcher is necessary to preserve the improvisational quality of situated action? How can the social, potentially contentious nature of design be reflected in the evaluation of one production and contemplation of the next? While I will return to some of these themes later in the dissertation, they are among the aspects highlighted by the second of the two metaphors I would like to discuss.

Design-as-Conversation

Donald Schön (1983, 1987, 1992) articulates an alternative conception of design activity as reflection-in-action, organized along the lines of Dewey's theory of inquiry. Schön applies this frame to phenomena ranging from actual conversation in architectural education[23] to professional development in design and other disciplines, as well as in a generalized conception of organizational learning.[24] As Schön develops the concept of reflection-in-action, he portrays the designer's stance as an ongoing transaction or a "reflective conversation" with the design situation. While Schön concurs on the relevance of design to activities in a broad range of professions, he articulates a number of differences between his and Simon's positions. A number of researchers have employed or incorporated Schön's notion of reflection-in-action and reflective conversation in theoretical and observational

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[21] Simon 1996, pp.102; 122-123

[22] Simon 1996, p.130; p.162. It is worth noting that Ehn's (1988) criticism cites Simon's first edition (1969). Material in Simon's chapter six, "Social Planning," (as well as chapters two and four) was added in the second edition (1981). This contains the more expansive and flexible conceptions of search heuristics, goals, and representations to which I refer.

[23] See Schön's rendering of an exchange between architecture student "Petra," and instructor "Quist" in Schön 1983 (Ch.3), Schön 1987 (pp. 44-57) and Schön 1992 (pp. 134-5).

[24] Argyris & Schön, 1978

studies of designers and design teams.[25] Given that the focus of this research will be face-to-face interaction in real-time design, the metaphor of conversation seems particularly apt and worth exploring.

Schön sees real-world design as inevitably involving situations of "uncertainty, uniqueness, and conflict" to such an extent that instrumental problem solving and optimality play at best secondary roles (Schön 1987, pp. 41-42). Instead, he points out the active role of the designer in *constructing* problems, and their reliance upon complex, socially and professionally-shaped appreciative systems. Designers use such appreciative systems to make judgements about design *moves*—actual or contemplated changes to the design situation. In these judgements, designers must remain open to both the intended and unintended consequences of design moves (Schön 1992).

Schön is very aware of metaphor in his descriptions and the role of metaphorical language more generally in problem setting—an essential but often-ignored antecedent to problem solving.[26] His metaphor of design-as-conversation highlights different aspects of design activity compared to the design-as-search framing. First, it tends to foreground interaction and bi-directional exchange between participants in the design situation rather than simply between an agent and its environment. The metaphor of conversation also entails the reciprocal nature of speaking and listening, which Schön meant to apply figuratively to the designer's awareness as well as literally in conversation. Indeed, an essential aspect of reflection is precisely the ability to listen to the "back-talk" of the design situation (Schön 1983, pp.163-4).[27]

Schön describes the designer's awareness as equally a reflective conversation with the *materials* of the design situation. He sees this both in terms of direct perception in a physical situation (such as an architectural site) and in interaction with various representations, including sketches and models. Both involve a rapid iteration of appreciative perception and action—followed again by appreciative perception—which Schön terms a "move experiment" in a cycle of "seeing-moving-seeing" (Schön 1992, pp. 134-5).

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[25] Cf. Valkenburg & Dorst (1998), Brereton (1999) discussed in more detail in Ch. 3.

[26] See Schön's (1973) chapter in Ortony (1993) for a compelling description of the ways in which alternate metaphorical framing gives rise to antagonistic positions and incommensurable logics in urban planning debates. A more general description of the process of framing, frame conflict, and frame reconstruction is found in Schön & Rein (1994).

[27] Another level of reflective practice for Schön dealt with practitioners' abilities to question and re-evaluate their framing as well as their action (c.f. Schön 1983 pp. 49-52). Argyris & Schön (1978) extended this notion to the level of organizational activity with their distinction between single-loop and double-loop learning.

Simon also foregrounds the roles of representations in his thinking about design. He equates solving a problem with the construction of a representation that has the effect of making the solution transparent, and further identifies the creation of effective representations as one of the foundational areas of design inquiry.[28] Ehn agrees with Simon's stance on the importance of alternative representations, but objects to the notion of transparency: "Nevertheless, the fundamental difference is that to Simon the problem is given and a new representation is only a question of making it transparent." (Ehn 1998, p.180) In subsequent discussion of design and social systems, Simon does make clear that he is open to a variety of representations and appreciates the functions they can play beyond making a single solution transparently obvious:

> An appropriate representation of the problem may be essential to organizing efforts toward solution and to achieving some kind of clarity about how proposed solutions are to be judged. Numbers are not the name of this game but rather representational structures that permit functional reasoning, however qualitative it may be. (Simon 1996, p.146)

Schön's conception of representation use still seems richer. Schön observes architects, both individually and in student-teacher interactions, constructing "virtual worlds" or "design worlds" as they interact with drawings. This involves perceiving marks on paper as a gestalt or a pattern which the designers inhabit, as they move pencils, in a sort of vicarious travel "through a remembered or projected place." (Schön 1992, p. 138) In the flow of seeing-moving-seeing, the architects' appreciative system allows them to affirm the intended consequences of their moves. Openness to the unintended consequences of moves sometimes leads designers to a generative reframing of the problem at hand. In Schön's account, reframing involves reciprocal transformation of both the evolving design and the architects' understanding of the site. This is the essence of reflective conversation with the design situation (Schön 1992 pp. 141-2).

Schön's conversational metaphor calls to mind the unpredictable, spontaneous and improvisational nature of conversation to help understand the contingency of design situations and of any particular solution. The question arises (as it did earlier in connection with Agre's critique of the search metaphor), what sorts of competence are involved in performance in these situations? Sawyer (2002, 2003a, 2003b) addresses this question, drawing his evidence from studies of children's acquisition of conversational skill and of adult participants in theatrical and jazz improvisation. In these settings, individuals' discrete contributions are layered in a temporal sequence to produce an outcome that has its own overall or total character. This outcome is fundamentally unpredictable at the outset, despite

[28] Simon 1996, p.132; also Larkin & Simon 1987.

depending only upon the individuals and their contributions. Sawyer has termed this, "collaborative emergence," and developed ideas about what is involved in conjunction with a notion of group creativity (Csikszentmihalyi & Sawyer 1995).[29] Sawyer describes successful performance in terms of a balance between coherence and inventiveness, with participants engaging in constructive appropriation of pre-existing structures and elements of each others' contributions.[30] In order for this to be possible, performers must have certain experience and knowledge in common, they must possess a keen inter-subjective awareness and be engaged in a rich and complex communication. As Sawyer points out, there are important differences between the performance-based art forms he studied and collaborative design in organizational context. However the understanding of emergence arising through interaction will be a subject to which I return in Chapters 8 and 9.

Summary of Insights from Comparison of Metaphors

Having discussed the alternate views of design-as-search and design-as-conversation, we can see that each view draws attention to different, relevant aspects of design activity. To avoid an overly narrow conception I would like to draw together certain elements of both. I plan to take forward the following points from design-as-search, based on their relevance to real-time design in the JPL context:

- exploration of a space of alternatives and an assessment of the alternate, future worlds they constitute relative to actual and preferred states
- a strategy of decomposition or factorization of the alternative space into relatively autonomous sub-problems that can be solved without major impact on other sub-problems

To enrich the search perspective from the critiques and the alternate framing of design-as-conversation, I plan to take forward the following elements:

- The problem space is not given with the design task and the evaluative criteria are neither static nor objective—nor are they necessarily agreed upon.
- The searcher is not a unitary agent who reflects in a detached manner and acts unilaterally on that basis. Designers are engaged participants, potentially affected by their interactions with each other and with the design situation.
- Designers construct their design worlds through iterative cycles of seeing, moving, and seeing. The essence of reflective conversation lies in making moves and listening to the back-talk of the situation.

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[29] This highlights as essential the social context within which even solitary moments of insight and individual creative acts are embedded, and the necessity that creative products and people are deemed so only with reference to a broader community or "field."

[30] For Sawyer this arises from an interplay between upward and downward causation. Upward causation originates with the individuals and their contributions; downward causation is manifest as the emergent interactional 'frame' created by the unfolding performance exerts a constraining effect on participants' subsequent contributions.

- Moves may have both intended and unintended consequences; these are evaluated within a socially-constructed (and continually evolving) appreciative system.

With specific regard to representations in design, I take the following complementary points:

- From design-as-search: an appropriately-constructed representation facilitates reasoning and can make a problem resolution—in the form of a particular solution—more readily apparent.
- From design-as-conversation: representations are also a part of the design situation. They create a field within which moves may be played out; listening to their back-talk can lead to solutions as well as to a generative reframing of the problem.

Design as Social Process and Group Activity

Design activity can be characterized in abstract and formal terms that say little about the nature of the agent or agents doing the designing. Examples include formulations of abstract reasoning or argument structure (cf. Olson et al. 1992, 1995, Shum et al. 1997, MacLean et al. 1991), reciprocal processes of divergence and convergence (cf. Austin & Steele 2001, Stempfle & Badke-Schaub 2002), and exploration of problem and solution spaces (cf. Dorst & Cross 2001, Cross 2002).[31] When the nature of the designing agent is implicitly or explicitly addressed, it is often in terms of an individual activity—albeit one that may take other individuals into account in various ways.

There is some disagreement among design researchers as to whether more fundamental insight is gained by attending to individual, cognitive processes (admittedly taking place in a social context, cf. Love 2003), or to the multiple roles evident in groups (which are presumably internalized and enacted by individuals when they are working alone, cf. Goldschmidt 1995). My position is that whatever the nature of the individual cognition involved, design in the real-time setting must be seen as a social or collective process to a significant degree. When one looks at the outcome of any industrial or commercially-significant design process of real-world complexity, and asks how it came to be the way it is (or why it was undertaken at all), the answer is almost certain to involve the layered contributions of a great many people, made both directly and indirectly. Furthermore, in many cases these contributions combine in a manner that is not linear or decomposable, resulting in what Sawyer (2003a, 2003b) describes as collaborative emergence. This is particularly true of design carried out in a highly interactive manner, in real time. Such a

[31] These are described in more detail in the following chapter, in conjunction with a number of observational category schemes for design activity.

process is fundamentally *collaborative* in that no individual could possibly bring the outcome about by themselves, and *emergent* in that it can neither be predicted at the outset nor is it fully determined by any one individual's contributions. It is not possible to adequately understand the way such a process unfolds, or appreciate the significance of the outcomes, without attending to the social and collective dimensions of design activity.

The activity at the heart of this study, therefore, unquestionably requires characterization of design at a group level, distinct from either an abstract process or an individual activity.[32] How do individuals respond to the demands of designing in groups? What behaviours and processes have been identified? While Schön refers to real conversations, his primary focus appears to be on designers' awareness more than their actual verbal communication. Beyond the *metaphor* of conversation, what must we take into account to see design not just as social activity, but as social activity revolving around representations?

To answer these questions I will turn first to three observational studies of design groups—one in a contrived (though comparatively realistic) setting, the other two of working designers in authentic organizational situations.[33] A brief review provides a basis for determining which theoretical frameworks are likely to be most useful in understanding the roles of shared external representation in design collaboration. After a discussion of these frameworks, the themes identified in these descriptive studies will be elaborated and enriched by a review of additional, theoretically-informed, ethnographic studies.

Communicative Behaviour in Design Groups

Observational studies of design groups have identified patterns of social interaction, highlighting certain communication and coordination functions of artefacts and representations. Minneman (1991) undertook such a study of communication, including ethnographic observations and workshop-based interventions, with corporate R&D groups engaged in the design of complex electro-mechanical office machines. For Minneman, the key issue is participants' ability to maintain the coherence and purposefulness of their collective design effort across different interactions and settings:

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[32] I reject the idea that a "fundamental" understanding of design involves an either/or proposition between individual/cognitive and group/social processes. I think that Love's (2003) emphasis on precise and exclusive definitions (favouring the individual/cognitive perspective) as the sole path to theoretical coherence is too rigid and reflects a counterproductive emphasis on what Lakoff (1987) describes as the classical theory of categorization. Categories must be meaningful, but should not become so restrictive that they exclude relevant phenomena. Whatever the insights provided by developments in cognitive neuroscience, a comprehensive understanding of design activity cannot exclude observations of phenomena at the group and organizational level.

[33] I do not wish to suggest that individual and laboratory studies are not potentially relevant—indeed I will review a number of these in the following chapter. However, I think it is better to focus initially on group and situated studies to anticipate phenomena and identify appropriate overarching theories.

> We need to come to grips with how designers establish, monitor, and maintain shared understandings in situations of constant change, how they assume, track, and transfer responsibility in these settings, how they display their commitment to aspects of the ongoing effort and trust of other members of the group, in addition to understanding how they produce the traditionally accepted artefacts of design practice. (Minneman 1991, p. 64)

Through his study, Minneman argues that understanding design as a group-level, socio-technical activity requires observing how participants attend and respond both to the particulars of the design and to the shifting alignments and commitments of the other participants:

> The moment-to-moment work is given meaning by interest-relative negotiation. Designers engage in an on-going effort to establish relevance of particular topics to the design effort, to come to understandings vis-à-vis their respective perspectives on topics, and to produce convincing arguments that result in other participants adopting their views (moreover to have those participants take action consistent with those views). (Minneman 1991, p. 155)

Addressing some of these phenomena in a more controlled setting, Cross & Cross (1996) provide an analysis of communicative interaction within an ad-hoc group of professional designers working on a contrived (albeit realistically formulated) mechanical design task. Because of the artificial bounding of the task to a single working session, maintaining coherence across different settings is not an issue for this group, nor is the preservation of ongoing relationships or the actual execution of any design. Even so, Cross & Cross observe the designers engaging in collaborative development and detailed consideration of various alternatives to the challenge they are given. They see group members assuming emergent roles based on their displays of expertise and acknowledgement by the others. In addition to canonical design activities (e.g. understanding and analyzing problems, proposing and developing solutions), Cross & Cross note what might nominally be considered process defects. These include lapses in collective memory and discrepancies between individual interpretations that are allowed to go unchecked. Interactional asymmetries are observed between members that impact whose contributions are registered by the group, and how unplanned, “opportunistic” conversational topics are handled (vis-à-vis stated plans and what the exercise requires the group to complete).

These studies highlight inherently social, communicative processes carried out in conjunction with canonical design activities that include:

- establishing roles and relationships (either by explicit agreement or as they emerge, de facto, in patterns of behaviour)

- engaging in negotiation (querying each other's positions to develop understanding; advocating and employing persuasive tactics; avoiding and resolving conflict)
- gathering and sharing information (based on a dynamic understanding of each others' expertise)
- managing each others' attention (and determining who is listened to)
- planning and managing process (including skilfully preserving ambiguity in conjunction with negotiation and as required by the complexity of the problem)

Social psychologists have devoted extensive study to related phenomena in small groups, including group formation, task performance, roles, status, conflict, negotiation, and decision (cf. Hare 1992, 1982, Shaw 1981, Steiner, 1972). Historically, findings in this area have been generalized from sources including therapy groups, training groups, naturally-constituted work groups and laboratory groups. Developmental stages have been proposed to form a trajectory through which interaction in different groups may move (e.g. from orientation and patterning, through conflict and adaptation, integration and rule formation, to functional role distribution, cf. Tuckman 1965, Tuckman & Jensen 1977, Hare 1982).[34] Processes in each area may be understood in terms of more basic theoretical constructs and dimensions along which individuals and groups are thought to differ (e.g. drawn from functional, field, dramaturgical and exchange theories, cf. Hare 1982). These can, however, be generally divided into *task processes* and *socio-emotional processes* (Bales 1999, Hare 1992). The former are things the group needs to accomplish to achieve a practical objective; the latter reflect the work necessary for the group to organize and sustain itself, to resolve conflict and maintain working relationships amongst its members.

The JPL setting has a number of features that can be expected to reduce the time and energy concurrent design teams devote to socio-emotional processes.[35] The design team is an extant, on-going group with a clear leader facilitating each session. Team members have well-defined roles, agreed-upon boundaries of domain expertise and serve at the discretion

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[34] Care must be taken inferring the relevance of these conclusions for any particular setting. Findings from observations of therapy or training groups may not be relevant to self-directed work groups like those engaged in research and development or real-time design meetings. Behaviour witnessed in formative stages of ad-hoc and laboratory groups may not reflect on-going work in naturally-constituted work groups with relatively stable membership. Artificial tasks that are the basis of some laboratory performance studies (e.g. comparing individuals to groups, different leadership styles, prescribed communication patterns) may bear little resemblance to design tasks of real-world complexity.

[35] This is not simply because of the technical nature of the activity. For example, Owens (1998) observed status in an R&D organization to be dynamic and informally enacted (vs. static and formally defined), analyzing meetings as "status auctions." In particular, Owens found that mid-level individuals actively contested status through technical exchanges, in part by proposing alternate framings of the essential challenges presented by projects and the avenues by which success could be achieved (tending to advocate those congruent with their own experience and technical skills).

of the leader. The engagement is modelled as a focused expert consultation; the design team is tasked with identifying issues and fleshing out detail to make the clients' proposal more thorough and credible. The clients are a small group with a durable commitment to the project, likely to have strong task cohesion. This practice is situated within the JPL ecology (a "market" for expertise) and reinforced by team members' participation in similar projects on a regular basis. These features mean we are unlikely to witness fundamental disagreements over how the process is conducted, over priorities or essential purposes, or see group members challenging each others' legitimacy, expertise, or the leader's judgment.

The JPL setting is therefore one in which task processes are likely to be particularly visible and readily studied, while some of the more socio-emotional processes associated with group dynamics may be less in evidence. This is not necessarily a problem, since reducing these dimensions of complexity will facilitate the development of methods highlighting task processes. (Indeed, this may also be a factor enabling the outstanding performance of these teams.) However this does have potential implications for generalization to other settings, which will be addressed and further discussed in Chapter 9.

Communication and Coordination Functions of Design Artefacts

Ethnographic and laboratory studies of design groups also draw attention to the involvement of a wide variety of artefacts and representations in the communicative activity of designing. In his ethnographic observations, Minneman (1991) highlights the apparently essential use of relatively ad-hoc, informal representations:

> While some researchers have argued that engineering design involves a set of special cognitive skills involving manipulation of mental images, analysis methods, and problem solving techniques, ... there is considerable evidence in these data that the central element of group engineering design practice is, instead, a particular facility with rather mundane text-graphic representations. (Minneman 1991, p. 145)

Minneman continues:

> While engineering drawings and simulation models are commonly thought to be the site of the bulk of engineering representation, a much wider range of examples are prominent in engineering design practice. Talk, gesture, sketching, lists and tables, formal drawings, calculations, video, photographs, and embodiments all show up as contributing to the representational and communicative activity in group designing. (Minneman 1991, p. 145)

Cross & Cross (1996) similarly note how the design team they observed engaged in a variety of representational activity as they worked. In addition to talk, gesture and interactive sketching, they created and used lists and made reference to background documents and physical hardware present in the room.

The demands of real projects in real organizations add layers of complexity. In a comparative ethnographic study of design in two different organizational settings, Perry & Sanderson (1998) also focused on communicative practices and the coordination functions of various artefacts in group design work.[36] Beyond such canonical design artefacts as formal drawings, models, prototypes, informal drawings and sketches (large and small), these included procedural artefacts like task lists and schedules with roles and responsibilities, as well as various approvals, contracts and letters of intent. In addition to working with each other, designers used these resources extensively to interact with those outside their organizations.

Like Minneman, Perry & Sanderson emphasize how often these interactions have the character of negotiation, and suggest the number and range of process artefacts is related to the level of inter-organizational complexity. They point out that the artefacts not only preserve outcomes and relevant design knowledge, but also serve to locate and orient people toward their collaborative project:

> Artefacts form a part of the process of product design whilst at the same time orienting the participants to the cooperative aspect of their work. Artefacts often reveal information about their 'location' within the process and who has acted on them. (Perry & Sanderson 1998, p. 287)

Thus, design artefacts hold information both about the evolving state of the design (as it is envisioned to exist in a preferred future), and about the network of tasks, collaborators and commitments that must mesh over time to bring this state about. Taken together, the studies I have mentioned highlight the following communicative and coordination functions of a range of artefacts and representations:

- envisioning the designed object and facilitating discussion of constraints, operating principles and processes
- assisting in managing the collective work process
- documenting permissions and making manifest webs of commitment
- facilitating discussion within a team as well as with a variety of outside agents and collaborators
- carrying information about who is involved and the stage of the design as well as the current specifications and configuration of the designed object

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[36] Perry & Sanderson (1998) observed the design of a mechanical product in a small manufacturing firm and a building design in a multi-national construction engineering firm. They compared communication structures and activities, highlighting roles of artefacts in the design process.

Through these observational studies, we see that a variety of social processes may be in play within design groups. We also see that, beyond encapsulating design specifications, artefacts and representations provide tangible resources for negotiations and persistent traces of the agreements and commitments necessary for action to bring designs about. By providing these resources, shared artefacts and representations create a field within which design interaction takes place and through which work is carried out.

Based upon these observations of group design activity, I will now turn to a discussion of theoretical perspectives which may be useful to better understand this type of purposeful, situated, collective and object-mediated work. Then, in the following section I will review several ethnographic studies that draw upon these theoretical traditions to elaborate the themes identified above.

Relevant Theoretical Perspectives

The descriptions above make clear certain key attributes of the work taking place in groups engaged in collaborative design. First, the course of the activity involves a dynamic interplay between individual contributions and collective reception and interpretation. Second, the work activity is situated; it takes place within—and cannot be understood without taking into account—a broader social and organizational context. Third, the work essentially relies upon interaction with shared artefacts and representations in a variety of ways.

Different theoretical perspectives have been developed to address work with these characteristics, many having arisen in response to shortcomings of overly-abstract conceptions—in both sociology and cognitive science—to account for the phenomena involved. Whilst researchers disagree over the specific merits, and different approaches may be more or less appropriate for different questions, several theoretical perspectives have been identified as relevant to this type of work.

Nardi (1996), Star (1996), and Heath, Knoblauch & Luff (2000) give overviews of major approaches that have developed for the study of naturally situated workplace activity, including symbolic interactionism, situated action, actor-network theory, activity theory and distributed cognition. The authors point out various aspects of convergence between these perspectives, despite their distinct roots in pragmatism (Mead, Dewey), phenomenology and ethnomethodology (Schutz, Garfinkel) Soviet social psychology (Vygotsky, Leont'ev) and sociological studies of science—as well as from within cognitive science itself. Broadly speaking, these perspectives all share the following orientations:

- they call attention to the ways in which context and situation impinge upon individuals' mental processes—operating through an array of material, social, organizational, institutional, and cultural factors
- they encompass broader time horizons to include historical understandings and imagined futures—as well as the here-and-now—as potential determinants in thought and action
- they provide a more central place for social interaction in development, learning and work activity
- they attend to the variety of ways in which artefacts, tools and representations take part in cognition and embody practice, culture and history via processes of mediation
- as a result of the above, they tend to relax traditional distinctions such as those imposed between self and other, mind and environment, thought and action

Each of these perspectives provides more specific, useful insights, which I will now review to enrich our understanding of the ways in which objects, artefacts and representations are implicated in work practice and interaction.

Symbolic Interactionism

In contrast to abstract structural and functional descriptions of order in society, symbolic interactionism asserts that both social order, and individuals' constructions of their own identities, arise through the exchange of meaningful symbols—principally motivated by the demands of joint action. Based on the philosophical pragmatism of Mead and Dewey, and the sign theory of Peirce, it was closely identified (in the mid-20th century) with the University of Chicago and epitomized by extraordinarily detailed studies of sub-culture and individual identity in urban and occupational settings.

The perspective has been prominently articulated and advocated by Blumer (1969), with seminal studies conducted under the auspices of Hughes and subsequent methodological refinement by prominent students of both (e.g. Strauss, Becker). The perspective remains influential in both sociology and social psychology. It emphasizes close, multi-perspective (often participant) observation of the empirical social world—particularly scrutinizing the objects and meanings of the groups of people under study. On the symbolic interactionist view, the dynamics of social order arise through networks of interlinked action, as individuals pursue and coordinate their own lines of action on the basis of sets of shared meanings.

> ... as individuals acting individually, collectively, or as agents of some organization encounter one another they are necessarily required to take account of the actions of one another as they form their own actions. They do this by a dual process of indicating to others how to act and of interpreting the indications made by others. Human group life is a vast process of such defining to others what to do and of interpreting their definitions; through this process people come to fit their activities to one another and to form their own individual conduct. (Blumer, 1969, p. 10)

For Blumer, the word "object" has a broad meaning, encompassing anything to which it is possible for participants to reliably refer based on a persistent and material presence in the environment or a sufficiently routine and patterned usage born out by experience in common.

> The position of symbolic interactionism is that the 'worlds' that exist for human beings and for their groups are composed of 'objects' and that these objects are the product of symbolic interaction. An object is anything that can be indicated, anything that is pointed to or referred to—a cloud, a book, a legislature, a banker, a religious doctrine, a ghost, and so forth. (Blumer, 1969, p. 10)

That joint action is coordinated through semantic objects, and that it occurs principally through the exchange of tokens of shared meaning, is an essential aspect of the symbolic interactionist view. Star (1996) lauds the symbolic interactionist perspective for providing enduring, rich accounts of social life, but advocates looking elsewhere for frameworks to take less-ostensibly observable, but arguably essential cultural, historical, and material factors into account. This conclusion is shared by Nardi (1996); both advocate activity theory for this purpose (as discussed below). Heath & Luff (2000) note wide acceptance of the symbolic interactionist perspective within 'mainstream' sociology, but emphasize the need for a deeper understanding of the basis of joint action, in terms of more than the presumption of shared meanings. This leads us next to the situated action perspective.

Situated Action

It has been noted that abstract conceptions of reasoning, planning and action found in some forms of cognitive science do not adequately account for real-world human behaviour in situated work settings. In response, the situated action perspective, prominently articulated by Suchman (1987), emphasizes the contingency of action upon dynamic perception of situations. Advocates of this perspective agree with pragmatists, such as Mead, about the construction of social objects through interaction. They are less satisfied however, with the symbolic interactionist emphasis on meaning—or the presumption of stable or shared meanings—as the primary underpinning of joint action.

Drawing upon ethnomethodology (Garfinkel) and conversation analysis (Sacks, Schegloff), situated action pays close attention to the ways in which coherent and coordinated interaction is achieved, often through subtle behaviours and relying upon a variety of material and environmental resources. Studies undertaken from this perspective are characterized by extremely fine-grained attention to taken-for-granted practices and everyday sense-making activities that make successful interaction possible.

> The notion that we act in response to an objectively given social world is replaced by the assumption that our everyday social practices render the world publicly available and mutually intelligible. It is those practices that constitute ethnomethods. The methodology of interest to ethnomethodologists, in other words, is not their own, but that deployed by members of the society in coming to know, and making sense out of the everyday world of talk and action. (Suchman, 1987, p. 57)

According to Heath, Knoblauch & Luff (2000), the perspective also seeks to address a tendency within sociology to otherwise disregard material artefacts:

> [Situated action] directs analytic attention towards the socially organised practices and reasoning in and through which participants produce, recognise and co-ordinate their (technologically informed) activities in the workplace. ... [It examines] the ways in which participants reflexively, and ongoingly constitute the sense or intelligibility of the 'scene' from within the activities in which they are engaged. Technology, in the ways that it features in practical accomplishment of social action, is placed at the heart of the analytic agenda. (Heath & Luff 2000, p. 19)

Heath & Luff (2000) present a variety of studies exemplifying the situated action approach. These illustrate how even nominally-individual tasks may be carried out in an interdependent manner, critically requiring participants' mutual awareness of each other's activities.[37] This frequently relies upon quite subtle and nuanced behaviour in speech and gesture, as well as participants' skilful utilization of technologies and mundane material resources. Taken together, these studies offer a compelling critique of the conventional tendency to see technologically-mediated work in terms of a single person interacting with a computer screen, or of viewing technology solely as a conduit through which interactants exchange messages.

Thus, on one hand, studies in this tradition truly exemplify a triadic communication model. This highlights individuals' interaction with each other *in the presence* of artefacts and technologies, and portrays them responding in both overt and subtle ways to each other as well as to the technology and its interactive behaviour. On the other hand, as Nardi (1996)

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[37] These include studies of doctor-patient consultation, journalists in a real-time news service, mass-transit system control rooms, and computer-aided architectural design. The perspective has become influential in the emerging field of computer-supported cooperative work (CSCW).

notes, the situated action perspective tends to produce highly particular accounts with less relation to more general constructs that might apply across settings within a domain. This includes what I will refer to as domain-relevant theories of performance—that is, theories accounting for the quality of performance in terms practitioners might use to inform their practice and differentiate good from bad.[38]

Situated action studies frequently direct analytic attention toward relatively low-level communicative behaviours associated with awareness and attention. Apart from instances of communicative breakdown, such processes tend to be taken-for-granted, and therefore somewhat removed from the instrumental concerns of practitioners under normal circumstances. As Heath & Luff (2000) point out, inattention to such bedrock communicative processes can mean that performance is jeopardized, or adversely impacted in unforeseen ways, by the introduction of information systems or distance-collaboration technologies. Their analysis of computer-aided design in architecture exemplifies this analytic focus on the mechanics of coordination (between architects involved in making a change to a wall). *Why* architects would engage in moving a wall—or decide to put a wall anywhere in the first place—with regard to any sort of design principle, theory or imperative, is not part of the account.[39]

Nardi (1996) also identifies a certain discomfort around ideas of representation within the situated action perspective. This is conveyed by Heath & Luff (2000), who describe the concept as a problematic carryover from cognitive science, de-emphasizing it on the grounds that representations (certainly in the form of plans) have less to do with practical action than is commonly thought. I will argue that, in the context of design, it is not possible to meaningfully understand the activity without acknowledging *design representations* as central participants. I will now turn to three perspectives that, in different ways, offer the possibility of doing justice to this aspect of design practice.

Actor-network Theory.

Developed initially through sociological studies of science and technology, actor-network theory is concerned with the dynamics of emergence and persistent structure in scientific

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[38] I believe this is also essentially what Devine (2002) refers to in discussing the need to consider type-specific theories of effectiveness for teams of various types.

[39] A related but distinct body of theory arises from naturalistic (cognitive-anthropological) studies of learning in traditional (e.g. apprenticeship) and other everyday settings. This *situated learning* perspective calls attention to the role of shared practices and identity in bounding social groups, and sees participation in these practices as the primary means by which knowledge is acquired and transferred (cf. communities of practice: Lave 1991, Lave & Wenger 1991, Brown & Duguid 1991, Wenger 1998). While this perspective is more likely to foreground practitioners' theories of performance, it does not typically employ such fine-grained analysis of interaction with artefacts.

enterprise and technological innovation. Principal proponents (e.g. Latour, Callon, Law) are sceptical of conventional analytic categories for many social phenomena, arguing that these have been formed primarily in terms of the residuals left unexplained by other disciplines. To avoid obscuring essential relationships and address social phenomena in their own right, these authors advocate instead pursuing a "sociology of associations" (Latour 2005). This emphasizes tracing the various connections between actors in heterogeneous systems, to untangle controversies and attend to the work required to maintain allegiance in the face of competition and change.

> Who will win in an agonistic encounter between two authors, and between them and all the others they need to build up a statement S? Answer: the one able to muster on the spot the largest number of well aligned and faithful allies. This definition of victory is common to war, politics, law, and, I shall now show, to science and technology. My contention is that writing and imaging cannot by themselves explain the changes in our scientific societies, except insofar as they help to make this agonistic situation more favourable. ... Rather, we should concentrate on those aspects that help in the mustering, the presentation, the increase, the effective alignment or ensuring the fidelity of new allies. We need, in other words, to look at the way in which someone convinces someone else to take up a statement, to pass it along, to make it more of a fact, and to recognize the first author's ownership and originality. (Latour 1986, p. 5)

A central, and more controversial claim arising from this perspective is that actors must be seen to comprise both human and non-human entities. For example, in the context of science, technological actors include the techniques and instrumentation that make possible the conversion of complex, unruly phenomena to compact, mobile "*inscriptions*" — that can be circulated and published as scientific findings. Order in heterogeneous systems arises from progressively greater intertwining within a collective of humans and non-humans (Latour 1999). Relatively stable network alignments and configurations come to operate coherently as a single actor ("punctualisation" Latour 1986; Law 2003, 1992) or a "black box" (Latour 2005)—until some breakdown occurs that exposes the constituent elements, opening the associations to potential reformation.

On this view, the dynamics of order and change are as much driven by the *conscription* of humans by non-human actors (a process of *interessement*, cf. Akrich et al. 2002) as by the intentional use of technologies by humans. This leads proponents of the actor-network perspective to accord a certain agency to technologies, artefacts and representations.

> Indeed, the argument is that an organisation may be seen as a set of such strategies which operate to generate complex configurations of network durability, spatial mobility, systems of representation and calculability -- configurations which have the effect of generating the centre/periphery asymmetries and hierarchies characteristic of most formal organisations. (Law 2003, p. 7)

Beyond its account of innovation, many aspects of the actor-network perspective are in accord with characteristics of design activity recounted above. These include the portrayal of associations in terms of negotiation, allegiance and commitment, and the obvious importance of artefacts and representations on a number of levels. The perspective, however, essentially dictates a more symmetrical treatment of human and non-human actors in understanding these processes. The actor-network perspective also emphasizes the instability of order in configurations, which are maintained only by virtue of being continually performed. This requires on-going acts of *translation* (Latour 2005, Law 2003) and processes of *figuration* (Latour 2005) by which actors present themselves to one another so as to side-step differences and defuse resistance.

Focusing on the mechanics of translation in open systems of collaborators, Star & Griesemer (1989) and Star (1993) provide insight through the conception of a boundary object. These are assemblages of artefacts, representations, standardized forms and techniques occupying positions of mutual intelligibility on boundaries between heterogeneous social worlds with intersecting interests. The boundary object imparts sufficient structure to maintain shared understanding and satisfy joint informational requirements in open systems of collaborators, remaining able to accept a multiplicity of meanings from different sides.

> [Boundary objects] are both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites ... They have different meanings in different social worlds but their structure is common enough to more than one world to make them recognizable, a means of translation. (Star & Griesemer 1989, p. 393)

The concept of a boundary object is employed in two of the ethnographic studies of design described below in more detail. However, the concept was primarily formulated to account for asynchronous collaboration in open systems rather than directly coupled work in face-to-face design.[40] Though it is undoubtedly useful, the conception of a boundary object by itself is not sufficient to encompass all the roles of shared representations in design collaboration.

Activity Theory

Activity theory views consciousness as intertwined with purposeful activity, in a manner that encompasses social, historical and cultural factors as well as the use of tools and artefacts. It was developed initially by Soviet social psychologists in the early 20th century (Vygotsky, Leont'ev, Luria) who were dissatisfied with the then-dominant approaches of

[40] Star & Griesemer (1989) explicitly elaborate translation in the interessement model, referring to Latour and others without mentioning by name actor-network theory—possibly because the term was not yet in common use.

behaviourism and psychoanalysis. Through its subsequent, international development (cf. Engeström 2001, 1999b; Kuutti 1996), activity theory continues to view collective work and individual development in terms that are fundamentally social. Its effects have been felt principally in education, with increasing interest from human-computer interaction (Nardi 1996), and developmental work and organization research (Engeström 1999c, 2001).

> Activity theorists argue that consciousness is not a set of discrete disembodied cognitive acts (decision making, classification, remembering), and certainly it is not the brain; rather, consciousness is located in everyday practice: you are what you do. And what you do is firmly and inextricably embedded in the social matrix of which every person is an organic part. This social matrix is composed of people and artefacts. Artefacts may be physical tools or sign systems such as human language. Understanding the interpenetration of the individual, other people, and artefacts in everyday activity is the challenge activity theory has set for itself. (Nardi 1996, pp. 7-8)

> To be able to analyze such complex interactions and relationships, a theoretical account of the constitutive elements of the system under investigation is needed. ... Activity theory has a strong candidate for such a unit of analysis in the concept of *object-oriented*, *collective*, and *culturally mediated human activity*, or *activity system*. Minimum elements of this system include the object, subject, mediating artefacts (signs and tools), rules, community, and division of labour. (Engeström & Miettinen 1999, p. 9)

Activity theory utilizes an elaborate concept of mediation to account for the ways in which cultural and historical knowledge are embedded in, and systemically reproduced by elements of an activity system. This essentially involves a triadic relationship between the acting subject, the object of activity, and a community or society; mediating elements are interposed between each of these, including persistent social structures (institutions, rules, division of labour), artefacts and tools. (Engeström 1999b, Kuutti 1996).

Compared to actor-network theory, the activity theory perspective offers a richer portrayal of motivation, principally by conceiving of activities as object-oriented. As Nardi (1996) and others note, this insight is both extremely useful and potentially confusing—owing to the multiplicity of meanings associated with the English word "object."[41] In activity theory, an object is the focus of an activity—as an *objective*, but in a transcendent manner apart

[41] Engeström & Escalante (1996) provide an explication of the term in its original philosophical context (German, "Gegenstand" vs. "Objekt"). To avoid confusion, Gregory (2000) refers to "teleological objects and motives," while Christiansen (1996) prefers the term "objectified motive." I will adopt use of the term objectified motive, or object-motive to refer to an object in the activity-theoretic sense.

from any short-term goal. Neither an abstraction nor a generalization, the object is the receiver of the activity and has a concrete specificity in every case, even if it is immaterial.[42]

> An activity is a form of doing directed to an object, and activities are distinguished from each other according to their objects. Transforming the object into an outcome motivates the existence of an activity. An object can be a material thing, but it can also be less tangible (such as a plan) or totally intangible (such as a common idea) as long as it can be shared for manipulation and transformation by the participants of the activity. (Kuutti 1996, p. 27)

In activity theory, the object is situationally given in the context of a practice at the same time it is socially constructed—perceived in terms of other mediating tools and artefacts. The object is a projection that is continually updated and transformed as the activity unfolds. The distance between the object and an outcome in any instance provides motivation to complete, to improve, to learn, and to alter practice. Approached but never reached, the object is a moving target (Engeström 2001).

> Practical activities have this strong organizing potential due to their objects. Objects should not be confused with goals. Goals are primarily conscious, relatively short-lived and finite aims of individual actions. The object is an enduring, constantly-reproduced purpose of a collective activity system that motivates and defines the horizon of possible goals and actions. (Engeström 1999a, p. 170)

Another, particularly useful insight from activity theory is the recognition that activities comprise a hierarchy of levels. Below the level of the object-oriented *activity* is an intermediate level of consciously formulated, individual *actions* directed toward shorter-term goals. Below this, at the lowest level, routine *operations* are carried out almost automatically on the basis of necessary instrumental conditions (Engeström 1999b; Kuutti 1996). Thus there is a pairing between levels within the activity and the target to which each is oriented. Relations of upward and downward causation also exist between levels, so that the activity dictates certain actions, which in turn dictate particular operations; at the same time, inability to perform an operation may lead to reformulation of the action, which may in turn result in alteration of the activity.[43]

Heath, Knoblauch & Luff (2000) note that, by relating phenomena across levels, between individuals, persistent social structures and artefacts, activity theory potentially embodies a solution to "the vexed problem of macro and micro." (p. 307) Nardi (1996) concurs,

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[42] For example, in the practice of medicine, the *patient* is identified as such an object—one whose transformation into a state of health gives purpose and direction to the activity. It might be that design can be characterized as an activity in which the object *is a representation* with particular properties, including an essential and instrumental identification with a fictive, preferred future.

[43] Cole (1999), based upon Wartofsky (1979), also identifies specific types of mediating artefacts (primary, secondary and tertiary) based on the scope of the mediating function at each level.

describing activity theory as “a powerful and clarifying descriptive tool rather than a strongly predictive theory.” (p. 7) For Star (1996), activity theory offers, “the most sophisticated approach I have found toward understanding the historical and material specificity of cognition, and a way to do away with arguments about perception and cognition that are either idealist or determinist.” (p. 296) However, comparing the relevance of actor-network and activity theory for the research I intend to conduct, certain tensions can be identified that shed light on the limitations of each.

In the design of a complex product or technological artefact, different domains and disciplines are almost always involved, comprising distinct activities with their own objects, mediating artefacts, etc. Engeström (2001) and Engeström & Miettinen (1999) identify the need to grapple with multiple, intersecting activity systems as a principal challenge for further development of activity theory. They mention the concept of a boundary object (cf. Star & Griesemer (1989) and Star (1993), discussed above) in this context. This highlights two inconsistencies that are important to note.

First, as formulated in actor-network terms, boundary objects are solutions to recurring problems of coordination and translation that arise in collaboration across social worlds. Star & Griesemer (1989) developed the concept to describe the materially-stabilized intersection of utterly different social worlds that sustained an early natural history museum. In this process, a number of boundary objects (which Star & Griesemer class as repositories, ideal types, terrains with coincident boundaries, standardized forms and labels) ensured a necessary continuity of practice across the diverse interests of the museum directors, various collectors, trappers in the field, and university administrators. While a boundary object is a salient feature of practice in each world, its importance stems from the imperatives of *collaboration*; it is not, in itself, an objectified motive. Thus a rather fundamental contradiction in terms arises: in activity theory parlance, a boundary object would probably be classified as a mediating tool or artefact rather than an object, because it does not necessarily motivate or provide essential direction to any activity.

Such a semantic difficulty is potentially confusing but not intractable. There is a second, more fundamental issue around what constitutes the basis of sharedness. To perform its role, the boundary object necessarily presents a minimal but robust structure that is *shared* across contexts. The robustness of many of the forms identified by Star & Griesemer—at least in conventional practice—is derived in part from their concrete form and material presence. As the situated action perspective makes clear, co-present, interacting individuals extensively rely upon concrete, physical and material resources in their environment as an economical and effective basis for shared reference and disambiguation.

Engeström (1999c, 2001) discusses the importance of shared objects—in the activity theoretic sense of an objectified motive—in interacting activity systems. Engeström's (2001, p. 136) depiction of shared objects portrays the "unreflected, situationally given 'raw material'," as the *least shared* manifestation—because it has not undergone collective construction. The possibility that shared mediating artefacts might also be an important basis is not addressed. Engeström's depiction therefore seems to preclude the existence of objects that are readily shared on the basis of their concrete, material physicality, without embodying a co-constructed objective—in other words, precisely what we understand boundary objects to be.

The resistance of activity theorists to unequivocally differentiate between material and non-material artefacts is understandable. Vygotsky's foundational insight of the mediated relationship between the subject and the object was an essential step to overcome the rigid, deterministic behavioural accounts the early activity theorists sought to replace. As Kuutti (1996) makes clear, the triadic relationship between the non-mediating constituents of an activity system are those between the subject, the object and the *community*. (Compare this to the triadic communication model in the situated action perspective, of co-present human participants and physical artefacts.) In order to understand the asynchronous, varied and diffuse interplay between the individual subject and a community, society or culture, the account of the mediating function must transcend co-present individuals. In this case deemphasizing concrete materiality may be appropriate. However, as studies of situated, collaborative design activity make clear, concrete, material artefacts *are* important for a variety of reasons. If one takes the position not to recognize distinctions between what is external and internal, or between the material and immaterial in one's conceptual framework[44], then one cannot possibly make statements about the roles of shared external representations in design.

A second tension relevant to design and the interests of designers exists between the activity theory and actor-network theory accounts of innovation and change. On one hand these are seen as resulting (in activity theory) from internal contradictions *within* an activity system, vs. (in the ANT account) from breakdowns, competing claims, shifts in the interessement and conscription of key actors. Engeström & Escalante (1996) discuss the shortcomings, in their view, of actor-network theory to account for the failure of a particular innovation: a novel multimedia postal service kiosk. After discounting any sort of Machiavellian betrayal from within, or nefarious meddling from outside the development team, they highlight the

[44] Engeström (1999c, p. 381) explicitly advises against differentiating between external, physical mediating artefacts and internal, cognitive ones.

lack of a shared object—significant disparities between the objectified motives apparently held by key stakeholders. This in turn is used to account for the tenacious commitment of the kiosk's developers to their product concept, and their imperviousness to mounting evidence of a mismatch between it and the desires of users and the requirements of the postal service.

Engeström & Escalante point out that actor-network theory does not address the inner dynamics of participants' activity, or delve into *why* an actor might pursue a particular course of action in other than a very narrow sense. Indeed on one level, in accounting for cultural re-production as a dialectic between internalization and externalization (Kuutti 1996, Engeström & Miettinen 1999), activity theory seems to recognize creativity and vision more naturally than does actor-network theory. However, I am not convinced that identifying contradictions within activity systems is a more effective or economical approach to explaining such failures of innovation, compared to tracking the networks of competing claims and failures of interessement that would constitute an actor-network account.[45] However, as Engeström & Escalante also point out (citing Button 1993), actor-network accounts provide little insight into the concrete actions, and communicative practices—in essence the interactional work—through which actor-network processes are brought about.

Distributed Cognition

For some time, recognition has come from within cognitive science itself of a need to take the physical environment, social and material context more fully into account in theorizing about cognition and cognitive processes. Various approaches seek to move the focus away from disembodied symbol processing through observation of individuals engaged in everyday cognitive tasks in real-world settings. These approaches include situated learning (e.g. Lave & Wenger 1991, Wenger 1998), situated cognition (e.g. Brown et al. 1989, Clancey 1997, 2002), socially-shared cognition (e.g. Resnick et al. 1991, Nye & Brower 1996) and distributed cognition (e.g. Hutchins 1995, Norman 1993). Hutchins summarizes the shortcoming these perspectives have sought to address thusly:

> The early researchers in cognitive science placed a bet that the modularity of human cognition would be such that culture, context, and history could be safely ignored at the outset, and then integrated later. The bet did not pay off. These things are fundamental aspects of human cognition and cannot

[45] Competing claims could include, for example, opposition from both the postal workers' union and an internal development group, resentment of a restrictive contract (all mentioned by Engeström & Escalante but not strongly implicated in their explanation), or perhaps a nascent recognition that these functions could eventually be accomplished via the internet to satisfy the same constellation of stakeholders—as is now in fact the case.

> be comfortably integrated into a perspective that privileges abstract properties of isolated individual minds. Some of what has been done in cognitive science must now be undone so that these things can be brought into the cognitive picture. (Hutchins 1995, p. 354)

Amongst these perspectives, Nardi (1996) identifies distributed cognition as a particularly promising complement to activity theory by virtue of its detailed focus on external artefacts and representations. Distributed cognition frames canonical cognitive processes (memory, decision making, inference, reasoning and learning) in terms of the propagation of information across representational states (Hutchins 2001). Proponents argue, however, that in real-world settings these phenomena often cannot be meaningfully localized to individuals; instead they are essentially distributed between individuals, across various external artefacts and over time (Hutchins 1995, Hutchins & Klausen 1996, Hutchins & Hazlehurst 1991, Norman 1993, Zhang 1997). By attending to the interplay between structures that are internal to individuals and those embodied in external representational artefacts, distributed cognition shows particular interest in precisely what activity theory chooses to overlook.

The desire to understand in details the propagation of information across representational states leads distributed cognition researchers to focus their attention on relatively structured task environments, such as those found in shipboard navigation, piloting aircraft, etc. In such situations, distributed cognitive systems are required to perform reliably and accurately under time and other pressures; failures may have severe consequences, potentially including loss of life. These often complex, multi-person, technologically-mediated tasks nonetheless can be seen to embody what is essentially a computation—that is, from a system-level perspective they take inputs and transform information to bring about an output (e.g. taking sightings to bring about a change in course, cf. Hutchins 1990, 1995).[46]

The structure inherent in these tasks presents strong constraints which make it possible to infer more about internal processes that are not themselves directly observable. However, such structured tasks bear little resemblance to the more open-ended and contingent nature of design activity. Also, the representational artefacts that are employed tend to be more exclusively structured around the performance of specific computations than is the case in design. The ability of this approach to handle phenomena encountered in design is

[46] Beyond the purely computational structure of the tasks involved, Hutchins describes how distributed cognition systems in these settings also respond to more ecological needs of group support and maintenance. These include the need to train novices and continually integrate new members, and to function robustly even with the loss of individual members, equipment malfunctions or other unforeseen circumstances.

consequently limited. However, several of the principal insights from distributed cognition are relevant to the research I will undertake.

First, echoing the earlier discussion of design activity, distributed cognition systems can be seen to exhibit behaviours that arise from their *social organization* which are not reducible to properties of any of the constituent individuals or technologies (Hutchins 1991, Zhang 1997). Second, rather than "amplifying" any particular innate capability, external artefacts and representations operate in conjunction with human cognition to *change the terms of the human task* from one that is difficult to one that is more straightforward.[47] As a result, the cognitive processes taking place within the person are not the same as they would be were it possible to perform the task without the artefact. Finally, following Simon's notion of representations as acting to make solutions transparent, in accomplishing a given task as part of an overall cognitive system (persons plus artefacts), some representations can be seen to be more effective than others. (Zhang 1997b, Chuah et al. 2000, Norman 1993, Hutchins 1990)

Distributed cognition researchers differ with regard to the strength of their descriptive statements about the internal structures involved in cognition (i.e. describing them as internal, or mental representations, as discussed in the following section). Aside from positing certain functional constraints, Hutchins (1995) is agnostic with respect to internal mental structures; in later work Hutchins (2005) elaborates on the internal cognitive operations associated with artefacts with reference to conceptual blending theory. Conceptual blending (Fauconnier & Turner 2002) is the generalized human capacity to map conceptual structure between mental spaces or domains to create a new mental space with emergent properties. This capacity accounts for specific manifestations, such as linguistic metaphor, as well as more general achievement of "conceptual compressions" of vital relations, such as those involved in understanding change, identity, time, space, cause-effect and part-whole relations (Fauconnier & Turner 2002).

In keeping with distributed cognition's focus on what are essentially computational activities, Hutchins (2005) describes "material anchors" as artefacts whose physical structure contributes substantially and directly to the conceptual structure in the blend space. His principal examples are computational aids that enable otherwise daunting and complex calculations to be carried out through a series of simple and robust perceptual operations. Hutchins indicates his conception of a material anchor is narrower than that of Fauconnier &

[47] In navigation, this involves converting the act of solving an algebraic equation to a series of simple perceptual operations and manipulations over physical artefacts, the structure of which embody the constraints of the equation (Hutchins 1990, 1995).

Turner, who describe a far greater range of material objects figuring in all manner of imaginative processes.[48]

Design representations appear to fall somewhere between these extremes. They have a determined material structure (with pictorial, symbolic and diagrammatic aspects) that is more intentional and instrumental than most examples described by Fauconnier & Turner. However, though they may have important computational components, these representations facilitate conceptual operations that are more open-ended and imaginative than the computational aids Hutchins describes. As a result, taking Nardi's (1996) assessment into account, it appears there is still work to be done to synthesize activity theory with insights regarding external representation found in distributed cognition.

Summary of Points from Theoretical Perspectives

Based on this review of relevant theoretical perspectives, I plan to take the following aspects forward in order to better understand situated, collective, real-time design activity:

- the idea that interaction creates—at the same time it depends upon—tokens of shared meaning and mutually-intelligible action. That beyond shared meanings, effective joint action frequently rests upon a variety of nuanced communicative behaviours afforded by shared reference and physical co-presence.
- the appropriateness of a triadic communication model that encompasses bi-directional interactions, directly between human participants as well as over and with external artefacts and representations
- the broad relevance of the conception of a *network*, whether construed loosely in terms of interlinked action (as in symbolic interactionism), in a more specific account of synchronic associations between human and technological actors (as in actor-network theory), or in a cultural-historical account of mediation between elements of an activity system (as in activity theory)
- the notion that activities involve or can be observed at different levels of subjective awareness, that different approaches may be appropriate for research questions at different levels

[48] Hutchins discusses fictive motion (a metaphor), the method of loci (a memory technique), the Japanese hand calendar (a calculation), Micronesian "Etak" navigation (a practice), the compass rose as a tide computer, as well as clocks, dials and slide rules. Fauconnier & Turner (2002) discuss timepieces, gauges, money, souvenirs, gravestones, cathedrals, writing, speech and signs as material anchors.

- potentially useful aspects of actor-network and activity theory, as well as their respective shortcomings: (a) how actor-network theory foregrounds dynamics of allegiance, conscription and punctualisation but does not describe the detailed, interactional work through which these processes are accomplished; (b) how activity theory recognizes the importance of artefacts and tools (vis-à-vis levels of awareness) in the constitution of an objectified motive, but does not offer a detailed account of what transpires between the material and immaterial, particularly at the intersection of activity systems; (c) the relevance of distributed cognition in this regard—apart from the fact that its locus of attention is on structured, essentially computational tasks that cannot encompass the breadth of design activity
- finally, that these perspectives differ with regard to whether they incorporate a notion of *representation*, what sorts of properties they identify and whether or not they prominently differentiate between phenomena that are internal vs. external to individual human beings (discussed in more detail in the final section of this chapter)

To elaborate these themes in the context of design, I now turn to several situated ethnographic studies that make more explicit use of the theoretical perspectives outlined above.

Theoretically-informed Ethnographic Studies of Engineering Design

Having drawn attention to essential aspects of design as a group activity, and having reviewed a number of theoretical perspectives to understand situated work involving artefacts and representations, I now briefly review three more theoretically-informed ethnographic studies of real-world design practice in organizations. These studies utilize some of the concepts identified above, and illustrate how they have been employed with regard to design. They also illuminate some of the important remaining questions this work will endeavour to address.

Henderson: Conscription Devices and Meta-indexicality

Henderson (1999, 1995a, 1995b) conducted ethnographic studies of situated engineering design practice, attending particularly to their use of technologies for external representation. Her study focuses on a time of transition, from the use primarily of paper-based drawings to the adoption of computer-aided design (CAD) tools. The dynamics of this transition allow Henderson to more fully expose a variety of functions played by such representations, particularly in the case of the more traditional, paper-based media.

Henderson employs a number of concepts from actor-network theory to make sense of her observations. She sees that drawings—widely shared and subject to multiple readings by different departments—function as boundary objects in a variety of settings. However, Henderson confirms that the conception of a boundary object is not adequate to describe all the roles of visual representations in engineering design. Beyond communication and coordination, she highlights their role as a "social glue" in organizing the design-to-production process.

> The analysis reveals that visual representations, including prototypes, are not only devices for communal sharing of ideas but are also a ground for design conflict and company politics, exactly because they facilitate the social organization of workers, the work process and the concepts that workers manipulate to produce a collective product. (Henderson 1999, p. 10)

Henderson captures this directional, more "political" dimension, drawing a distinction between the coordinating function of boundary objects, and the more instrumental functions of design representations as "conscription devices." The distinction highlights power issues, and the fact that design representations are implicated in management decisions regarding allocation of resources in which some will win and others will lose.

Closely observing designers' behaviour over pencil drawings, Henderson identifies another essential property of design representations as "meta-indexicality." In elaborating this concept, Henderson portrays the richness and depth of interaction with representations in this context in a way that goes beyond what is conveyed solely by the actor network-theoretic conceptions of boundary objects and conscription:

> Why are visual representations so powerful? I have suggested that it is their meta-indexical quality—their ability to be a holding ground and negotiation space for both explicit and yet-to-be-made-explicit knowledge — that allows them to be more than the sum of their parts as well as more than Latour's 'centre of calculation.' ... one very important capacity of the visual lies in its malleability—its ability to be drawn interactively and shaped and redrawn and reshaped by members of an engineering design group. In this process, the visual representation integrates and informs the collective and changing cognition of those designing it. Equally important is the particular way visual representations facilitate the joining of not only multiple meanings but multiple forms and formats of coded and un-coded, verbal, visual, mathematical, and tacit knowledge. This ability to serve as a gathering ground for multiple ways of knowing is the meta-indexical property. (Henderson 1999, p. 199)

Henderson argues that, compared to CAD representations, sketches and drawings better support meta-indexicality through their flexibility and malleability. These properties, she argues, complement the "multivisual competencies" of engineers that are essential to creativity in individual and group design work. Drawings more readily accept information in different formats, carrying marks and modifications—Latourian *inscriptions*—made in a variety of ways by different people. By virtue of these properties, representations serve as both individual thinking tools and as interactive communication tools. Epitomizing these properties, sketches are "the real heart of visual communication" in engineering design (Henderson 1999, p. 81, p. 203).

In seeing design representations as boundary objects, conscription devices and carriers of inscriptions, Henderson's discussion makes clear the relevance of actor-network conceptions to situated, collective design activity. Her conception of meta-indexicality as an essential property points toward the interactional work (cf. Engeström & Escalante 1996) performed by representations. However, though she refers to combinations of various forms of knowledge—including tacit knowledge—and the "mobility, stability, and combinability" of representations, this is not an explicit account of how actor-network processes are accomplished vis-à-vis design representations. With regard to the individual thinking, interactive communication and collective cognition Henderson refers to, we need a more detailed description of what these entail.

Carlile: Boundary Objects and Knowledge Transformation

Carlile (2002) undertook an ethnographic study of interdepartmental communication in engineering product development in order to understand the dual character of knowledge as both a source and a barrier to innovation. He examined the way knowledge was structured within the four primary functions involved (sales/marketing, design engineering, manufacturing engineering and production), and observed the roles of various boundary objects in facilitating communication across functional boundaries. While Henderson (1999) highlights the ability of a representation to bring together and hold diverse knowledge in a variety of formats through the property of "meta-indexicality," Carlile offers additional insight into the knowledge processes taking place.

From a knowledge point of view, functional specialization in product development organizations gives rise to boundaries of difference and interdependence. For novelty to lead to innovation, individuals in different functions must make a tradeoff. In order to develop the new knowledge necessary to realize an innovation, they must be willing to forgo or modify some of their existing knowledge—in which they may have invested significant personal energy and identity.

> The cross-boundary challenge is not just that communication is hard, but that to resolve the negative consequences by the individuals from each function they have to be willing to alter their own knowledge, but also be capable of influencing or transforming the knowledge used by the other function. (Carlile 2002, p. 445)

Emphasizing the distinction between *within* and *across*-functional interaction, Carlile distinguishes between syntactic, semantic and pragmatic dimensions of boundaries.[49] The pragmatic dimension must be addressed for novelty to lead to innovation, because only this takes into account individuals' incentives to engage in the transformation of knowledge required for an innovation to be successful.

> A pragmatic approach assumes the conditions of difference, dependence and novelty are all present, and so recognizes the requirement of an overall process for transforming existing knowledge to deal with the negative consequences that arise. Here, transforming knowledge (Carlile 1997) refers to a process of altering current knowledge, creating new knowledge, and validating it within each function and collectively across functions. (Carlile 2002, p. 445)

As Carlile notes, the numerous and complex ways "knowledge" may be said to come into play in routine interaction makes it difficult to assess empirically. To facilitate observations and highlight the differences and interdependencies between functions, Carlile employs an analytical distinction between the *objects* with which people work (things they manipulate, including numbers, parts, tools, schedules) and the *ends* they pursue (including figurative descriptions of the objective or desired state of affairs). Carlile then provides vignettes of cross-functional interactions, using the example of an assembly drawing in a particular exchange to illustrate the ability of some objects to span pragmatic boundaries better than others.

Carlile proposes that to be effective, boundary objects must allow participants to represent, learn, negotiate, and alter their knowledge. Overcoming syntactic, semantic and pragmatic boundaries requires (respectively): establishing a shared syntax, providing interactants with a way to specify their differences and dependencies, and creating a field within which they can jointly transform their knowledge.

Both Henderson and Carlile find that design engineering and product development require elaboration of the basic concept of a boundary object. Henderson articulates the additional function of a "conscription device" along lines suggested by actor-network theory. Carlile identifies a subset of Star & Griesemer's (1989) typology of boundary objects (objects, models and maps) which he proposes have the characteristics necessary to span pragmatic boundaries and support knowledge transformation. These claims have different emphases but are not really contradictory. Both confirm the basic utility of the concept of a boundary

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[49] These reflect, respectively, the information-processing (e.g. Galbraith 1973), interpretive (e.g. Dougherty 1992), and community-of-practice (e.g. Lave & Wenger 1991, Brown & Duguid 1991) approaches to knowledge in organizations. Carlile argues that even the community-of-practice perspective does not necessarily highlight the pragmatic dimension until emphasis is placed on cross-community (rather than within-community) knowledge transformation.

object in understanding complex real-world design. In describing functions beyond translation and coordination, both convey a similar sense of encounter, mixing and synthesis. While Henderson's conception has a satisfyingly granular feel with respect to the actual media and the way they are used, Carlile's identification of the prerequisites for knowledge transformation (establishing a shared syntax, specifying differences and dependencies) gives a more concrete idea of the processes involved. Both Carlile and Henderson refer to the particular utility of prototypes, again with a slightly different emphasis.[50]

However, questions remain regarding the nature of the interactional work taking place over these representations. Whereas Henderson's term "conscription device" metaphorically suggests what is involved, Carlile's description of knowledge transformation (and the associated representational activity) in the end seems somewhat abstract and non-specific. It identifies prerequisites, but does not indicate what might motivate, constrain or provide direction to the actual transformation. Carlile's examples of the objects and ends employed by each of the four functions are compelling and vivid.[51] This distinction parallels, and tends to confirm the relevance of the activity-theoretic notions of artefacts and objectified motives—though it makes no mention of activity theory. However, in his account of knowledge transformation, the vividness, tangibility and motivating aspect of the objects and ends is not retained.

Compared to the notion of conscription in the actor-network account, the construct of knowledge does not by itself have a direct, consequential relationship to innovation. Aside from knowing that *some* new knowledge will be required, on what basis can we say that any particular knowledge that arises through interaction leads to innovation? At the level of interaction, in terms that are meaningful for design, we would like to know what knowledge transformation involves, what motivates it and what it looks like as it is accomplished.

Bucciarelli: Object Worlds and Collective Story-making

Bucciarelli (1988, 1994) also conducted ethnographic studies of professional engineering designers, focusing on the ways in which uncertainty and ambiguity are accommodated and

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[50] While the knowledge transformation function (described by Carlile) directs participants' attention to parts and particulars, the conscription function presumably arises from the effect of the whole or totality. Carlile also refers to pragmatic boundary objects as "integrating devices" (Carlile 2002, p. 453).

[51] Objects include: price and volume numbers, contracts (sales); drawings and parts (design eng.); prints, raw & finished stock, equipment (manufacturing eng.); millions of parts, schedules, machine utilization (production). Ends include: getting the "right" numbers and closing deals (sales); passing design reviews, meeting specs (design eng.); few operations, high volume process (manufacturing eng.); product out the door, minimum scrap, people working (production).

reconciled within what is nominally a rational and instrumental practice. Bucciarelli emphasizes the ways in which the consciousness of these designers is inextricably intertwined with objects and artefacts. He constructs an account of engineering practice as a form of mediated seeing, formulated in terms specific to engineering design. By identifying essential features of the discourse engineers use to communicate with and persuade each other, Bucciarelli sheds greater light on design knowledge and design thinking in this context.

Bucciarelli describes the ways in which engineers' awareness is directed toward, and shaped by the physical artefacts, phenomena, symbolic and mathematical relationships that are the stuff of engineering design. He formulates the term "object world" to convey this immersive, encompassing aspect:

> … to designate the domain of thought, action, and artefact within which participants in engineering design […] move and live when working on any specific aspect, instrumental part, subsystem or sub-function of the whole. (Bucciarelli 1994, p. 62)

> Mind and hand, thought and object are wrapped up together. The mind poses an explanation; the object is poked and responds. An instrument senses a small voltage signal over microseconds and, if properly tuned, transforms that information to human scale. The 'reading' becomes part of thought, part of a reconstruction of the object. This is an object-world experience. We detect in this episode the way the object infiltrates thought and how thought configures the object. (Bucciarelli 1988, p. 163)

Reminiscent of Dougherty's (1992) "thought worlds," Bucciarelli contends that different people—even engineers with different specializations—may regard the same physical object or phenomena very differently by virtue of the different object worlds they inhabit. However, a common structure or framework of rhetorical practices exists which allows engineers to engage each other across object-world differences:

> More than a common vocabulary and syntax, it is a web of tacit understandings of what is to be considered an honourable claim, a significant conjecture, a valid 'proof,' or a laughing matter. It is an accepted rhetoric for describing, proposing, critiquing, and disposing that girds all design conversation, fixing what constitutes a true and useful account. (Bucciarelli 1994, p. 83)

Bucciarelli articulates the defining characteristics of this rhetoric or "cosmology": a discourse which favours abstraction, sparseness and reduction, qualified estimation, measurement, constraint and conservation principles (e.g. making tradeoffs), cause-and-effect chaining and hierarchical decomposition. These constitute the essence of what it is to *see* as an engineer. In their interaction with hardware, natural phenomena and each other, the engineer's objective is the construction of a compelling deterministic account—a creative and rhetorically skilled process of "story making" (Bucciarelli 1994, p. 88). Bucciarelli's vivid descriptions provide us with additional insight into what knowledge transformation entails—at least in engineering encounters—as well as the meaning of "conscription" in interactional terms.

Bucciarelli refers repeatedly to Latour and clearly regards physical hardware and prototypes to be participants alongside humans in design activity. He makes less strong statements about drawings and more evanescent representations such as sketches, considering them analogous to "speech acts" in the process of story making (1994, p. 97). Determined to convey the dynamic and collective nature of designing, Bucciarelli resists any tendency to see "the design" as singularly encapsulated in formal drawings and specifications:

> In this way design is a social process, i.e. if we ask 'what is the design?' at any time in that process my response would be, following Durkheim, that it exists only in a collective sense. Its state is not in the possession of any one individual to describe or completely define, although participants have their own individual views, their own images and thoughts, their own sketches, lists, diagrams, analyses, precedents, pieces of hardware, and now spread-sheets which they construe as the design. This is the strong sense of 'design is a social process'. (Bucciarelli 1988, p. 161)

> The thesis of this book is that the process of designing is a process of achieving consensus among participants with different 'interests' in the design, and that those different interests are not reconcilable in object-world terms. […] The process is necessarily social and requires the participants to negotiate their differences and construct meaning through direct, and preferably face-to-face, exchange. (Bucciarelli 1994, p. 159)

Bucciarelli's concept of an object world is a useful way of understanding designers' subjective awareness and the discourse that underpins effective rhetoric in engineering design. In many ways reminiscent of activity-theoretic distinctions, it also emphasizes the particularly powerful role of tangible, material artefacts. Bucciarelli portrays the collective and social nature of design activity: its distribution across people, its evolution over time, its embodiment in multiple, overlapping views that are only fully reconciled at the end of the process—if at all. To whatever extent they are achieved, coordination and coherence must be continually renewed and negotiated—indeed this is the *work* at the heart of *design interaction.*

Summary of Theoretic Refinements from Ethnographic Accounts

These ethnographic studies of organizationally situated design illustrate the utility of a number of concepts from the theoretical perspectives above, and suggest ways in which they may be made operational in design activity. This also sheds light on questions raised by the gaps between the various theoretical perspectives with regard to the particular and purposeful nature of design activity. These related to the interactional work associated with actor-network processes, the behaviour of artefacts and tools at the intersection of activity systems, and the dynamics between material and immaterial with regard to open-ended and imaginative activities like designing.

Henderson's reference to *conscription* in the context of representations is suggestive of the character of the interactional work performed by prototypes and design representations in actor-network terms. Her conception of meta-indexicality includes the materiality of drawings and the affordances they provide in face-to-face interaction. It emphasizes the function of gathering and juxtaposing knowledge in different forms, but lacks detail on the nature the knowledge work representations help to accomplish, or an account of what gives this work direction and purpose. Carlile provides more detail on the work that representations must accomplish to effectively span or mitigate boundaries and support innovative multi-disciplinary design activity. Though he describes the functional constraints such boundaries place on representations at different levels, the process of *knowledge transformation* itself is still formulated in rather general terms.

By conveying the rich texture and physicality of the object-worlds of engineers, Bucciarelli provides an account of their subjective awareness and mediated seeing reminiscent of that found in activity theory. Describing the negotiation of differing interests and intersecting object-worlds, he portrays the interactional work involved in design as the construction of a mutually-acceptable *story* with the right kinds of discourse characteristics. What is still missing is a detailed picture of the way in which different object-world discourses are brought together—around shared representations—to accomplish the specific interactional work that results in the achievements of conscription, knowledge transformation, and collective story making.

While the theoretical perspectives differ with regard to notions of representation and distinctions between external and internal mental structure, these ethnographic studies underscore the particular power of the tangible representational artefacts employed in design. Because the question of representation is complex and contested, it is necessary to take an explicit stand on precisely what I mean by the term in the context of this study. This final topic is the subject of the following section.

Bounding the Concept of Representation

The theoretical resources discussed above differ as to whether or not they embrace a notion of representation, and in the extent to which they distinguish between external, material and internal, mental structure. It is my intention to focus first on *external* representations that are also *shared*, in that they are jointly available to participants. I will subsequently devote analytic attention to the manner and degree to which these representations are jointly constructed in design interaction. My goal in this section will be to make clear the position I am taking and offer supporting reasoning—not to resolve the complex and vexed philosophical issues around notions of representation more generally.

As we saw above, Actor-network theory highlights the importance of external artefacts—particularly technological artefacts and representations—as essential to the production and dissemination of inscriptions; Latour, however, sees their importance in terms of the effective mobilization of allies, not as matters of perception or cognition. Activity theory delves into individual consciousness and mediation by tools and artefacts, but argues against a distinction between internal aspects and external, physical manifestations (cf. Engeström 1999c)—a position I find unsuitable for the objectives of this research.

The perspectives that focus primarily on co-present, face-to-face interaction tend to make more prominent differentiation between what is internal vs. external to individuals. Among these, situated action and distributed cognition take very different stances with regard to the notion of representation. While situated action draws attention to external artefacts as essential resources, it is sceptical of the notion of representation from cognitive science. Limiting attention to immediately-observable behaviour, it avoids speculating about the meanings artefacts hold for participants or what else they may stand for. Distributed cognition goes much farther to infer the dynamics between external artefacts and internal mental structure, though prominent advocates differ in the extent to which they are prepared to describe internal structure in terms of representation.[52] These differences offer a useful starting point.

Externality

What does it mean to describe something as a representation, and why might this be problematic? Some objections stem from conventional use of the term within cognitive

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[52] Whereas Zhang (1997) and Norman (1993) refer matter-of-factly to *internal* representations, Hutchins (1995, p. 131) states that it is possible only to infer certain functional specifications of internal structures that must be present, since their organization and propagation cannot be directly observed.

science in connection with symbol-processing models of cognition. As Agre (1997, 2003) points out, this usage is structured by root metaphors of knowledge as an internalized likeness of the world, and representation as the creation and manipulation of images or written texts. Agre asserts that, particularly in artificial intelligence (AI), discourse often relies upon these metaphors to blur distinctions between representational artefacts that exist in the external world and purported internal mental representations. Confusion is compounded when the word is used ambiguously to refer both to such internal structures and to the algorithms and data structures embedded in electronic devices—with the effect of collapsing human cognition onto the algorithmic processing of computers.

While conventional usage within cognitive science conveys a certain idea of representation, other senses of meaning are available. English lexicologist and cultural critic Raymond Williams (1983) identifies distinct senses of meaning for the English word *represent*, first arising in the 14th century from the older *present*—as in "to make present." Initially these included to stand for or in place of another (e.g. to appear in front of or in place of a person of authority), and to make present (to the eye or to the mind) that which is not there. Extensions followed shortly thereafter along the lines of "to symbolize" (e.g. to stand for something inherently abstract, such as the crown for the kingdom). Williams describes further elaboration, from the 17th century onward, of notions of representation as standing for a person or group—either as a typical example or in the political sense of representational government—and in the sense of a mimetic visual likeness or an accurate reproduction, reflected in the 20th century notion of *representational* art.[53]

Historical development of the word *represent*—and by extension *representation*—presents us with alternatives to the notions enshrined in AI, namely that of representations as composed of abstract symbols, and the (interestingly, nearly antithetical) notion of a veridical likeness that motivates the metaphor of an internal model or mirror of the world. Taking Agre's critique to heart, it seems the use of the term "representation" to refer to internal mental structure is likely to introduce unjustifiable entailments from our familiar experience of working with texts and images, leading me to believe its use is more misleading than revealing in this regard.[54]

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[53] The Oxford Concise Dictionary of English Etymology (1986) provides a consistent listing for *represent*: to bring into one's presence [obsolete]; to bring before the mind; to display to the eye; to symbolize; to stand in place of; to speak for (as in parliament). Derived from Old French *représenter* or Latin *repraesentare*; formed on RE + *praesentare* PRESENT (RE having the general sense of "back," or "again").

[54] For specific points of contention compare Norman 1993, Ch. 3, with the critique in Agre 1997, Ch. 11. Recent work, such as in embodied cognition, further suggests the diversity of internal structure potentially involved.

For the purposes of this thesis I will take a position in accord with Hutchins (1995) which is to avoid using the term representation to refer to internal mental structure, and to make only limited inference about individuals' internal states based on what is outwardly observable. In focusing on external representations, it is the older, perhaps less polar meanings—to make present (once or again) to the eye or to the mind, and to stand for in the manner of a proxy—that I would like to emphasize. [55]

Sharedness and Persistence

The next move I propose is to focus on external representations that are *shared*, in that they are jointly available for participants to implicate in their interaction. This differs from the execution of an individual task with the aid of an external artefact or display (e.g. Zhang 1997b)—even when such tasks occur within distributed cognition systems involving a number of people. In the situations I wish to address, representations' functions as communicative resources are at least as important as any computational results they aid or embody.

With his formulation of the concept of common ground, Clark (1996) provides a useful way of understanding what I wish to convey through the term "shared." According to Clark, common ground is the "great mass of knowledge, beliefs, and suppositions" that conversational participants believe they share, and upon which they rely for the coordination of meaning and understanding (Clark 1996, pp. 12-13). However, it is essential to recognize that such sharedness is problematic. People cannot know for certain what another person knows, believes or supposes; nor is the mere existence of an artefact or information in the environment sufficient for something to be deemed meaningfully shared. Communication rests upon our assumptions about these things, and inferences based upon observable behaviour and other attributes. These assumptions and inferences are subject to certain regularities that can be discerned, and this helps us understand both the richness of communicative behaviour and the work performed by material artefacts and representations.

Engaging successfully in conversation involves the management of an accumulation of common ground. Since common ground is not something that can be directly perceived, much of it remains implicit in everyday interaction. According to Clark, people infer the extent of their common ground primarily on two bases: communal and personal. Communal common ground is that which is inferred from perception of personal attributes (national, cultural, professional identity, organizational membership, interests, education etc.) or

[55] Indeed, it is the sense of external, material structure acting as a proxy for internal, conceptual structure that is employed by Hutchins (2005) in his notion of a material anchor.

presumed to be common or universal human experience. Personal common ground is that arising from shared experience participants have had together, including their recollection of prior interaction up to that point, and things that are available to their simultaneous perception (Clark 1996 p. 106). While common ground cannot in itself be observed, it *is* possible to observe people's behaviour in managing the *shared basis* of their common ground. Participants in conversation continually present, monitor and evaluate evidence—conveyed both explicitly and tacitly—to ensure the basis of their common ground is adequate for their purposes at hand. Conversational partners decide what level of evidence is required and engage in clarification and repair when they perceive the need to do so.[56]

While participants' interaction with each other provides an essential basis for their personal common ground, utterances and gestures are ephemeral, so participants must rely upon each others' memory. Persistent representations that have a simultaneous perceptual availability provide a particularly useful basis for personal common ground, since they can be viewed, indicated, touched and manipulated. They can also serve, as Clark points out, to make present the current state of a joint activity. In referring to *shared* external representations, I intend to mean those external representations that are (or have been) jointly available *and* implicated in interaction in such a way as to give participants justifiable confidence the representations serve as a *reliable basis for common ground*. This confidence is enhanced for representations that have a salient and *persistent* presence in the environment.

Co-construction

Finally, I propose to make a distinction between representations that enter into interaction in a predetermined form and leave unchanged, vs. those that are co-constructed in a meaningful way by participants. Clark's view of conversation as a joint project, in which common ground is actively and cooperatively managed, portrays communication as an inherently collaborative and constructive activity. Beyond the general conversational interactions portrayed by Clark, how does construction of common ground occur in conjunction with representational activity in collaborative design?

Representations can be approached with relatively little co-construction in mind. As a point of departure, consider the ubiquitous PowerPoint presentation. These purport to achieve rhetorical effectiveness through a clear and compelling message. However, this message—and to a large extent its performance—are encoded (or "freeze-dried", per Schrage 1995) in a relatively static and predetermined form. The tool's inherent schematization enforces a

[56] Individuals routinely ignore negative evidence up to some threshold for the sake of completing their conversational project with the least *joint* effort (Clark, p. 226). Clark proposes this as an extension of Grice's (1975) cooperative principle.

relentlessly hierarchical structure and a linear presentation (Tufte 2003). While hyperlinks may relieve the linearity and make additional information available on a discretionary basis, the structure of this information is still largely predetermined by the author, who as presenter is likely to have exclusive control over the pointing device as well. While questions and comments may be raised by members of the audience, these contributions are unlikely to be registered with the same salience or persistence as the predetermined presentation content.

I take no issue with the cause of clear and compelling information presentation; the reliable recovery of meaning and information from text, diagrams and maps is a prerequisite for effective reasoning and action over such representations (cf. Tufte 1983, 1990, 1997; Bertin 1983, 1981; MacEachren 1995, 2001). With regard to joint or co-construction however, the essential distinction I wish to make is between the use of external representation to re-present a previously formulated message—albeit in an effective or compelling manner—and shared representations that are *jointly constructed*, in such a way as to respond and embody contributions from a number of participants. What does it mean to co-construct a design representation? A few examples will serve to illustrate what I hope to convey.

Understanding the Co-construction of Design Representations

Analyzing conversational exchanges between programmers working side-by-side, Flor (1998) identifies four facets in the common ground necessary to successfully collaborate on a software design task. These include a shared understanding of the task, the compositional nature of the system being modified, the behaviour of the system, and the specific proposed modifications.

For Flor, however, what is being co-constructed is “a shared internal representation,” essentially equated with the programmers’ common ground. Flor uses the term “representation” in precisely the manner Agre (1997, 2003) critiques—that is, after making a nominal distinction between internal and external, Flor uses the term frequently without distinction. This has the effect of blurring descriptions of presumed mental structures with the actual contents of visual displays, thereby conveying a concrete and independent status to interactants’ common ground. The general problem with using the representation *metaphor* for internal mental structure, and subsequently collapsing it with external representation in this way is that it tends to make the interplay between internal structure and external representation appear transparent, a non-problematic issue of the movement and depiction of information. The important point here is to avoid equating a persistent shared external representation with common ground. Instead we must keep the construction of a basis for common ground in discourse conceptually separate and analytically distinct from external representational activity.

Fleming (1998) portrays the co-construction of design objects in discourse by analyzing studio conversations between professors and students. He discusses three functions of talk in this context: indexing, constituting, and elaborating. Indexing talk is that which picks out features and aspects of artefacts (e.g. naming, locating, guiding attention); the nature of these features is then established through constituting and elaborating talk, which also serves to fix form and authorship with regard to agency and intention. Fleming draws attention to the reciprocal, mutually constitutive relationship between words and material artefacts in the "coming-into-being" of an object in the design studio. The object serves to elicit and anchor discourse through which it is defined, understood and rendered substantial. [57] At certain points, according to Fleming, the design may be constituted *solely* in talk if no material artefact or representation has yet arisen.

Fleming illustrates co-construction of design objects accomplished through participants' acts over time. As a linguist, he brings considerable insight to the use of language but has nothing like a comparable typology for the analysis of non-verbal or representational activity.[58] Tang (1989) documents designers' multi-modal interaction over shared external representations. The principal modality, talk, is often accompanied by listing, drawing and significant gesturing—each of which figures in the accomplishment of workspace activity. In his observations, Tang notes that the immediate manner in which ideas are received by the group has a strong impact on the "career" of an idea. In particular, while some ideas remain associated with particular individuals, others seem to become group property. Periods of highly engaged interaction also tend to mark what are later seen as key junctures in the design reasoning of the group. Thus we see that a sort of social vetting of ideas is essential to collective design activity, part of the process whereby a group comes to a decision.

While Tang encounters difficulty with ideas per se as robust units of analysis, his account makes clear that the manner in which individual contributions are received by the group, and the overall level of engagement of members in various modalities, are potentially important indicators (Tang 1989, pp. 107-109). Barron (2003) similarly notes the importance of group reception in learning and problem-solving performance. Barron finds problem solving

[57] Fleming (1998) describes such objects as becoming stable and "rhetorically consequential" (p. 49). In a studio setting, this type of shared understanding—put into practice—becomes the basis of the appreciative system discussed by Schön.

[58] It's also the case that Fleming was observing presentations and critiques rather than the type of dynamic work-in-progress we see in real-time design.

success in student triads most strongly associated with the ways the groups manage their attention and the extent to which they develop a collaborative orientation.[59] This can be seen in the relatedness of individuals' contributions with respect to one another, the climate of receptivity to proposals, co-regulation of attention to form a shared problem space, and the energy of interaction—as reflected in talk, body movement and engagement with shared external representations (in the form of a shared workbook in Barron's case).

Bødker (1998) describes the ways in which different representations employed in software design engender or require co-construction, making the point that these may be more or less appropriate for different purposes. Bødker primarily adopts an activity theory perspective, however she affirms the need to consider the external, material presence of representations that exist independently of designers. Bødker presents a typology of the things representations need to *make present* to collaborating software developers, including the designed object, the context, and the process of designing.

In discussing prototypes, formal descriptions, ad-hoc representations, and scenarios, Bødker proposes thinking about representations first in terms of a dynamic between affordance and resistance. Affordance makes the work of collaborative designing easier. Resistance may also be useful when it embodies constraints designers must take into account, but unhelpful when it obscures aspects of the situation or context that are important to users or other stakeholders. Bødker identifies the need for balance between representation of the existing and the new, pointing out that some representations particularly afford the creation of novelty while others are better suited to development and technical refinement. Bødker makes a second distinction between representations whose primary purpose is to facilitate within-practice relations between designers, as opposed to boundary crossing when designers work with users and managers. Here the essential dynamic is between the fluidity and openness more useful in supporting designers' direct collaboration with each other, versus the stability and closure that enable the crossing of boundaries.[60]

We can see from Bødker's account that all representations require completion in one form or another. Ad-hoc representations like drawings and sketches are the most fluid, but may not be robust or intelligible outside the very specific context of interactions between designers. Abstract formal descriptions are the most closed and perhaps the most transportable, but

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[59] On the basis of quantitative aspects of her study, Barron (2003) was able to exclude a number of plausible alternative explanations, including individual performance and the frequency with which correct proposals were voiced (but not necessarily picked up or acted upon by the group).

[60] Bødker makes the specific argument that while abstraction is one way of achieving closure to aid in boundary crossing, this is usually at the expense of loss of information about context of use. Bødker argues that scenarios are useful because they provide a transportable way of recreating context without resorting to abstraction.

require knowledge of the terms and formal language as well as imaginative projection back into any particular use context. Prototypes make very definite statements about the precise nature of what is envisioned and allow these to be tested in the context of use, but do not by themselves convey the reasoning behind any particular feature or alternatives that may have been considered. Scenarios allow for the context of use to be recreated in a performative way, but also presume a significant level of reliable background knowledge for the performance to be meaningful.

Bødker's ultimate point is that different types of representation are useful for different things, and that successful practice rests upon on skilful use of a variety of representations rather than reliance on a singular approach. She provides insight into the different types of knowledge that must be made present in a persistent and shareable way. She gives us an idea how different types of representation may participate and undergo co-construction in different ways, and when each may be more or less appropriate. However Bødker does not give an account of the specific types of acts that might be involved in any instance. Furthermore, in advocating that we think of representations as containers for ideas, Bødker risks the shortcomings of what Reddy (1993) describes as the conduit metaphor—namely, suggesting that ideas can be un-problematically placed in representations, reliably held and recovered for later use. Representations can be co-constructed in that attributes and meanings can be associated, establishing features and contextualization in ways that are more or less recoverable, but this always requires some level of shared experience and knowledge in common as well as a collaborative orientation on the part of participants.

I prefer to think of representations as resources for establishing, preserving and co-constructing the common ground necessary for purposeful and coordinated activity in design collaboration. To properly understand this we must avoid the unhelpful entailments of both the representation metaphor for internal structure, and the container metaphor for external representation. Representations are not common ground in and of themselves, rather they stand in reciprocal interaction with it. Co-construction involves individual acts and suggestions, collective reception, interpretation and evaluation; these may pertain to the designed object itself, the context or the process. Co-construction cannot be adequately understood solely in terms of discourse or changes to persistent, shared representations alone—rather it is the interweaving of the two that is important. Taking both into account, it will be necessary to maintain an analytical distinction so that relationships can be understood and differential effects on design interaction can be discerned. This is precisely what I will set out to accomplish in the current research.

Summary

In this review I have considered metaphorical attributes of design as both an abstract process and a subjective activity; this draws attention to certain search-like and transactional aspects of the activity I propose to study. I have focused on design as a group or collective activity; in this regard previous research has highlighted various aspects of interaction between designers and other stakeholders, as well as a variety of roles played by artefacts and design representations.

Based on a characterization of design as collective and organizationally-situated work, I identified specific theoretical perspectives as resources, from which a number of concepts emerged as potentially relevant. These help us understand such joint activity in terms of the exchange of meaning and the implication of artefacts and representations, the dynamics between subjective awareness and the formation of allegiance and commitment, and the interplay between cognition of individuals and material structure in the environment. Ethnographic accounts of situated design activity confirm the utility of a number of these concepts and suggest specific ways in which they must be adapted to the design context. I have also discussed the ways in which I intend to bound my conception of representation in this study, providing reasons why I believe this to be appropriate.

Through this discussion, gaps can be seen between the various perspectives and the insights from ethnographic accounts. We have refined ideas about how representations may be implicated in constructs generally associated with group performance (from Chapter One), such as task cohesion, shared mental models, collective identity and environments that are appropriately supportive and challenging. We have greater clarity on the processes essential to collaborative design (i.e. conscription, knowledge transformation and collective story-making), but we do not have a detailed account of the interactional work through which these are accomplished, or the communicative and representational acts that might be involved. We can not yet know, then, how persistent, shared external representations might be particularly useful in achieving the performance of real-time design environments, or how representations in these sorts of environments might better support collective efforts to bring about preferred futures. It is these gaps I hope to address, at least in part, through the research I will undertake.

3. METHODOLOGY

Collaborative design involves synthesizing viewpoints, reconciling differences and consolidating commitment to a particular course of action. In the preceding chapter, I outlined the need to understand in greater detail how the interactional work of design collaboration is accomplished with the aid of persistent, shared external representations. This will require a detailed account of the way communicative acts and representational activity are interwoven in processes more generally described in terms of “conscription” (Henderson 1999), “knowledge transformation” (Carlile 2002), and collective “story-making” (Bucciarelli 1994).

This chapter addresses how best to register, hold and analyze the types of complex interaction and the activity that will be the target of my study. It explores issues related to robust case study design, situated work observation and detailed analysis of design interaction. Central to this will be a review of a variety of observational category and coding schemes developed specifically for design activity. Because video data are most useful for fine-grained study of situated work, I will also address methodological aspects of video interaction analysis. It is also necessary to impose a certain structure on the inquiry to ensure that meaningful and robust conclusions can be drawn from a single case. These topics will be discussed prior to the review of observational coding schemes.

Together, these establish the basis for appropriate data collection and analysis to address the roles played by persistent, shared representations in real-time design. In the next chapter, these considerations will be reflected in the initial research design, taking into account salient aspects of the JPL setting. The unfolding of the field research activity will then be described, including responses to evolving insights and unforeseen circumstances that were encountered.

Case Study Methods

The standing design and proposal development teams at Jet Propulsion Laboratory represent a leading-edge concurrent design practice that achieves a high level of performance (cf. Oxnevad 2000, Mark 2002). Featuring intense, co-located sessions with project leaders, scientists and specialists in different domains of aerospace design, the practice emphasizes real-time design decision making. It is also notable for the extent to which it incorporates advanced analysis and modelling tools and the prominent use of shared visual displays. These aspects make the concurrent design practice at JPL well-suited as a site in which to study the use of shared representation in design collaboration. To take advantage of this opportunity, I will discuss relevant considerations from case study method and video interaction analysis below.

Yin (1994) and Stake (1994) discuss concepts, methods and strategies for case-based research intended to enhance study quality and promote the development of generalizable findings. The purpose of the discussion here is not to articulate all aspects of the current study's design; rather it is to introduce a number of terms and concepts that will be referred to in subsequent chapters, as well as in evaluating the overall results and conclusions.

Case Study Designs and Purposes

Yin (1994) describes the case study as a distinct research strategy (alongside experimental, survey, archival and historical research approaches) that is particularly appropriate to address "how" and "why" research questions and contemporaneous, real-world practices. The appropriate case study design depends upon the type of opportunity presented by each case, the phenomena involved and the intended purpose of the overall study. An important early decision is whether a particular study will involve single or multiple cases. When is a single-case study appropriate and what can be learned from it? Yin (1994) allows that findings in multiple case designs are more likely to be generalized and are often considered more robust. However, he emphasizes that single-case studies are appropriate for rare or extreme cases, since these present unique opportunities for insight when few—if any—comparable settings exist. I argue that the JPL setting *is* such an exemplary and potentially informative case.[61]

Yin (1994) describes three purposes for case studies: *descriptive*, *exploratory* and *explanatory*; only the latter are intended to produce causal explanations. Exploratory studies seek to accomplish more analysis than purely descriptive ones, but do so in situations where the depth of understanding does not yet exist to warrant focusing on specific causal propositions or hypotheses. On balance, an exploratory study gains more by remaining open to unexpected phenomena than would be possible with the narrow focus required for hypothesis testing. I undertake this study with a clear orientation toward the importance of shared external representations, based on insights from a body of situated and laboratory studies of design (and other workplace) interaction. This is consistent with the level of rationale and the degree of directedness Yin indicates are appropriate for exploratory case studies—provided they clearly articulate their purpose and the criteria by which their success should be judged.

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[61] Additional background information on the JPL practice is provided in Chapter 4.

In the current study, I wish to understand how participants' interaction with each other, and with various shared representations, contributes to the success of the real-time concurrent design team. Essentially, this is an inquiry into the nature of the work performed by representations in this context. Any analysis constitutes a manner of seeing. This study's purpose is not to explore advanced practices or the performance of this particular team in aerospace design per se. Rather, my goal is to consolidate a manner of seeing design interaction that puts a greater emphasis on the active and constructive roles of shared representations in the collective work of designing—that is, envisioning preferred futures and charting courses of action to bring them about. The research I report below will be a single-case, exploratory study of an unusual, and exemplary case of collaborative, real-time design. I undertake it to provide insight into the communicative and representational activity that is essential to success in such highly-interactive contexts.

Regardless of a study's particular purpose, Yin emphasizes that generalization of case-study findings should be considered on an analytic rather than statistical basis. Rather than comparing studies or making specific predictions on the basis of quantitative results, emphasis should be placed on the utility, applicability and transportability of the analytic approach.[62] Accordingly, the following are criteria for case study quality are suggested.

Criteria for Case Study Quality

Yin (1994) describes four aspects by which the quality of a case study design can be judged: construct validity, internal validity, external validity, and reliability. I will briefly introduce and discuss each below as they will impact the current study's design; I will revisit them as the results are interpreted and discussed.

- *Construct validity* deals with the relationship of the analytic constructs to the case and its objectives. That is, do the constructs apply appropriately and do they adequately encompass the phenomena under study? Can they be applied in a way which is not overly subjective in collecting and interpreting the data?
- *Internal validity* relates primarily to experimental or case research that seeks to support claims of causality. It deals principally with issues of sampling, variable control, and the exclusion of possible external causes and spurious effects. According to Yin, internal validity per se is not an applicable criterion for exploratory case studies; however the root issue remains: whether or not inferences about relationships between the phenomena observed are made in a robust manner.

[62] Stake (1994) argues for the intrinsic value of richly descriptive cases, and is less concerned than Yin with explicit generalization (cf. "learning from the particular" and "naturalistic generalization," pp. 238-240). He does distinguish between cases undertaken for instrumental vs. intrinsic matters of interest.

- *External validity* deals with the generalization of findings. How applicable are findings likely to be to other cases? Do they contribute to a theory that will prove useful, convey insight or have implications in other situations?
- *Reliability* deals with the minimization of errors and bias. If another researcher were to follow the methods described, would he or she arrive at the same findings and conclusions?[63] Since it is usually not practical—or even possible—for a different researcher to repeat *the same* case, reliability in case studies often rests upon thoroughness, clarity of method and quality of documentation.[64]

Robust Analyses in Case Studies

A number of factors contribute to the overall robustness of analyses in case studies; several of these are particularly afforded by the JPL setting. Factors discussed below include appropriately *bounding* the case, discerning relevant *units of analysis*, identifying clear *predictor and criterion variables*, and employing some form of *triangulation* when making interpretations.

Both Yin (1994) and Stake (1994) discuss the importance of appropriately bounding a case study. Boundaries drawn too narrowly exclude important or decisive factors, compromising the validity of the study's findings. Overly-broad boundaries make cases unmanageably complex, inclusive of so many phenomena that theoretical refinement in any particular area becomes difficult. Observations in the JPL setting will be more limited than would be the case in an ethnography (e.g. Hammersley & Atkinson 1995, Schwartzman 1993).

However the JPL context affords bounding in ways that other concurrent design settings do not. Design activity is concentrated in co-located sessions, typically 3-4 hours in length. Emphasis is placed on exploring ramifications and making design decisions *in* these sessions—with customer feedback and subject to cross-domain scrutiny. This means that design reasoning is both relatively explicit *and* localized in time and space, enabling a more comprehensive record of relevant interaction to be made.

Yin (1994) discusses the importance of deriving appropriate units of analysis from the central propositions and concerns of the case study. Units of analysis are entities discerned

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[63] Reliability is a precondition, but should not be confused with replication. Yin distinguishes between literal replication, which denotes the same findings arising in nominally similar cases, and theoretical replication wherein findings from two or more diverse cases lend support to the same theory—and not to rival theories.

[64] In the application of coding schemes, the degree to which different researchers code the same data identically is referred to as inter-coder (or inter-rater) reliability. Opposing views of the importance of inter-coder reliability are presented by Nyerges et al. 1998 and Morse 1997.

within the data and used as the basis for analytic comparisons.[65] Yin distinguishes between *holistic* case designs, in which the entire case comprises a single unit of analysis, and *embedded* designs in which multiple units of analysis are identified.

As I will describe in the chapters that follow, resolution of tensions concerning units of analysis will be one of the principal learning outcomes—and an area in which challenges remain at the conclusion of this research. In the JPL setting, clearly-defined domains of expertise and the regularity with which the teams work on design projects offer potentially useful delineation for units of analysis. However, the interdependent and contingent nature of design reasoning between domains presents complications, as do the novel and innovatory aspects of every project undertaken at JPL.

To make analytic comparisons between units of analysis, one of the principal modes of case-study analysis Yin (1994) describes is pattern matching. In explanatory (or causal) studies this requires a clear conception of dependent and independent variables.[66] More generally, pattern matching requires articulation of the outcomes of interest (desirable or undesirable), and the various potentially-contributory factors, as part of a strategy for making the most informative comparisons and contrasts.

> The role of the general [pattern matching] analytic strategy would be to determine the best ways of contrasting any differences as sharply as possible and to develop theoretically significant explanations for the different outcomes. (Yin 1994, pp. 109-110)

In complex human systems, the assumption that "variables" can be isolated and manipulated independently of one another, and correspondingly simplistic notions of causality, are often misleading. Accordingly, I intend to employ the terms "*criterion variable*" and "*predictor variable*" (Wuensch 2004) to refer to outcomes and contributory factors in this situated, non-experimental study.

A final factor in the robustness of any qualitative research is *triangulation*. Yin (1994) discusses this primarily as a matter of obtaining evidence from multiple sources. Stake (1994) elaborates triangulation more generally as an approach to clarifying meaning, verifying observations and interpretations, and illuminating the diverse ways in which "the same" phenomena may be perceived. In assessing predictor and criterion variables,

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[65] For example, the units of analysis employed in Barron's (2003) study of student problem-solving performance (discussed in Chapter 2) were individuals and triads.

[66] In experimental research, independent variables are those that are manipulated, and dependent variables are those whose behaviour is observed. Proper experimental design excludes extraneous and confounding factors so that an inference of causality can be made on the basis of correlation between the behaviours of independent and dependent variables.

triangulation is desirable both with respect to what can be said to have occurred in interaction, as well as in the assessment of outcomes.

The methods of interaction analysis, particularly from video data, and the observational coding schemes discussed below provide additional insights into the identification of appropriate units of analysis and predictor/criterion variables. These are highlighted again in the design and conduct of the research activity, presented in the following chapter.

Interaction Analysis

The objective of this research requires observing authentic, organizationally situated work interaction, unfolding in real time amidst shared representational artefacts and technologies. This level of analysis is comparable to the situated action studies discussed in the preceding chapter, and I anticipate the use of video data will therefore be essential. For this reason I include a brief overview of general considerations in video interaction analysis prior to reviewing actual coding schemes for design activity.

The availability of video recordings greatly facilitates fine-grained study of interaction between people and material artefacts (cf. Heath & Luff 2000). In their discussion of techniques and methods for video interaction analysis, Jordan & Henderson (1995) call attention to several potential foci for this type of analysis:

- *The structure of events*: includes beginnings and endings (both official and unofficial), segmentation and transitions; shifts in topic and/or in the modalities of engagement w/ artefacts; entry into patterns or "projectable" interaction sequences[67]
- *The temporal organization of activity:* distinction between macro vs. micro levels of analysis (detailed below); external demands that drive patterns in interaction; rhythm and periodicity (e.g. intense vs. slack times), etc.
- *Turn-taking*: in speech, movement, engagement w/ artefacts; whether these are talk-driven or instrumentally-driven; apparent "interruptability," proactive vs. passive engagement, etc.
- *Participation structures*: shared attentional focus, task orientation, visual and auditory availability; principled or patterned inclusion or exclusion of participants
- *Trouble and repair*: breaches between participants with regard to intentions or understandings; breakdowns involving environmental resources and technologies

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[67] "Projectability" is a term drawn by Jordan & Henderson from Conversation Analysis (cf. Schegloff) denoting the creation of reliable expectations on the part of participants with regard to the way subsequent conversational events are likely to unfold, including the range of responses deemed appropriate in a given situation.

- *The spatial organization of activity*: configuration of individuals in space, their orientation, access to resources etc.; 'ownership' of territory where interaction takes place; arrangement of furniture, its fixity or responsiveness
- *Artefacts and documents*: creation and inscription, trajectories of use, involvement in activity segmentation; apparent 'ownership', whether they are private or shared

These foci convey the authors' accumulated wisdom regarding the phenomena that tend to be most informative for interaction analyses in general. Beyond the obvious attention to artefacts and documents this study will require, I would like to expand upon three of the topics that will prove particularly useful in structuring the inquiry at hand.

Macro vs. Micro Levels of Analysis

In contrast to long-term temporal patterns and macro-scale orderliness embodied in projects and organization structures, Jordan & Henderson describe the concern of interaction analysis with the temporally fine-grained, moment-by-moment unfolding of interactional events:

> Interaction Analysis provides a focus on the shape of an event, its high and low points, the relaxed and frenzied segments, and the temporal ordering of talk and nonverbal activity. Above all it gives access to the ways in which participants experience and make visible the temporal orderliness and projectability of the events they construct. (Jordan & Henderson 1995, p. 61)

This raises the issue of *levels* of analysis. Design can conceivably be studied at any of a number of levels, including that of the individual (considered intra or inter-psychologically), small group, community, organization, industry, profession, or culture.[68] In any case, in focusing on a relatively micro-level of video analysis it is important to retain an awareness of how any particular episode is situated within a larger web of activities (Bødker 1996), and to highlight how these connections may be manifest in interaction.

Micro-level analysis involves the actual sequence and content of individuals' conversational contributions in continuous episodes of coherent interaction, usually measured in minutes. Analytic judgements are based participants' awareness of events and behaviour bounded by this context, not on events that occur later, or of which participants could not have been aware at the time. Macro-analysis, on the other hand, refers to longer timescales—hours, days or weeks—over the course of which discrete and temporally non-contiguous events and developments may be selected and interpreted to reflect the evolution of projects and

[68] Some modes of analysis, such as that of the community-of-practice (cf. Lave & Wenger 1991) or activity system (cf. Engeström et al. 1999) cut across conventional levels. Others, such as actor-network theory (cf. Latour 2005) argue that these levels are primarily artefacts of prior theorizing whose existence should not be assumed a-priori.

outcomes. My analytic focus will be on the accomplishment of interactional work (consistent with the theoretical resources I identified in the previous chapter); I will also endeavour to highlight where phenomena may bear upon extant theorizing at other levels, recognizing that comprehensive analysis may involve both micro and macro levels.

Segmentation and Units of Analysis

Because interaction analysis at the micro level tends to be labour intensive and time-consuming, it is important to focus attention as carefully as possible on bounded segments that are likely to be the most analytically productive. (This is consistent with Yin's (1994) description of the analytic strategy of pattern matching.) For this purpose, Jordan & Henderson advise attending to various aspects of participants' own segmentation of their activities. These takes the form of announced beginnings and endings, informal transitions and participation structures—regularities in the individuals present for a common task or sharing an attentional focus.

The JPL setting presents particular affordances for segmentation and for observing participation structures. Patterning of the work of mission and spacecraft design, developed in this practice over the years, is reflected in the distinct domains of expertise and certain recurrent tradeoff decisions between design approaches. These present opportunities for segmentation, and a possible basis for units of analysis, the nature of which I will come to better understand after entering the research setting (as I describe in subsequent chapters).

Attention to Trouble and Repair

In the midst of otherwise seamless and fluid task performance, Jordan & Henderson advise that instances of trouble and repair may be particularly revealing:

> Anthropologists have known for a long time to pay particular attention when the normal stream of activity is broken in some way. Careful analysis of the breach can often reveal the unspoken rules by which people organize their lives. As a matter of fact, the analysis of visible breaches of the local rules for social interaction is one of the best methods for coming to an understanding of what the world looks like from somebody else's point of view. Analysis of hitches in interaction may also reveal some of the constraints in the material world that routinely cause trouble. (Jordan & Henderson 1995, p. 69)

Similarly, Bødker (1996) highlights the use of breakdowns to identify the ways in which activities intersect and interfere with one another, or points at which artefacts fail to offer adequate support. While periods of highly productive design interaction will obviously be of interest, this suggests that instances of confusion, frustration and communicative repair should also play a role in analytic pattern matching.

With considerations of case study method and video interaction analysis in mind, I will now review a range of observational coding schemes for design activity. Rather than developing emergent coding categories from scratch (cf. grounded theory, Strauss & Corbin 1990, 1994), I intend to draw upon the categories embodied by these schemes, determining which are most useful based upon my actual data. This appropriately reflects the exploratory (vs. descriptive) orientation of this study, and enhances construct validity by establishing continuity with a substantial body of prior research on design interaction.

Observational Categories and Coding Schemes

Collaborative design involves synthesizing viewpoints, reconciling individual differences and consolidating commitment to a particular course of action intended to bring about a preferred future reality. Essentially, this is a process of collective reasoning. A number of observational coding schemes have been developed, which I proceed to describe in this section, ranging from abstract and formal conceptions to more mundane descriptions of the acts involved. Among the more salient distinctions are those between design reasoning as fundamentally directed vs. iterative, between various aspects of process and content, as well as shifts in communicative modality, the use of external media and the temporal locus of discourse. An additional, fundamental distinction is between coding that is essentially *categorical*, and *structural* coding that emphasizes referential connections over categorical judgments.

Design Reasoning: Formal Logic

Some coding schemes seek to consolidate design reasoning into the logical structure of formal argument, while others focus on categorizing the variety of acts involved. The poles of this continuum correspond generally to the two metaphors from Chapter 2—that is an abstract or formal conception (e.g. design as search) vs. a transactional one (design as conversation).

Focusing first on logic, schemes developed for design rationale capture seek to formalize design reasoning in an argument structure. This is motivated by the need for organizations to recall the reasoning behind product definition and design choices after the groups directly involved have disbanded. Olson et al. (1992, 1994, 1995) present a categorical coding scheme based upon a conception of design reasoning as a process of argumentation involving *issues*, *alternatives* and *criteria* (IAC). Shum et al. (1997) and MacLean et al. (1991) report a similar coding system based on *questions*, *options* and *criteria* (QOC). In both cases, design rationale is embodied in the relationships between the problematic aspects and alternatives identified, and in positive or negative assessment of these against various criteria.

Olson et al. perform a sequence analysis on transitions between their core IAC categories to discern a "grammatical" sequence for "direct design activity" (Olson et al. 1995, p. 229). Frequently, this involves a transition from a management topic that leads to the identification of an issue, followed by a looping discussion of alternatives and criteria (Olson et al. 1995, p. 231). Olson et al. point out that their coding scheme does not track relationships between issues or which participants make specific contributions. Represented in this way, design rationale may appear singular and unitary, not reflecting systematic disagreement or differences of opinion among participants.

Shum et al. (1997) develop a graphical tool to provide real-time support for groups wishing to explicitly understand the argument structure of their design decisions and to capture their design rationale. As Shum et al. point out, collaborative development allows the degree of group "ownership" of any such representation to be assessed. They also note, however, that prototype rationale capture systems appear to slow interaction and to impose an additional cognitive burden on design teams. It appears that, to whatever extent design reasoning involves QOC or IAC argumentation, constructing an explicit representation on this basis (at least with current tools) is not a transparent operation for real-world design teams.

Design Reasoning: Action (or Transaction) Structure

Other schemes emphasize the transactional structure of design reasoning by categorizing the types of acts involved. This is reflected by category names that tend to be transitive verbs rather than nouns. The focus of some schemes is quite fine-grained—describing the constituent elements—while others seek to convey a more overall description of the shape and direction of design processes.

An example of the more fine-grained type of scheme was introduced in the preceding chapter (in the context of co-construction of design representations). Fleming (1998) presents a compact typology of essential linguistic acts in design: *indexing*, *constituting* and *elaborating*. Indexing talk is that which picks out distinct features and foregrounds the compositional nature of the object at hand. Constituting talk fixes aspects of form with respect to the agency of the designers and their intentions. Elaborating talk locates these features more extensively with regard to the design context, enduring principles, pedagogical objectives etc.

For example, in discussing a brochure she is creating with a colleague, a graphic designer might *name* a particular part—identifying an introduction for example. She might proceed to describe (or *constitute*) this in terms of the use of a particular font or other typographic feature, mentioning intentional attributes such as a warmer or more engaging tone. The colleague might concur and *elaborate* this decision in terms of a more general principle, such as the need to draw the eye or invite the reader to enter the text at a particular point. According to Fleming, it is the combined effect of all three types of talk that renders design objects durable and "rhetorically consequential" (Fleming 1998, p. 49). Co-construction comes about through the combined effect of these kinds of talk, and their potential contribution by multiple individuals in social situations of collective designing.

A similarly fine-grained perspective on design reasoning, based on Schön's concept of reflective practice, is presented by Valkenburg & Dorst (1998). This typology consists of four acts: *naming*, *framing*, *moving* and *reflecting*. The first act, *naming*, deals with identification and isolation of features while *framing* establishes (often metaphorically) relationships between these and possible goals and actions. The third act, *moving*, is essentially an intervention—an experiment or proposed alteration within the context created by the frame. Finally, *reflecting* involves assessment of the results of moves with respect to desirable outcomes.[69]

Though these categories are defined on the basis of acts rather than formal logic, the schemes remain somewhat abstract in that they do not explicitly include some of the more mundane activities that comprise design conversations. Brereton et al. (1996) propose a coding scheme that explicitly recognizes additional aspects of conversational interaction and collective reasoning in group design process. This scheme comprises the following categories based on participants' acts:

- calling and engaging focus
- proposing or adding to a partial solution
- supplying supporting rationale, justifying on the basis of abstract principles
- illustrating by way of use-scenarios
- acknowledging
- calling into question
- requesting or expressing need for further information

[69] Mabogunje (1997) investigated the relationship between naming per se and the performance of student design teams during an extended project course. Applying automated content analysis to design documents and specifications, Mabogunje found a positive correlation between teams' final grades and their naming activity, manifest in the steady development over time of a rich, project-specific language for requirements and solutions.

- aligning with or distancing themselves from approaches or aspects of evolving solutions

Analyzing the same data as Brereton et al., Cross & Cross (1996) [70] present a scheme highlighting aspects of teamwork and social process. These include *establishing roles*, *gathering information*, *analyzing problems*, *building concepts cooperatively*, *employing persuasive tactics*, and *avoiding and resolving conflict*. Taken together, these schemes identify the constituent elements and acts through which collective design reasoning proceeds.

Linear Progression vs. Iteration

Whereas the schemes above focus on the constituent acts, other schemes offer more of an overall description of the way in which design reasoning unfolds. These often embody two distinct schemas: one a linear progression or trajectory derived from a sequential model of problem solving, the other emphasizing iteration or a recursive co-evolution.

Austin & Steele (2001) report on the temporal progression of conceptual design conversations in architectural design. They employ a descriptive category scheme for activities ranging from conception of the business need and functional requirements to the detailed development and costing of options. Despite their initial assumption of a relatively linear process (*interpret*, *develop*, *diverge*, *transform*, *converge*), they find notable iterative patterns in their observational data. Significant iteration occurs within sub-activities in each phase, and also in significant backward looping to previous phases. Steele et al. (2000) suggest this pattern reflects the discussion of solutions giving rise to a better understanding of the problem, requiring back-tracking to revisit and revise both.

Recognizing backward loops as evidence of problem redefinition, Austin & Steele point toward a concept more fully developed by Dorst & Cross (2001) and Cross (2002). This is a view of design activity that essentially involves a co-evolution of understanding in problem and solution spaces, with each exerting a mutual constraint upon the other. [71] Bridges between the evolving problem and solution spaces are experienced by designers as emergent insights—often accompanied by enthusiasm and excitement.

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[70] Cross, Christiaans & Dorst (1996) is a comparative volume in which data from the same experimental study (designers working individually and in a group on a laboratory design task, known as the Delft Protocols Workshop) were analyzed by diverse researchers (including Brereton et al., Mazijoglou et al., Cross & Cross cited here).

[71] Dorst & Cross (2001) attribute the co-evolution model to Maher et al. in Gero, J.S. & Sudweeks, F. (Eds.). (1996). *Advances in Formal Design Methods for CAD*. London: Chapman & Hall.

Stempfle & Badke-Schaub (2002) also describe designers' intentional action in goal and solution spaces, proposing basic cognitive operations that correspond to notions of convergence and divergence.[72] The first two cognitive operations, *generation* and *exploration* widen the problem space, while the second pair, *comparison* and *selection* narrow the problem space. On the basis of transition frequencies, Stempfle & Badke-Schaub (2002) found *solution generation* most frequently followed by a repeated loop of *analysis* and *evaluation,* a cycle they assert constitutes "the core of the collective thinking process" (p. 487). Stempfle & Badke-Schaub interpret this behaviour as a reflection of the need for designers to maintain the set of issues and alternatives they consider within a cognitively manageable range.[73]

Also linking abstract conceptions of divergence and convergence to empirically-observable behaviour, Eris (2002) correlated question-asking in student teams, engaged in a laboratory design exercise, with their task performance. Eris reviews alternate categorization schemes for questions, finding the greatest explanatory power in a distinction between deep reasoning questions (DRQs, citing Graesser 1988, 1993, 1994), and what he terms "generative design questions" (GDQs). While DRQs are specific questions asked with an apparent expectation on the part of the speaker of a single (i.e. correct) answer, GDQs are asked without any such apparent expectation (i.e. in an open-ended or speculative manner, for the purpose of soliciting alternatives, etc.). Eris interprets GDQs as essentially reflecting a divergent mode of thought, while DRQs are indicative of convergence. Eris finds a positive correlation between team performance and *combined* GDQ and DRQ asking rate, with no strong correlation for either category considered by itself. Eris interprets this finding to support the idea that productive design activity involves a balance between diverging and converging discourse.

Process vs. Content

A number of schemes employ some distinction between the content of design reasoning and various aspects of process. Here, "content" generally refers to discussion of problems, solutions, criteria etc. seen as the core activity in design reasoning. "Process" can refer to

[72] With regard to personal preferences in problem solving, the terms "converger" and "diverger" were used by Hudson (1968) to describe the performance of English schoolboys on open-ended tests intended to complement conventional IQ tests. Convergers were those who excelled on standard IQ tests but dramatically under-performed others—whom Hudson labelled divergers—on open-ended alternative tests. Hudson characterized convergers as those particularly attracted to the notion of a single right answer, while such a notion seemed almost repellent to the divergers.

[73] Stempfle & Badke-Schaub (2002) identify two process variants with regard to solution generation and evaluation: one process generates and rapidly evaluates ideas until a satisfactory solution is found, while the other undertakes a greater level of analysis of each idea prior to evaluation. The latter is more likely in groups that explicitly adopt some form of normative process.

designers' reflecting upon their own process, i.e. with regard to the order of tasks or problem-solving tactics. Stempfle & Badke-Schaub (2002) make a such a distinction, reporting that the teams in their study engage in process-related exchanges compared to content-focused ones in a ratio of approximately 2:1. They propose, however, that the same basic thinking operations (i.e. *exploration*, *generation*, *comparison* and *selection)* underlie analogous processes in both the content and process domains. Minneman (1991) also identifies distinct "facets" of design conversation that include process, roles and relations, in addition to discourse addressing the designed artefact itself.

Another dimension of "process" arises when design work is embedded in organizations, consequently giving rise to concerns that are more logistical, programmatic or political in nature.[74] Coding schemes such as that of Olson et al. (1995) have categories for *project management*, *meeting management* and *summarizing*, in addition to the core categories for design reasoning. This facet of real-world design activity is likely to be particularly salient comparing student or laboratory studies to those that are more organizationally situated. In the latter, conversation about the envisioned artefact in the future context is likely to be interspersed with discussion of the very real constraints of the organizational here-and-now—in addition to the designers' meta-discourse to manage their collective process in real-time.

Shifts in Modality, Medium and Temporal Locus

A number of studies use coding categories derived from the communicative modalities and media employed by participants in design conversations. These include, for example, shifts between periods of interaction dominated by speech alone vs. drawing, symbolic writing or engagement with artefacts. In general, studies attending to these shifts have not proposed such strong overall process models as those reviewed above; they do nonetheless suggest that certain activities or sequences of activities are essentially involved in productive designing.

Reid & Reed (2000) employ a coding scheme to distinguish between *figural* and *conceptual* design arguments employed by members of the student teams they observe. Figural arguments involve visual activity—such as sketching, pointing or figural gesturing—while conceptual arguments are primarily non-visual. As dependent measures, Reid & Reed use the rate of turn-taking to convey the tempo of the design interaction and the level of participation of group members.

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[74] These may require a different theoretical basis for abstraction, such as found in sociology or organization theory (cf. Hargadon & Fanelli 2002, Hargadon & Sutton 1997).

> Thus, high turn rates indicate periods of highly interactive design reasoning, characterized by brief contributions and a brisk exchange of arguments, often between several group members. Low turn rates indicate fewer interactive periods consisting of 'megaturns' (Dabbs & Ruback, 1987), in which individual group members hold the floor more or less continuously while others offer brief comments or questions. (Reid & Reed 2000, p. 364)

To understand the temporal structure of these episodes, Reid & Reed performed exploratory spectral analysis, looking for periodicity in figural and conceptual argumentation, turn taking and participation. They found cycles on the order of five to ten minutes, in which a period of figural (e.g. sketching) activity appeared to lay the groundwork and then give way to highly interactive conceptual discussion. [75]

> This analysis suggests that figural reasoning plays a prominent lead role in the majority of design episodes, not only entraining the phasing of group participation and turn-taking cycles, but also entraining cycles of conceptual reasoning. (p. 368)

Whereas Reid & Reed (2000) employ a fairly simple distinction between figural argument and conceptual argument, Tang (1989, 1991) and Tang & Leifer (1991) find that the prominent modalities employed in design conversation include *symbolic writing*, *drawing* and *gesture* as well as speech. Attempting to track ideas from proposal to acceptance, Tang finds each type of workspace activity potentially serving three functions: *storing information*, *expressing ideas*, and *mediating interaction*. In particular, Tang (1991) notes that gesture accompanies over 30% of the workspace activity in some segments. Also interesting is the observation of repeated or iconic gestures employed by participants to index earlier episodes of talk, as a way of reintroducing a previous topic or idea.[76]

Mazijoglou et al. (1996) focus particularly on the interplay between design discourse and the evolution of sketches in a shared drawing space. This study combines a relatively straightforward discourse typology of *problem*, *solution*, *constraint*, *requirement*, *information need* and *process*, with an elaborate coding scheme for drawing activity comprising *non-symbolic* (doodles and squiggles), *alphanumeric* (labels and writing), *other symbolic* (underlining, arrows), *pictorial orthographic* (plans, sections) and *pictorial perspective*. Three analytic representations are used to develop and present findings:

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[75] Studying individual designers, Akin & Lin (1996) attempted to correlate episodes of multiple-modality activity (e.g. drawing, writing, etc.) with demonstrably novel design decisions (NDDs). They found the emergence of a majority of NDDs co-occurred with episodes of heightened triple-mode activity during otherwise relatively quiescent periods. This may be indicative of the lead/lag relationship found by Reid & Reed.

[76] Brereton (1999) also codes transitions between modalities of conceptual argument and engagement with hardware, finding that students in teams learn abstract engineering concepts most effectively when their discourse involves frequent transitions between modalities. This appears to be the case both with regard to rough prototypes created by students and in their dissection of existing products.

transcriptions of discourse (coded by turn) and networks reflecting transitions to and from episodes of drawing activity as well as the structural (i.e. precedence) relationships between various elements of drawings.

Mazijoglou et al. find more solution-focused discourse associated with increased visualization, while information-focused discourse is associated with writing activity. This study illustrates the use of distinct categories for discourse and for drawing acts, and the possibility of relating these analytically. It also highlights how the development of drawings occurs in conjunction with the advancement of design reasoning in discourse, and suggests the possibility of tracking referential structure between the two. Discussion of certain issues or ideas may become localized on the drawing space such that discourse transitions are coordinated with, and facilitated by, shifts in the locus of activity in the drawing space.

Linking discourse to drawing space evolution, Mazijoglou et al. draw attention to a class of utterance called concrete, third-person deictic references.[77] In using discourse deixis to track participants' use and reference to the drawing space, Mazijoglou et al. note, however, that many instances of expressions such as "it" and "its" did not relate to anything in the drawing space, but instead, "seemed to refer to abstract design solutions shared by the designers and held in their minds" (p. 397). Thus, while the locus of drawing activity can index discussion of certain issues or ideas, it can not convey the entirety of reasoning in a design conversation.

The movement of the design group's attention across the drawing space noted by Mazijoglou et al. is elaborated by Taura et al. (2002). This study employs a fairly straightforward, linear problem solving sequence (*awareness of problem*, *suggestion*, *development*, *evaluation* and *conclusion*) in conjunction with the notion of a "gazing point" that encompasses time, aspects of objects and 'non-objects.' Possible gazing points include the state, constraint, or purpose of the design object, background knowledge, documents or apparatus, the presumed use scenario, relevant past experience or future plans, and relevant past design activities. Taura et al. propose that a "gazing point control process" operates in parallel with the designer's problem solving; they illustrate this by mapping specific gazing points onto design proposals at various points in the design process.[78] Their articulation of the attributes and diversity of gazing points is useful to suggest the kinds of things that may

[77] These are short, pronominal words, such as *he*, *she*, *it*, *this*, *that*, *here* and *there* (also described as indexical expressions) whose meaning can be interpreted only with recourse to the context of use.
[78] Taura et al. compare two individual designers (an experienced designer vs. a student), so their results are not directly relevant to this thesis. However their method is notable in that it integrates after-the-fact review of videotaped sessions with the designers themselves, during which an interview protocol is used to query the designer's reasoning and rationale for observed shifts in their gazing points.

be represented in a design conversation, beyond the drawing activity studied by Mazijoglou et al.[79]

These studies draw attention to a number of phenomena, but also illustrate the potential difficulty of relating patterns in cross-modal activity to meaningful conclusions about the productivity of design reasoning. What is missing is a more direct connection between particular patterns of representational activity, and beneficial process attributes or demonstrably noteworthy outcomes.

Structural vs. Categorical Coding

Analysis such as that employed by Mazijoglou et al. (1996) involves registering connections between designers' conversational contributions and various parts of drawings. While they emphasize categorical attributes in their findings (i.e. mapping types of drawing act onto formal process stages), Mazijoglou et al. mention the possibility of restructuring the analytic representation of design activity in a manner that "links all workspace activities to drawings and other artefacts in the design space" (Mazijoglou et al. 1996, pp. 404-405). This suggestion is a step toward a fundamentally different coding approach, one that emphasizes judgements of structural *connectedness* over category membership.

Developing such an approach, Goldschmidt (1992, 1995) and Goldschmidt & Weil (1998) present a method known as "linkography." Rather than categorizing moves solely on the basis of a formal typology, linkographic coding establishes links between moves on the basis of a perceived referential commonality in the context of the design object.[80] A particular move may be linked to one or several other moves, which may have preceded or followed it. Goldschmidt identifies the density of such linkages as an indicator of the productivity of conceptual design conversation, both on empirical grounds and based on the idea that productive design conversation is inherently generative and integrative.[81]

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[79] Minneman (1991) also distinguished between substantive "facets" in discourse (artefact, process, relations/roles) and temporal "trajectories" (making sense of the past, understanding the current state, proposing future action).

[80] "In practice, a link between two moves is established when the two moves pertain to the same, or closely related, subject matter(s), such as a particular component of the designed entity, its properties and functions, a concept or a design strategy, and so on" (Goldschmidt & Weil 1998, p.90). Goldschmidt and Weil define the criteria for assessing connections in terms of "common sense" (ibid., also cf. Goldschmidt 1995, pp. 195-196).

[81] Goldschmidt relates her conception of productive designing to gestalt psychologist Max Wertheimer's (1945) view of productive thinking as that which gives rise to genuine ideas, understanding and creativity as opposed to rote thinking and routine. Goldschmidt (1992, 1995) uses metrics to relate overall link density to productivity of design conversations, also identifying "critical" moves deemed to have been particularly generative or integrative based on their unusual density of connections.

Linkography is of interest as an orthogonal approach to content coding that transcends the descriptive limitations of specific, categorical schemes with respect to the content of design reasoning. There is an essential, constructive aspect to productive design conversation: its development necessarily entails movement and its outcomes embody some form of novelty. This movement is impossible to render (at a level of topical specificity) with a categorical scheme, precisely because the object of discourse is continually evolving and changing. As Goldschmidt and Weil note, a detailed understanding of design reasoning requires attending both to the categorical composition and the structural connectedness of discourse.

> [design reasoning] moves forward but also makes sure that it is congruous with what has already been achieved, and it validates what has been done thus far with an eye on ways to proceed from that point. ... We propose that this pattern represents a cognitive strategy that ensures the efficiency and effectiveness of reasoning in designing: it ensures continuity while also guaranteeing that progress is made, and it serves the need of sustaining a solid and comprehensive design rationale for the entity that is being designed. The success of this strategy hinges on an equilibrated relationship between structure and contents, such as we found inherent in design reasoning. (Goldschmidt & Weil 1998, p. 100)

The types of referential connection highlighted by linkography appear to be most relevant to idea generation and brainstorming activity. Though undeniably of interest, this is only a fraction of what takes place in real-world, situated designing. In the latter, referential linkages are likely to be far more complex and require more explicit criteria and differentiation than Goldschmidt provides. Laboratory settings, without an independent way of assessing the quality of design process, make it difficult to meaningfully ground a notion of productivity that is based on generative and integrative aspects of conversation alone.

While Goldschmidt does not explicitly identify them as such, linkographs are essentially network representations.[82] Understanding Goldschmidt's measures of structure as network metrics opens the door to more elaborate network conceptions and methods, such as those I will describe later in this thesis.

Summary

The purpose of this chapter has been to lay the methodological groundwork for a systematic inquiry exploring the roles of persistent, shared external representations in design collaboration. Toward this end, I identified elements of structure, based on considerations of case study method, that will enable me to draw valid and meaningful conclusions from this single, exemplary case. These include the need for clear boundaries, appropriate units

[82] I am indebted to Helga Wild for the observation that linkographs are a form of network representation.

of analysis, a conception of predictor and criterion variables and triangulation in analytically-meaningful interpretations.

Actual determination of these elements of structure depends upon specific features of each case, and on the overall objectives of the research. Accordingly, I will discuss each further in the following chapter, as I enter the field setting. The objective of this research is to gain an understanding of the ways in which communicative acts and representational activity are interwoven to accomplish the interactional work of collaborative design. This is a process of synthesizing perspectives, reconciling differences and consolidating collective commitment to a course of action to bring about a preferred future reality. Specifically, this research aims to highlight the active involvement of persistent, shared representations in collective design reasoning, and to develop a method for making this visible that can be applied beyond the context at hand.

Techniques and analytic foci for video interaction analysis suggest additional considerations. These include a distinction between micro and macro levels of analysis, utilization of participants' own segmentation of their activity, and close attention to trouble and repair as well as productive interaction. Case study analysis involves contrasting these as clearly and sharply as possible to afford theoretically meaningful interpretations. For this purpose, a number of observational coding schemes were reviewed. These provide resources for categorical distinctions characterizing both the content of design reasoning and the ways in which the process unfolds, including attributes of formal reasoning, constituent acts and mundane activities that comprise design conversations.

Design reasoning has aspects of both sequential progression and iteration, during which participants utilize various communicative modalities and external media. It involves frequent shifts—in the locus of discourse, between communicative modalities and in engagement with artefacts and representations. Productivity in design conversation also requires an essential movement and development that, in its topical specificity, escapes abstract or categorical formalism. This underscores the need to attend to the evolution and connectedness of discourse, as well as its categorical composition.

The productivity of design conversation is evidenced by the engagement and excitement of participants, as well as in the generative and integrative impact of their contributions. This study offers an opportunity to combine micro-level observation of communicative and representational activity with externally-valid assessment of outcomes and process quality, grounded in the context of an authentic design practice. It is also an opportunity to see which aspects of these observational schemes resonate with the way people actually work together—at least in the particular type of design activity I observe—and what other phenomena may need to be taken into account. These are the subjects to which I turn in the following chapters.

4. FIELD RESEARCH & MACRO ANALYSIS

In Chapter 3, I discussed methodological issues and general aspects of the research design. This chapter describes how the design evolved as I entered the field setting and the research activity began to unfolded. It also describes the macro-level analysis I used to grapple with the resulting large and complex data set, and the process I used to parse and select bounded periods of interaction (which I refer to as episodes) for subsequent micro-analysis.

Macro-analysis was essential to gain an understanding of the overall body of recorded interaction and how it could be parsed into manageable units, as well to develop criteria for the selection of episodes likely to be most analytically informative. The macro-analytic units (which I refer to as threads) each tell different tales with regard to the use of shared representations; these threads later proved useful as complementary units of analysis in their own right. The next chapter will describe development of the micro-analytic technique. Then, results of both levels of analysis are then presented in the two chapters that follow.

This phase of the research also involved dealing with unanticipated issues that shaped the research in unexpected ways and contributed to a number of learning outcomes. An unforeseen administrative delay of over a year required me to work extensively from notes and text transcripts. After video data became available, I came to realize the profound effect analytic representations of data can have on one's reconstruction of events. The process of parsing interaction data also proved more challenging and complex than I had initially anticipated; I return to these difficulties with additional insight in Chapter 9. Of course, some of the interview and observation protocols proved overly cumbersome, and new ones had to be developed on the fly to take advantage of emergent opportunities. During the field research and prior to the availability of video, I benefited greatly from collaboration with another researcher having a different focus and theoretical perspective on the same primary data.[83] There were many times when a second set of eyes and another perspective on the same events proved invaluable.

[83] My colleague in the field and early macro-analytic portions of this research was Monique Lambert, of the Department of Civil Engineering, Stanford University. While I focused on shared external representation, Monique approached the team's performance as a transactive memory system. Following our collaboration in the field, discussion and coding of the major macro-analytic threads, we pursued our analyses separately. The remainder of the work I present here—including episode selection, network formalization, micro-analysis, syntheses of both levels of analysis, and the conclusions I draw with regard to design conversation and representational support—are the results of independent work.

Preparation for Fieldwork

The standing proposal development teams at JPL represent a leading-edge concurrent design practice, remarkable for the accelerated performance it achieves and the real-time manner in which participants carry out their work. The process foregrounds highly interactive decision-making between domain experts and key project stakeholders, and relies upon sophisticated modelling and analysis tools. The co-located environment affords rapid information exchange and complex, opportunistic interaction—directly between participants (through verbal and other modalities), as well as through shared visual displays and electronic data-sharing networks (Mark 2002). Though it is by no means typical, these characteristics make the setting a particularly interesting site for study, with potential implications for other settings and emerging practices.[84]

My field research collaborator and I conducted a preliminary visit to the JPL site in January 2002. The purpose of this trip was to witness the setting firsthand, and to discuss research arrangements with the NPDT team leader, who was our principal JPL sponsor and liaison.[85] Prior to providing more detail on the particulars of the setting, I offer a brief discussion to put the JPL practice in context, based on information gleaned over the course of the field research activity.

Background on JPL Practice

JPL is a federally-funded research and development centre operated by the California Institute of Technology under contract to the US National Aeronautics and Space Administration (NASA). Primarily, work at JPL involves the design, construction and operation of robotic scientific probes and exploratory missions throughout the solar system and for the study of Earth from space.

During the mid-1990's, NASA undertook a concerted effort to increase the scientific productivity and reduce the costs associated with space exploration.[86] Increasingly, JPL's

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[84] In the previous chapter, I discussed the conditions under which an exploratory study of a single, exemplary case is appropriate, as well as the criteria by which the quality of such a study should be judged (Yin 1994). In this chapter I discuss development of the necessary structures, within the constraints and particulars of the setting and the data. In Chapter 9 I revisit and reflect upon these considerations and how well the objectives have been achieved.

[85] The team leader of the NPDT is a six-year JPL employee, who holds a doctorate in aerospace systems design. During his tenure, he has had a formal role contributing to the development of the concurrent design practice. Aside from a genuine interest and generous commitment of time, his sponsorship entailed no direct financial or material support. Though he advocates and supports the use of shared representations in real-time design, he made no direct theoretical, methodological, analytic or interpretative contribution to the work I present here.

[86] Assessments of the results of this "faster-better-cheaper" paradigm have been mixed (cf. Mosher et al. 1999, Spear et al. 2000, IFPTE 2003). Though most attention has been focused on the manned

funding is awarded through a competitive proposal process. Thorough design consideration and reliable technical, schedule and cost information are factors that—along with scientific merit and congruence with NASA's strategic priorities—enhance a proposal's likelihood of success.

The concurrent design practice we observed at JPL involves early-stage design activity associated with proposal development.[87] Though, strictly speaking, these studies are conceptual and hypothetical, they are an integral part of work at the laboratory. The financial health of the institution as a whole depends upon a steady stream of successful proposals bringing in funding for new missions. Individual scientists and engineers similarly must be able to bill their time to funded projects, and advantages accrue to those whose services are in demand. The technical contributors we interviewed balanced their time between advanced-stage, development projects and early-stage proposal work as a way of gaining broader exposure for their expertise and of "getting in" on new projects "in the pipeline." A stock of quality proposals is a resource used by JPL to respond to specific announcements of opportunity from NASA and elsewhere. Seen in this light, proposals in the JPL environment are analogous to products; the ability to rapidly produce and reconfigure reliable proposals in response to technical developments and changes in funding priorities is an essential core competency.

Preliminary Site Visit

At the time of the field research, NPDT concurrent design sessions were conducted in the Centre for Space Mission Architecture and Design (CSMAD), at JPL in Pasadena, California. This is one of several project design rooms at the facility, each equipped with computer workstations, seating at shared tables, and several large projection display screens that can be switched to display the monitor of any computer in the room. The CSMAD has provision for six such displays. The two front screens are somewhat larger and are usually the focus of discussion; the other four provide redundancy, shared display for a smaller group or ambient awareness for the rest of the team.

(shuttle) program, the unmanned program has experienced notable successes and failures during this time. Successes—including Mars Global Surveyor, Pathfinder and the twin Mars Exploratory Rovers—have captured public imagination at the same time they have exceeded technical expectations and returned valuable scientific data. Embarrassing failures, including Mars Polar Lander and Mars Climate Observer—which sent hundreds of millions of dollars of hardware smashing into the planet in 1999—have been traced to deficiencies in management practice, testing and verification during development stages (report of the MPIAT, Young et al. 2000). While these failures can be related in part to aggressive cost and schedule constraints, there has been no indication or suggestion that such problems stem from early-stage conceptual design practice. On the contrary, evaluations of the practice we encountered within JPL were uniformly enthusiastic and positive.

[87] Proposal development is "pre-Phase A" activity; phases A through D correspond to program funding, development, assembly and test up to launch; phase E corresponds to post-launch operations.

Figure 4-1 Panorama of the Team in Action
Inside the Centre for Space Mission Architecture and Design (CSMAD) at JPL

Like other concurrent design teams at JPL, the NPDT operates on the principal of bringing together key project stakeholders—including customers and scientists—with a team leader and a standing team of aerospace design experts for interactive decision-making.[88] The room has seating for the team leader and key stakeholders (such as customers) around a central table, with four other tables clustering the domains that typically interact most closely. In total, the room accommodates approximately 20 participants. Besides a few extra seats along the back wall, there is little unused space and all occupants are in fairly close proximity.

The preliminary visit allowed observation of the setting and the design team in action. We noted several prominent features that had an impact on the early research design:

- The team leader segments the design activity, making explicit transitions and directing conversation from the central table.
- The team leader tends to shift focus from one domain expert to another, sometimes requesting only a quick update, other times engaging in a prolonged, detailed discussion drawing in other experts and stakeholders.
- As topic shifts are made, the front displays are often changed to the display of the domain principally involved.
- As Mark (2002) notes in Team-X sessions, activity also occurs in "sidebar" discussions involving small sub-groups of participants working on issues in parallel with the main discussion.[89]

It seemed clear that the team leader's announced transitions—to initiate discussion of issues pertaining to different design domains—represented the type of inherent segmentation Jordan & Henderson (1995) suggest employing as a basis for analysis. Since these shifts were also frequently associated with changes in the display of shared representations, it

[88] The leader of NPDT has advanced the use of more sophisticated CAD and modelling tools in design sessions; apart from this emphasis NPDT operates within the established concurrent design practice at JPL. Respondents with project and program management responsibilities indicated NPDT was one of several concurrent design teams they could choose from on a routine basis, depending upon the precise needs and objectives of any particular project.
[89] While the room is smaller and the number of sidebars is not as great as in Team-X (Mark 2002) side conversations are difficult to capture since participants speak more softly, usually in dyads or triads, and often refer to individual screens not recorded on the overall room video.

seemed these transitions might delineate potentially useful embedded units of analysis (Yin 1994).

Patterns in the Work: Domains, Chairs and Tools

Space mission design involves distinct domains of technical expertise. Design reasoning and decision-making in these domains may be carried out relatively independently, or may be highly inter-dependent and interactive. In addition to the team leader, the following are some of the technical domain experts (referred to as "chairs"), and aspects of spacecraft or mission design that fall under their purview:

- Avionics: electronics dealing with spacecraft command, control, and onboard data handling (including processors, memory, etc.)
- Orbital: projecting the alignments and relative positions of planets and the sun, for the evaluation of orbits, trajectories, and visibility angles for communications from various landing sites on Mars
- Instrument / Payload: operating principles, requirements and specifications of key data-gathering instrumentation, including power consumption and data rates
- Telecom: requirements, specifications and capabilities of various communication systems, including data rate capacities and constraints of different telecommunication links with Earth
- Power: requirements and specifications of different power sources (including solar cells and batteries); provision for adequate power sources to meet the spacecraft's needs
- Mechanical: physical configuration and structural integration of system components within overall mass and volume constraints; design of deployable or articulating members such as masts, booms, landing legs, robot arms etc.
- Thermal: provision for control of spacecraft internal temperatures to maintain sensitive components within their operating ranges under extreme environmental conditions.

Each of these chairs has at least one dedicated representational tool that can be displayed on the large shared screens. Among these, noteworthy examples of representations associated with particular chairs are a 3D CAD system (associated with the Mechanical chair), orbital simulation, power simulation, thermal simulation, as well as various spreadsheets—particularly employed by the Avionics and Payload chairs.

The System Station and Cross-cutting Parameters

An additional, important chair is that of the "system" or "system station." This does not correspond to any technical design domain; rather, this chair tracks certain key parameters that have a broad relevance across multiple spacecraft subsystems and are critical to ensuring overall mission performance. These essential system-wide parameters include:

- *mass*: does the overall combined mass of all components, subsystems and structure remain within the capacity of the anticipated launch vehicle (taking into account the mass of fuel required for the planned trajectory)?
- *power*: do the overall combined power requirements of all components and subsystems remain within the capacity of various batteries, solar panels, and any other power sources and supplies?
- *data rate*: does the overall rate at which data is being acquired by scientific instruments and processed by on-board computers remain within the capacity of the spacecraft's on-board storage and the communication link back to Earth?
- *launch and landing dates*: required to project expected technological capabilities (e.g. processor and memory speeds in the year 2008 for a 2011 launch) and to predict environmental conditions at the landing site, including availability of solar power and visibility of Earth for telecommunications.
- *landing site*: taking into consideration the scientific objectives, risks (hazardous terrain, critical manoeuvres), orbital alignments and their implications for fuel and payload mass, availability of solar energy and ease of communication

External Experts

Occasionally, some special expertise is required that is not normally present on the team. Scientists and engineers with diverse expertise within the JPL community can be called upon to offer information or advice, to answer questions or perform analyses as required. Not routinely members of the team, these external experts may be contacted by telephone during a session, or asked to attend for one or two sessions.

Interactive Decisions: Baselines and Trades

Many of the important decisions required in aerospace mission design are extremely *interactive*, in that choices are interrelated and interdependent, and have different (perhaps conflicting) impacts on different domains and subsystems. While computers facilitate the process, resolving such complex decisions often requires discussion and negotiation amongst the domain experts, the team leader and key project stakeholders. (Indeed, the difficulty of doing this in an asynchronous manner, along with the need to streamline the proposal process and reduce mission costs, provided the impetus for the development of JPL's standing proposal teams.) Two terms one hears participants use frequently as this process unfolds are "baseline" and "trade."

As a practical approach to solving complex and interactive problems, the concurrent design team tries to establish a *baseline* early on. This usually consists of a set of choices or values for key attributes that are based on experience from other designs, proven flight hardware, and previous missions.[90] In some cases it will become clear that a shortcoming or conflict is arising with the baseline, or that an alternative might offer significant advantages. When this occurs, a *trade* between the baseline and an alternative is proposed. This requires considering the cross-domain and system-level ramifications of the two alternatives. In principle the team leader polls the experts in the relevant domains, involving the customer, other experts and stakeholders as required. If the alternative is deemed superior, it becomes the new baseline; the change is announced and the system station is updated.

Data Collection Setup and Limitations on Access

Observing and videotaping a design team whose "natural" practice revolves around intense, bounded concurrent sessions conveys practical advantages for analytic observation. Equipment for audio and video recordings was already in place in the facility, though optimal camera angles and microphone placement had to be determined. Based on observations during the initial visit, two ceiling cameras were adjusted to capture the four most frequently-used screens. (These included the two front screens that were most often focal, as well as the side screens over the CAD and Orbital/System tables.) A third camera/recorder was manually placed to capture the remaining two screens when possible, though the difficulty of changing tapes during sessions meant the coverage was not 100%.

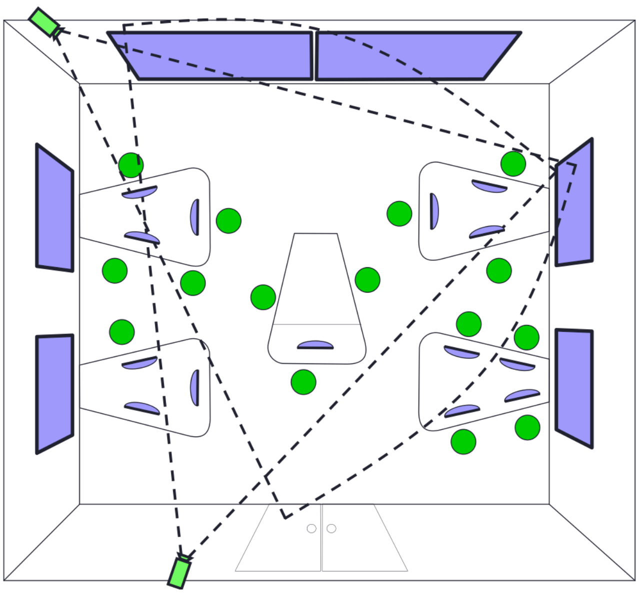

Figure 4-2 CSMAD Room Layout and Camera Placement
Showing locations and approximate view angles of the two ceiling-mounted cameras in place in the design facility. A third camera was used to record the two screens not covered by the two ceiling cameras.

[90] Use of a previously demonstrated hardware or solutions, particularly those that have "flown" in a successful mission, is described as "heritage." As an attribute, heritage was invariably seen as reducing risk and described in favourable terms.

The analogue audio recording system already present in the facility provided the best coverage for conversations around the central table. These typically included the team leader, and various customers or experts participating via speakerphone. Because the team leader actively facilitates discussions and major decisions are reviewed with key stakeholders at the central table, we felt confident essential discussions would not be missed with this recording arrangement.

Access to the JPL site is restricted and visitors must be escorted at all times. The scientists and engineers must charge their time to projects and efficient utilization is a key concern. As a result, apart from observation of the design sessions themselves, our mobility was limited and we initially had access only to conduct in-depth interviews with the team leader.[91] A post-session interview protocol for the team leader was jointly developed to accommodate both investigators' research questions, and included three topics:

- confirmation and clarification of all action items in terms of wording, responsible individual, expected date and anticipated type of work involved
- general impressions of the pace and productivity of the session (Questions were posed in terms the team leader had employed to describe his work during preliminary observations and conversations.[92])
- specific impressions of productivity at various points, revolving around review of a timeline constructed during the session, showing events and apparent "punctuation points"

The Team Leader interview protocol is presented in Appendix A. An example timeline is presented below in Figure 4-5.

Field Observation

The design study we observed took place in spring of 2002 at JPL.[93] Though we attended a kick-off meeting in January, approximately two months passed before the team leader alerted us that the design study was ready to begin in earnest. In this section I will give an overview of these observations including the specific project, the team members that were

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[91] We were eventually granted additional access for 1-hr interviews with all team members and the JPL customers near the conclusion of the cryobot lander study, as well as several other project and program managers who provided additional background information.

[92] These included analogies to a conductor and a musical ensemble, and specific terms and oppositions like "singing" vs. "dragging" to refer to the pace of sessions and describe productive utilization of all team members.

[93] Concurrent design projects are referred to as "studies" within JPL. I will refer to the team's project activity as the "design study" or "cryobot lander study" to avoid confusion with my own research inquiry.

involved and some of the key challenges. I will also discuss several aspects of our initial planning and research design that had to be revised as events unfolded.

The Design Study

The design study we observed was an investigation into the application of a new, compact, high power system (CHPS)[94] with the potential to revolutionize Mars surface exploration and scientific study. The CHPS promises to supply dramatically greater power over a longer mission life than it has previously been possible to consider. This design study was an opportunity for scientists to imagine doing new types of science on Mars, and for spacecraft and mission designers to explore solutions to unprecedented technical challenges.

The project was funded in part by an internal JPL group charting Mars exploration and outpost missions in the medium-term future, with remaining funding from a separate governmental agency undertaking the development of the CHPS. Rather than explore possibilities in the abstract, these customers chose to use the JPL concurrent design process to develop two specific (though hypothetical) mission applications. These would utilize the CHPS in static "lander" and mobile "rover" configurations, with the following objectives:

- illustrate compelling applications of the CHPS enabling new science and exploration on the surface of Mars
- identify and explore significant technical challenges stemming from the integration of the CHPS with other spacecraft hardware and systems

After the initial kick-off, eight design sessions were held. All participants attended the first session in person. This focused on operational details of the CHPS and various alternative science applications in geology (understanding the history and forces that have shaped the face of the planet over time) and astrobiology (looking for evidence that forms of life may have existed at some point). For the remaining seven sessions, several participants attended remotely by audio or video teleconference. Of these seven sessions, five were devoted to the static "lander" mission and two to the mobile "rover." The five lander design sessions, which all took place in the month of April, constitute the core of my data set.

The Cryobot Lander

Early in the process, a strong candidate science payload for the static mission was identified. This called for a landing on a region covered by permanent ice, and the deployment of a compact cylindrical package known as a "cryobot." With sufficient electrical power, the

[94] This generic description was agreed upon with the internal JPL study customer. I will use it throughout the rest of this dissertation, though more specific descriptions have since been published by JPL scientists and others.

cryobot is capable of melting its way downward, acquiring data on physical and chemical properties of layers of ice as it penetrates them. As the cryobot passes through preserved layers that have accumulated over long periods of time, scientists are able to directly sample ancient conditions and reconstruct climatic history.

(a) (b)

Figure 4-3 (a) Previous Illustration of Deployed Cryobot (b) Final Design from Cryobot Lander Study
Image source: JPL artists renderings

With sufficient power available to melt ice, the depth to which a cryobot can penetrate—hence its reach back into Mars' climatic history—is limited only by the length of its tether and the time available. The CHPS was an ideal enabler for such a mission because of the high continuous power requirement of the cryobot and the clear advantages of a multi-year deployment. The CHPS would allow boring multiple holes, kilometres in depth, with the potential to reconstruct millions of years of Martian climatic history.[95]

The Customers and the Team

Because of the dual funding sources, there were two sets of customers for the cryobot lander study. Inside funding from JPL came from a group charged with projecting mid-range future Mars exploratory and manned outpost missions. The delegate from this group (henceforth referred to simply as "the JPL customer") was highly engaged in both programmatic and technical discussions, and expressed personal enthusiasm for the CHPS technology and its promise for Mars exploration. This customer was physically present during all design sessions.

[95] Even in a static lander (as opposed to rover) mission, the cryobot can bore branched holes by being partially withdrawn and steered by differential heating of the nose. Additional possibilities (identified during the study) involved the use of a robotic arm to position the probe at different points around the lander.

Additional funding was supplied by an external agency, the developer of the CHPS technology. The delegate from this agency (henceforth "the agency customer") was not as active in technical discussions, and was only physically present at the first design session. Several technical participants from the agency *were* centrally involved in design discussions relating to the CHPS and its integration with other spacecraft components. They also were physically present only at the first design session, participating subsequently by video or audio teleconference. We did not have access to interact with either the external agency customer, his delegate, or the external agency technical participants, apart from observing their participation in design sessions and presentations given at a management update meeting.

In the actual sessions, these project-specific stakeholders were joined by the leader and the standing team. The following table provides information on all these participants.

Table 4-1 Project Stakeholders and Design Team Members, Chairs and Experience

Standing Design Team

member	*role/chair*	*JPL years*	*C-D years**	*NPDT years*	*time devoted*
ZD	Leader	6	6	2	50%
IE	Mission Arch.	16	1.3	1.3	20%
HJ	Mech. CAD	3.5	2.5	1	30%
LA	Power	21	2.5	0.5	~
KR	Payload	20	2	2	20%
LE	Avionics	10	4	0.3	35%
UK	Telecom	22	4	1	20%
HY	System	0.9	0.8	0.1	25%
OV	Orbital	6	3	2	~
YH	Power (sim. tool)	~	~	~	~
NC	Thermal CAD	5	0.5	0.5	20%
YK	Mech. CAD	1.1	0.5	0.5	60% (p/t)
		10 (avg)	2.5 (avg)	1 (avg)	

Project-specific Stakeholders

member	*role/expertise*	*affiliation*			*time devoted*
HL	customer	JPL (3 yrs)			60%
MW	power system design	Agency			n/a**
EN	power system design	Agency			n/a
LC	power system design	Agency			n/a
RD	customer	Agency			n/a
GG	cryobot payload	JPL (13 yrs)			~

(*) C-D years refers to the length of time the participant has been engaged in concurrent design activity at JPL, including membership on other teams.
(**) n/a reflects the fact we were unable to interview the Agency participants to ascertain how much time they devoted to the project *outside* the formal sessions. As for in-session participation, as shown below in Table 5-2, MW and EN ranked third and fifth, respectively behind ZD, HL and IE, based on conversational turns. Technical agency personnel were therefore highly involved participants in-session; they also published papers describing the study in their own professional journals.

Key Design Challenges

After the initial kick-off meeting, design sessions were conducted between March and May of 2002. My colleague and I observed 8 of the 9 sessions conducted for the overall JPL study, including all 5 in which the cryobot lander design took place. These 5 sessions ranged in length from 1 hr 45 minutes to 4 hrs 25 minutes in length.[96] With two observers present, it was possible to discuss events and developments from first-hand experience of the primary data apart from any prior commitment to a particular theoretical perspective. This reflection and reconciliation of observations from different perspectives was invaluable at many points in the data collection and early analysis phases. These discussions provided the basis for an initial qualitative analysis to identify key developments and outcomes, significant changes and notable "breakdowns" in the design team's process.[97]

In the Cryobot Lander Study, it was essential for the team to understand certain specific departures from precedent, and to formulate credible design responses to some key challenges. These included:

Science Objectives appropriate for a High Power Source

Participants repeatedly remarked how the availability of 3.5kW of power removed traditional constraints, and challenged scientists to "think outside of the box" with regard to exploratory goals and scientific observations. It also meant that some of the patterns established by previous mission designs were no longer relevant, though the full extent of implications was not immediately apparent. The choice of the cryobot payload was made relatively early and was already the baseline for the static mission study by the time video data collection was in place. Determination of a satisfactory landing site *did* take place during the period of research observation; this decision underwent significant and analytically revealing changes over the course of the cryobot lander study.

Electronics survival in a high radiation environment

Space missions routinely require electronics to withstand intense radiation of different types. Sensitive instrumentation can be particularly susceptible to damage or disruption by high energy (or ionizing) radiation. Mitigating steps, such as the use of shield materials or physical layouts isolating electronics from radiation sources, are common considerations in spacecraft design. The Cryobot Lander Mission was unusual, however, in that the CHPS

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[96] The formal sessions comprising the core data set totalled 16 hours 45 minutes over a 2.5-week period. Most participants arrived somewhat before and stayed after the formal start and end times.

[97] Identification of the key challenges, the particularly important design outcomes and the overall innovative nature of the study were substantiated by interviews, and supported in accounts of key participants subsequently published in professional journals. (Elliott et al. 2003 describe the challenges as "unique" and the result as "trailblazing;" also cf. Lipinski et al. 2002, Poston 2002.)

would generate high levels of certain types of radiation once it began operation on the surface of Mars. In particular, it was expected that a large mass of shielding would be necessary, and it was unclear if this could be accommodated within the tight "mass budget" of most space missions.

Geometry of radiator, Dissipation of waste heat without melting the ice

To generate electric power, the CHPS uses a heat engine. To operate efficiently, these require a large radiator to dissipate heat. Because the atmosphere of Mars is very thin, this relies primarily on thermal radiation to the Martian surface and sky.[98] Early on, when the Cryobot mission and a polar landing site were suggested, it was noted that thermal radiation might raise the temperature and melt ice around the lander, perhaps causing it to sink into the ice. It was also unclear how a radiator of the size and shape initially conceived by the agency developers of the CHPS could be accommodated within the launch vehicle.

In-Session Observations

Over the course of our observations, other aspects of interaction became apparent. In some ways these departed from the expectations formed on our initial visit and earlier descriptions. For example, during particularly interactive periods, discussion shifted fluidly and frequently between topics involving several domains. Sometimes this took the form of a quick exchange of information, other times it resulted in an "organic" transition to an entirely different set of issues for a significant period of time. Transitions to unrelated topics also occurred when progress on a particular issue was stalled, or could not continue until a team member completed some work independently. These moves were apparently made so as to utilize team members' time most efficiently, rather than on the basis of any content relationships between topics of discussion.

Overall there were times when interaction was energetic and participants exchanged information rapidly and confidently. Sometimes spontaneous comments were heard, referring to the results as "cool" and the process as "fun." On one occasion the customer inquired about the possibility of bringing his son to see the process on family day. In another instance, the team leader remarked on a newly-displayed CAD image saying, "we could get into Art Centre with this!" Other times frustration was palpable and confusion temporarily held sway. A great deal of time was spent dealing with equipment problems

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[98] Though this thermal radiation is an electromagnetic phenomenon (what we perceive as radiant heat), it is of a much lower energy than ionizing radiation, and does not have the same damaging effects on electronics.

and glitches with collaboration technology.[99] Other problems arose when the results of interactive discussions were not captured or participants failed to incorporate them in subsequent work. Once, when polled on progress, a domain chair expressed the need for information that had been exhaustively discussed in the previous session, causing the team leader to say with some exasperation, "we put all that together, didn't we?" The customer chimed in dryly, "yeah, we *sure talked* about it."

In descriptions of the JPL process, emphasis on the use of numerical models, search of problem spaces and constraint satisfaction make it sound highly deterministic, almost algorithmic. What we observed showed a significantly greater degree of flexibility and latitude in decision making. While some constraints like the published mass capacities of launch vehicles were taken as relatively hard and static, other constraints—seemingly of equal importance, were less rigid. For example, different experts provided radiation damage thresholds for different types of electronics that were not always in agreement; these were sometimes reconciled without anyone citing specific evidence. A nominal value for one threshold was taken forward, though the expert mentioned an uncertainty factor the size of which would have had a dramatic effect on the result.

My intention here is not to suggest these instances were in any way mistakes or problems. In such early-stage design studies, any outcome would have to pass through many more hands and undergo years of further development, validation and testing before flying on an actual mission. The domain is one, however, in which numbers are required to advance a design, and designers are surrounded by representations that require numbers. Numbers for things that don't yet exist, or that cannot be measured, are inevitably speculative. In what we observed, the acceptance of any number seemed to rest on the associated expert's credibility as much as any published source or complex calculation (though these were sometimes involved).

There also seemed to be a collective sense of when credibility of the study as a whole required keeping some constraints inviolate, while others were more flexible and subject to discretion. For example, while no design would be credible if it required developing a new launch vehicle to carry it into space, the precise value of the radiation threshold did not appear to be critical. A number was needed; what was important was that the design *made*

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[99] I did not specifically assess the amount of time spent dealing with problems related to collaboration technology, though these related primarily to sharing data and screens with remote participants (including keeping track of whose screen the remote participants were seeing). The micro-analysis I describe below tended to minimize the impact of these difficulties, since significant breakdowns often prompted topic shifts that either bounded episodes or rendered them overly complex (as discussed in conjunction with episode selection in the following chapter).

sense. Choices between specific approaches seemed similarly based on a kind of collective, intuitive assessment—informed by numbers, but not decided by them. We also never saw voting or a methodical tabulation of attributes associated with different alternatives, as one might expect from some decision theories.

Work-related activity also occurred outside the formal bounds of the design sessions. Candid discussion often took place between the study lead and JPL customer before and after sessions, with regard to programmatic aspects of the study progress as well as substantive design content. Team members reported spending as much as 4-8 hours doing off-line or preparatory work for each (approximately four-hour) session, gathering information, running analyses, and preparing results for presentation. These factors mean we as researchers cannot claim full knowledge of all the antecedents of key design decisions, nor can we reconstruct all aspects of design reasoning. However, because of the collective nature of the work and the practice of making important decisions interactively, we felt confident that key design developments were reliably surfaced during the formal sessions. We also had the opportunity to gather information from interviews and other sources that allowed us to triangulate interpretations of the events witnessed in sessions.

Outside and Background Interviews

Post-Session Interviews with Team Leader

An important source of information, beyond direct observation in sessions, was the team leader who made himself available for 30 minutes to 1 hour after each session. As it happened, there was not always time to get through the interview protocol however, and because it came last, reconstruction of the timeline was only possible after three of the five sessions. I did not feel this was a critical methodological problem because the leader made comments about specific episodes and developments during the general feedback portion of the interview as well. The team leader was also not present during the first half of the fifth session, so he was unable to provide any evaluation for this period. This meant that, as data, the team leader's evaluations of productivity were not as granular or consistent as I would have liked. I believe I found a reasonable way of incorporating them in the macro-analysis, as I will describe below.

Team Member Interviews

In the days following the final design session for the cryobot lander, we were able to arrange interviews with all JPL team members, the JPL customer and several other managers. (These are also presented in Appendix A.) An interview protocol was developed for team members regarding their overall perceptions and confidence in the design. This also solicited explanations and rationale for some of the most noteworthy developments. Questions were asked in three areas:

- organizational affiliation, tenure with JPL and the concurrent design team
- recollection of rationale for specific, noteworthy developments, and key specifications that underwent significant change over the course of the design. (For the latter, we queried recollection of any specific event or pivotal information as having led to the change.)
- questions regarding participants' experience of design sessions in general, how they manage their attention in sessions, workload and other priorities, etc.

JPL Customer and Background Interviews

Background interviews with the current and two former customers were conducted, as well as with a senior manager involved in the overall proposal process, a program manager and a senior technical manager responsible for the concurrent design facility. These interviews were useful in helping us develop an understanding of how the standing concurrent design teams fit in JPL's proposal development process. They also were used to substantiate the performance of the team and to give a better feel for the meaning of specific claims.[100]

Management Meeting and Journal Publications

The researchers attended a meeting in which the JPL customer presented the results of the Cryobot Lander Study to the external agency managers that had contributed funding. This presentation supported our observations, attesting to the key design challenges and the features that were considered most noteworthy and innovative. In the intervening period, several publications have also described the outcome of the study, confirming the challenges and key outcomes from the customers' points of view (Lipinski et al. 2002, Elliott et al. 2003, Poston 2002).

Macro Analysis

At the conclusion of JPL's CHPS design study, our field observation came to an end and the next task was to gain an overview of the large and complex data set. Through observations, interviews and discussion, my colleague and I had formulated a clear idea of the key design challenges, the innovative solutions, remarkable developments and problematic aspects of the team's interaction.

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[100] For example, this included accelerated "design maturity" (a more thoroughly considered design in a significantly shorter time), that one respondent quantified in terms of saving several months of development work compared to more conventional means.

Subsequent activity involved a qualitative analysis to structure and better understand the data. Out of necessity, owing to a lengthy delay in obtaining video data, this process principally involved thematic coding of transcript texts. On the level of research process, some real surprises and principal lessons arose from this experience. Additionally, the segmentation I initially had in mind as a basis for parsing units of analysis—making use of the team leader's announced transitions between different domains and chairs—proved to be far from adequate. Indeed, the issue of how to meaningfully tease apart data into manageable chunks for micro-analysis remains one of the principal challenges; this is an issue I will return to address in Chapter 9.

Phase I—Qualitative Analysis and Thematic Content Coding

In conjunction with my fieldwork colleague, shortly after completion of field observations, we undertook qualitative thematic content analysis to code in-session discussions. It soon became clear that the design discussions did not break down simply along the lines of the different domains of expertise. For example, a discussion that involved the power system engineer could also pertain to the science payload, the start-up timeline, or other subjects. Instead, we found ourselves coding in terms of what we characterized as conversational "threads" (cf. McDaniel et al. 1996). These were recurring discussions that, though not entirely independent of one another, by and large involved different subsets of the team and different representations.

As summarized below in Table 4-2, three of these threads (radiator configuration, sensitive electronics and radiation types & effects) closely relate to the central challenges of the mission and to innovative aspects of the resulting design. The remaining three (landing site selection, data rate & telecom architecture and start-up timeline) involve determinations that would typically be required by any scientific Mars mission. Each of these threads tells a story; each had a significantly innovative outcome or an interesting development at some point that relied in part on a persistent shared external representations.[101]

[101] These six threads were the longest and most elaborate. I am not discussing several other, relatively short and less complex threads that were not as analytically interesting for purposes of this research.

Table 4-2 Design Issue Threads

thread	*key questions / noteworthy developments*	key feature major change	productive convergence	problematic interaction	breakdown
Radiator Configuration	How will the radiator fit in the aeroshell? Will waste heat melt ice beneath the spacecraft? • • • Went through several different configurations, with one expert describing the final configuration on two occasions before it was finally adopted the third time—why?	+	+		
Sensitive Electronics	How will the electronics survive the radiation? Will the required shielding make the spacecraft too heavy? • • • An emergent idea to use a deployable mast became a key component of the final design.	+	+		
Landing Site Selection	Where can we land to do high power science for a five-year mission? Will there be enough sunlight to power the spacecraft? Will there be adequate visibility to communicate the data? • • • The landing site switched dramatically from the north, to the south pole, and finally back to north with pivotal input from outside experts and compelling satellite images.	+	+		
Data Rate & Telecom. Arch.	How much data will there be? How will we communicate it back to Earth? • • • Underwent a sudden and significant change near the end of the design. Was it a misunderstanding, or why did it not occur earlier?	+	+	-	-
Power and Start-up Timeline	How much power will we need prior to the CHPS start-up? Will the source be solar or batteries? • • • A breakdown occurred when the group assumed a complex timeline discussion had been captured when it had not. Why was this so difficult?		+		-
Radiation Types & Effects	How much radiation will there be? What effects will it have on sensitive electronics? How will the design reduce radiation levels and/or mitigate damaging effects? • • • There was a lack of shared terms and evident frustration at times around the types and effects of radiation and the various proposals for mitigating design features.		+	-	

At this point, I was confident that a number of analytically interesting events, reflecting a range of phenomena related to persistent shared representations, were contained within this more structured subset of the data. Threads, however, were not yet suitable for micro-analysis since they comprised large amounts of temporally discontinuous interaction, with individual periods varying from a few exchanges to tens of minutes in length. Thread coding was also not exclusive; a single exchange could relate to more than one thread—for example, when a discussion of radiation also related to the instrument platform, or when the timeline discussion included an exchange about radiator configuration. This lack of distinct independence complicates any quantitative comparison.

To take the analysis to the next stage, it was now necessary to parse the data into smaller, robust units for actual micro-analysis, and to select specific episodes that would be likely to offer the most informative contrasts.

Initial Parsing

Reviewing transcripts and audio recordings, I initially relied on the team leader's announced transitions to parse interaction into discrete episodes. Approximately thirty hours of recorded interaction comprising five design sessions were parsed into seventy-two episodes, ranging from under ten minutes to over one hour in length. I expected these episodes to serve as my principal units of analysis.

Many transitions were clearly made to keep work progressing in a parallel manner on different subsystems. In these cases there was no apparent content relationship between the newly-initiated discussion and that which had preceded it, and the transition was relatively clear-cut and unproblematic. However, I also noted several problems. The boundaries between some episodes seemed rather fuzzy, with transitions unsuccessfully attempted and continuation of similar issues resurfacing. In some rather long episodes, discussion seemed to flow into quite different topics that involved different domain experts, without any "official" transition. Other transitions rather clearly involved returning to pick up work in progress or to complete a previously unsuccessful transition.

Of course, since interaction with shared representations could not be reconstructed with any reliability from audio recordings alone, the video data became essential at this point. This became my next focus and I set concerns about parsing temporarily aside.

Phase II—Video Review

A significant delay of almost one year transpired before the video data from the design sessions was obtained.[102] When the video finally became available, the first task was to

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[102] Authorities at JPL unexpectedly withheld video over concerns about content and export-control restrictions. These were eventually resolved through a series of time-consuming and labour-intensive reviews, in which JPL requested removal of specific information deemed potentially subject to export control. At these points I have substituted more general descriptive terms, enclosing these with square brackets [].

review the entire record to log instances of significant interaction with shared external representations.

During this review I noted a number of interesting and surprising things. For example, some particularly energetic periods—with participants moving around the room and speaking simultaneously—resulted in confusing audio or the simple designation, “unintelligible,” in transcription. Ironically, some of the more dynamic interaction, as evident in the video record, had essentially disappeared from the text-based analysis! Conversely, relatively well-ordered conversation—clearly recorded and transcribed—appeared almost sedate and unenergetic by comparison. Also, despite my initial expectations about the necessity of incorporating shared representation in productive interaction, I was surprised to find that an early episode I identified as pivotal on the basis of the transcripts, one during which the most conspicuously innovative design feature was first proposed, actually involved the use of no persistent shared representation at all!

Figure 4-4 Video Review Setup
Two camera angles were simultaneously reviewed alongside a master spreadsheet timeline to tabulate in-session criterion variable indicators and instances of interaction with shared representations.

I also noted significant gestural activity occurring at times, both directly over representations (as a way of animating them) and in otherwise verbal exchanges, as participants illustrated contributions “in the air.” These gestures substantially augmented what was expressed in language. Back-and-forth exchanges involving particularly expressive gestures indicated a stronger level of engagement between participants at times than was evident in the audio alone.

As a result of video review, it became apparent that my micro-analytic approach would have to encompass language—particularly imagistic language—and gesture, in addition to the use of persistent shared external representation. It was also clear that the strongest form of my initial hypothesis, namely that persistent shared external representations were *necessary* for collaboration, was unsustainable.

Triangulation and Selection of Episodes for Microanalysis

With an overview of the entire data set, and video data firmly in hand, I formulated specific indicators to enable selection of particular episodes for micro-analysis. These related, on one hand, to predictor variables I associated with the various ways participants might engage with shared representations: requesting a display, drawing attention by indicating visible features, standing and gesturing, or drawing on a whiteboard.

On the other hand, I formalized several indicators relating to a criterion variable of the productivity of the design conversation. To triangulate this, I utilized information from three sources. First, key innovations in the final design were determined at the conclusion of the Cryobot Lander Study, on the basis of interviews with the study lead and team members, with the JPL customer, and from the content of a management presentation to the agency customer. In addition to these outcomes, I added certain demonstrable process breakdowns or major unanticipated changes associated with the major threads, again bolstered by interviews.

Second, post-session interviews with the study lead were transcribed and coded for his positive and negative statements regarding session productivity. To compensate for the fact these interviews did not involve a timeline reconstruction in every case, statements relating to specific events were isolated from non-specific statements about the conduct of sessions in general.[103] A third source was observed behaviour, noted during the actual session observations or during review of the videotapes, that appeared to reflect participants' excitement or satisfaction (or the converse). These indicators and the sources upon which triangulation was based, are summarized in the following table:

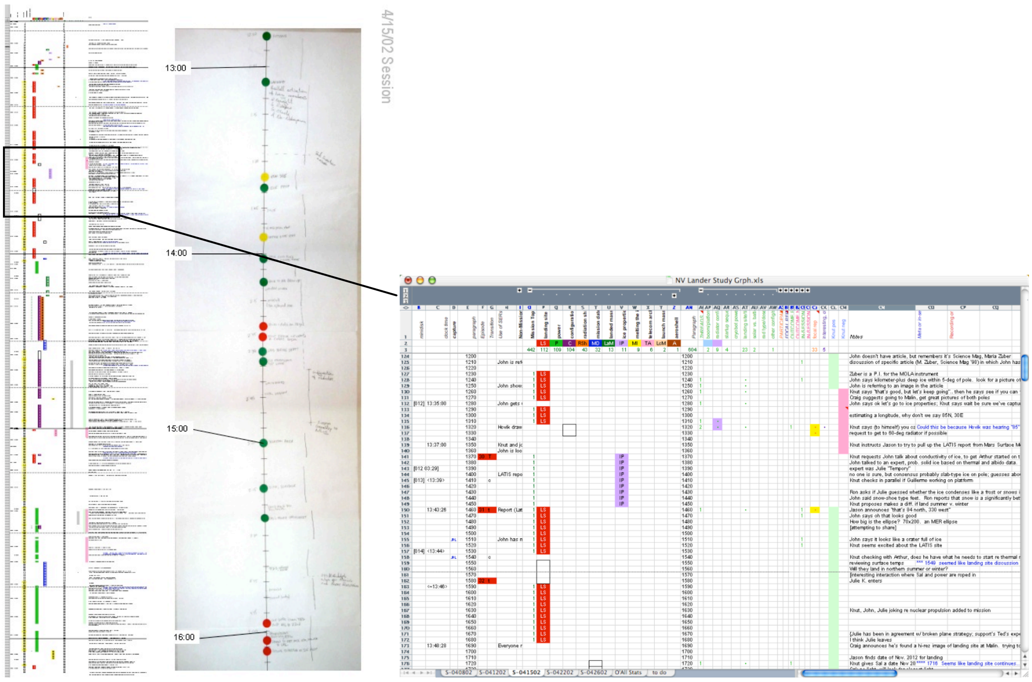
Table 4-3 Indicators for Criterion Variable Triangulation

criterion variable triangulation	*positive indicator*	*negative indicator*
significant outcomes or major changes	• key innovative features • unanticipated and significant change in essential specification or system station parameter	• demonstrable process breakdown

[103] Comments made by the JPL customer in his individual interview were also taken into account where they related to specific events.

criterion variable triangulation	*positive indicator*	*negative indicator*
leader or customer evaluation (post-session interviews)	• positive evaluation of productivity or result	• negative evaluation of productivity or result
observed behaviour (in-session / video review)	• expressions of satisfaction • evident excitement, lively and animated exchanges involving multiple participants	• expressions of frustration or dissatisfaction • evident confusion or difficulty in communication

To actually tabulate these indicators, I needed a more compact analytic representation for each session, one that was capable of bringing the coded transcripts, videotapes, post-session interviews and in-session notes into alignment. For this purpose I created an Excel spreadsheet that collapsed five conversational turns from the transcript onto a single line, with columns to cross-reference video time stamp, audio recording time-stamp, and clock time. Additional columns reflected the initial thread coding and the various indicators for predictor and criterion variables, including the team leader's post-session interview evaluations (and post-session timelines). Examples of these timelines are shown below in Figure 4-5.



(a) (b)

Figure 4-5 Master Timeline and Post-session Interview Timeline
(a) Master timeline (Excel) alongside paper timeline constructed during session for use in post-session interview. (b) Master timeline close-up showing columns used for indexing video, coding and triangulation.

Besides bringing the major constituents of the data into alignment, and representing them in a more visually compact manner, the Excel master timeline allowed positive and negative indicators to be counted and summed. Because the team leader's comments could not be temporally localized in the same way as the other two factors, these were not rendered as countable marks; instead, they were assigned to the contiguous length of the thread involved if they were not specific enough to localize to any particular period of conversational exchange. Interaction with persistent shared external representations was similarly tabulated with countable marks in each spreadsheet row. It was now possible to construct a graph to relate episodes of varying lengths to the number of positive and negative indicators accrued to each from the various triangulation sources. These graphs are presented below in Figure 4-6.

From these graphs it is possible to see that some episodes score particularly high, compared to the median for all episodes (which is represented as a dark line). White lines on these graphs reflect subsequent selection considerations, which are described in the following section.

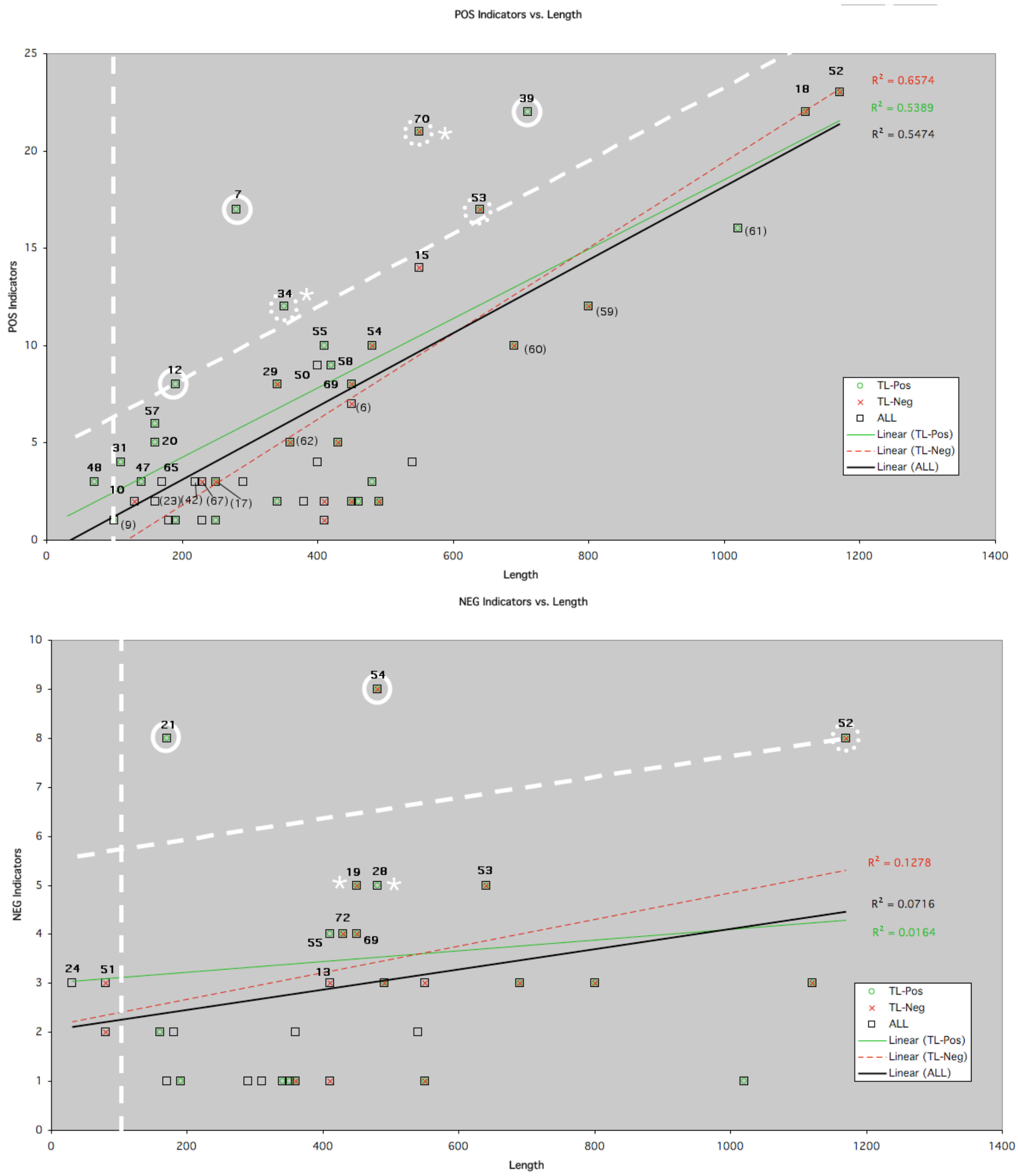


Figure 4-6 Episode Selection based on Positive and Negative Indicators
Graphs of number of positive and negative indicators[104] vs. episode length.[105] Indicators based on in-session observations, post-session interviews and outcomes. Dark line represents linear average for all episodes; white lines indicate final selection criteria developed in response to problematic aspects of initial parsing, as discussed below. (Legend: TL-Pos and TL-Neg refer to positive and negative post-session evaluation by team leader, with linear averages for each subset also depicted.[106])

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[104] Because these graphs show sums, they no longer, strictly speaking, reflect triangulation since selection could in principle have been based entirely upon a single category of indicator. As it happened, this was not the case for any of the selected episodes and I found it more straightforward to sum indicators for the purposes of this graph.

[105] Length is based on the number of conversational turns in text transcripts. Because of the way paragraphs were numbered by the qualitative analysis software, length actually correspond to *twice* the number of conversational turns.

[106] My expectation was that the average for those episodes positively evaluated by the team leader would be above the overall average based on the other two sets of indicators (and vice versa for negatively-evaluated episodes). While this was true for shorter episodes, the correlation broke down for longer episodes (as indicated by the crossing lines). The team leader's evaluations were related to events, not episodes. Longer episodes accumulated large numbers of both positive and negative

Though the initial parsing procedure allowed me to construct these rather useful graphs, as mentioned above, parsing was problematic in several regards. Some episodes that were quite long, such as Episode 18 and 52, seemed to have significant internal structure including periods of quite disparate activity. This diversity was reflected in large numbers of both positive and negative evaluations by the team leader, which disrupted the expected correlations between these and the other indicators. To be more confident about the nature of these episodes as units of analysis, I decided to undertake a more complex approach to parsing, based on an elaborated typology of transition types which I will now describe.

A More Complex Logic for Topic Shifts

I revisited my earlier approach to parsing, to try to understand the evidently complex structure embodied in longer episodes, and the fact that some short episodes seemed to be continuations or resumptions of earlier work.

Rather than treating transitions as a single type, my first elaboration was to impose a high level distinction between those transitions that appeared to be principally governed by a logic inherent to the conversation itself, and those that appeared to have been dictated by external process considerations. I termed the former “organic” transitions, because they reflected the natural flow of conversation; I dubbed the latter “process” transitions. Among process transitions were the team leader’s clear-cut announcements using language like, “ok, now we will move to the next item.” Accordingly, I referred to these most process-dominated moves as “next” transitions. I have arrayed a variety of other situations I encountered in the data on a continuum between these two poles, as shown in Figure 4-7.

Clark (1996), in his discussion of discourse and topic transitions, presents a description of the nested structure of subprojects in conversation.[107] He proposes five conversational transitions: entering new projects, initiating a subproject (“push”), returning from subproject (“pop”), initiating digression, or return from digression. Overall, Clark’s typology is helpful as a way of understanding many of the transitions I identified in my data, including returns to previous topics, transitions triggered by events such as appearance of a display or an external expert. Other transitions I observed appear to fall outside Clark’s typology. These include shifts conspicuously forced (or resisted) by a member of the team other than the lead, as well as moves made to a different issue or prior topic while the team waited for something else to happen, in effect “killing time.”

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evaluations, which disrupted the expected correlations. I took this as a further indication that long episodes contained significant, meaningful internal structure that required closer examination.

[107] Clark (1996) pp. 341-345 favours the notion of conversational subprojects over topics per se.

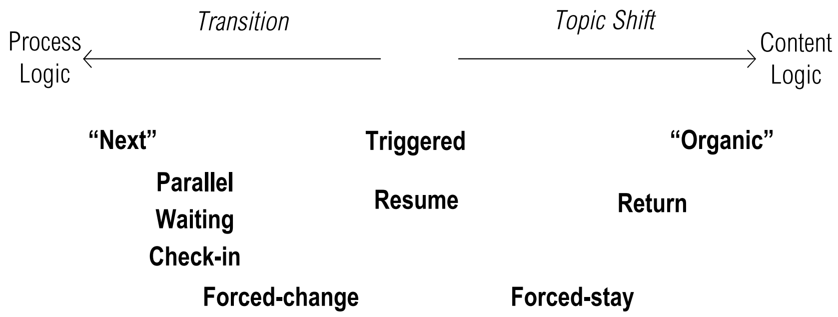


Figure 4-7 Elaborated Typology of Transitions and Topic Shifts
Transitions range from "organic" topic shifts, entirely governed by a logic inherent in the content of the discussion, to a "next item" transition, governed by an external process logic, such as efficient use of time (e.g. "while we're waiting.."), or an arbitrarily-ordered list.

With this more elaborate typology in hand, I revisited all five sessions and re-coded transitions accordingly, differentiating between process and content-logic transitions. I formulated a diagrammatic scheme to keep track of the results, shown below in Table 4-4. Overall parsing diagrams for all five sessions are depicted in Figure 4-8.

Table 4-4 Scheme for Diagramming Topic Shifts based on Conversational Sub-Projects

	topic		resume previous topic (i.e. w/ continuity of work)
	directly-related or follow-on topic		
	enter subproject		relating to / picking up previous topic (w/o continuity of work)
	return from subproject		
	attempt-failed PROCESS transition		
	attempt-failed CONTENT transition/topic shift		

The direction of temporal flow is essentially vertical from one topic to the next; a step to the right denotes entry into a sub-project, while a step to the left denotes either a return or a process transition. (The latter depending upon whether a content relationship existed or not, as reflected by the presence or absence of a line linking the two topics.)

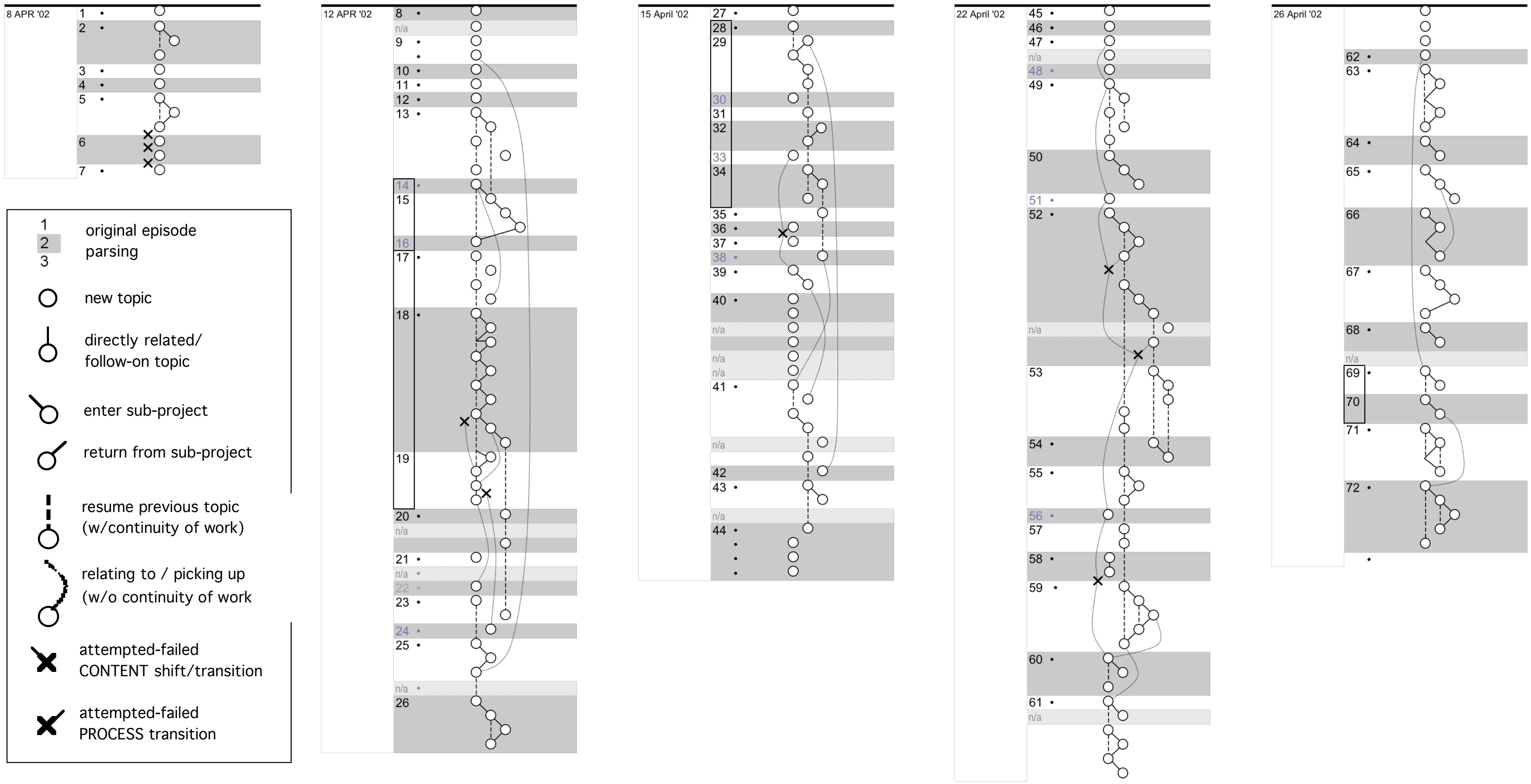


Figure 4-8 Revised Parsing of Sessions on the basis of Conversational Sub-Projects
A more elaborate typology of transitions and topic shifts based on conversational sub-projects (Clark 1996) illustrates why parsing episodes is not clear-cut. Many episodes had significant internal structure, while others were resumptions and continuations of previously suspended topics or work happening in the background. (Gray cross-hatching indicates periods dominated by extended discussion of coordination issues or collaboration technology.)

Essentially, this approach allowed me to understand and more satisfactorily depict the internal complexity of some episodes, and to verify others as continuations of work that had been ongoing or proceeding in the background. This refined parsing approach provides a way of identifying and excluding episodes of questionable analytic coherence that might be problematic in micro-analysis.

Final Selection of Episodes

To make a final selection, I formulated a final set of criteria as follows: I considered the episodes that were substantially above median in terms of indicators in Figure 4-6. I excluded episodes less than 100 transcript paragraphs in length (approximately 50 conversational turns) as too short. I also excluded episodes that showed a particularly complex internal structure of subprojects, returns, etc., as well as others that were direct returns or continuations, to ensure the content logic of each selected episode would be relatively coherent and self-contained.

Based on these criteria, five episodes were selected for microanalysis, while several others were excluded, as depicted in Figure 4-9. Episodes 7, 12 and 39 were selected on the basis of high levels of positive indicators, Episodes 21 and 54 were selected on the basis of high levels of negative indicators. Episode 70 was also selected on the basis of positive indicators; however it was later dropped from the population for being too much a continuation of Episode 69 (the two episodes taken together were relatively long and not as significantly above the median). Episodes 34, 52, 53 were similarly "deselected" on the basis of an overly-complex internal structure.[108]

[108] Episodes 19, 28, 34, 53 and 70 are marked with an asterisk; as I will discuss later, interesting events that occurred during these episodes will be taken into account in macro-analytic results I describe in Chapter 7.

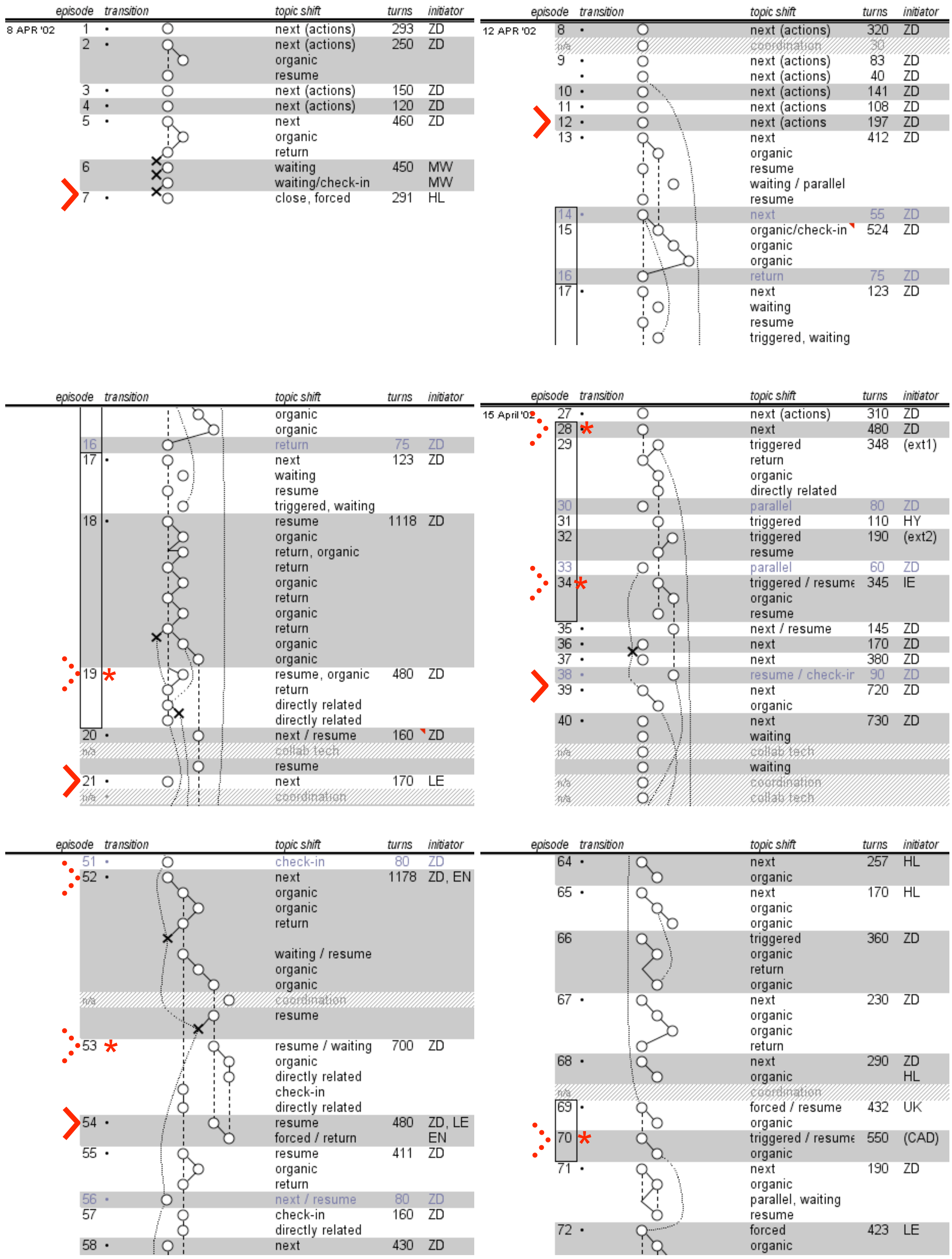


Figure 4-9 Internal Structure of Episodes Selected and Excluded
Note that the selected episodes have relatively simple internal structure. Several other triangulated episodes are excluded either because they have a more complex internal structure or because they were continuations of previous episodes. (Detailed parsing diagrams for all five sessions are included in Appendix A.)

The final, selected episodes are summarized below in Table 4-5. As I was now confident that these episodes embodied the most analytically informative phenomena in a form that could be manageably analyzed, I proceeded to develop the micro-analytic technique. This is the subject of the following chapter.

Table 4-5 Summary of Selected Episodes (Thread, Attributes and Content)

episode	*selection basis*	*thread*	*key outcome*	*use of shared reps*	*problematic interaction*	*noteworthy content*
7	**+**	sensitive electronics	√			• brainstorm leading to emergence of a key feature: the idea to place sensitive electronics at the end of an extensible boom or mast.
12	**+**	radiator config.	√	√		• an intermediate stage along the way to development of a key feature: the horizontal radiator; apparent agreement turned out to be unstable
21	**-**	radiation types and effects		√	√	• a non-convergent exchange between experts during a narrated spreadsheet presentation; a "skew" conversation
39	**+**	radiator config.	√	√		• elaboration of a key feature (the horizontal radiator) in its final form; energetic collaboration, interaction over several shared representations
54	**-**	radiation types and effects	√	√	√	• a key insight arises in the midst of disagreement and frustration during a narrated spreadsheet presentation

5. MICRO ANALYSIS

In the preceding chapter, I described the unfolding of the field portion of the research and the macro-analysis I undertook to understand the content of the data, and through which I discerned a number of bounded episodes for more fine-grained analysis. These episodes were selected on the basis of high densities of positive and negative indicators relating to productivity (which I assessed on the basis of a combination of in-session observations, design outcomes, and interviews), and a relatively straightforward structure of internal topic shifts.

Having selected the episodes likely to offer the most analytically-informative contrasts, in this chapter I describe the iterative development of a micro-analytic technique. This began with exploratory coding of a larger number of episodes using categories drawn from the schemes reviewed in Chapter 3. As I gained confidence in which codes were most applicable to the data, I began formal coding of the five selected episodes. I soon encountered difficulty, however, trying to adequately grasp the structure and content of the interaction within a purely categorical analysis. I made the decision to switch to a network-based analytic representation, which proved far more effective for my purposes.

Development of the coding scheme and the network formalization proceeded in an iterative manner, with coding of the selected episodes undertaken in an order determined to introduce complexity in stages. As changes and elaboration of the coding scheme were required by the data, I re-coded all episodes to ensure overall consistency. By the time this process was complete, I felt confident the coding scheme was adequate to render the important phenomena in the selected episodes. I proceeded to evaluate and perform additional numerical analyses on the fully-coded episodes; the results of this activity are presented in the following chapter.

Exploratory Coding

As a first step in the development of a micro-analytic technique, I undertook exploratory coding on a number of episodes, drawing upon the observational schemes I discussed in Chapter 3 as sources for potentially useful categories and distinctions. In addition to all five selected episodes, I included several others also highlighted during the selection process. Before entering into the details of exploratory coding however, I would like to provide additional background on the coding process in general, particularly with regard to the distinction between micro and macro-analytic approaches.

Micro-analysis is performed on episodes.[109] In discussing threads and episodes in the previous chapter, I emphasized thematic relationships in content coding. Micro-analysis requires assuming a perspective at the level of participants' situational awareness in interaction, and the coding is more pragmatic in nature—that is, it depends upon the manner and context of use. In essence this means respecting the coherence of interaction in a manner that is in some ways orthogonal to thematic content coding.

Micro-analysis is laborious and time consuming. A continuous recording of interaction in a real-world setting contains a great deal of information, not all of which is relevant to a particular research question. My central interest lies in understanding the ways collective design reasoning and representational activity are interwoven to accomplish interactional work in this setting. Because the subject of this chapter is the development of coding to make this process visible, I would like to begin with some high-level distinctions my colleague and I imposed on the content; this is necessary to convey an idea of the types of interaction I focused on. This also provides a way of introducing some additional concepts, pertaining to the layering of conversation, that will be useful in resolving some of the fine structure of interaction I will grapple with below.

Initial Distinctions

At the outset of coding, my colleague and I agreed upon several high-level distinctions with regard to the content in different types of interaction. These included distinctions between discourse pertaining to the actual design of the spacecraft vs. that relating to project or program management, difficulties with collaboration technology, and coordination issues such as scheduling meeting times, locating missing individuals, etc. These distinctions are summarized in the following macro-level codes:

Table 5-1 Macro-level Content Coding and Examples

code	*description / example*
Mission	• discussion directly pertaining to some aspect of the cryobot lander design, the CHPS, mars surface exploration or spacecraft mission design
Coordination	• asking the whereabouts of a particular person • arranging a time to meet; calendars and scheduling • discussing whom to contact off-line with a question

[109] Episodes and threads are distinct units of analysis. Threads are a useful way of drawing together discrete, temporally non-contiguous periods of interaction on the basis of thematically-related content. Episodes are continuous periods of coherent interaction with clear temporal boundaries—characteristics that are necessary to facilitate micro-analysis.

code	*description / example*
Collaboration Technology	• problems or delays in switching a shared display to a different system • problems or delays sharing screens for remote participants • joining audio teleconference or retrieving dropped participants • looking for a system administrator (e.g. to provide a password or help restart a computer)
Project and Program Mgmt	• discussing who should attend a project review meeting with higher-level management, and what should be presented • which billing codes should be used for participants' time
Other Non-mission	• discussion of bringing children to see the lab on family day[110]

Distinctions such as these can be better understood by drawing upon Clark's (1996) account of the structure of conversations. Clark describes conversations as joint projects involving coordinated but distinct lines of action on three dimensions.[111] Clark's notion of layers provides a way of understanding how some discourse may be grounded in a "joint pretence" (such as that of the imagined spacecraft and its performance on Mars) and carried on relatively distinctly from other discourse relating to more immediately aspects of the here-and-now. In this case, I found that project and programmatic considerations of the organization, and issues or breakdowns arising from collaboration technology involved different realms of conversational grounding, hence represented separate layers of conversation.

While these layers are distinct, they are not independent of one another; Clark's theory suggests that participants utilize a second, meta-communicative "track" to reflect upon the progress of their conversation and to manage movement of conversation between layers. To understand the structure of design reasoning in this instance, I focus primarily on interaction involving discourse grounded in the joint pretence of "the Mission," taking place in the imagined future. All episodes, including the ones selected for micro-analysis, consisted primarily of this type of discussion, but had embedded periods of programmatic discussion, collaboration technology. In particular, I found it useful to attend to meta-communication regarding these layers (in addition to the core focus on mission design reasoning), as I will describe in more detail below.

[110] Though not coded as design discourse per se, an exclamation like, "This is really cool, I'd like to bring my son in to see this!" would have been tabulated as a positive in-session indicator in episode triangulation.

[111] Clark (1996, p. 388) describes the structure of conversation in terms of layers, levels and tracks. I mention only layers and tracks here; Clark's notion of action levels will be useful in the discussion of conversational repair, below.

Collective Design Reasoning

Working primarily with text transcripts, I now embarked upon exploratory coding of a number of actual episodes, working loosely within the confines of previous observational schemes reviewed in Chapter 3. To better grasp categories and work with the underlying distinctions these schemes comprised, I experimented with various ways of grouping and clustering specific codes. Overall, I found codes falling into three areas:

- design reasoning structure (including argument structure, notions of convergence and divergence, problem and solution spaces)
- constituent acts and actions (e.g. making proposals, negotiation & discussion, persuading, assuming or assigning roles, managing process)
- shifts in engagement and communicative modalities (such as between drawing, artefacts, talking, gesturing, referring to past, present or future)

In exploring the data, the codes for reasoning structure that I found to be most readily useful were those derived from argument structure. Some of the other reasoning-related constructs, such as convergence, divergence, problem and solution spaces did not lend themselves as well to fine-grained coding. While I was able to identify instances I could relate to these constructs (such as the deep reasoning vs. generative design questions of Eris 2002), large amounts of un-coded text would have remained. Similarly, naming and framing, though in principle micro-level constructs, in practice did not seem sufficiently specific to the content in most instances. My initial coding was done on paper hardcopies with ample white space. As I became more confident about which codes were most applicable, I moved to a qualitative analysis software package (QSR's NVivo). An example coding screen is shown below in Figure 5-1.

I found myself able to consolidate the constituents of design *argument structure* into three categories: issues/problems, options/solutions, and constraints/criteria. However, I noticed that deploying these categories was not entirely straightforward, in that they tended to be interleaved. I found that a series of contributions generally pertaining to one aspect of argument often had other aspects embedded within it. I also found that registering the effect of any contribution required coupling the category of argument with a *manner of presentation*. For example, when one participant proposed an issue, another might support the proposal by expressing agreement (with the issue); a third might lend additional support by proposing an alternative, while yet a fourth might disagree with the original issue, perhaps invoking something else. All of these contributions pertain to the original issue, but do so in different ways that embody different orientations to the *specific* elements being discussed. This nested structure proved difficult to capture with purely categorical coding.

I also found additional coding distinctions were necessary. Whereas design reasoning was anchored in the joint pretence of the mission, more immediately-grounded exchanges often took place, in which participants directed each other's attention, requested and provided information, or engaged in repair and clarification. These exchanges seemed to operate over shorter periods of time; they often seemed more neutral than exchanges directly involving design reasoning. (Clarification of what someone else has said, or inquiry into a general property can be accomplished without necessarily conveying any particular alignment on the part of the speaker.)

Other utterances seemed to constitute reflections on process or progress more than actual contributions to reasoning per se. In addition to making explicit transitions and topic shifts, at various times the leader and other participants appeared to offer a sort of review or summary to refocus discussion. While these moves still pertained rather directly to the design discussion, they appeared to adopt a different tone or voice. I propose that these types of contributions reflect the layer and track structure to which Clark (1996) refers. In particular, reflective statements on process and progress appear to be made for the benefit of the team, the type of meta-communication Clark assigns to a separate track alongside discussion of the business at hand.

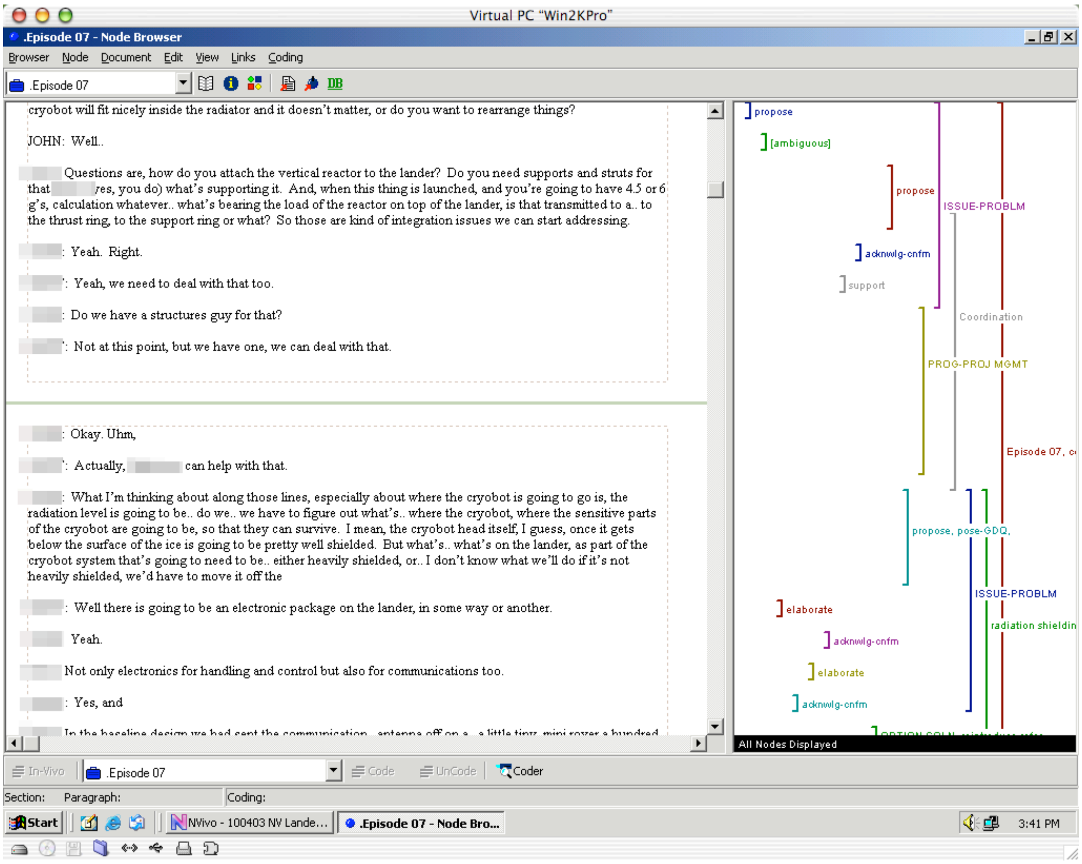


Figure 5-1 QSR NVivo Screen
Transcript text is on the left, and categorical coding of portions is shown by vertical stripes on the right.

As I formalized my coding within NVivo, it became increasingly clear that this type of analysis could only convey a limited understanding of the activity. For example, knowing which participants made what percentage of a particular type of act (e.g., issue proposals) might provide insight into the general nature of an individual's engagement, but this revealed nothing about *which* proposals had drawn what degree of support from different participants. (I include a table showing participants' overall contribution rates below in Table 5-2.)

Table 5-2 Participants' Overall Contribution Rates to Mission Design Discussion

member	*role/chair*	*% of turns*
ZD	Team Leader	35%
HL	JPL Customer	25%
MW	Agency/Power System Design	8.8%
IE	Mission Architect	5.9%
EN	Agency/Power System Design	4.7%
HJ	Mechanical CAD	3.7%
LA	Power	3.5%
KR	Payload	3.2%
LE	Avionics	2.8%
UK	Telecommunications	2.3%

member	*role/chair*	*% of turns*
HY	System Station	1.9%
OV	Orbital	1.0%
LC	Agency/Power System Design	0.9%
YH	Power (Simulation Tool)	0.6%
NC	Thermal CAD	0.5%
RD	Agency/Customer	0.1%
YK	Mechanical CAD	0.0%

Similarly, with purely categorical coding it was not easy to track *which* options were proposed in response to *which* issues, or the order in which contributions in different categories were made. In short, a number of seemingly important relationships in the data were very cumbersome to capture with a purely categorical approach to coding. These included relationships between specific elements of design reasoning, as well as between individual participants and the contributions they made.

As I discussed in Chapter 3, other coding systems take a fundamentally different, structural approach (Goldschmidt 1992, 1995; Goldschmidt & Weil 1998). This essentially emphasizes *connections* rather than categories. It was clear there was more to the design reasoning I was seeing than I would be able to capture with categories alone. Consequently, I began to investigate an alternative analytic representation to track the relationships between participants and their contributions, namely a network.

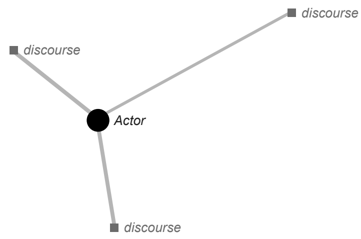
Adopting a Network Approach

A network is a representation of a set of entities (referred to as "nodes") and a number of pair-wise relationships between them (often depicted as lines and referred to as "arcs"). Networks representing configurations of people are generally referred to as social networks (c.f. Scott, 2000; Wasserman & Faust, 1994). Alternately, networks representing relationships between words or elements of discourse are generally referred to as semantic networks (e.g. Corman et al. 2002).[112] Both types of network are referred to as *homogenous*, in that all entities are of the same logical type.

It soon became clear that what I required was different from either of these conventional network forms. Though other connections eventually came into play, the initial class of connection I needed to highlight was that between actors and the reasoning content of the utterances they made. Keeping track of relationships between individual participants and

[112] A linkograph is essentially a semantic network, in that it registers connections between contributions on the basis of their content.

their specific contributions to discourse requires what is known as a bi-modal network, one consisting of two classes of entity: actors and discourse. When members of one class are connected only to members of the other, the resulting network is referred to as bi-partite. Based on the principal connections I observed in my data, I formulated the concept of a bi-partite actor-discourse network as a new analytical representation for design discourse. [113]



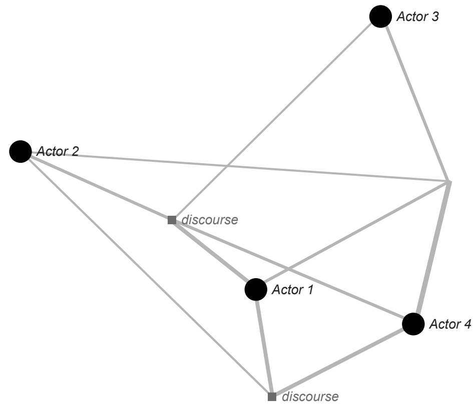


Figure 5-2 (a) An Actor connected to Discourse, (b) A Bipartite Actor-Discourse Network

Constructing such a network from actual design interaction requires making a number of additional determinations. Among the questions that arose were what sub-types would be necessary for both actor and discourse nodes, and what acts would give rise to arcs between them. It is these questions I will now turn to address.

Nodes: Actors and Discourse

In reviewing my exploratory coding, it was clear I would need nodes for different kinds of actor and several types of discourse. The minimum set of discourse nodes would have to include the three elements of design reasoning, as well as another type corresponding to non-controversial items of information and matters-of-fact. As for actors, several distinctions were necessary for different categories of participants, including those physically present and those taking part by video or audio-only teleconference.

Up to this point, my exploratory coding was still entirely performed on transcript texts; consequently, very little detail could be inferred about interaction with shared representations. However, the theoretical resources I identified in Chapter 2 all, in one way

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[113] I wish to emphasize that the decision to adopt a network as an analytical representation was primarily a result of the difficulty I encountered trying to use a purely categorical tool to render design reasoning from transcript texts. It was not directly motivated by actor-network theory per se, or the desire to incorporate representations as actors in the analysis, though these aspects rapidly fell into place once the network approach was adopted.

or another, highlighted representations as potentially active participants in interaction.[114] Also, unlike speech, the design representations I wish to focus on have a persistent presence in the environment. Indeed, as I mentioned in the previous chapter, the recurring participation patterns in threads were as often characterized by the involvement of particular representations as they were by a particular subset of the human participants. For these reasons I chose to class persistent representations as *actors*, tending to place them on a par with human participants rather than discourse. These initial node categories are shown in the following table (in the manner they are graphically depicted in subsequent network diagrams):

Table 5-3 Categories and Symbols for Node Types

actor node types	*discourse node types*[115]
● *participant*	■ *[issue/problem]* (magenta)
● *remote participant / audio-visual*	■ *[criterion/constraint]* (cyan)
● *remote participant / audio only*	■ *[option/solution]* (green)
○ *representation*	■ *[info/matter-of-fact]* (orange)

In the right-hand column above, discourse node categories are reflected by the colours indicated (which are, regrettably, not easily distinguished in monochrome reproductions). A fifth category of discourse node, image/schema (pink) was later added—an elaboration described below. This colour coding is used in the explanatory diagrams that follow, and in the results reported in the following chapter.

Arcs: Communicative Acts, Alignment and the Spatial Metaphor

A network provides a compact way of analytically representing the relationships that had been difficult to capture in the purely categorical approach. As I detail below, the coupling I observed between elements of argument in design reasoning and participants' manner of presentation can be mapped directly onto the network conception of nodes and arcs. Furthermore, with such a representation it is possible to depict participants' shifts in alignment, as they make subsequent contributions, far more effectively than can be done with categorical judgements alone.

[114] Situated action embodies a triadic communication model; distributed cognition focuses on propagation of representational states across people and material artefacts. While activity theory does not emphasize a distinction between external artefacts and internalizations, it assigns an important mediating role to artefacts in general. Actor-network theory treats technological artefacts as actors on a par with human participants.

[115] I eventually found it necessary to add a fifth type of discourse node, "image/schema," as described below.

Having set out a basic typology for nodes, the next step was to map the manner of presentation onto a uniform attribute of arc strength. For this purpose, I adopted a scale with several intermediate strength values between strong alignment and strong distancing.[116]

Figure 5-3 Basic Arc Strength Scheme for Alignment
The scheme is essentially a 5-point (e.g. Likert) scale for degrees of support arrayed around neutral (3), with an additional point (6) for acts going beyond support to constitute active contributions or definitive statements, essentially conveying "this is what we should do". Details of the coding scheme are provided in Appendix B.

By constructing a network of relations, each of which is an individual expression of alignment, it is possible to build up an overall spatial representation in which distance becomes meaningful in terms of actors' relationships to one another. Essentially, this "spatial metaphor" can be expressed as PROXIMITY = AFFINITY.[117] Through their contributions, introducing and discussing elements of design reasoning, participants align or distance themselves from the various issues, options, criteria etc. that have been placed in the discussion. The specific interpretation of alignment and affinity with respect to each element of design reasoning is summarized in the following table:

Table 5-4 Application of the Spatial Metaphor to Elements of Design Reasoning

reasoning element	*strong arcs = ALIGNMENT*	*weak arcs = DISTANCING*
issues and **problems**	"This will be an issue or a problem"	"This will not (or will no longer) be an issue or a problem"
constraints and **criteria**	"This is important" "This will be satisfied or well served (by the option under discussion)"	"This is not important" "This will not be satisfied or well served"
options and **solutions**	"This is a good idea" "This is what we should do"	"This is not a good idea" This is not something we should do"

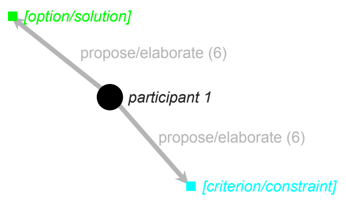
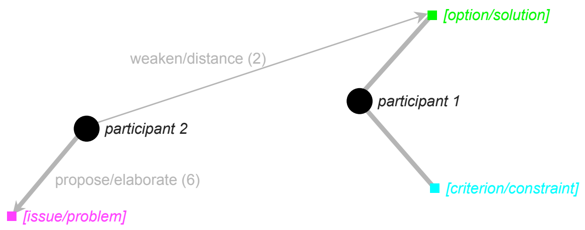
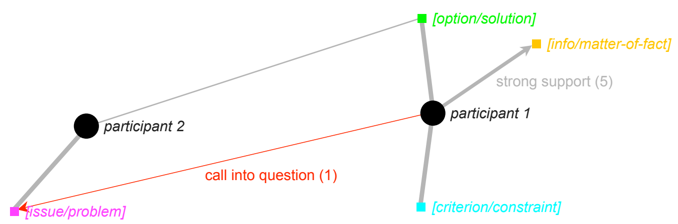
For the spatial metaphor to be meaningful, however, all arcs (corresponding to different communicative acts) must have an attribute of strength that is meaningful in terms of affinity. Accordingly, I apportioned strengths within this range to meta-process acts, and

[116] Used in this way, the term "alignment" and "distance" are taken from Brereton et al. (1996). A very similar notion is expressed by Minneman (1991) regarding how participants monitor each other's commitments in design interaction. Latour (1986, 1990) also uses the term "alignment" in connection with the recruitment and mustering of allies in actor-networks. This use is not only consistent, but essential to the theoretical integration I will propose in later chapters.
[117] Following the metaphor notation of Lakoff & Johnson, 1980.

assigned a neutral strength to other acts, such as those associated with information movement and attention management.

Putting these pieces together allows us to depict the effects of a sequence of design discourse acts in terms of a consistent spatial metaphor for alignment. A brief example is shown below in Table 5-5, with more elaborate examples contained in Appendix B.

Table 5-5 Example Sequence of Design Discourse Acts and Corresponding Network Diagrams[118]

network diagram	*act description*
	a participant proposes an option/solution, mentioning a criterion/constraint it will satisfy.
	a second participant distances themselves from the option/solution by proposing an issue or a problem that will arise.
	the first participant calls this new issue into question on the basis of a piece of information.

Initial Network Coding

With this basic scheme as a starting point, I was prepared to begin coding in earnest. This initial framework was rather minimal and my plan was to develop a more elaborate coding scheme as a data-driven exercise. I approached the selected episodes in order, so as to introduce increasing elements of complexity in the following stages:

- Episode 7: (positively selected) collaborative discussion involving no persistent shared representations; significant emergent feature in final design

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[118] I employ certain conventions in these explanatory diagrams that are not used generally in the findings presented elsewhere in the dissertation. In this sequence, new arcs in each frame have arrowheads indicating the direction of the act; arcs are labelled according to the type of act and the corresponding arc strength is shown in parenthesis.

- Episode 12: (positively selected) collaborative discussion with initial reference to CAD representation only; limited amount of repair and disagreement
- Episode 39: (positively selected) highly interactive collaboration over several representations, including a whiteboard drawing and CAD models
- Episode 21: (negatively selected) tangential discussion departing from a spreadsheet presentation; apparent failure to converge on any issue and difficulty using consistent terms
- Episode 54: (negatively selected) tangential discussion departing from a spreadsheet presentation; extensive repair, evident frustration and implicit disagreement, also gave rise to a significant collaborative outcome

Because it involved no persistent shared representations, and evidenced minimal problematic interaction or disagreement, my initial coding effort was directed toward Episode 7. I set out to identify suitable analysis software that would support categorical distinctions but do so within a more fundamentally network-based representation. Because of the temporal and dynamic nature of the data, I selected a package specially designed to represent dynamic network data: SoNIA (Social Network Image Animator, Bender-deMoll & McFarland 2002, 2006).[119]

Essential Determinations Required to Construct a Network from Interaction

To actually construct a network from interaction data, additional determinations are necessary. Participants' discourse must have some number of referents *in common*, and utterances over some period of time must be *accumulated* and *aggregated*. Also, because depictions of these networks take the form of two-dimensional (2D) diagrams (called layouts), it was necessary to explore several factors governing the construction of these diagrams, and gain insight into certain limitations on their interpretation.

Shared Reference and Shared Referents

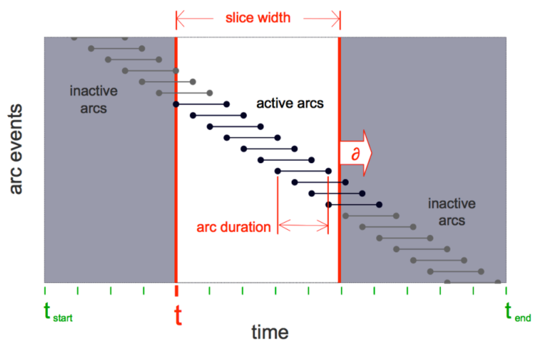
To build up a network from a series of conversational contributions, one must be able to make certain justifiable assumptions: first, it is necessary to determine to what a particular utterance is intended to refer, and second, when subsequent utterances can be understood as referring to "the same" thing. For many theorists, the notion that we can ever truly speak about the same thing is problematic. Since it is not possible to know with certainty to what participants intend to refer in any given instance, we must instead rely on their behaviour to infer *when they believe* they are speaking about the same thing to an extent that allows them to achieve their conversational purposes.

[119] SoNIA is a general purpose tool for temporally aggregating network data and producing animated 2D layout diagrams. While it proved indispensable during the micro-analysis, the actor-discourse formalization, coding scheme and application to design activity are entirely my own work.

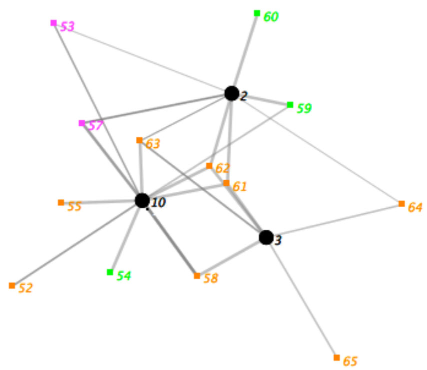
To understand the semantic content of most conversation, it is necessary to recognize that participants generally engage cooperatively (Grice 1975). In this regard, they endeavour to speak about "the same" thing to an extent that is adequate for their purpose at hand; they employ a variety of means to monitor and verify—on an ongoing basis—that this is so, and engage in observable repair when they believe a problem may exist (Clark 1996). Accordingly, I developed coding categories for conversational repair, clarification and verification utterances.[120] In the absence of observable indications to the contrary, I assumed participants intended to speak about the same thing in consecutive utterances. I based my judgements about what it was they were referring to on the content of the utterance, on context (including other observations and interviews), and on my own professional background in engineering and physical science.

Accumulation and Aggregation

Construction of a network requires an accumulation of arcs between a set of nodes, each arc having some attribute of length or value for strength. SoNIA allows flexibility in determining what temporal interval (referred to as a "slice") is used to aggregate arcs arising from individuals' communicative acts. This is diagrammatically depicted below in Figure 5-4.



(a)



(b)

Figure 5-4 (a) Temporal Aggregation of Arcs in a Slice, (b) A Network Layout
In the diagram at left, communicative acts are depicted as occurring consecutively in time.[121] In the network diagram at right, large black nodes correspond to actors, small nodes are discourse (colour coded by type as above); grey lines are arcs, corresponding to communicative acts.

Based on experiments with initial network coding, I found that short aggregation intervals produced very simple networks—often dyads of actors with perhaps one or two discourse

[120] Clark (1996) describes conversational repair associated with four levels of action (pp. 147-153); I defined repair codes based on Clark's levels 3 and 4, which are associated with clarification of reference and acceptance of a joint project, respectively.
[121] In actual coding, a single act might give rise to several arcs simultaneously.

nodes in common. These were in constant flux and conveyed little or no sense of coherent interaction over time. On the other hand, long slices resulted in overly complex networks that were difficult to interpret and whose response was sluggish compared to what transpired in interaction. I found it necessary to adjust this temporal aggregation window (or "slice") to a compromise value for the animated network diagrams generated by SoNIA—one that resulted in networks of sufficient complexity to reasonably reflect what the discussion at any given time was "about", without becoming overly complex and cumbersome. I found a reasonable compromise value for this aggregation window to be 2.5 minutes.[122]

Since talk itself does not persist in the way that external representations like drawings and models do, in what way is it meaningful to say that utterances accumulate? The common ground required to carry on a coherent conversation relies upon the fact that participants retain some memory of prior utterances—both their own and those of their partners. While I make no specific claim about the precise nature of this memory, the fact that *some* memory is required for participants to make sense of their interaction seems to me to justify an aggregation interval of some sort. Conversational cooperation entails a requirement for perspicuity and least joint effort (Grice 1975, Clark 1996). This requires that participants formulate their contributions bearing in mind what their interlocutors are likely to remember. It is reasonable to assume that normally skilled conversationalists are fairly good at making this estimation, and know when to incorporate explicit reminders for their partners when too much time may have elapsed for memory alone to be reliable.[123]

Interpreting Network Structure: Layout Diagrams

Essentially, the network formalization embodied in SoNIA is a way of efficiently summing a large number of individual, fine-grained analytic judgements so that their cumulative effect can be reflected in a network structure. This, in turn, is portrayed as a 2D layout diagram of a particular network slice; multiple slices can be animated to highlight the network's temporal evolution and dynamic response to interactional events (Bender-deMoll & McFarland 2006). Larkin & Simon (1987) emphasize that diagrams convey the greatest benefit to reasoning when they leverage innate human perceptual/cognitive skills so as to make conclusions relatively transparent and obvious. The benefit conveyed by a 2D

[122] As I describe below, I later adopted a scheme in which different types of acts were assigned longer or shorter network durations. To implement this in the network representation, I found it more convenient to use a fixed, short-duration aggregation window (5 seconds), and to assign arcs different durations in a database lookup table. This arrangement is far more flexible and would, in principle, allow one to implement an arbitrarily complex logic for arc duration—a direction I discuss for further work in Chapter 9 and Appendix E.

[123] Though I did not code the entire data set systematically in this regard, instances of such explicit reminders I encountered during coding (e.g. "you know, what we were talking about before") referred to events separated by a time *greater* than 2.5 minutes.

network diagram inheres in its portrayal of the analytic result of network distance in conjunction with pertinent attributes of nodes and arcs.[124] At this point I was primarily interested in achieving a qualitative correspondence between the visual behaviour of the animated network diagram and my impression of the interaction occurring at a particular point in time. I focused principally on the overall clustering of actors and their relative proximity to one another and to the discourse that was the primary locus of discussion at any given time. When these seemed consistent with what was happening in the video, I felt the coding scheme was moving in the right direction; when I noticed inconsistencies I revisited either the coding scheme or my criteria for making uniform and consistent coding decisions (which I kept in a running log as I coded each episode)—a process I discuss in more detail in the section below on iterative elaboration and refinement.

I also anticipated that full-episode cumulative aggregate diagrams might be a valuable way of comparing episodes on an overall basis. As indicated in Figure 5-5, I accomplished this by setting the slice width to encompass the entire episode, thereby taking all acts into account in a single network.[125]

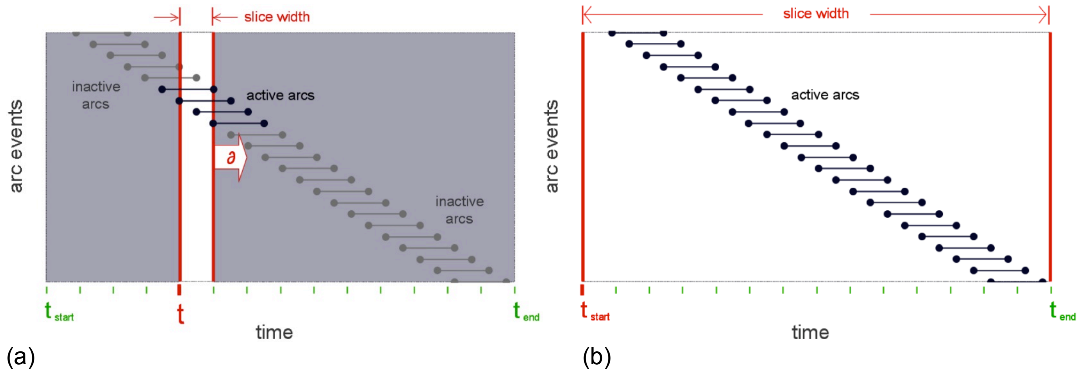


Figure 5-5 Slice Width/Aggregation Interval (a) Narrow for Real-time and (b) Wide for Cumulative Aggregate Layouts
The SoNIA tool determines which arcs are active—hence which are included in mathematical network construction, on the basis of a slice aggregation window of a specified width.

As I completed coding of the first episodes with a scheme that seemed to give reasonable results in animated layouts, I focused my attention on comparing cumulative aggregate network diagrams for each episode. At this point, I felt it was necessary to develop greater

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[124] Another salient aspect of animated diagrams is motion. I discuss a number of potential refinements to make more effective use of this and other attributes in Appendix E.
[125] An additional factor in aggregation is how multiple arcs between the same two nodes are to be combined in a single slice. SoNIA offers three choices for determining a resultant strength value in the case of multiple arcs: counting, summing or averaging. I found that averaging gave the most appropriate reflection of alignment in real time animations. As I discuss below, summing proved more useful and reliable for cumulative aggregate layouts. Implications of these decisions, and ways of overcoming some of the resultant limitations are discussed in Appendix E.

confidence about the precise nature of the information conveyed in the layout diagrams. This turned out to be a major consideration that dictated significant changes in my approach.

Reliability of Layout Diagrams

Some distortion of higher-dimensional (i.e. mathematically "true") network distances becomes inevitable in 2D layout diagrams of networks of any appreciable complexity.[126] In order to minimize these distortions, SoNIA uses an algorithm to determine node positions in layouts (due to Kamada & Kawai 1989). This employs a mechanical analogy in which arcs are modelled as springs and an iterative process of "annealing" is applied. Starting from some initially-chosen positions, nodes are allowed to move so as to relax these springs until a layout that minimizes arc distortion energy is achieved. Two facts are important to note: first, though minimized, some distortion remains inevitable in layouts of networks of this complexity. Second, because the algorithm may only find a local (rather than a global) minimum, final layouts are likely to depend to some extent upon analytically-extraneous factors, such as the starting positions of the nodes. The first is an issue of accuracy while the second raises concerns of repeatability.

While such layout diagrams will never be "accurate" in a graph-theoretic sense, I felt it was important to be sure the 2D layout results weren't visually misleading. As a first step I set out to verify that layouts were not unduly influenced by initial node positions. I undertook a study of layout stability with respect to randomized node start points, which is presented in detail in Appendix E. I found that specific node positions in layouts were *not* sufficiently stable to be taken as reliable in and of themselves.

While I was not relying on precise measurement of layout distances, two observations caused me some concern. Though the arc lengths between actor and discourse nodes generally appeared reasonable and proportionate, the relative positions of actor nodes with respect to *one another* sometimes changed in qualitatively significant ways. Similarly, there was no indication that discourse nodes corresponding to closely-related topics, or facets of the same topic that were addressed by participants in a comparable manner, would end up near one another in the layout. As a result, it was not possible to reliably infer that the positions (vis-à-vis design reasoning) advocated by any pair of actors were necessarily more similar, by virtue of their layout proximity alone, than another pair. Also, while discourse

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[126] For example, it is impossible to create a two-dimensional layout diagram of a fully and symmetrically-connected graph of even four nodes (i.e. a regular tetrahedron) without distorting the lengths of some edges so that they become unequal in the layout. Increasing dimensionality of the layout diagram provides little relief; in a three-dimensional layout diagram the same problem is encountered with five nodes.

nodes that were focal points of interaction were relatively central in the layout, closely related topics were not necessarily adjacent to one another, making it more difficult to visually extract what a particular interaction had "been about." I adopted four changes to my approach in order to mitigate the effects of this instability.

First, some investigation showed that the repeatability of cumulative aggregate layouts could be significantly improved if networks were built up a few arcs at a time, rather than solving the entire network simultaneously in a single slice. Consequently, I adopted an approach whereby a narrow slice width was used, with the durations of arcs specified so they would never retire.[127] This is graphically depicted in Figure 5-6, along with representative images of early and final layout stages from the stability study (detailed in Appendix E).

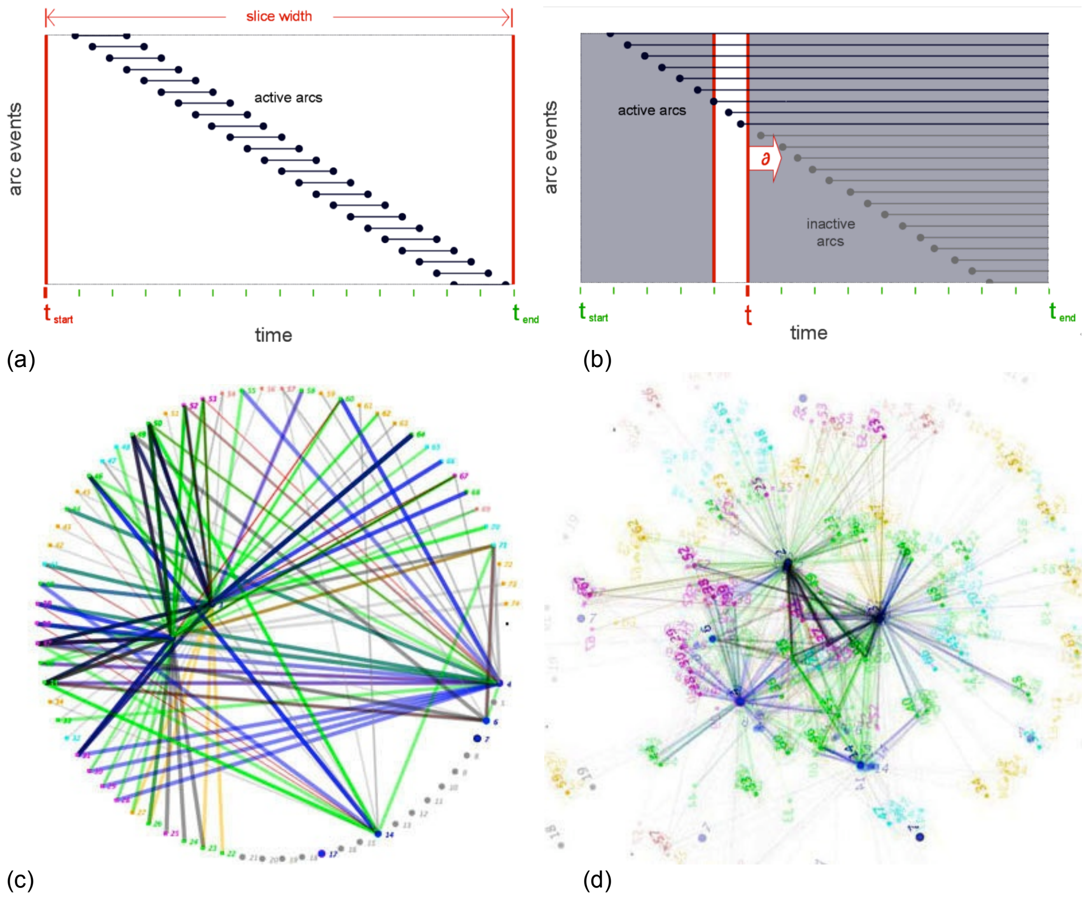
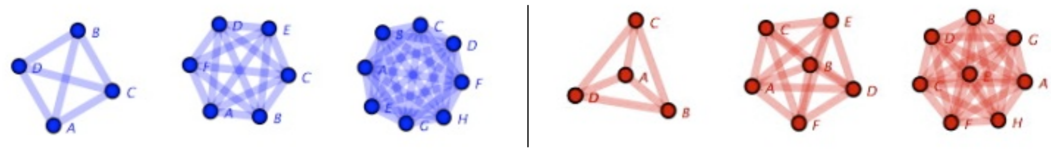


Figure 5-6 Cumulative Layouts and Stability Overview
(a) & (b) depict alternate approaches to constructing cumulative aggregate layouts. (c) shows an early stage corresponding to the approach in (a), in which all arcs are introduced in a single slice (with node starting points lying on a large circle). This did not produce layouts with any degree of repeatability. (d) shows an overlay of 7 layouts generated with the approach depicted in (b), which represents good repeatability, at least with regard to the principal actors and discourse elements.

[127] This was facilitated with a coding spreadsheet I developed in Excel, examples of which are presented in Appendix B.

Second, further investigation revealed that layout instability was a function of the number of actors with comparable, high densities of connections. Specifically, I found that layouts with more than 5 symmetrically-connected actors were increasingly likely to give unstable and visually misleading layout results.[128] What I mean by "visually misleading" is illustrated by the sample graphs in Figure 5-7. While a particular layout may not be precisely repeatable or entirely stable, it is not necessarily visually misleading. By and large, I found this to be true of the animated layouts of real-time slices. While the exact locations and adjacency relationships between actor nodes were not always preserved, the overall form—in terms of visual density, tightness of clustering, who was in and who was out—as well as the focal representations and discourse elements at any point in time were reliably portrayed.



(a) (b)

Figure 5-7 Symmetrical vs. Asymmetrical Layouts of Fully-Connected Graphs
All graphs are fully connected and symmetrical in that each node is connected to every other node by arcs of the same strength. None of these layouts is geometrically accurate because the lengths of the arcs are not identical. For my purposes, the *layouts* in (a) are symmetrical and not visually misleading because they convey a uniform and equal level of engagement even though some node pairs are closer to each other than others; the layouts in (b) are asymmetrical and visually misleading because they portray a particular node as having a privileged or more central position when in fact this is not the case. (Furthermore, *which* node is graphically awarded this status will be a matter of random chance, and highly variable from one run to the next.) For graphs of more than 6 nodes, asymmetrical layouts become substantially more probable than symmetrical ones (see Appendix E).

For full-episode cumulative aggregate layout diagrams, I adopted an approach to construct networks by *summing* the strength of all arcs between particular pairs of nodes, rather than averaging. Not only does this provide a better reflection of the *cumulative* impact of a participant's contributions over time, it becomes much less likely that a large number of actors will develop highly symmetrical connections of comparable strength (compared to averaging). Thus it is easier to avoid creating the conditions that give rise to highly unstable and misleading layouts.

Third, to make the animated layouts more readily interpretable as to what the conversation was "about" at any particular point in time, I began to code arcs directly between discourse

[128] While a geometrically accurate 2D layout of a fully-connected, symmetrical graph of 4 nodes is not possible, the most probable (distortion-minimal) layouts of 4 and 5 node graphs are not what I consider to be visually misleading, as discussed here and detailed in Appendix E.

nodes having certain, particularly close relationships to one another.[129] This has the effect of linking and organizing topically-related discourse nodes, making it easier to visually discern the way in which a conversation is developing.[130] The fourth, and most consequential step I took was to begin investigating the use of numerical, structural network metrics to augment the qualitative information I obtained from layout diagrams. This proved to be an extraordinarily fruitful, and complex undertaking which I shall discuss in more detail in the following chapter.

Overall, I found that visual interpretation of layout diagrams has to be tempered somewhat from a purely intuitive reading based on the spatial metaphor alone. While the overall symmetry, tightness of clustering and visual density of connections conveys useful information, layout proximity of any particular pair of nodes is not necessarily a reliable reflection of network distance—particularly in the absence of strong arcs directly linking the nodes (as is generally the case between pairs of actors). For this reason, I used the overall form and response of the animated network layout diagrams primarily as a guide to inform changes to the coding scheme, not as definitive results in and of themselves.[131]

Depicting the "Connectedness" of Discourse

In complete coding of Episode 7, I identified several other issues. Rather than analytic results per se, I see these early experiences of network coding in terms of a process of model building.[132] Such a process emphasizes considerations of consistency and parsimony in the development of a relatively compact system that is able to give rise to behaviour that, in some sense, resembles that of a target system—in this case, my interaction data. The modifications I describe below are the first "back-talk" of the analytic representation I was in the process of constructing.

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[129] In general, networks depicting relationships between words, concepts or elements of discourse are termed *semantic* networks. I discuss these semantic network arcs in greater detail in the following section.

[130] Vis-à-vis the coding scheme for alignment, semantic network arcs involve more complex and subjective judgments, and their relative strength is a function of visual more than theoretical considerations. Consequently, they were *not* taken into account in any of the quantitative network metrics I employed, and are portrayed separately from the cumulative layouts of actor-discourse networks in the results I present in the following chapter. I do, however, offer suggestions as to how they might be used in a more analytically-consequential manner in future work in Appendix E.

[131] As I discuss in the next chapter, the limited reliability of interpretations based on layout diagrams alone was one reason I adopted the use of conventional metrics to mathematically assess network structure. The micro-analytic results I report are based on a combination of layout diagrams and numerical metrics, which are not subject to the same distortions. I discuss various ways the reliability of visual interpretation of layout diagrams might be improved for future work in Appendix E.

[132] Snodgrass & Coyne (1992) discuss the significance of models as essentially metaphorical rather than predictive in nature, and emphasize their value in driving iterative cycles of interpretation.

Implicit References and Image-Schemas

Coding a period of brainstorming in Episode 7, I noticed that it was difficult to account for the connectedness of the discourse from one contribution to the next relying solely on the words participants used.[133] In this sequence, participants proposed a variety of ideas how to protect sensitive electronics. I realized that the commonality relating some contributions frequently took the form of an implicit reference, schema or image (such as a particular range of distance, or a process like melting ice). I found it necessary to add an additional node type, that of an "image/schema" to account for such implicit connections, as well as more explicit images and metaphors incorporated in some contributions.

Because these references were implicit, I found it necessary to code arcs to nodes from previous utterances that were not actually voiced in subsequent contributions. Once one starts down this path, however, one finds that a great deal can be implicit in an utterance. To enhance reliability and keep such coding to a reasonable level, I formulated a pair of rules:

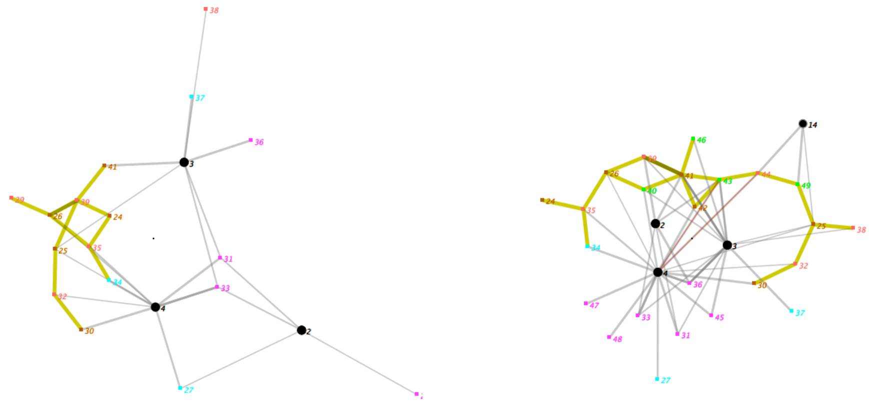
- "Stay close to the discourse:" beyond what is actually said, keep implicit reference to the minimum necessary to account for connectedness.
- The "rule of one:" when coding implicit references as the basis of connections between contributions, limit carryover into subsequent contributions to a single conversational turn.

Semantic Network Arcs

I also found that adding arcs directly between discourse nodes enhanced the visual interpretability of layout diagrams. Initially I had hoped that discourse nodes that were thematically related (i.e. that pertained to the same issue or option) would be located near one another in 2D layout diagrams simply by virtue of the similarity with which they were addressed by different participants. My early experiences revealed this not to be the case.

To make the line of connection through discourse more readily apparent in real-time layouts, I began to code semantic associations directly between discourse elements. Essentially, this is a way of binding certain nodes that are closely related in discourse to ensure they remain proximal to one another in layouts. In particular, I used such semantic arcs to relate specific options to implicit image/schemas or gestural exchanges picked up in subsequent contributions. Examples of these semantic associations are shown in Figure 5-8.

[133] This is not surprising, as context dependency is an essential aspect of language. Clark (1996) provides an account of the way in which individuals' use of language, with respect to what is implicit, is nonetheless subject to certain regularities regarding reasonable expectations and how these are managed through observable behaviour (including repair).



(a) (b)

Figure 5-8 Example Semantic Association Arcs
Episode 7, (a) slice 30 and (b) slice 47. Yellow semantic network arcs link elements of the same contribution in discourse. From left to right, development of discourse during a period of brainstorming interaction shows a number of option/solution proposals linked by implicit image-schema content. (1 slice = 5 seconds of interaction; these network slices are separated by ~1.5 mins.)

Episode 7 also included the emergent proposal to place sensitive electronics on an extensible boom, an idea that prompted a number of variants and elaborations. Since these proposals were all closely related variants on the boom idea, I began coding a second type of very strong arc to link such collaborative productions. Whereas the yellow semantic network arcs delineate a linear progression, I used red arcs to make clusters of such collaborative productions particularly visible.[134]

Figure 5-9 Example Collaborative Product Arcs
Episode 7, slices 102 and 132. Red collaborative product arcs link a cluster of closely-related variants of the electronics-on-a-boom idea. (A smaller cluster appears below, corresponding to variations on shielding.)

[134] The basis upon which different types of semantic association were coded is detailed in Appendix B. Arc strength values (vis-à-vis the scheme for alignment strength) were determined primarily on the basis of visual rather than theoretical considerations. In recognition of the more subjective nature of these judgements, semantic network arcs were *not* taken into account for any of the numerical structural metrics I report in Chapter 6.

Juxtaposing Real-time Network Layouts with Video

My early network animations were standalone and acts were somewhat arbitrarily clustered in slices based on design “moves” (cf. Goldschmidt 1992, 1995). On the suggestion of an advisor, I recoded each act with a precise time code from video to construct animations corresponding to real-time interaction. It then became possible to play these alongside the source video data of recorded interaction.[135] An example is shown below in Figure 5-10.

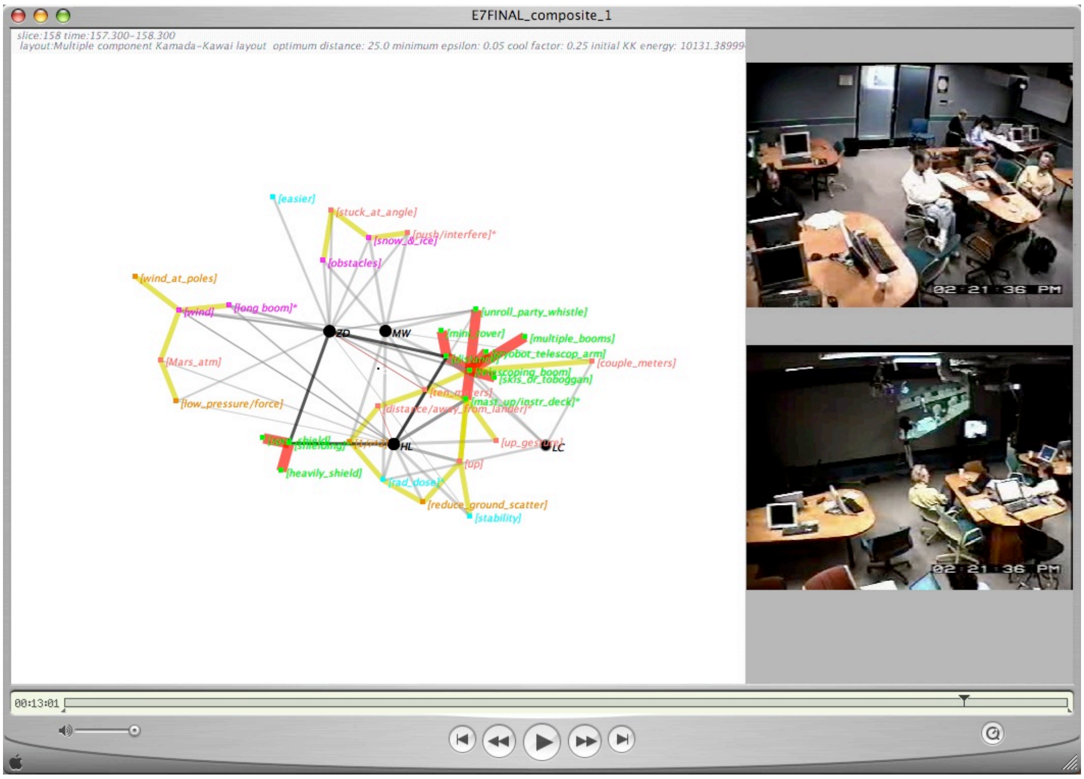


Figure 5-10 Real-time Network and Video
Episode 7, slice 158. Juxtaposition allows dynamic network response to be compared to source interaction data after each round of coding. In this frame, two actors are physically present in the room, two others are participating remotely by speakerphone.

The ability to review network animations alongside video of actual interaction allowed me to more directly and critically assess the coding scheme on the basis of network behaviour. This, together with the additional complexity presented by subsequent episodes, motivated a number of elaborations and refinements I now proceed to describe.

Iterative Elaboration and Refinement of the Coding Scheme

At this point I began coding additional episodes. The interactional complexity these contained motivated several elaborations and further development of the coding scheme,

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[135] I am indebted to Daniel McFarland for the suggestion that real-time network animations might be usefully juxtaposed with source video data.

which I will now describe. After each major change, I recoded all episodes to ensure consistency and the comparability of later results.

Adjusting Temporal Durations to Favour Design Discourse

Comparing the real-time animations to the actual recorded interaction, one of the first things I noticed was that, in relation to design reasoning, not all types of act seemed equally consequential. In particular, questions and other neutral information-movement tended to dilute the significance of strong alignment or disagreement expressed in design discourse. Summary statements and other meta-process acts sometimes embodied strong alignment, but often seemed to reflect "snapshot" assessments. Though SoNIA allows different slice widths, it proved more convenient to assign arcs corresponding to information movement and meta-process acts a shorter duration than those associated with design reasoning. This was facilitated by the spreadsheet coding approach I had already developed for cumulative aggregate layouts.

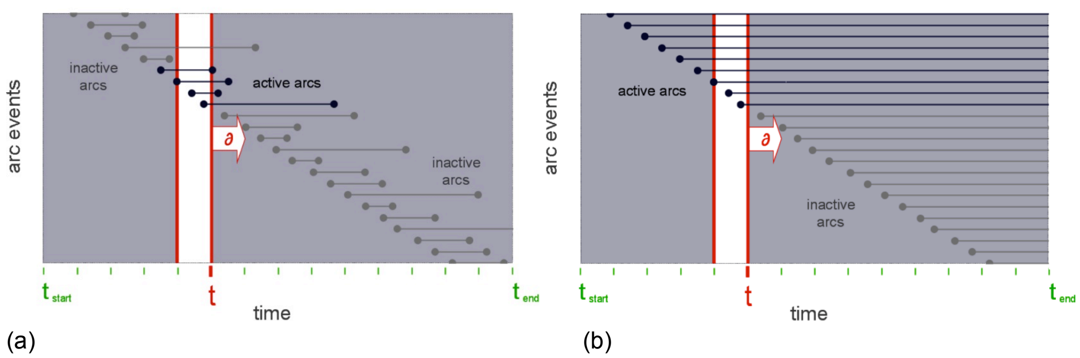

Figure 5-11 Varying Arc Duration in (a) Real-Time and (b) Cumulative Aggregate Layouts
Arcs were assigned different durations based upon the type of communicative act involved (see also Table 5-6). Networks were constructed using a single, narrow slice width corresponding to 5 seconds of interaction. (Cumulative aggregate layouts were still made by setting all arc durations to exceed the end of the episode.)

These changes involved shortening the duration of arcs for information movement and meta-process acts. Conversely, a relatively *longer* duration seemed appropriate for other arcs, such as those coding inscription. Because of their persistent presence in the environment, it seemed reasonable that these discourse elements might remain in networks longer than discourse elements registered in talk alone. Because my predictor and criterion variables were principally associated with inscription and collaborative production, I assigned both types of arc a comparably long duration (120 slices = 10 mins.).[136]

[136] This was done for the purpose of making the layout diagrams more intuitively interpretable. Aside from the fact inscription was taken into account, the numerical results I present in the next chapter do not incorporate these admittedly arbitrary values.

Depicting Interaction with Shared Representations

Interaction with shared representations began to enter into the analysis with Episode 12, though each subsequent episode introduced additional aspects. Considering how the coding scheme should respond, the first question was how to integrate the action of representations in the same framework as human participants and discourse? Particularly after coding Episodes 21 and 54, which had extensive, relatively non-interactive periods of spreadsheet narration, the next question became how to account for different types of interaction and reflect different levels of engagement?

Essentially, I found demands of consistency and parity made it necessary to differentiate between two processes: the human actor's *engagement* with the representation, and the process of *inscription* whereby an element of discourse became inscribed or otherwise durably associated with a discernable feature of a representation.[137] To preserve parity with regard to engagement, I tried to maintain analogous relationships between, on the one hand, human actors and discourse, and on the other, representations and discourse. Accordingly, engagement is reflected by acts directly between human participants and representations. I assigned these a short duration, keeping them comparable to information exchanges and meta-process acts directly between human participants.

With regard to inscription, I initially coded a strong arc in all instances. I found, however, that prolonged periods of relatively neutral and non-interactive narrated presentation in Episodes 21 and 54 nonetheless accumulated rather large numbers of strong inscription arcs, even though the nodes were briefly described and not involved in subsequent discussion. Accordingly, I changed the scheme to provide for graduated levels of inscription. These ranged from relatively neutral explanations and descriptions to more active implication and acts that created or physically changed a representations' appearance. The strength of these levels is related to the manner of engagement of the actor, not the alignment they express with the discourse element in question. This approach, distinguishing between these facets of engagement and inscription, was necessary to allow for someone to engage strongly with a representation for the purpose of strongly disagreeing, for example, with a feature inscribed on it.

Accordingly, a rather neutral or matter-of-fact description in passing would result in a relatively weak inscription (strength = 3). A stronger more definitive incorporation,

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[137] While this is not the same as Latour's use of the term "inscription" (e.g. to denote a numerically-reduced, compact and transportable scientific finding), I believe it is compatible usage and a reasonable term to apply to discourse that has been durably *inscribed* in a representation. Indeed, in interaction, it seems likely that this is the form Latourian inscriptions would necessarily take, since verbal reports of scientific findings would probably lack the power Latour attributes to inscriptions.

particularly in conjunction with a proposal or elaboration would result in a stronger inscription (strength = 6). Finally, because an actual physical change altering the form of a representation (such as actually drawing) is an even stronger form of "speech", I gave this the highest strength level (10). Essentially, the approach can be summarized to say that the capacity for a representation to speak is conveyed to it by its engagement with a human participant. However, representations can also in a sense initiate the engagement by effectively suggesting something to a human participant, which the participant subsequently voices to others.

The overall structure of the coding scheme, in terms of the way parity is maintained between major classes of arc with respect to duration and nodes for actors, representations, and discourse, is summarized in the matrix in Table 5-6.

Table 5-6 Classes of Arcs: Types of Nodes Connected vs. Relative Duration
Colour in each box corresponds to arc colour in layout diagrams. This table reflects the systematic allocation of colour in the coding scheme in Table 5-7.[138]

	arcs between actors	*arcs between actors & discourse*	*arcs between discourse*
short duration	information & attention representation acts meta/process (dark gray)	information & attention neutral description meta/process (dark gray)	
normal duration		design discourse (light gray)	semantic association (yellow)
long duration		inscription (blue)	collaborative production (red)

Final Form of Coding Scheme

The following table presents the coding scheme in its final form. The essential actor-network parity between human participants and representations is reflected in the overall balance and comparability of codes for arcs directly between actors and between actors and

[138] Early versions of SoNIA supported only a limited palette of predefined colours which I allocated as effectively as I could.

discourse. Types of act not directly involved in design reasoning have a short duration so their effect on network structure is reduced. Acts directly between actors are of similarly short duration so that the actor-discourse network structure of design reasoning dominates. Inscriptions have a longer duration to acknowledge the persistence of the representations as compared to talk alone. More elaborate descriptions and distinctions are presented in Appendix B.

Over the course of iterative coding and review of the selected episodes, I elaborated the codes I defined for semantic network associations to distinguish between general associations in reasoning and two more specific cases: the attachment of particular (e.g. numerical or material) attributes and the incorporation of imagistic metaphor or physical "co-performance" of gestural schemas. While these distinctions may be useful in subsequent work, I did not find they had a noticeable impact on the interpretation of my diagrams. Consequently the arcs are indistinguishable and the distinctions played no part in the analyses I subsequently performed.

Table 5-7 Final Act Coding Scheme

design discourse acts	*arc strength*	*arc colour*[139]	*arc duration*	*applies to relations between: actor-actor*	*actor-discrs*	*discrs-discrs*
propose/reintroduce	6	light grey	normal		•	
elaborate	6	light grey	normal		•	
align	6	light grey	normal		•	
strong support	5	light grey	normal		•	
support	4	light grey	normal		•	
neutral reference	3	light grey	normal		•	
weaken/distance	2	light grey	normal		•	
call into question	1	red	normal		•	
oppose	*	*	normal		•	
information and attention						
call attention	3	dark grey	short	•	•	
ask/inquire	3	dark grey	short	•	•	
tell/provide	3	dark grey	short	•	•	
clarify/verify	3	dark grey	short	•	•	
repair	3	red	short	•	•	
acts with representations						
explain/describe	3	blue	short	•	•	
implicate	6	blue	short	•	~	
create/add/change	10	blue	short	•	~	
notice	6	blue	short	•	~	
inscription						
inscribe 1 (=explain/describe)	3	blue	long		• (rep)	
inscribe 2 (=notice, implicate)	6	blue	long		• (rep)	
inscribe 3 (=create/add/change)	10	blue	long		• (rep)	
semantic network associations						
incorporate/co-perform	10	yellow	normal			•
associate	10	yellow	normal			•
attach quantity/attribute	10	yellow	normal			•
collaborative production	20	yellow	long			•
weaken	0**	n/a	**			•
meta/process acts						
transition/close	3	black	short	~	•	
summarize (direction or choice)	6	black	short	~	•	
request to-do	6	black	short	•	•	
commit to-do	6	black	short	•	•	
defer	4	black	short	•	•	
decline	*	red	short	•	•	

* code defined but no instances coded in the data set
** codes of zero strength were used to weaken previously-established semantic relationships by reducing the average. This relies on the particular behaviour of the SoNIA program in this instance.
~ arc is defined but in a majority of cases another type of arc was more applicable

[139] The systematic relationships underlying these colour selections are depicted above in Table 5-6

6. MICRO-ANALYTIC RESULTS

The previous chapter described the initial development and iterative refinement of a micro-analytic coding scheme and a network formalization for design activity. This chapter presents results from the application of this coding scheme to the selected episodes. The results comprise animated and cumulative network layout diagrams, conventional network metrics, and the categorical composition of coding; these are correlated with observations and important outcomes in each episode.

I use these results as a basis to propose relationships between certain structural characteristics of actor-discourse networks and important aspects of design interaction. Specifically, in terms of the actor-discourse networks, micro-analysis highlights four factors that account for the variation between the selected episodes: overall alignment, mutual engagement, the level of participation of human actors and the degree of integration of representations. Events within each episode are discussed and episodes are compared in terms of these factors to develop a fine-grained understanding of how each comes into play.

An inherent limitation of this type of micro-analysis is that it cannot encompass relationships between events that transpire over longer timeframes or across temporally discontinuous periods of interaction. To fully understand the interactional work performed by shared representations, I found it necessary to take these types of relationships into account. (These involve some of the episodes that were flagged as noteworthy but excluded from micro-analysis for various reasons described in Chapter 4 above.) These macro-analytic results will be discussed in the following chapter. The interpretation and overall discussion of findings that follows in Chapter 8 will take both sets of results into account.

Overview

As I detailed in Chapter 4, the macro-analysis culminated with the selection of five episodes deemed likely to offer the most analytically useful comparisons. These were selected on the basis of the following considerations:

- appropriate temporal bounding (in terms of clear initiation and conclusion, sufficient yet manageable overall length)
- relatively straightforward internal structure (in terms of the major issue threads identified in the macro analysis)
- unusually high density of positive or negative indicators (triangulated on the basis of in-session notes, post-session interviews, documented outcomes, and review of the video record)

The following table summarizes analytically relevant characteristics of each of the selected episodes subjected to micro-analysis:

Table 6-1 Characteristics of Selected Episodes

episode	*selection basis*	*key outcome*	*use of shared reps*	*problematic interaction*	*thread*	*noteworthy developments*
7	**+**	√			sensitive electronics	• (~15 mins.) period of energetic brainstorming regarding a critical issue: how to protect sensitive electronics from radiation • emergent proposal for a key design feature (raised instrument platform to protect sensitive electronics) • culminating with agreement on a specific analysis to resolve tradeoff between two approaches
12	**+**	√	√	[140]	radiator config.	• (~12 mins.) energetic discussion of a significant intermediate stage in the development of a key feature (radiator configuration) • proposal for a horizontal radiator led instead to an apparently strong convergence around an alternate configuration • unstable consensus later unravelled when it became clear a key expert had not understood the precise nature of the alternative proposal
21	**-**		√	√	radiation types and effects	• (~8 mins.) narrated spreadsheet presentation regarding spacecraft electronics • a non-convergent exchange with no clear agreement whether or not a particular issue would present a problem • participants appeared to have difficulty using a common set of terms to describe radiation and its effects
39	**+**	√	√		radiator config.	• (~28 mins.) energetic discussion with definitive development of a key feature (horizontal radiator) in its final form • initial objection to a feature in CAD led to energetic discussion and strong convergence on horizontal disk radiator approach, with detailed instructions given to CAD; updated model triggered further discussion, leading in turn to further elaboration • several participants actively engaged around a whiteboard and shared CAD model

[140] By "problematic interaction" I mean trouble that was immediately obvious at the time, evidenced by participants' expressions of confusion or frustration, obvious breakdowns etc., not the more subtle issue of unstable consensus that characterized Episode 12, as I will detail below.

episode	selection basis	key outcome	use of shared reps	problematic interaction	thread	noteworthy developments
54	-	√	√	√	radiation types and effects	• (19 mins.) narrated spreadsheet presentation leading to elaboration of a key constraint (revised radiation design limits) • key insight to establish separate design limits for different types of radiation and strong convergence on an approach to apportion shield mass between lander deck and elevated platform • apparent frustration, misunderstanding and lingering disagreement between experts regarding the precise nature of radiation and appropriate shield materials

The following table provides an overview of the five stages in which micro-analytic results will be presented, with the associated formats:

Table 6-2 Categories of Results and Presentation Formats

result	*format*	*analytic mode*
network behaviour that mirrors relevant aspects of interaction	animated network diagrams juxtaposed with video data	• qualitative comparison • iterative coding and model building
participation of actors / integration of representations	full episode cumulative network diagrams	• qualitative interpretation with regard to session outcomes
structural network property of overall alignment	episode timeline vs. total degree graphs	• quantitative network metrics[141] • pattern matching with important session developments
structural network property of mutual engagement	episode timeline vs. discourse betweenness graphs	• quantitative network metrics[142] • pattern matching with important session developments
composition and temporal development of discourse	timeline with categorical coding overview	• categorical composition of coding • pattern matching[143]

Animated Networks and Real-Time Interaction

The selected episodes provided the basis for iterative development of the micro-analytic coding scheme, as detailed in the preceding chapter. Essentially, this development took on the character of model building. Based on exploratory coding, and following the decision to

[141] As I discuss later in this chapter, the structural network property of overall alignment is indexed by total degree, which is based upon the conventional network metric of degree centrality.
[142] The structural network property of mutual engagement is indexed by discourse betweenness, which is based upon the conventional network metric of flow betweenness centrality.
[143] Results of categorical composition of coding vs. time for each episode are presented in this chapter. The significance of the patterns is further discussed (in terms of an essential cycle of design reasoning) in Chapter 8.

adopt a network representation, I developed a coding scheme to combine elements of argument with constituent acts to characterize a collective process of design reasoning. This scheme comprises participants' expressions of alignment with design discourse, information and attention management, representational acts and inscription, semantic network associations and meta/process acts.

The selected episodes were coded in an order I determined would introduce increasing complexity in stages. At each stage, animated network diagrams were reviewed alongside the source video data to evaluate the qualitative correspondence. After major revisions, all episodes were re-coded and re-evaluated to ensure consistency. Major revisions included the elaboration of semantic network connections, adopting different durations for design discourse and durable representational acts, and graduated levels of inscription to mirror the strength of participants' engagement with representations.

The first stage in communicating results involves conveying the nature of the qualitative correspondence between real-time animated networks and unfolding interaction in the selected episodes. Principally, this is evident in the clustering of actors and the density of connections, evaluated on the basis of an overall spatial metaphor of PROXIMITY=AFFINITY (subject to specific limitations discussed in the preceding chapter). Additional categorical information for both nodes and acts is conveyed by colour. With respect to nodes, colour indicates the constituent elements of design reasoning, information and matters-of-fact, and implicit or explicit image-schemas. With respect to arcs, colour differentiates design discourse, representational acts and inscription, collaborative productions and semantic network relationships. Additionally, red is used to differentiate repair from other neutral information-related acts, and active disagreement and calling-into-question from less strong forms of distancing.[144]

I have selected a number of still frames below (Table 6-3 to Table 6-8), and three movie segments (summarized in Table 6-9 and represented by additional still frame sequences in Appendix C) to illustrate essential aspects of this correspondence.

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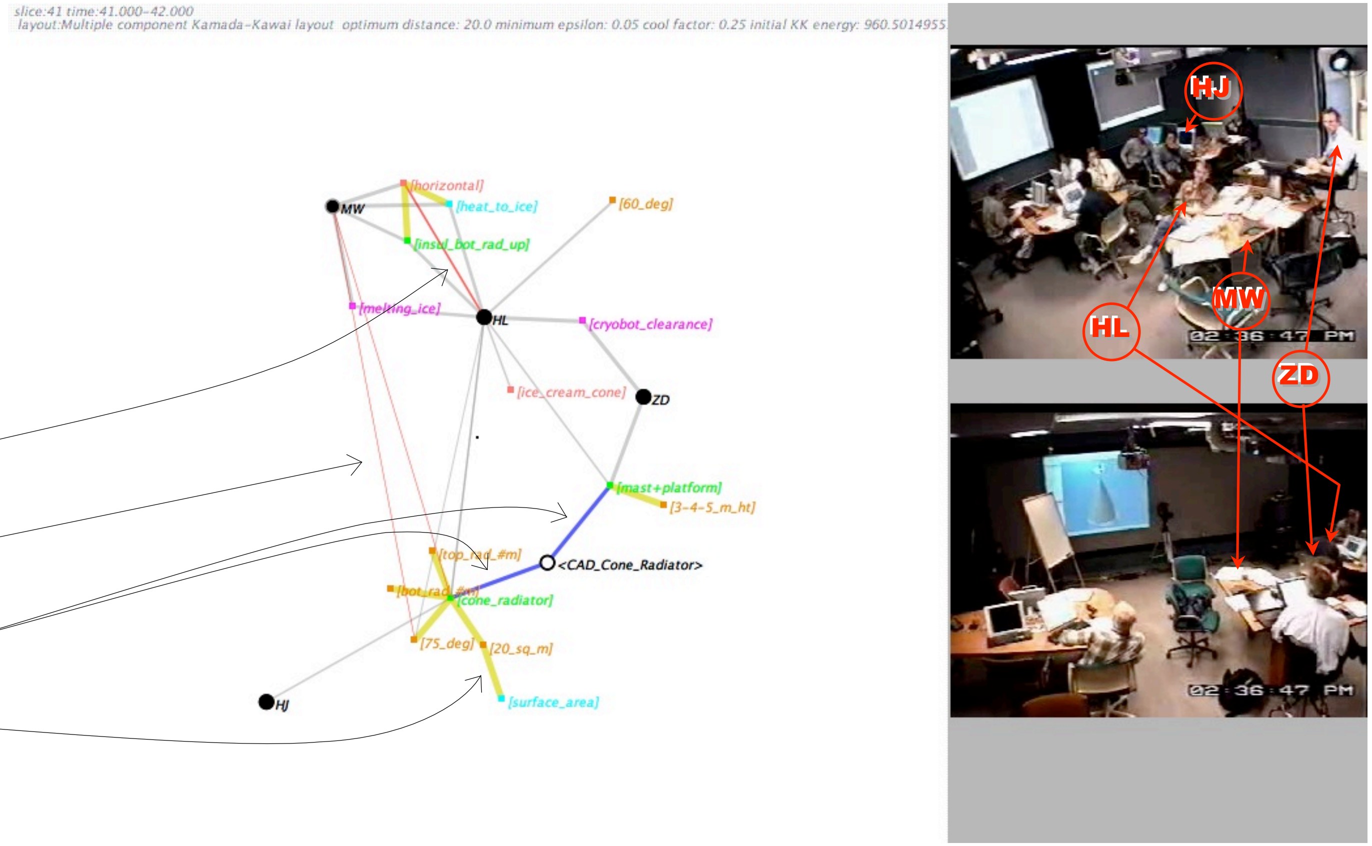
[144] Contradictory implications stemming from the use of weak arcs to reflect strong distancing statements are discussed in the methodological reflection in Chapter 9, and more extensively in Appendix E.

Table 6-3 Animated Network Diagram: Collaboration over Shared Representations #1

act description	*actor-discourse + semantic network diagram and video*
Episode 39 (slice 41): <u>Objecting to a design feature in CAD</u> **ZD**, **HL** and **HJ** have been describing a projected CAD model. **MW** (on speakerphone) calls a feature, the cone radiator, into question and proposes an alternative (horizontal) configuration. **HL** responds favourably but also expresses some confusion. *To notice:* • HL's communicative repair regarding "horizontal" • long red arcs indicate MW's strong disagreement with the cone radiator feature • CAD representation with two prominent inscribed features • attributes and criteria are associated with options by semantic network arcs	

arcs: PROXIMITY=AFFINITY <u>design discourse (light gray)</u>; <u>inscription (blue)</u>; <u>semantic network (yellow)</u>; <u>calling-into-question & repair (red)</u>

actor nodes: ● *participant present* ◉ *remote /audio-visual* ● *remote / audio only* ○ *<representation>*

discourse nodes: ■ *[issue/problem]* ■ *[criterion/constraint]* ■ *[option/solution]* ■ *[info/matter-of-fact]* ■ *[image/schema]*

Table 6-4 Animated Network Diagram: Collaboration over Shared Representations #2

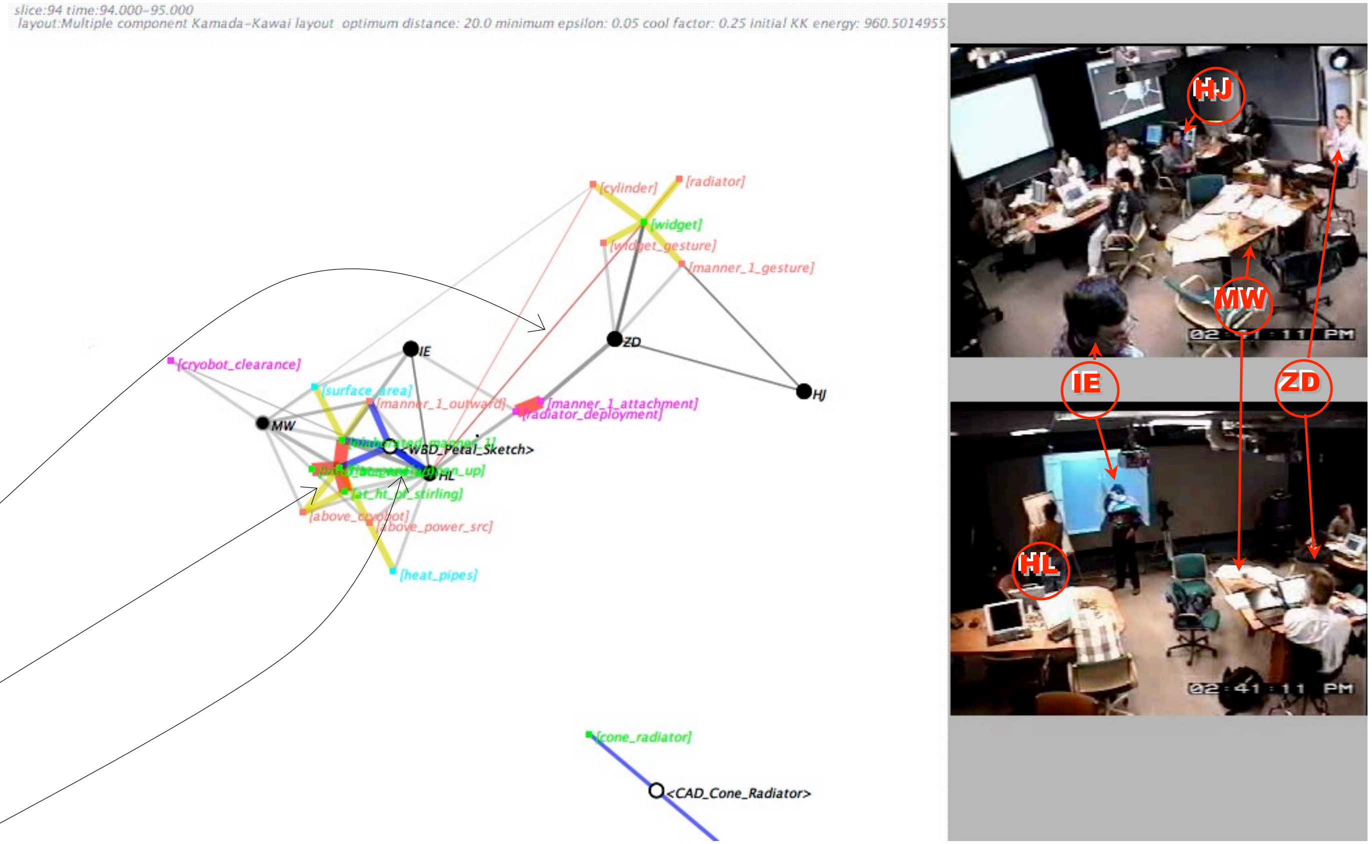
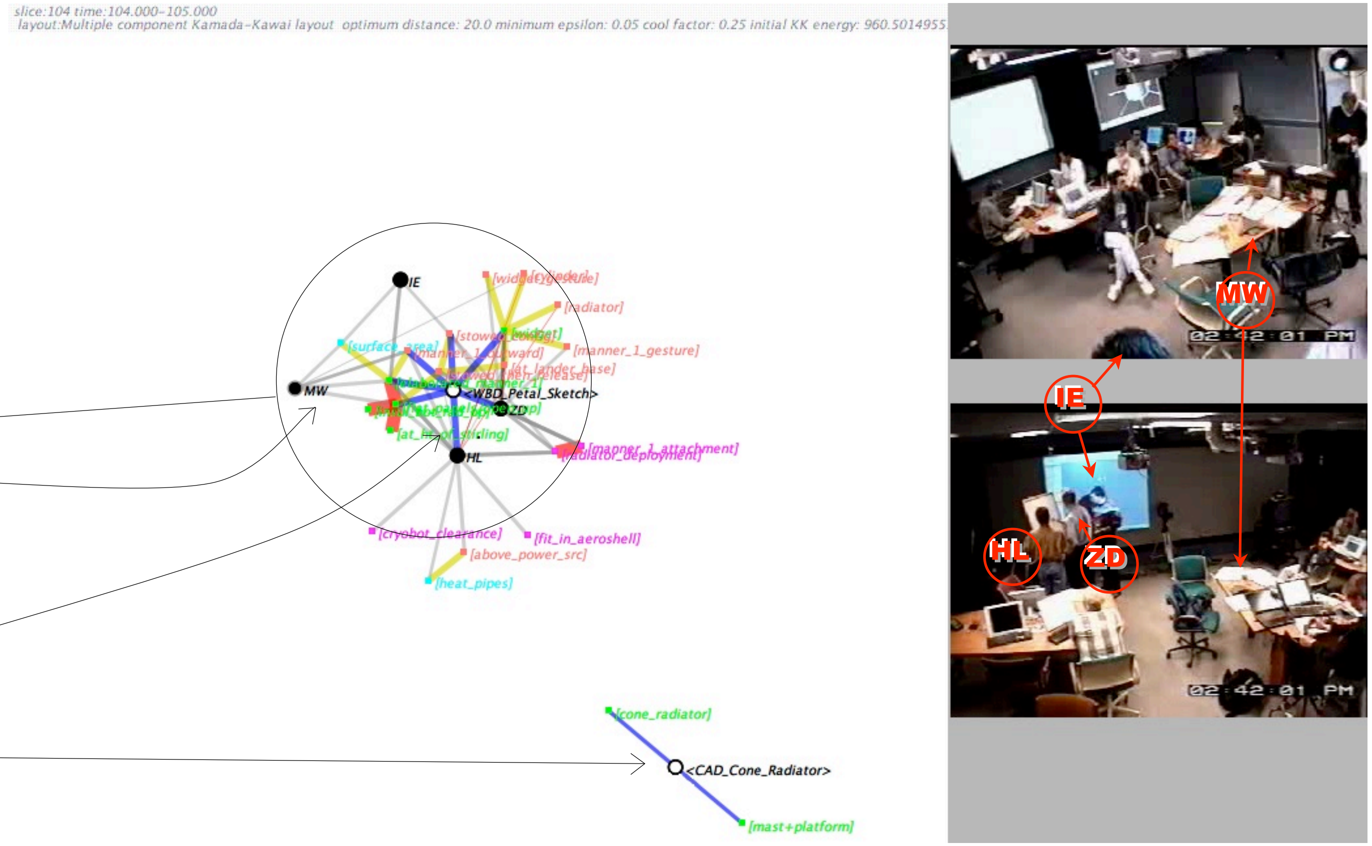
act description	*actor-discourse + semantic network diagram and video*
Episode 39 (slice 94): Disagreement over an elaboration of the new idea **HL**, **IE** and **ZD** have embraced **MW**'s idea. **ZD** elaborates an issue and proposes a solution in the form of a "widget". **HL** rejects the need for the widget as he and **IE** move to the whiteboard to clarify what they have in mind. **ZD** briefly engages the CAD operator **HJ** over the widget idea, then turns his attention back to **HL** who is drawing at the whiteboard. *To notice:* • long red arcs reflect HL's rejection of the widget idea • the whiteboard has become the focus of interaction while CAD has become peripheral • a cluster of collaboratively-produced options is now inscribed on the whiteboard. (an issue has also been collaboratively elaborated.) • HL is directly engaged in changing the whiteboard representation by drawing	 arcs: PROXIMITY=AFFINITY new arcs: collaborative production (very strong, red); representation change/inscription (strong, blue) actor nodes: *participant present* *remote /audio-visual* *remote / audio only* *<representation>* discourse nodes: *[issue/problem]* *[criterion/constraint]* *[option/solution]* *[info/matter-of-fact]* *[image/schema]*

Table 6-5 Animated Network Diagram: Collaboration over Shared Representations #3

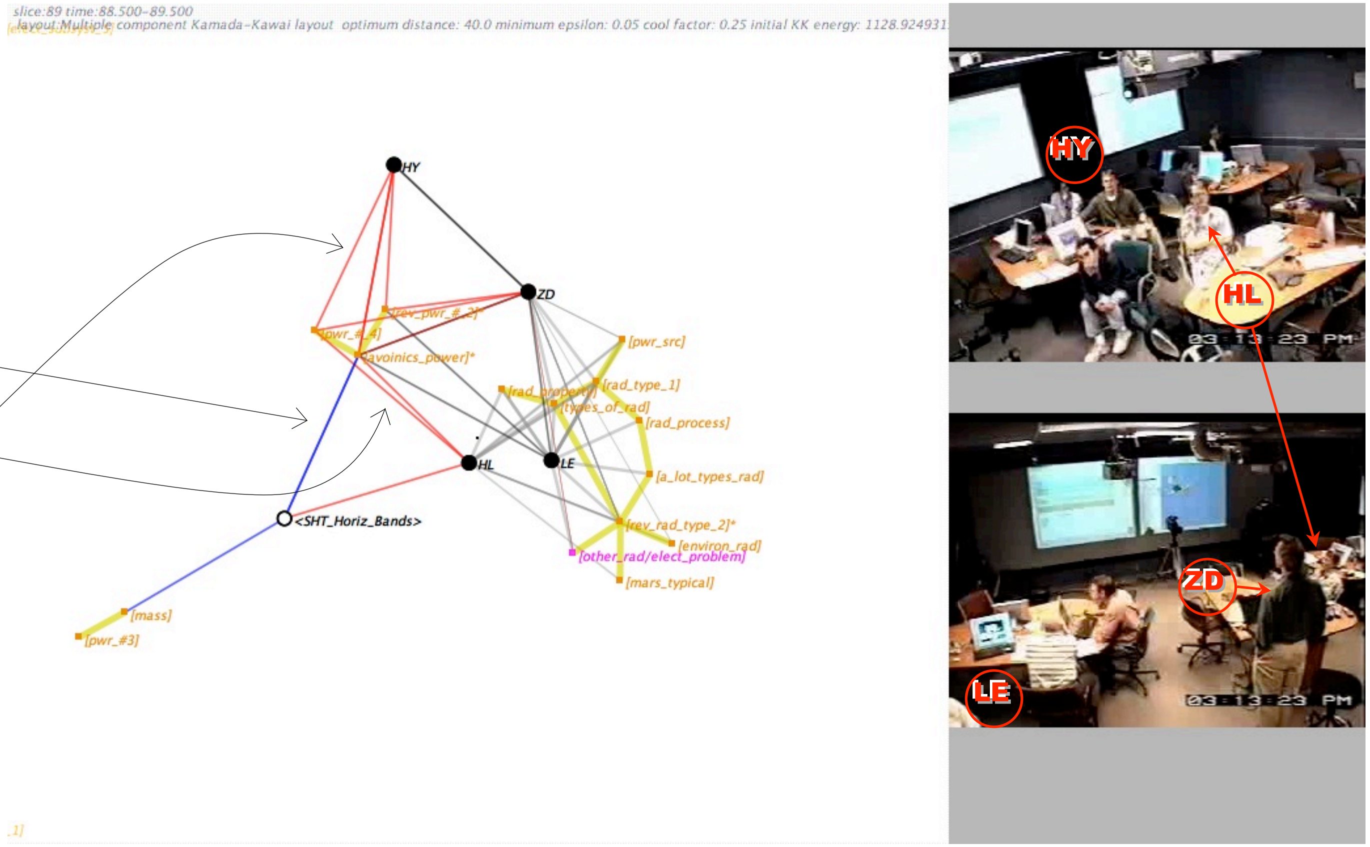
act description	*actor-discourse + semantic network diagram and video*
Episode 39 (slice 104): Convergence on the new configuration **ZD** has now moved to the whiteboard to clarify and reassert his widget idea. **ZD** and **HL** are drawing while **IE** looks on. *To notice:* • all aspects of the new solution have been inscribed in the whiteboard representation. Convergence is reflected by clustering of actors. • though he is remote, MW's verbal engagement with the initial proposal has maintained his position in the cluster • actors engaged in making inscriptions are directly linked to the representation by strong blue arcs • CAD representation has remained peripheral since the initial observation of a problem with the cone	

arcs: PROXIMITY=AFFINITY (no new arc types in this frame)

actor nodes: *participant present* *remote /audio-visual* *remote / audio only* *<representation>*

discourse nodes: *[issue/problem]* *[criterion/constraint]* *[option/solution]* *[info/matter-of-fact]* *[image/schema]*

Table 6-6 Animated Network Diagram: Confusion and Repair over a Design Detail

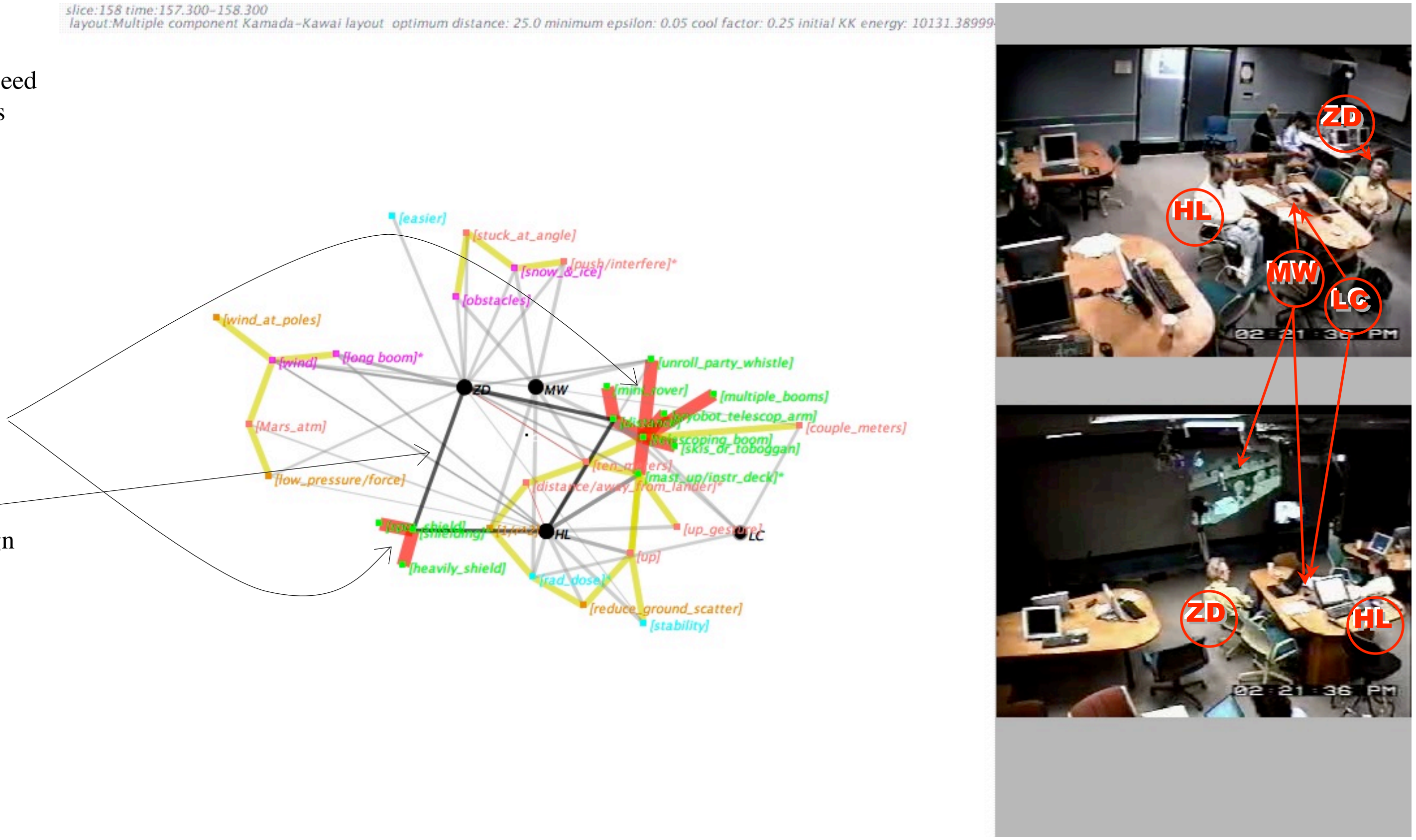
act description	*actor-discourse + semantic network diagram and video*
Episode 21 (slice 89): <u>Confusion over a number.</u> **HL** is confused about a figure LE has mentioned on a spreadsheet. ZD and HY become involved attempting to clarify what the correct number should be. *To notice:* • a value mentioned in a neutral description is relatively weakly inscribed • neutral strength red arcs indicate the subject of the repair exchange	

arcs: PROXIMITY=AFFINITY (no new arc types in this frame)

actor nodes: ● *participant present* ● *remote /audio-visual* ● *remote / audio only* ○ *<representation>*

discourse nodes: ■ *[issue/problem]* ■ *[criterion/constraint]* ■ *[option/solution]* ■ *[info/matter-of-fact]* ■ *[image/schema]*

Table 6-7 Animated Network Diagram: Agreement on a Trade Between Two Approaches

act description	*actor-discourse + semantic network diagram and video*
Episode 7 (slice 158): <u>Summarizing a choice</u> **ZD** and **HL** summarize the need to perform a tradeoff analysis before deciding between two design approaches. MW (on video conference) and LC (audio only) have also been actively involved in the discussion. *To notice:* • two distinct design approaches, one reflecting significant collaborative construction • meta-process acts summarizing the two design directions	

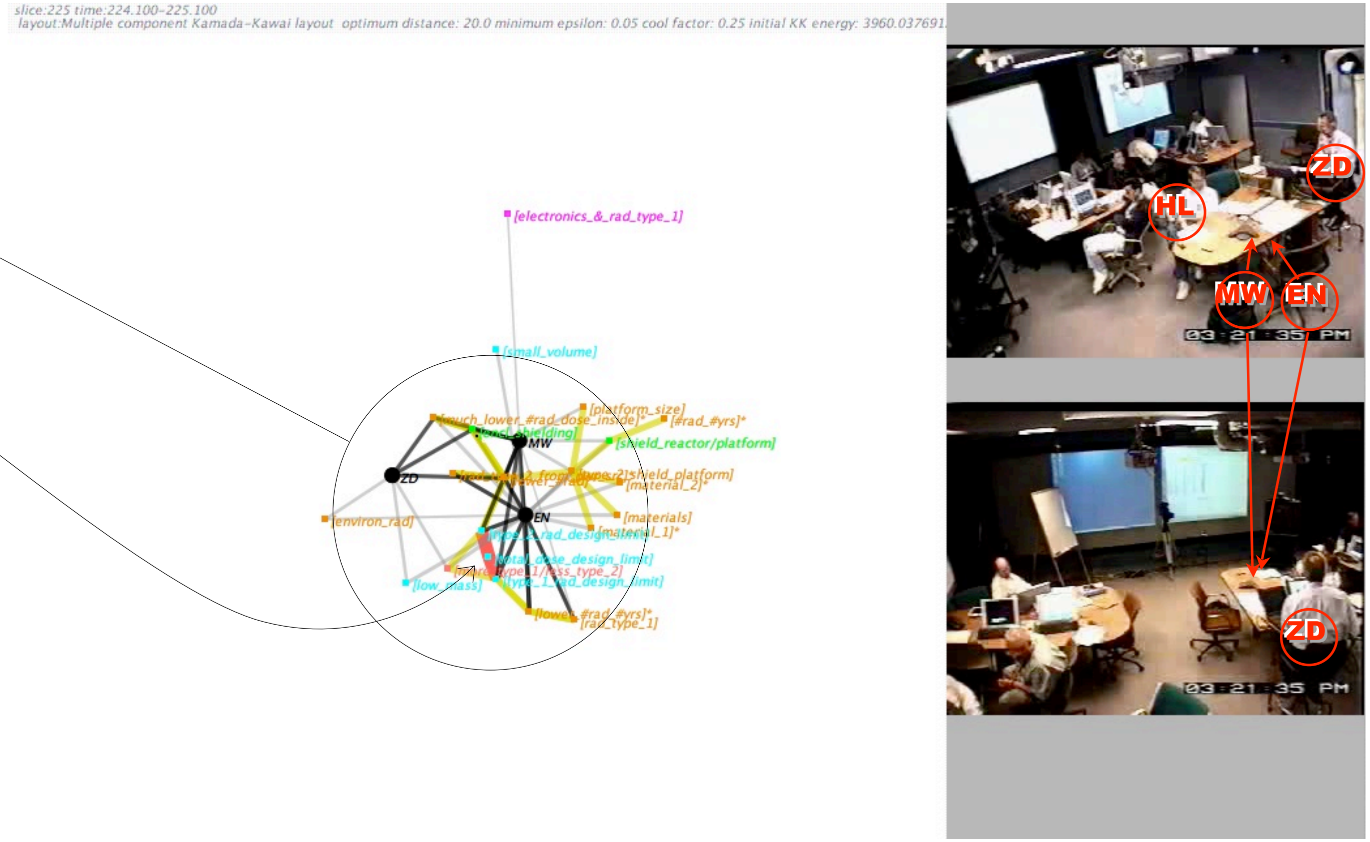
arcs: PROXIMITY=AFFINITY design discourse (light gray); meta-process/summarize design (dark gray)

actor nodes: ● *participant present* ● *remote /audio-visual* ● *remote / audio only* ○ *<representation>*

discourse nodes: ■ *[issue/problem]* ■ *[criterion/constraint]* ■ *[option/solution]* ■ *[info/matter-of-fact]* ■ *[image/schema]*

Table 6-8 Animated Network Diagram: Convergence on a Design Direction

act description	*actor-discourse + semantic network diagram and video*
Episode 54 (slice 225): "<u>Right, so we're agreed."</u> **ZD**, **MW** and **EN** summarize their agreement on a design direction. *To notice:* • clustering of actors reflects strong alignment with a number of discourse nodes in common • collaboratively produced radiation design limits represented by linked criterion/constraint nodes	See figure below



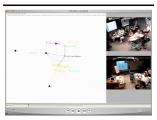
arcs: PROXIMITY=AFFINITY (no new arc types in this frame)

actor nodes: ● *participant present* ● *remote /audio-visual* ● *remote / audio only* ○ *<representation>*

discourse nodes: ■ *[issue/problem]* ■ *[criterion/constraint]* ■ *[option/solution]* ■ *[info/matter-of-fact]* ■ *[image/schema]*

In addition to the snapshots in the preceding tables, certain sequences highlight the behaviour of the network diagrams during interesting periods of interaction. I summarize three such sequences below. The most effective way of observing the behaviour of the networks is to view the animation movies; however each is portrayed in a sequence of still frames in Appendix C.

Table 6-9 Summary of Selected Movie/Image Sequences

sequence	*overall description*	*noteworthy aspects*
 **Episode 7** slices 35-67	Part of an energetic brainstorm as participants addressed the issue of how to protect sensitive electronics from the damaging effects of radiation. Various proposals for introducing distance between electronics and the power source are discussed.	• chaining in the semantic network on the basis of implicit image/schema commonalities between successive contributions • "migration" through different distance image-schemas creates an extended loop in the semantic network • a novel idea occurring late in the sequence—to shield an instrument package in ice—arises from a recombination of image-schemas from earlier, distinct contributions
 **Episode 12** slices 66-126	An early stage in the radiator design in which expert opinions were divided between two alternatives. A proposal for an alternate geometry is eventually favoured over the one ultimately adopted in Episode 39. Ambiguity, related to the lack of an effectively shared representation, appears to have played a role in one expert's inability to persuade his colleagues.	• clustering of actors as they align themselves with different alternatives and the issues they raise in advocating one alternative over the other. • lack of a solid consensus results in a characteristically elongated layout prior to the team leader's instruction to CAD to implement the alternative geometry.
 **Episode 39** slices 41-158	One expert objects to an interim design for a major component (the radiator) and re-introduces an alternative previously rejected. Discussion and repair triggers a period of shared whiteboard drawing with eventual convergence on a new design based on the alternative proposal. Instructions are given to the CAD operator to change the model.	• distancing that occurs as a result of disagreement between participants • the locus of activity shifting from the CAD model to the whiteboard drawing • entrainment of several participants around the whiteboard, ultimately resolving the disagreement and elaborating the initial proposal • gestural exchanges used to reinforce the image-schema content of the language

Cumulative Networks, Participation and Integration of Representations

In presenting a second stage of results, I wish to highlight the first two of four factors—aspects of network structure identified through micro-analysis—that appear to account for differences in the productivity of design interaction across the selected episodes. These factors are the overall level of participation of various actors, and the extent to which persistent shared representations are integrated in conversation. Cumulative aggregate layouts for entire episodes (as opposed to real-time slice layouts presented above) are particularly useful and revealing of this type of information. Pairs of cumulative aggregate networks for each episode are presented in Table 6-10 below, presented in order to make the contrasts between positively and negatively-selected episodes most apparent. (Larger versions of all detailed network results appear at the end of the chapter.)

Separate cumulative aggregate networks were constructed for the actor-discourse and semantic components of the coding for each episode.[145] The actor-discourse network shows the relative affinity between actors and different elements of discourse over each episode as a whole. The actor-discourse network also includes representation-related acts and inscription, making it possible to see the way human participants have engaged with various representations and the level of inscription of particular discourse nodes. The semantic network makes relationships between different elements embodied in the discourse itself visually apparent. Both networks include collaborative product arcs and inscription as proxies for the predictor and criterion variables so that these factors can be included in comparisons.[146]

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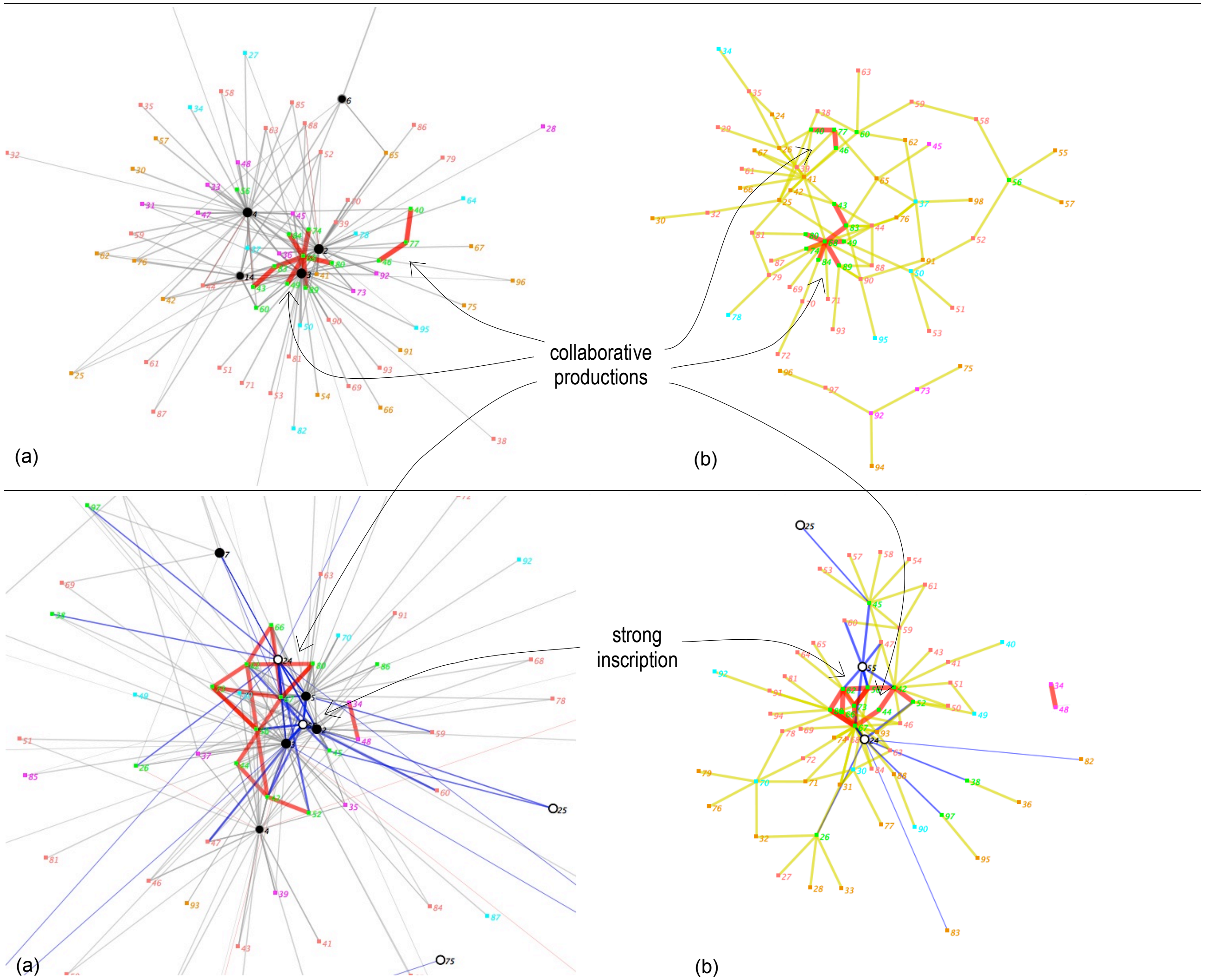
[145] In principle, a single combined network could be constructed, but in practice these layouts become cumbersome and over-constrained. Also, issues of consistency and the commensurability of strength values across different types of coding would have to be considered, and a uniform approach to coding single vs. multiple arcs adopted. In practice it may be more analytically productive to consider different components of networks independently. I present the results below as indicative of possibilities that may be more fully realized with specifically-designed tools and metrics tailored to this purpose, such as will be described in a later chapter.

[146] As described in the previous chapter, a cumulative build-up of slices and the use of a different aggregation mode (summing the strengths of multiple arcs, vs. averaging in the real-time layouts) were found to improve the stability of cumulative layouts. Even so, the proximity of any particular pair of nodes is not necessarily meaningful unless actual arcs exist between them. Thus the logic for the interpretation of these layouts is somewhat more diagrammatic than if one were to rely solely on the spatial metaphor PROXIMITY=AFFINITY. Certain visual differences also arise from the different aggregation mode and the fact that arcs never retire. The greater maximum value attained by some arcs in relatively longer episodes means some nodes become more tightly clustered in the centre of the layouts; making this detail visible can mean losing sight of some more peripheral nodes. Also, since arcs between collaborative products are coded only once (vs. others coded every time a statement of alignment is made), clusters of collaborative products become relatively larger and more open in longer episodes compared to shorter ones. This is particularly apparent in Episode 39, below.

Table 6-10 Full Episode Cumulative Aggregate (a) Actor-Discourse and (b) Semantic Network Layouts



aspects illustrated

Episode 7: selection based on <u>positive indicators</u>. A period of energetic brainstorming in which the novel design approach of an elevated instrument platform was proposed as a way of protecting sensitive instrumentation from radiation.

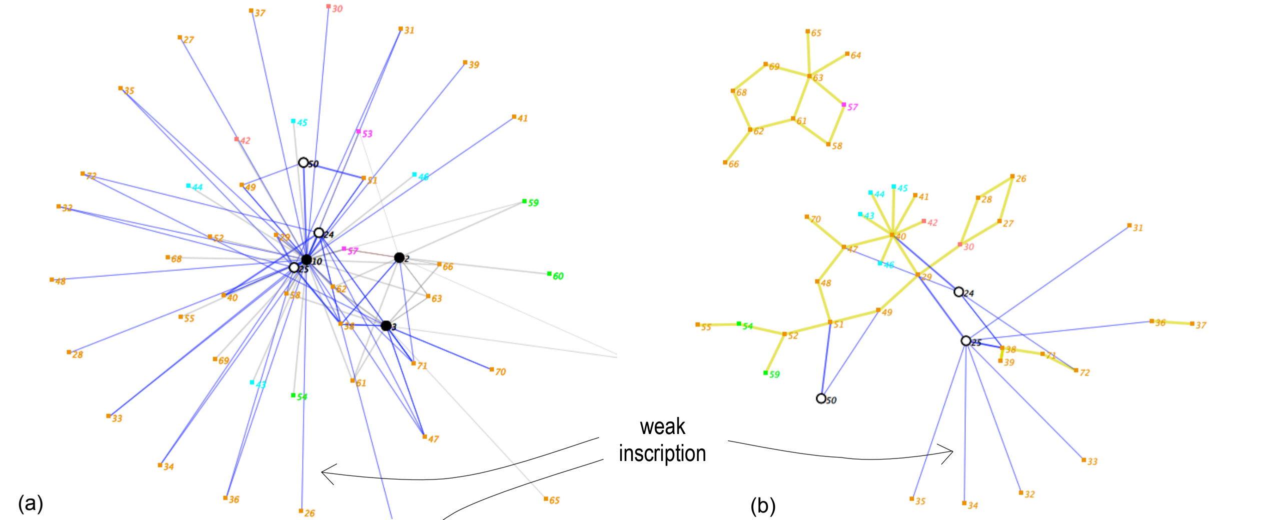
- two distinct collaborative productions, corresponding to alternate approaches of using a mast or boom, and enhanced shielding
- the actor-discourse network shows strong engagement of four actors, and the relative emphasis on elaborating the mast/boom idea
- the semantic network shows several discourse bridges (and an extended loop) between the two collaborative solution clusters, reflecting movement of discourse between solutions "on the lander" and those involving "distance"

Episode 39: selection based on <u>positive indicators</u>. Energetic interaction centring on whiteboard and CAD representations. A proposal for what would become the final, novel radiator design was reintroduced and collaboratively developed, following the rejection of an interim solution.

- a large cluster of collaboratively-produced options corresponds to the elaborated, horizontal radiator approach
- elements of the solution are strongly inscribed in one or both representations
- actor-discourse network shows several actors strongly engaged in representational acts, indicating a high degree of co-construction
- semantic network shows discourse principally organized around the collaborative product

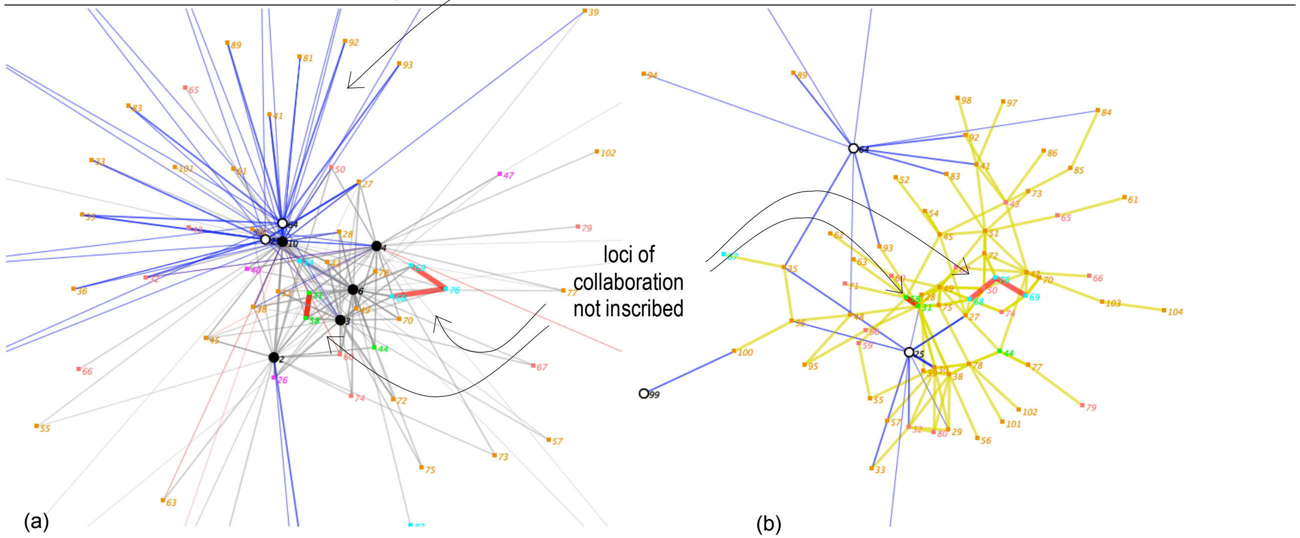
Table 6-10 Full Episode Cumulative Aggregate (a) Actor-Discourse and (b) Semantic Network Layouts

aspects illustrated



Episode 21: selection based on <u>negative indicators</u>. A narrated spreadsheet presentation involving tangential discussion of a related issue. Participants failed to agree on the relevance or severity of the issue, and appeared to have difficulty using a common set of terms for radiation and effects.

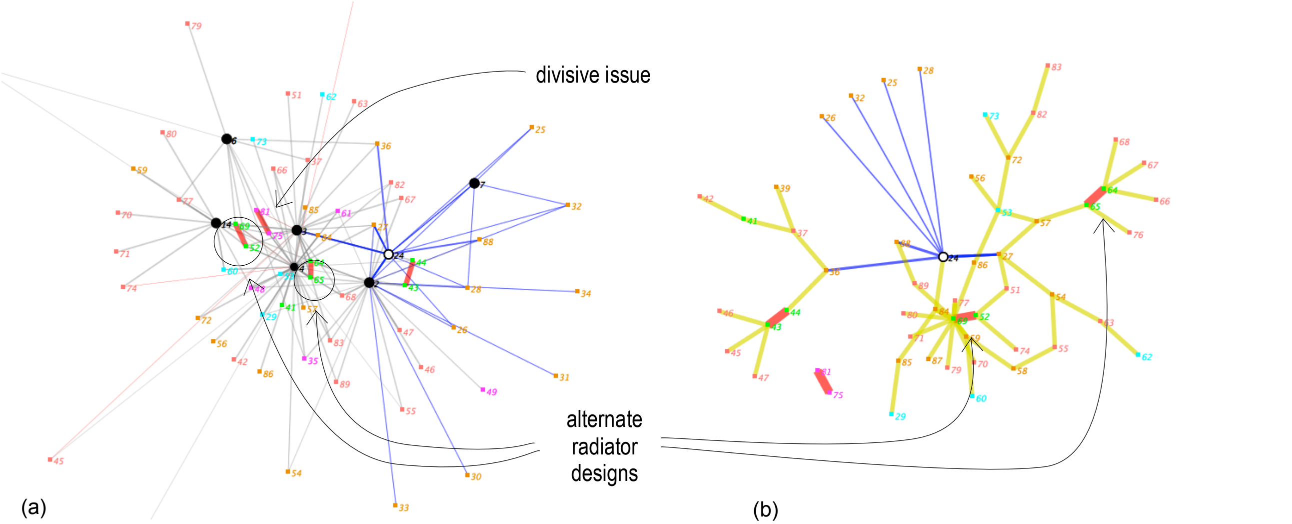
- absence of collaborative productions
- discussion dominated by information and matters of fact which are only weakly inscribed (reflecting brief, neutral reference)
- actor-discourse network shows only one participant strongly engaged with representations
- semantic network shows substantial discussion around an issue unrelated to anything inscribed in the representations



Episode 54: selection based on <u>negative indicators</u>. A spreadsheet presentation which led to a productive discussion of radiation and electronics. New design thresholds for different types of radiation were determined. This occurred however with little involvement, and even some distancing by the presenter.

- relatively few collaborative products, none of which are inscribed
- a-d network shows only the presenter strongly interacting with representations; these are distant from loci of collaboration
- semantic network shows substantial focus on information and matters-of-fact with design discourse and collaborative products less numerous and less focal

Table 6-10 Full Episode Cumulative Aggregate (a) Actor-Discourse and (b) Semantic Network Layouts



aspects illustrated

Episode 12: selection based on positive indicators. Apparently productive episode with unstable consensus around the adoption of an alternate radiator design proposal, despite initial objections, disagreement and confusion expressed by a key expert. Absence of an effectively shared representation of the alternatives or precise nature of the disagreement.

- representation tangentially involved in design discourse, only accessible to two of the five principal participants
- actor-discourse network shows engagement of experts with divisive issue and their respective alignment with alternate solutions, neither of which is inscribed
- semantic network shows relative isolation of collaborative productions in discourse

arcs: PROXIMITY=AFFINITY. types: design discourse (light gray); representational act & inscription (blue); semantic network (yellow); collaborative production (strong, red)

participant *remote /audio-visual* *remote / audio only* *<representation>* *[issue/problem]* *[criterion/constraint]* *[option/solution]* *[info/matter-of-fact]* *[image/schema]*

Once one learns to interpret them, animated diagrams and cumulative layouts can rapidly convey an intuitive sense of real-time interaction and qualitative patterns in overall participation. However, a more compact, longitudinal understanding of "the shape" of unfolding interaction is also desirable. I approached this through the use of conventional network metrics for aspects of network structure. Structural metrics also provide a way of circumventing difficulties and potentially-misleading interpretations that can arise from distortions of network distances inevitable in two-dimensional layouts (as mentioned in the previous chapter, and detailed in Appendix E).

Conventional Network Metrics

A number of metrics have been developed to assess important structural features of social networks (Scott, 2000; Wasserman & Faust, 1994). Three such metrics commonly applied are degree centrality, closeness centrality, and betweenness centrality (Freeman, 1978). To evaluate these metrics, I selected one of the most widely-used software packages for the analysis of social networks: UCINET (Borgatti et al., 2002).[147]

Of the three centrality measures, I deemed closeness centrality as implemented in UCINET to be inappropriate for this data set because the routine accepts only a directed binary graph as opposed to a valued graph as input.[148] Using this metric would therefore mean disregarding arc strength information, which is of course a central aspect of the coding scheme. For the same reason, I found the flow betweenness centrality metric implemented in UCINET to be more applicable than simple betweenness centrality (Freeman et al., 1991).

By comparing the structure of the five selected episodes, I propose two additional attributes are necessary to understand the productive engagement of actors with shared discourse. I describe these as *overall alignment* and *mutual engagement*. These can be assessed, respectively, on the basis of degree centrality and flow betweenness centrality, with modifications (and in the case of flow betweenness, certain caveats) I will now describe.

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[147] To conduct this type of research, it is essential to have either software tools ready-to-hand, or the programming skills to implement particular computational network metrics. Existing software tools make standard metrics relatively easy to use, increasing the likelihood that they can be applied consistently by other researchers. As I note below, the drawback is that when limitations are encountered, one has little recourse other than to look for a different metric. In this case I will use certain metrics to support conclusions about relationships between network structure and design conversation. I will also identify limitations and, in a subsequent chapter, propose ways they may be addressed in further work.

[148] A binary graph is a network in which only the presence or absence of a connection is tabulated, without any consideration of the strength of the connection.

Overall Alignment and Total Degree

Alignment is the term I have used (after Brereton et al., 1996) to describe the extent to which participants' statements manifest support, agreement, positive engagement and active contribution to elements of their shared discourse and design reasoning. The opposite of alignment is distancing—examples of which include withdrawing support, criticizing or calling into question an element of design reasoning. In the network representation I developed, these are mapped onto numerically-increasing values of arc strength.[149] I found the degree centrality metric to provide a useful basis for an overall measure of alignment.

In a network representation, the degree of any node is the sum of the values of all the arcs connecting that node to the rest of the network. The degree of a particular node provides an indication of the density of its connections, which is accepted as one index of the importance of that node in the network (Scott, 2000; Wasserman & Faust, 1994; Freeman, 1978). While it would be interesting to assess the importance of individual nodes over time in this way, my first objective was an index applicable to the group as a whole. I took the approach of summing the degree of all nodes to yield such an overall measure. Thus, the sum of degree, or "total degree" of the actor-discourse network reflects the combined strength of all arcs at any given time, hence the overall level of alignment expressed by all participants in the discourse.

While it was clear that semantic network arcs should not be included in the total degree[150], it was necessary to consider the inclusion of inscription arcs, since both their strength and relatively long duration impact the calculation. After a comparison of the effects of varying strength and duration of inscription on total degree (presented in Appendix C), I decided to include inscription at a uniform, intermediate strength (5) and with a duration equivalent to

[149] Even distancing represents a degree of engagement compared to making no mention of an element of discourse whatsoever—corresponding to a zero value in the network matrix. None of the mathematical network implementations employed in this research support a negative value for arc strength, which would be another way distancing statements might be intuitively conceived. Note that an obvious and intentional failure to respond—to pointedly ignore a direct question for example, would probably constitute an interpersonal, socio-emotional act (of the sort I did not address in this research) rather than a contribution to design reasoning.

[150] The strength values of semantic and collaborative product arcs are somewhat arbitrary with respect to the scale for alignment. These were added to the scheme primarily to improve the visual interpretability of 2D layout diagrams. The inclusion of semantic network arcs in the total degree metric—as a numerical reflection of overall alignment—would therefore be spurious. However, this by no means precludes the possibility of performing interesting numerical analyses on semantic networks. It should be noted, as a distinct possibility for further work, that results identical to the metrics employed in Goldschmidt's (1992, 1995) linkography can be obtained by evaluating the degree centrality of nodes in semantic networks, when arc direction is taken into account. Separate tabulation of the in-degree and out-degree of nodes replicates Goldschmidt's distinction between fore-linking and backward-linking moves. Because the semantic network is not an inherently valued graph (i.e. arc strength is not an essential attribute, unlike the alignment scale), additional possibilities open up, including the use of closeness centrality or betweenness centrality as structural measures.

that of design discourse (30 slices, or 2.5 minutes). These values seemed reasonable to register inscription in a relatively conservative manner, making it essentially comparable to moderately-strong advocacy in design discourse.

Figure 6-1 below presents graphs of the total degree of actor-discourse networks over time for each of the five selected episodes. The total degree curve provides a clear and responsive longitudinal index of the level of activity over the course of each episode, with peaks generally corresponding to important developments, and valleys corresponding to lulls and periods of confusion and repair. A ghost curve corresponding to zero-strength inscription is included for reference, allowing the relative contribution of inscription to total degree to be assessed.[151] The total degree metric is a reasonable index of the relative clustering of nodes and density of arcs visible in the real-time layout diagrams.[152] More detailed information relating interactional developments to various points on the total degree curves, including representative network layouts, is presented at the end of the chapter in Figure 6-13 through Figure 6-22

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[151] The divergence between the nominal curve and the zero-inscription curve is a function of the arc strength defined for inscription (relative to the alignment scale), the duration of inscription arcs and the rate at which inscription is coded in interaction. Since values for the first two factors have been chosen to be comparable to those for design discourse arcs, the divergence between the curves primarily reflects the rate at which inscription is occurring. See Appendix C for a comparison of the relative impact on the curves of different treatments of inscription.

[152] Measured layout distances over a test portion of one episode correlated closely with the total degree metric. As an effective measure of the total arc strength, it is reasonable to expect the total degree metric to directly reflect the clustering and visual density of real-time layouts. (The sum of the degree of all nodes in a graph is equal to twice the sum of the strengths of all arcs, since each arc is effectively counted twice.)

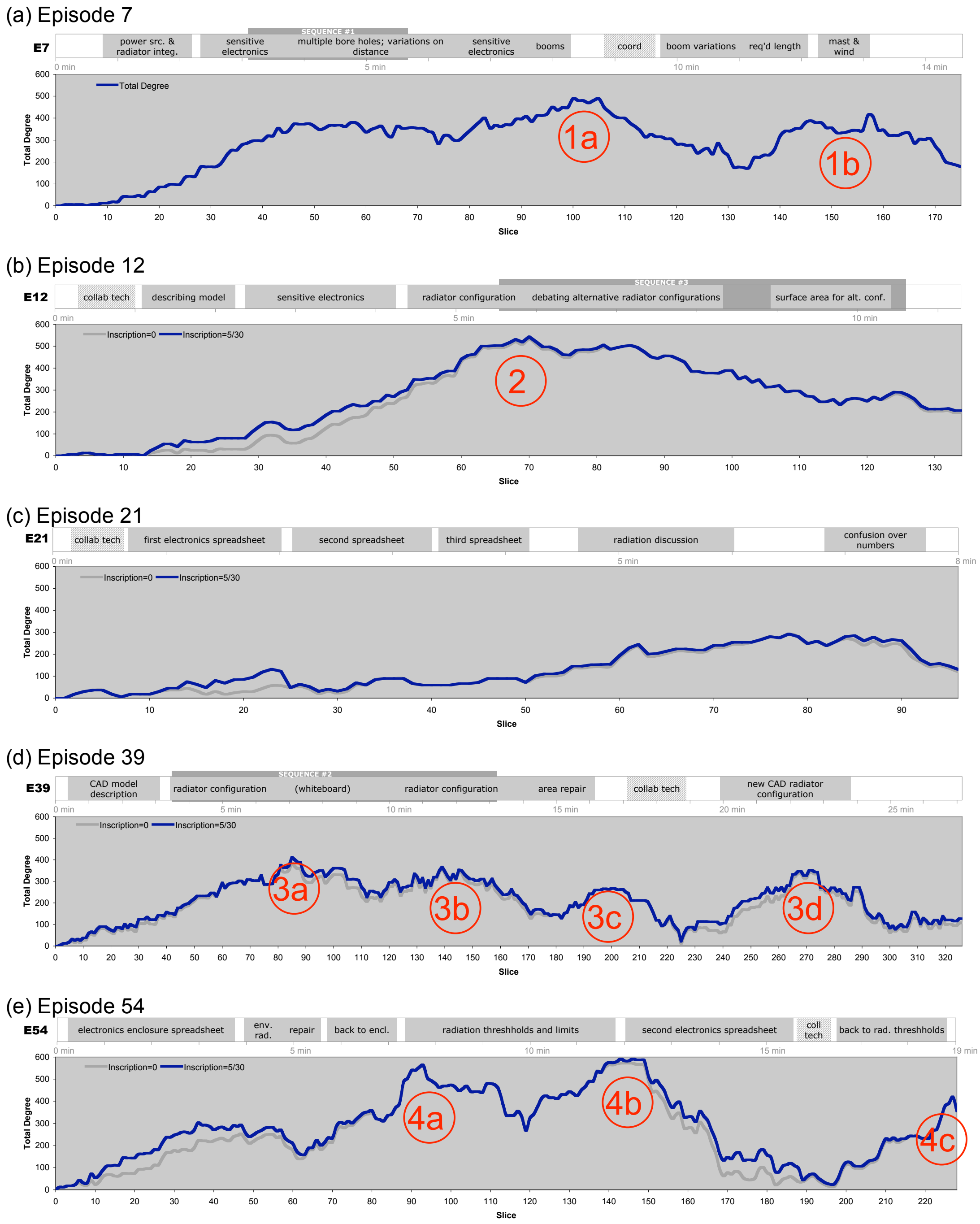

Figure 6-1(a-e) Total Degree Graphs and Timelines for Selected Episodes
Peaks in total degree correspond to key design developments in the following areas:
(1) sensitive electronics on a deployable boom or a vertical mast
(2) proposal of a horizontal radiator and an alternative configuration
(3) repeated proposal, acceptance and refinement of horizontal radiator design
(4) recognition and agreement upon specific design thresholds for different types of radiation
Additional detail and representative network slices are provided in larger diagrams at the conclusion of this chapter.

While the total degree appears to be a useful index of the level of activity, it does not by itself sufficiently reflect the differences underlying the positive vs. negative selection of the episodes. For example, while valleys in total degree of Episode 54 correspond to repair accounting for most of the negative indicators, its peaks are also the highest of any episode.

And, while the total degree attained in the negatively-selected Episode 21 is only half that seen in Episodes 7, 12 and 54, it is only about 25% less than the peaks seen in Episode 39—which was arguably one of the most productive sessions.

Because variations in total degree alone do not decisively discriminate between the positively and negatively-selected episodes in all cases, I decided to investigate an additional metric, hoping to shed more light on the differences. A number of negative indicators in both Episodes 21 and 54 related to participants' apparent inability to "connect" with each other and reach a clear common understanding; since constructive communication involves a degree of reciprocal engagement and bridging (cf. Stewart 1995), I looked to the centrality measure of betweenness.

Mutual Engagement and Discourse Betweenness

Betweenness is a measure of the extent to which a given node lies on paths that connect other nodes (Scott, 2000; Wasserman & Faust, 1994; Freeman, 1978). Flow betweenness centrality seemed like a promising diagnostic for the difficulties in the negatively-selected episodes, as a quantitative measure of the existence of discourse bridges between actors.[153] I refer to this property of bridging as "mutual engagement."

As with degree centrality, flow betweenness is a measure intended to index the relative importance of nodes on an individual basis within a network. In this case however, what I desired was a metric reflecting the conversation of the group as a whole. I took the approach of summing the flow betweenness centrality for the discourse nodes only, then comparing it to the sum for all nodes (i.e. including actors). The resulting percentage, which I refer to as *discourse betweenness*, reflects the overall extent to which discourse nodes act as bridges between actors.

The flow betweenness centrality metric assesses a different aspect of network structure compared to degree centrality, in a manner consistent with the idea of mutual engagement as distinct from overall alignment. While mutual engagement necessarily requires *some* level of alignment in common, the reverse is not necessarily true. Strong overall alignment does not necessarily entail high mutual engagement, since participants may be strongly aligned with different elements of discourse. Flow betweenness centrality responds quite sensitively to the specifics of any nodes' connections to the rest of the network; compared to degree

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[153] As mentioned above, simple betweenness centrality is not defined for valued graphs; it is also based only on a geodesic, or shortest path, not the set of all paths between pairs of points. The anticipated importance of multiple discourse "bridges" made the flow betweenness metric seem more suitable for this reason as well.

centrality, it can be much more strongly effected by individual arcs. (These effects are detailed in Appendix C.)

Betweenness centrality is also considerably more complex computationally. Because the computer tool only allows it to be calculated for a single slice at a time, a longitudinal graph proved to be an unreasonably arduous proposition. I adopted a sampling strategy to calculate flow betweenness at discrete slices, corresponding to total degree peaks and other areas of interest within each episode. As with the total degree metric, only the actor-discourse network was used for this calculation; arcs in the semantic network were ignored.

The results of these calculations are presented in Figure 6-2. Discourse betweenness thresholds are indicated on each graph to reflect relatively high, intermediate and low values, based on results from all episodes. Additional detail and representative network layouts at key check slices are also presented in Appendix C.

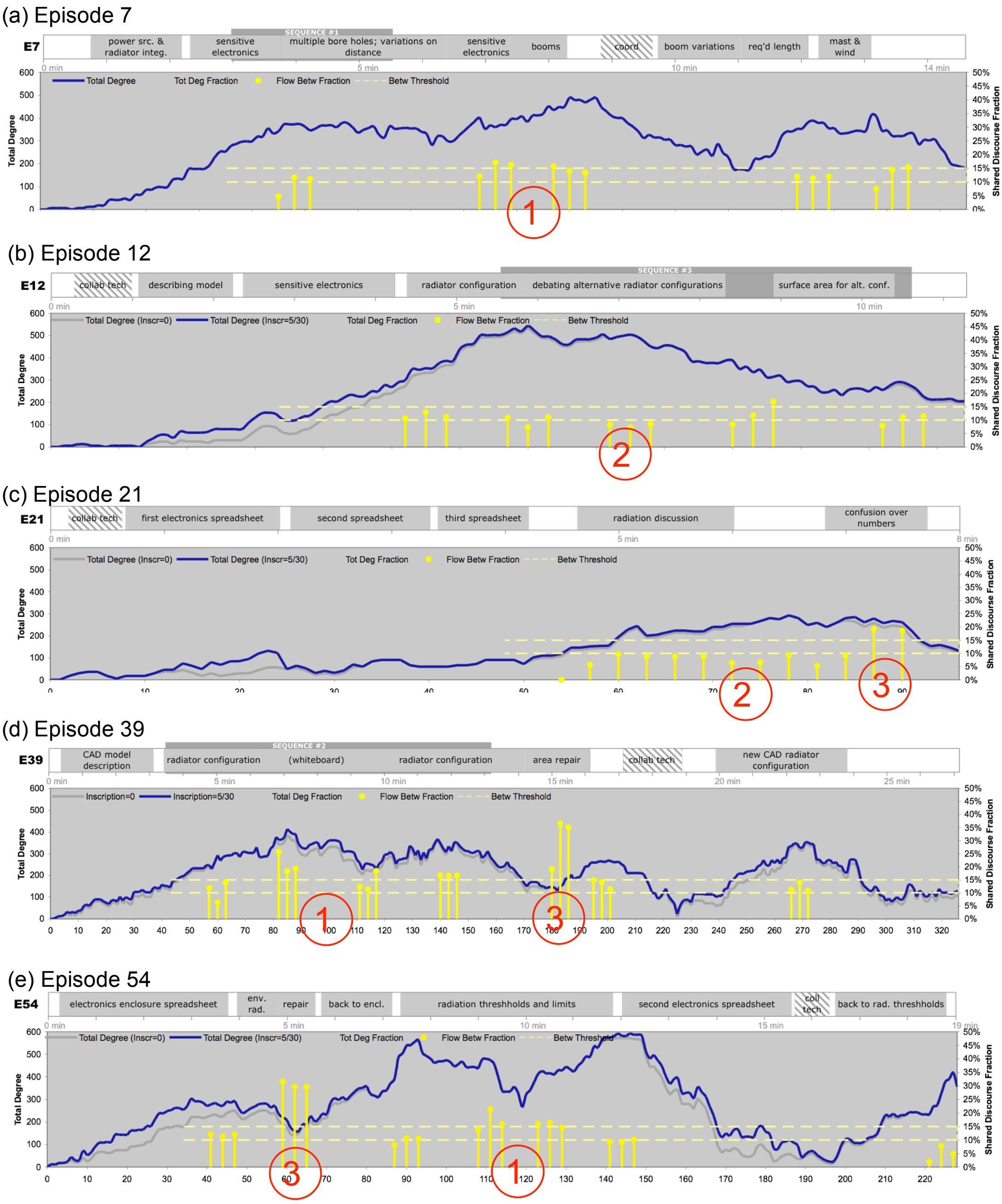

Figure 6-2(a-e) Discourse Betweenness at Check Slices across Selected Episodes
Discourse betweenness thresholds are indicated: <10% (low) 10-15% (norm) >15% (high)
Numbers indexing particular areas of the graphs above correspond to the following:
(1) strong mutual engagement associated with important design developments
(2) weak mutual engagement associated with problematic interaction
(3) very strong mutual engagement associated with periods of communicative repair.
Additional detail and representative network slices are presented in larger diagrams at the conclusion of this chapter.

Exploration of a metric for mutual engagement was motivated by the desire to enhance discrimination between the positively and negatively selected episodes (particularly between Episodes 21 and 39). It is interesting to note the relationships between overall alignment and mutual engagement presented by the data in this regard:

- Peaks in alignment coupled with high mutual engagement (>12-15%) are associated with instances of strong consensus around key design developments.
- Very high mutual engagement (>20%) in conjunction with low overall alignment is associated with periods of extended communicative repair.
- Very low mutual engagement (6-9%) in conjunction with relatively low overall alignment appears to reflect the sort of lacklustre interaction that characterized most of Episode 21, during which participants could not agree on the relevance—or even use a common set of terms to describe, a radiation-related issue.
- High overall alignment with low mutual engagement (<10%) appears to correspond to instances of systematic disagreement or flawed consensus.

It is the last condition that is perhaps the most interesting. In this regard, the “dual” nature of Episode 54—selected for negative indicators but which also witnessed a significant, emergent collaborative development—can be seen. In this episode the negative indicators related primarily to obvious disagreement and frustration expressed by experts who, it seemed, couldn't see eye to eye on aspects of the shielding solution enthusiastically embraced by others. Those who did agree forged a strong consensus on the approach which was ultimately taken. This pattern can be seen reflected in the comparatively low mutual engagement under the actual peaks in total degree in Episode 54, with quite strong mutual engagement arising between these peaks (when the actual details of the approach were decided).

Even more interesting is Episode 12, which involved a more subtly-flawed consensus between experts—one of whom, it later became clear, did not understand what it was he was supposedly agreeing to. The fact that neither I, as an observer, nor the team leader noticed this state of affairs at the time, underscores how difficult it can be for participants to monitor each others’ arguments in a complex discussion—particularly when some participants are remote and in the absence of any effectively-shared representation.

Overall, the results show a relatively higher discourse betweenness to occur in conjunction with periods of focused discussion and convergent interaction. That this is also true of periods dominated by communicative repair is consistent with an understanding of this metric as a reflection of mutual engagement as distinct from alignment. However, careful examination of the behaviour of the flow betweenness metric reveals its behaviour to be potentially problematic at times.[154] While the overall strength of the pattern supports the interpretations I have given, this leads me to suggest what may be a more appropriate metric and to propose its formulation and testing for future work (discussed below in Chapter 9 and detailed in Appendix E).

Categorical Composition of Coding

In Chapter 5, I described the decision to abandon a purely category-based coding approach in favour of a network representation. While node colour can convey some idea of the composition of discourse, network diagrams and metrics primarily illustrate structural connections. I wish to return to consider categorical dimension of coding to extract information about the composition and temporal development of discourse in the selected episodes. Coding overview graphs, presented below in Figure 6-3 through Figure 6-7, are most useful for this purpose. In terms of the categorical composition of coding, two differences between the selected episodes are particularly revealing: the degree of development of design discourse, and the extent to which closure was reached with commitment to pursue specific design directions and/or refined questions.

The positively-selected Episodes, 7, 12 & 39, all show a large number of instances of the strongest design discourse acts (propose, elaborate or align). Furthermore, these acts include all three components of design reasoning. Episode 54, though selected on the basis of negative indicators, also shows reasonably well-developed design discourse. By contrast, Episode 21 shows no strong design discourse acts. Positively-selected episodes all included meta-process acts marking convergence on a particular direction and/or specific follow-on work.[155] Episode 7 resulted in a clear and specific request for a tradeoff analysis between horizontal and vertical approaches. Episode 12 resulted in clear instructions issued to the CAD operator, though completion of the change did not occur until a later episode. Episode 39 also saw explicit instructions issued to implement a change in CAD; when this was completed, the result triggered a specific query which led to further refinement.

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[154] The metric appears to preferentially score nodes lying on unique flow paths between other nodes, compared to nodes on multiple or redundant paths. This may stem from the basic conception of flow betweenness in terms of nodes' having the potential to control the flow of information to other nodes (Freeman et al. 1991). While the behaviour of the metric is consistent with a metaphor of control, this is not entirely consistent with my conception of discourse nodes as bridges. Additional detail on this metric and problematic aspects is provided in Appendix C.

[155] Meta-process acts pertain to design discourse but entail an important shift in voice and conditional stance, wherein the speaker presumes to offer an objective assessment of the state of affairs on behalf of the group; e.g. they are no longer of the form, "I think we should do this," but more closely resemble, "this is where we are," "this is what we need," "this is what we have decided," or "this is what we will do."

Despite significant amounts of conversational repair, some disagreement and evident frustration, Episode 54 also ended with clear and explicit closure on refined radiation targets. By contrast, Episode 21 showed no indication of movement toward closure with enhanced specificity regarding a design direction, or even the issues involved. It was actually terminated rather abruptly when a remote participant—one of the primary external customers—announced his imminent departure, thereby provoking a topic shift to scheduling matters without any resolution of the problematic radiation discussion.

(Note that, following the coding overview diagrams below, I include several figures with more detailed results of the various stages of network analysis, prior to reviewing more macro-level analytic results in Chapter 7.)

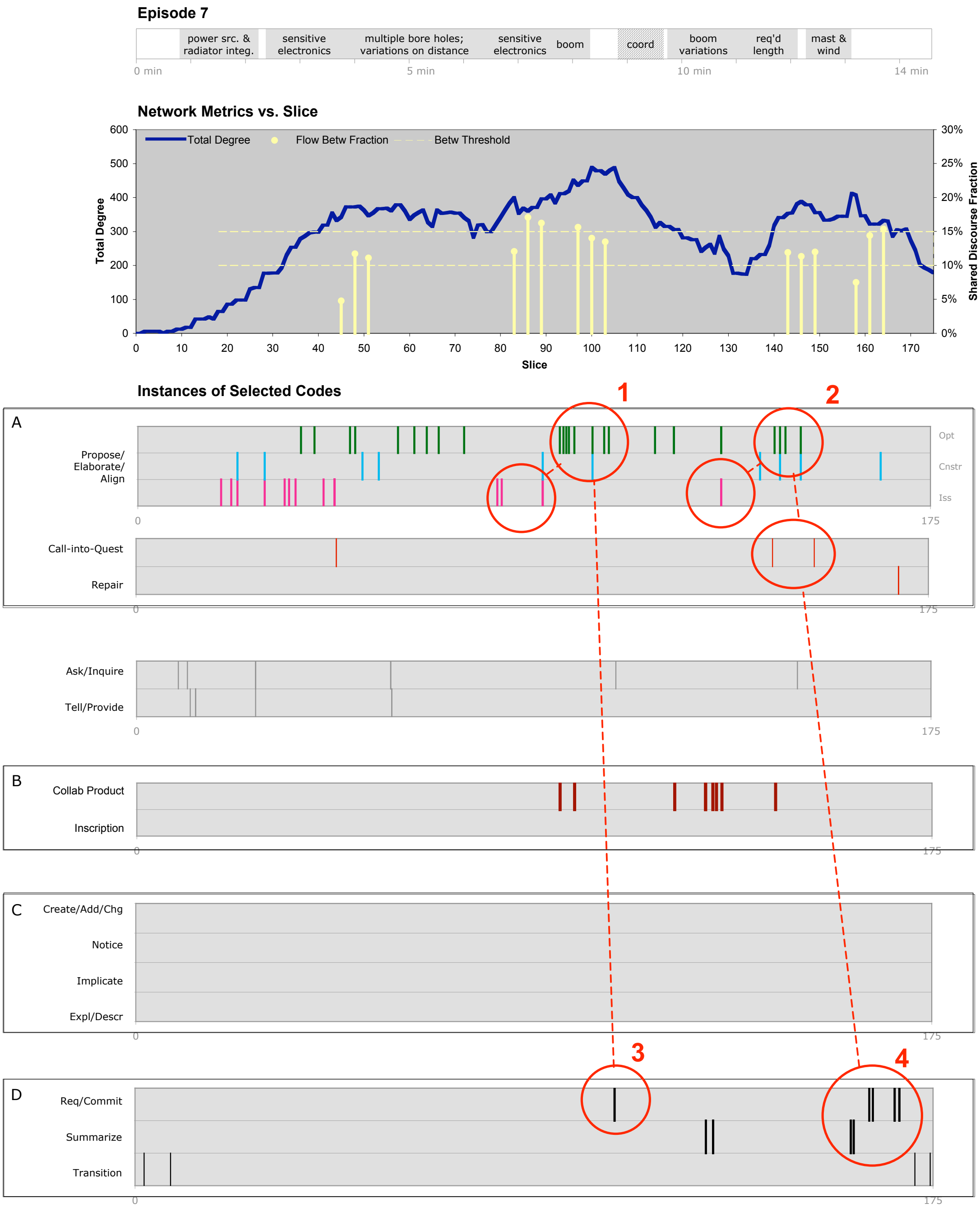


Figure 6-3 Episode 7 Timeline, Network Metrics and Coding Overview
A = design discourse codes and repair tend to most strongly impact the total degree metric
B = criterion and predictor variables (collaborative products & inscription)
C = representational acts (by human participants)
D = meta/process acts

Episode 7 was selected on the basis of positive indicators. Well-developed design discourse is evident in box **A**. Strong alignment and moderate to high mutual engagement are evident around key, emergent design solutions. These include a proposal to place sensitive electronics on a horizontal boom **(1)**, followed by the idea of a vertical mast **(2)** to circumvent issues with obstacles. The latter approach engendered some disagreement with regard to wind problems and possible mast length. An initial commitment to investigate the boom idea **(3)** eventually reached closure with enhanced specificity in the form of a request and commitment to provide a detailed analysis comparing the horizontal and vertical approaches **(4)**. Episode 7 did not involve the use of shared external representations, so there were no codes for inscription or representational acts by human actors.

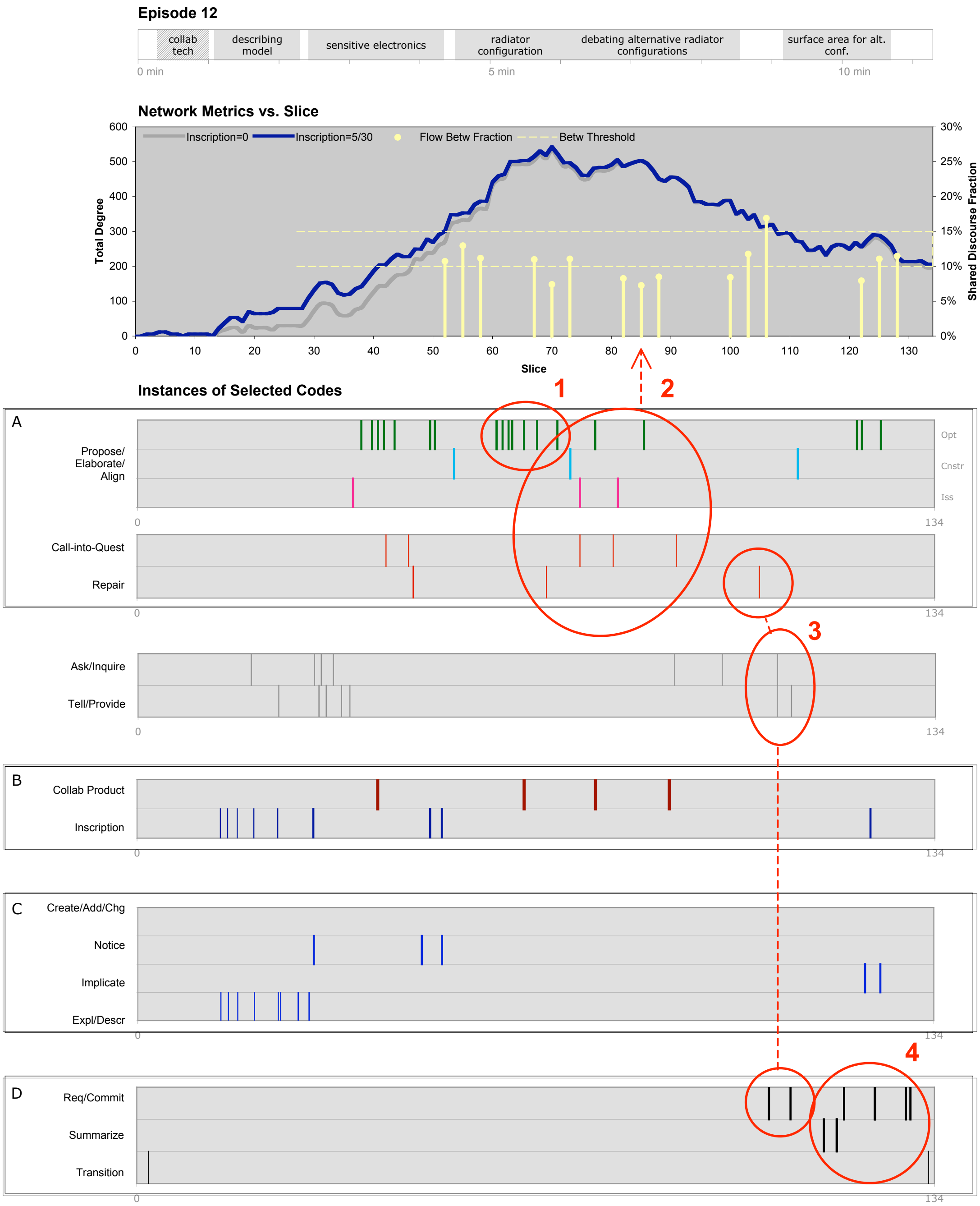


Figure 6-4 Episode 12 Timeline, Network Metrics and Coding Overview

A = design discourse codes and repair tend to most strongly impact the total degree metric
B = criterion and predictor variables (collaborative products & inscription)
C = representational acts (by human participants)
D = meta/process acts

Episode 12 was selected on the basis of positive indicators. Well-developed design discourse is evident in box **A**. A peak in alignment coincides with the proposal of two alternative radiator geometries **(1)**. A period of high alignment but relatively low mutual engagement reflects the ensuing debate over the alternate proposals **(2)**. Though the episode began with discussion of a shared CAD model, engagement with this representation dropped off (evident in boxes **B** and **C**) as neither of the alternate proposals was represented. An expression of confusion about what was being discussed led to an increase in mutual engagement when a dissenting expert was asked to clarify a parameter **(3)**. At this point the team leader effectively chooses one option and the episode closes with enhanced specificity in the form of a design direction articulated to the CAD operator **(4)**. The absence of a significant peak in alignment following the debate suggests the instability of this consensus, which did in fact unravel in a subsequent episode.

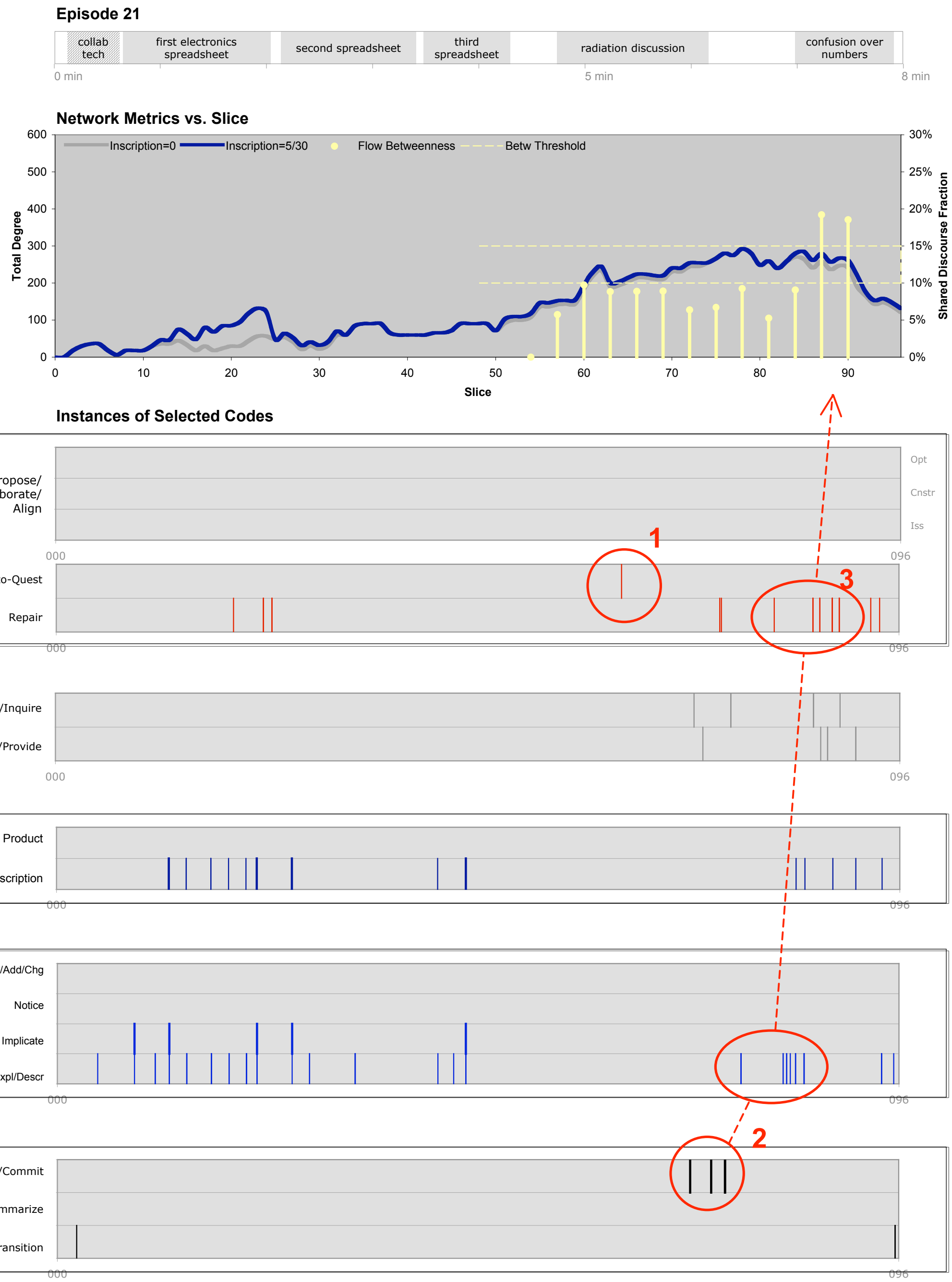


Figure 6-5 Episode 21 Timeline, Network Metrics and Coding Overview

A = design discourse codes and repair tend to most strongly impact the total degree metric
B = criterion and predictor variables (collaborative products & inscription)
C = representational acts (by human participants)
D = meta/process acts

Episode 21 was selected on the basis of negative indicators. The absence of strong acts in box **A** indicates a weakly-developed design discourse, one lacking strong alignment with any issues, options or criteria problematized by the group. The first half of this episode was a narrated spreadsheet presentation with relatively little interaction. In the second half, participants discussed an issue but had difficulty using consistent terms to describe radiation-related properties and effects, and disagreed **(1)** whether the issue would be of concern. The results were generally low levels of overall alignment and mutual engagement. Toward the end, an instruction to the system station to take down a certain piece of information **(2)** led to confusion over numbers on the different sheets, which at least raised the level of mutual engagement. The episode terminated abruptly with an important participant's departure, without conclusion or even a summary. (Note that not all coding is shown in the charts above; weak acts in design discourse were taking place during the blank periods in box A.)

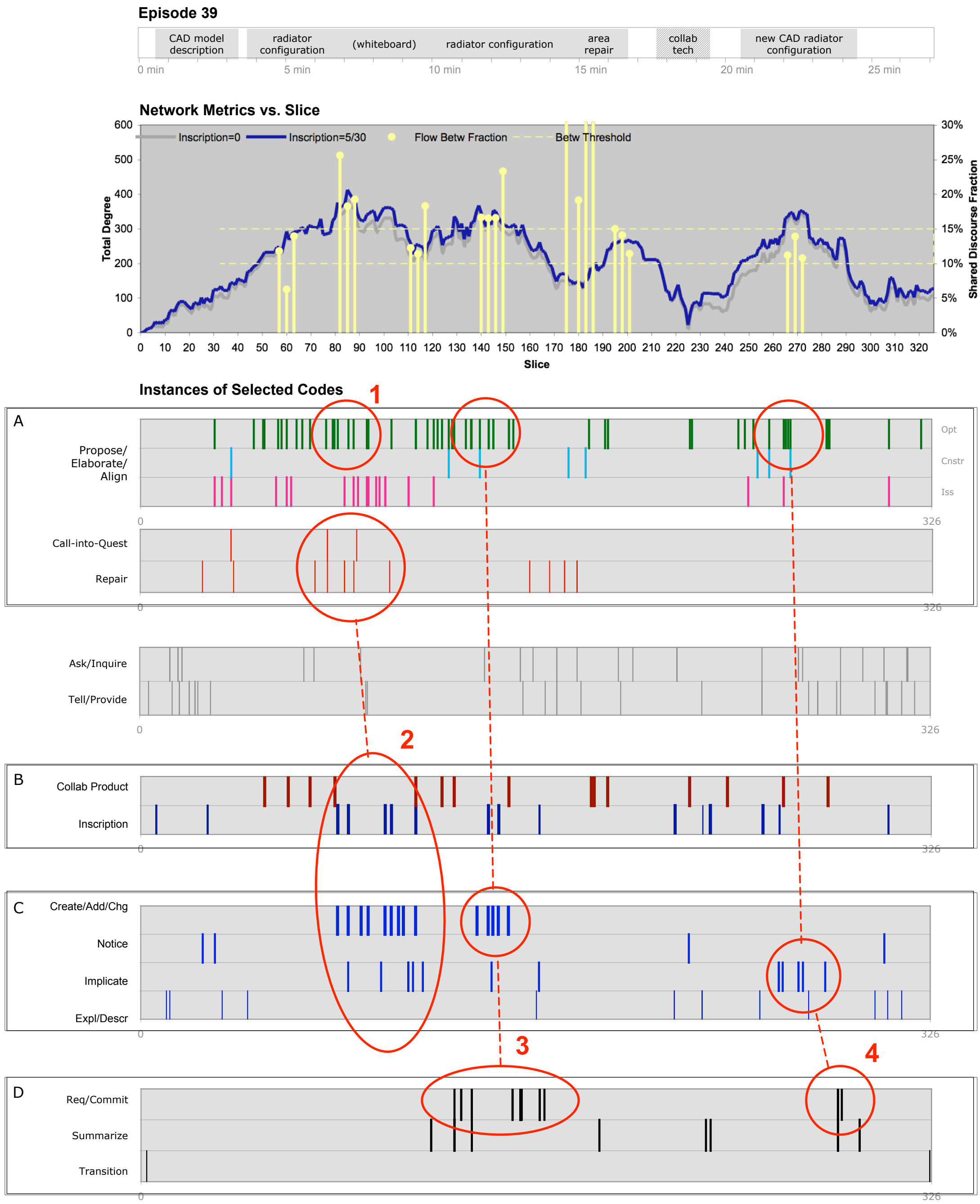


Figure 6-6 Episode 39 Timeline, Network Metrics and Coding Overview
A = design discourse codes and repair tend to most strongly impact the total degree metric
B = criterion and predictor variables (collaborative products & inscription)
C = representational acts (by human participants)
D = meta/process acts

Episode 39 was selected on the basis of positive indicators. Well-developed design discourse is evident (box **A**) Peaks in total degree with strong mutual engagement reflect convergence on a key design feature: the horizontal disk radiator **(1)**. (Valleys result from periods of repair and a delay with the collaboration technology.) Confusion and disagreement about an aspect of this solution led to a period of energetic whiteboard drawing **(2)**. (This episode saw more engagement and active collaboration over shared representations, evident in boxes **B** & **C**.) Resolution and further elaboration of the horizontal approach eventually led to instructions being given to the CAD operator **(3)**. Appearance of the updated CAD model with conclusive dimensions enabled a further elaboration of the deployment means and the instruction to pass the design along for thermal analysis **(4)**. Thus the team was able to advance the design two steps in this episode.

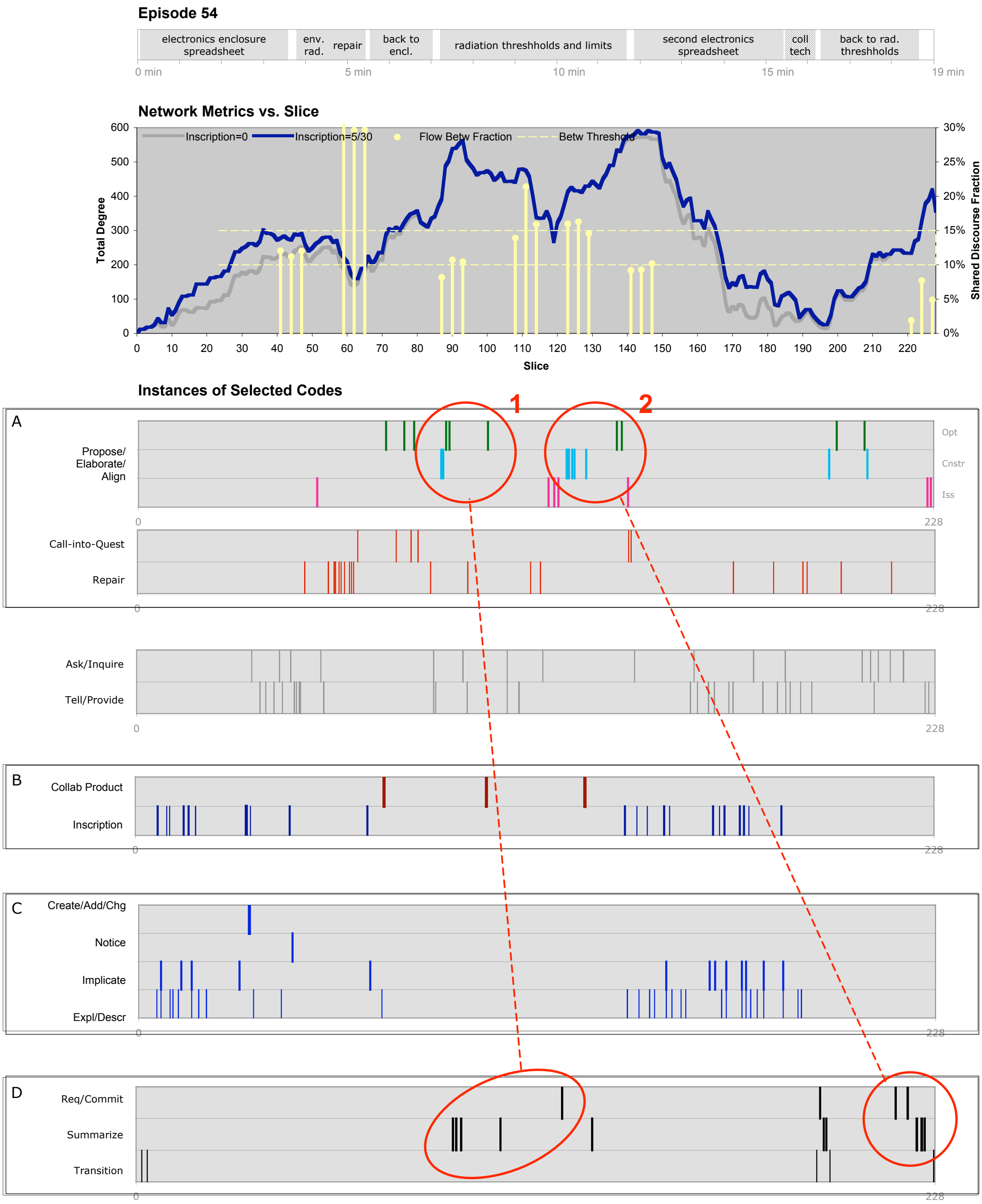


Figure 6-7 Episode 54 Timeline, Network Metrics and Coding Overview
A = design discourse codes and repair tend to most strongly impact the total degree metric;
B = criterion and predictor variables (collaborative products & inscription);
C = representational acts (by human participants); D = meta/process acts

Episode 54 was selected on the basis of negative indicators, but also scored above average on positive indicators. Negative indicators relate to the disagreement and intense periods of repair evident in the lower half of box **A**. The positive indicators relate to a key design emergence, so box **A** also reflects reasonably well-developed design discourse. The episode consisted of two periods of narrated spreadsheet presentation with a fairly energetic and collaborative design discussion between them. (The spreadsheet was a point of departure but was not strongly involved in the design discourse—evident by comparing boxes **B** & **C** with box A.) The design discussion saw the emergence of insights into radiation and shielding. This led to a refinement of the shielding strategy **(1)** and a significant revision of the radiation design thresholds **(2)**. Both these developments were consolidated by meta-process acts in box **D**. Note how mutual engagement is relatively low at the peaks of alignment. This reflects fairly systematic distancing by the expert narrating the spreadsheet from the emergent shielding proposals.

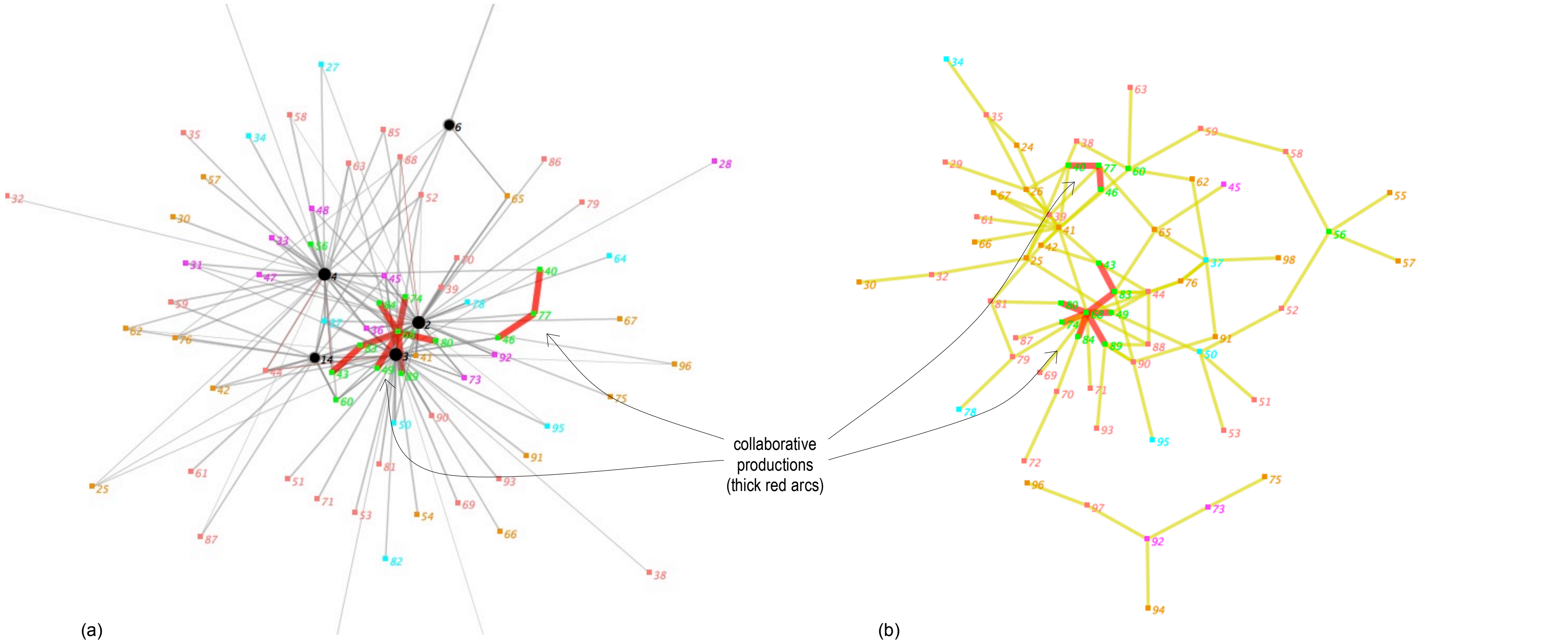


Figure 6-8 Episode 7 Cumulative Aggregate (a) Actor-Discourse and (b) Semantic Networks
In these cumulative networks, two collaborative product clusters are visible: the larger being a set of proposals related to putting sensitive electronics on a boom or mast (68 etc.), the smaller corresponding to different shielding approaches (77 etc.). The actor-discourse network shows relatively greater engagement of four actors (2,3,4,14) with the boom/mast idea cluster. The semantic network shows these two clusters principally connected by nodes relating to the sensitive electronic systems (41 etc.) and to the analysis requested for a tradeoff (65). The “island” of issues (92 & 73) are potential problems anticipated for long booms.
<u>Actor nodes</u>: **2**=ZD (team leader), **3**=HL (JPL customer), **4**=MW, **6**=EN, **14**=LC (all agency power system designers)
<u>Discourse Nodes</u>: **36**=where sensitive electronics?, **37**=radiation dose, **41**=sensitive electronics, **45**=shield possible? (mass), **65**=shield mass vs. distance table, **68**=telescoping boom, **73**=issue with boom length/weight?, **77**=shielding, **89**=vertical mast/instrument deck, **92**=Martian wind

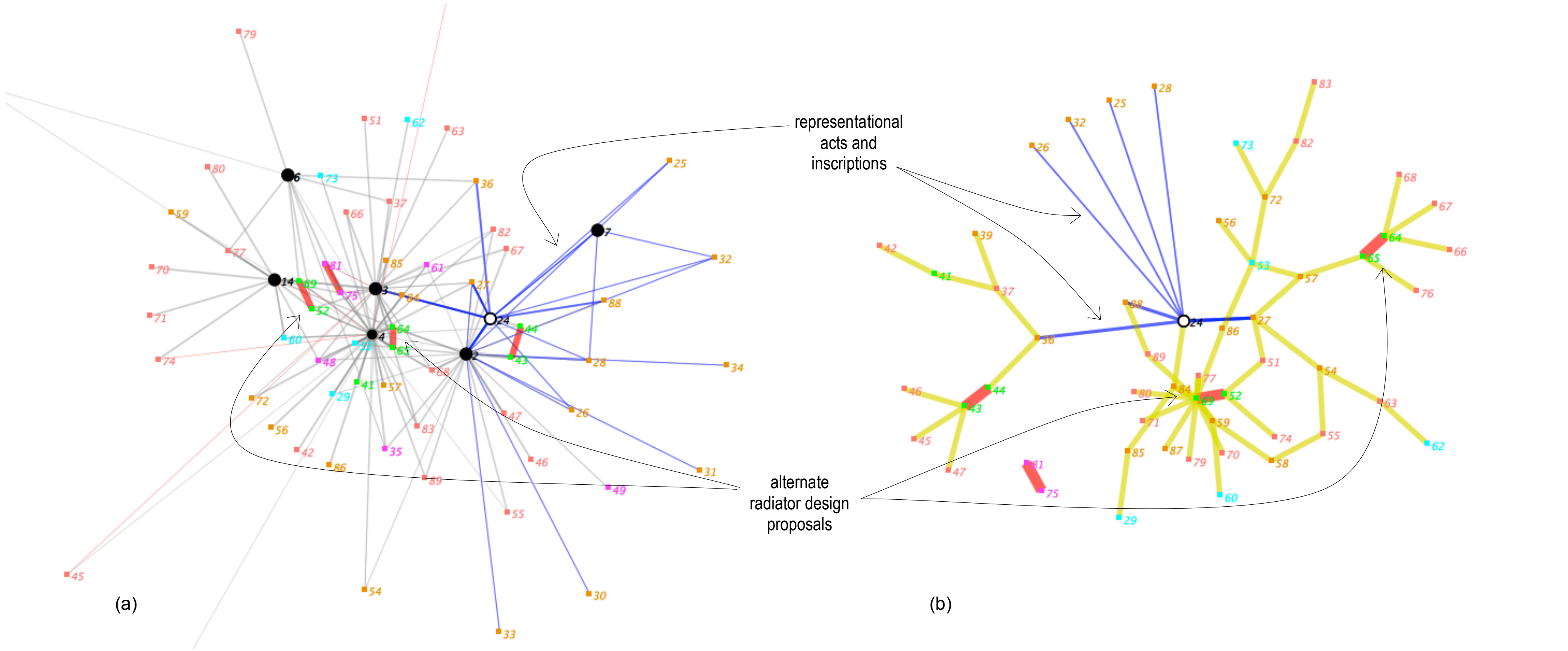


Figure 6-9 Episode 12 Cumulative Aggregate (a) Actor-Discourse and (b) Semantic Networks
The actor-discourse network shows the relative alignments of the agency experts with different radiator design proposals and the issues the experts debated. Specifically, the principal advocates of competing solutions (actors 4 & 14) are literally "on opposite sides" of the issues. Actor 3 is more closely aligned with actor 4. Actor 6 is less involved but appears more aligned with actor 14. Only actors 2,3 and 7 have significant interaction with the representation (actor 24), suggesting that the representation was not strongly integrated in the design reasoning. The semantic network shows the various foci of discussion. It also shows how features of the representation served as points of departure but makes clear that none of the collaborative products was directly inscribed.
<u>Actor nodes</u>: **2**=ZD (team leader), **3**=HL (JPL/customer), **4**=MW, **6**=EN, **14**=LC (all agency power system design), **7**=HJ (mechanical CAD operator); **24**=CAD model of lander (representation). <u>Discourse Nodes</u>: **27**=radiator, **36**=antenna, **44**=tall mast for electronics, **48**=melting into the ice?, **53**=radiator surface area, **61**=radiator shape/fit in aeroshell?, **65**=horizontal radiator, **69**=alternate-geometry radiator, **75**=[issue with] horizontal radiator?

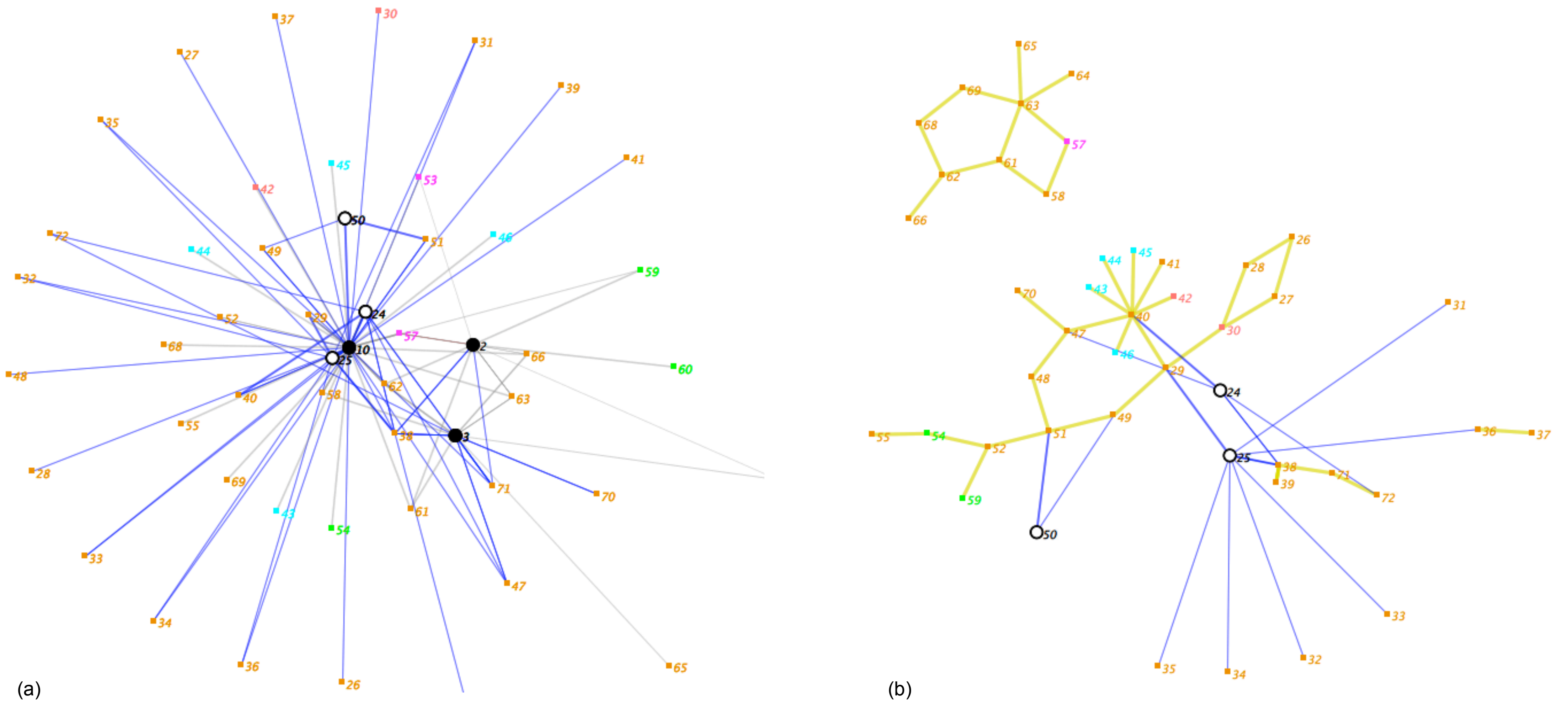


Figure 6-10 Episode 21 Cumulative Aggregate (a) Actor-Discourse and (b) Semantic Networks
This episode primarily involved a narrated presentation of three spreadsheets by LE with relatively little design discussion and no collaborative productions. Most interaction centred on matters of fact regarding radiation types and problematic effects on electronics. The principal issue in the interaction—problems for the electronics caused by particular types of radiation—was an island in the semantic network since LE specifically indicated it was not addressed by his spreadsheets.
Actor nodes: **2**=ZD (team leader), **3**=HL (JPL/customer), **10**=LE (avionics); **24, 25, 50**=Excel spreadsheets (representations). Discourse Nodes: **29**=new electronics card type, **38**=avionics power, **40**=lander electronics box, **47**=electronics mass, **57**=[other] radiation electronics problem, **61**=radiation (all types), **62**=[type 1] radiation, **63**=[type 2] radiation, **66**=high power source

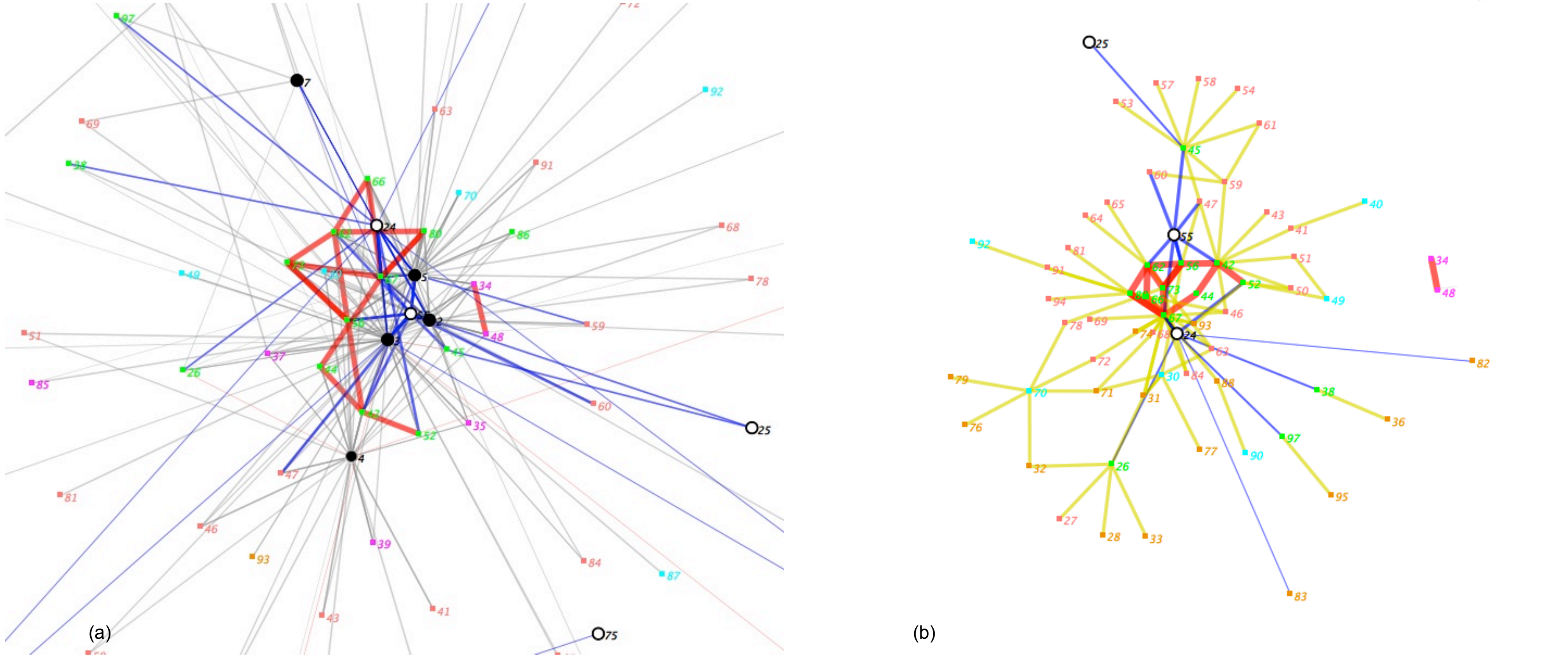


Figure 6-11 Episode 39 Cumulative Aggregate (a) Actor-Discourse and (b) Semantic Networks
These cumulative networks show two sets of collaborative productions: a large cluster of options elaborating the horizontal radiator proposal, and a pair of issues related to radiator deployment. The actor-discourse network shows five actors are engaged to varying degrees around two principal representations, a CAD model and a whiteboard sketch. Actor 4 initially reintroduced the horizontal radiator idea, which was extensively elaborated by actors 2, 3 and 5, who interacted strongly with the representations. (Actor 4 was remote and lacked visual or physical access to the representations.) The simplified disk radiator is inscribed in both the CAD and whiteboard representations. The semantic network shows the singular focus of interaction around the cluster of ideas for the horizontal radiator.
Actor nodes: **2**=ZD (team leader), **3**=HL (JPL customer), **4**=MW (agency power system designer), **5**=IE (mission architect), **7**=HJ (mechanical CAD operator); **24**=CAD model of lander w/new radiator, **25**=CAD model of original radiator, **55**=whiteboard drawing of radiator proposal (all representations). Discourse Nodes: **30**=surface area, **34**=radiator deployment?, **35**=fit in aeroshell?, **37**=cryobot clearance?, **39**=melting ice?, **42**=flat panels open up, **44**=insulate bottom/radiate up, **52**=location at height of power source, **67**=disk radiator.

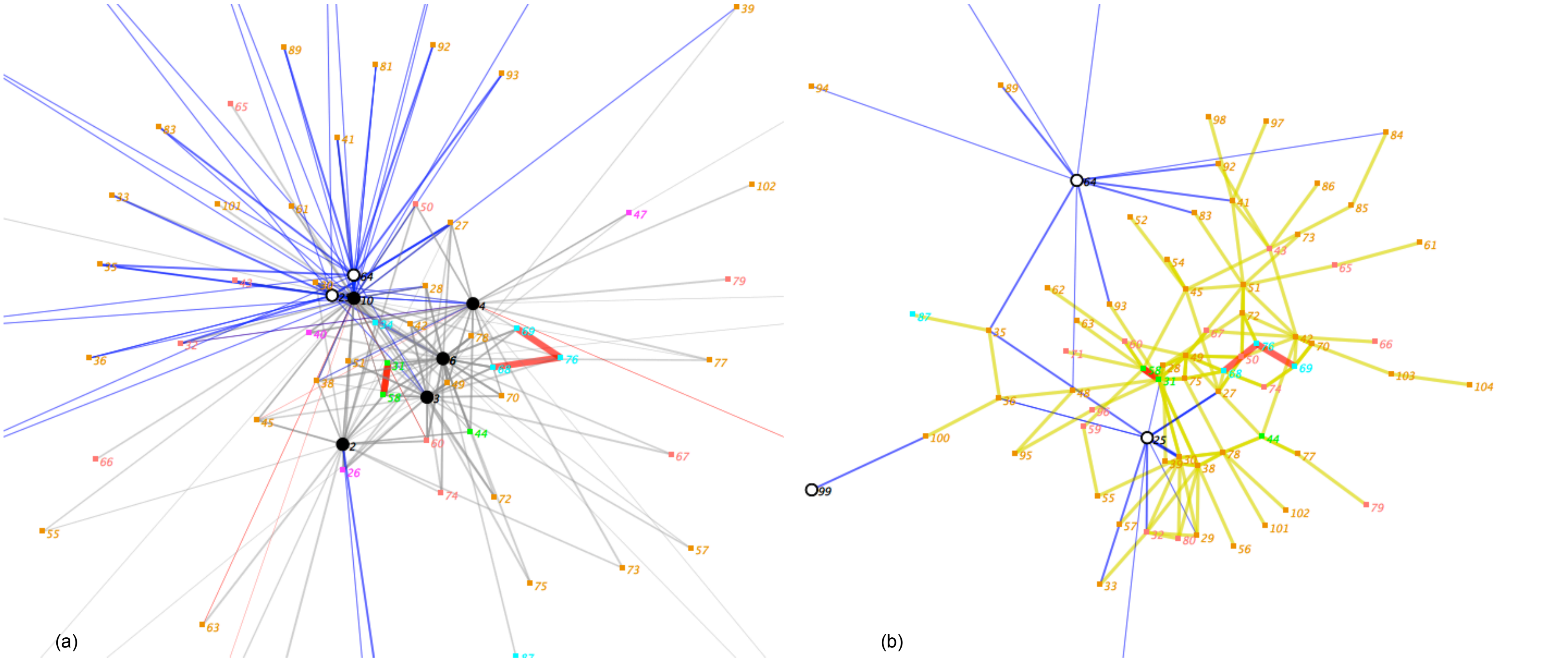


Figure 6-12 Episode 54 Cumulative Aggregate (a) Actor-Discourse and (b) Semantic Networks

LE's proximity to the two principal representations reflects the fact that much of this episode involved a narrated spreadsheet presentation with relatively little interaction. The principal outcome was a collaboratively-produced insight to establish different design limits for the two primary types of radiation (68+69+76); this arose as a tangent from the spreadsheet presentation, primarily involving HL, MW and EN. A less significant development was a proposed change to the enclosure (31+58). Neither collaborative production was inscribed in any shared representation. The fact that the locus of interaction had little to do with the spreadsheets is further reflected by the position of node 49—probably the most central in the semantic network—which appears between actors 3 and 6 in the actor-discourse network. Actor nodes: **2**=ZD (team leader), **3**=HL (JPL customer), **4**=MW, **6**=EN (agency power system designers), **10**=LE (avionics); **25, 64**=Excel spreadsheets, **99**=CAD model of instrument platform (all representations).

Discourse Nodes: **28**=radiation dose inside electronics enclosure, **31**=enclosure shielding, **34**=reduced mass, **38**=[material 2] enclosure, **42**=[type 1] radiation, **49**=[type 2] radiation from power source, **51**=total radiation dose, **58**=[change to enclosure], **68**=[type 2] radiation design limit, **69**=[type 1] radiation design limit, **76**=total radiation dose design limit

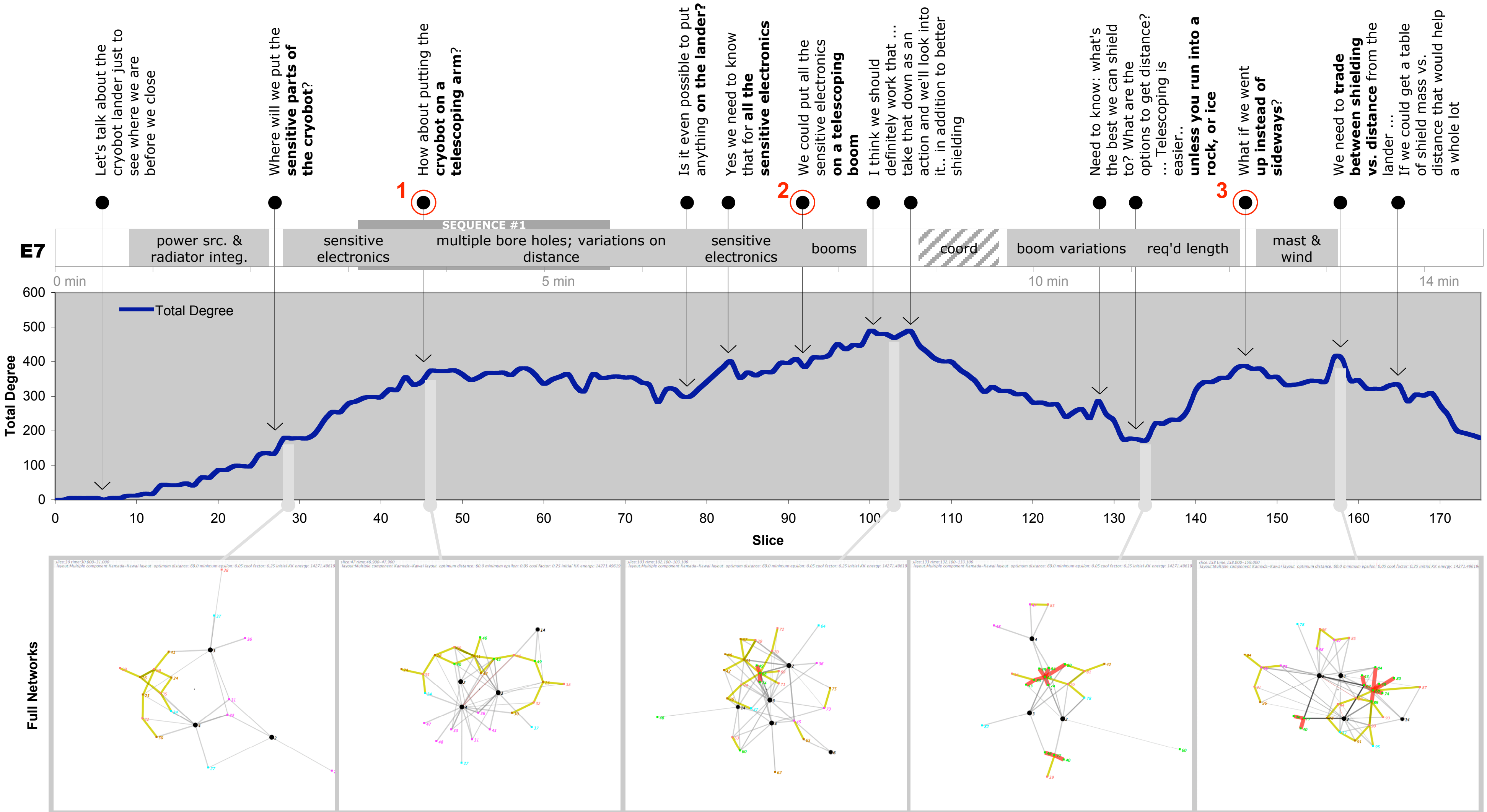


Figure 6-13 Episode 7: Timeline, Total Degree Graph and Selected Full Network Slices

Selected on the basis of positive indicators. An energetic brainstorming session in which the idea to place sensitive electronics on an elevated platform took shape. An initial proposal for the cryobot **(1)** was generalized to all sensitive electronics **(2)**. Finally, a vertical mast (vs. a horizontal boom) was proposed **(3)** to avoid potential obstacles.

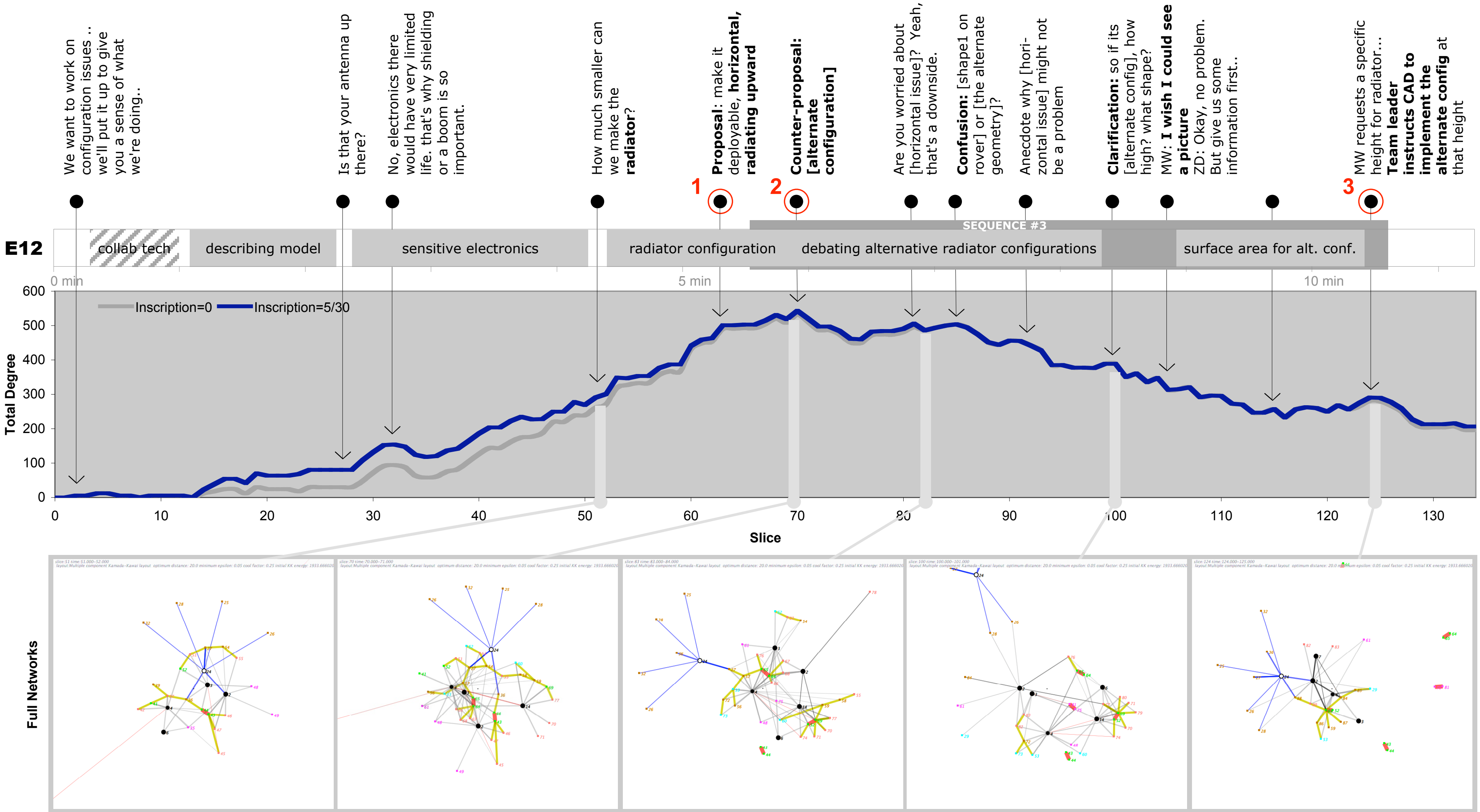


Figure 6-14 Episode 12: Timeline, Total Degree Graph and Selected Full Network Slices

Selected based on positive indicators. This episode involved two competing proposals for radiator geometry **(1 & 2)**. In the discussion, different experts sided with different proposals, without benefit of an effective shared representation. Consensus on the decision to go with the second proposal **(3)** unravelled in a later session.

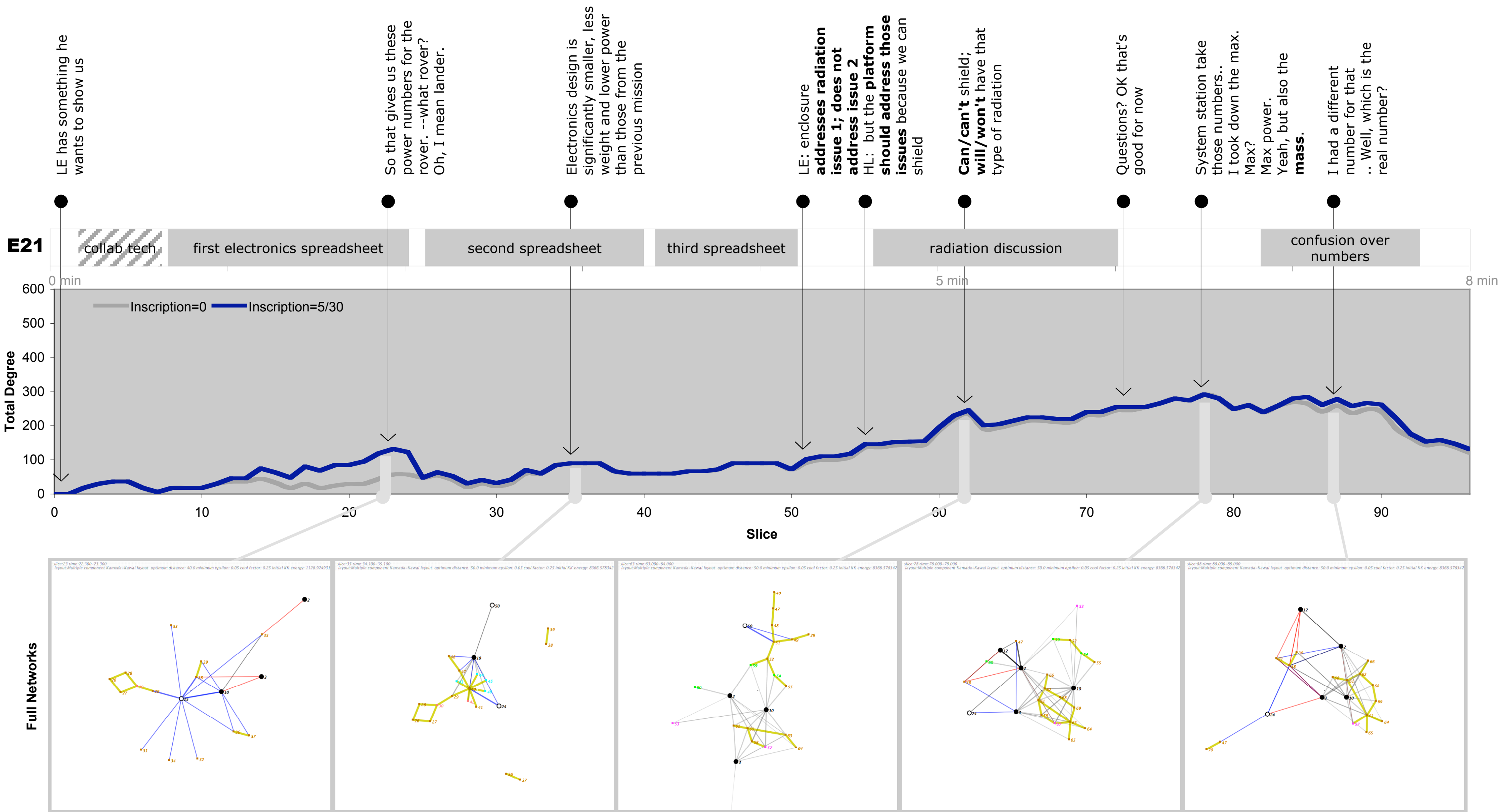


Figure 6-15 Episode 21: Timeline, Total Degree Graph and Selected Full Network Slices
Selected based on negative indicators. This episode began as a narrated spreadsheet presentation that developed into a discussion of radiation types and effects, during which participants disagreed about the nature and severity of the issue and appeared to have difficulty finding a common set of terms.

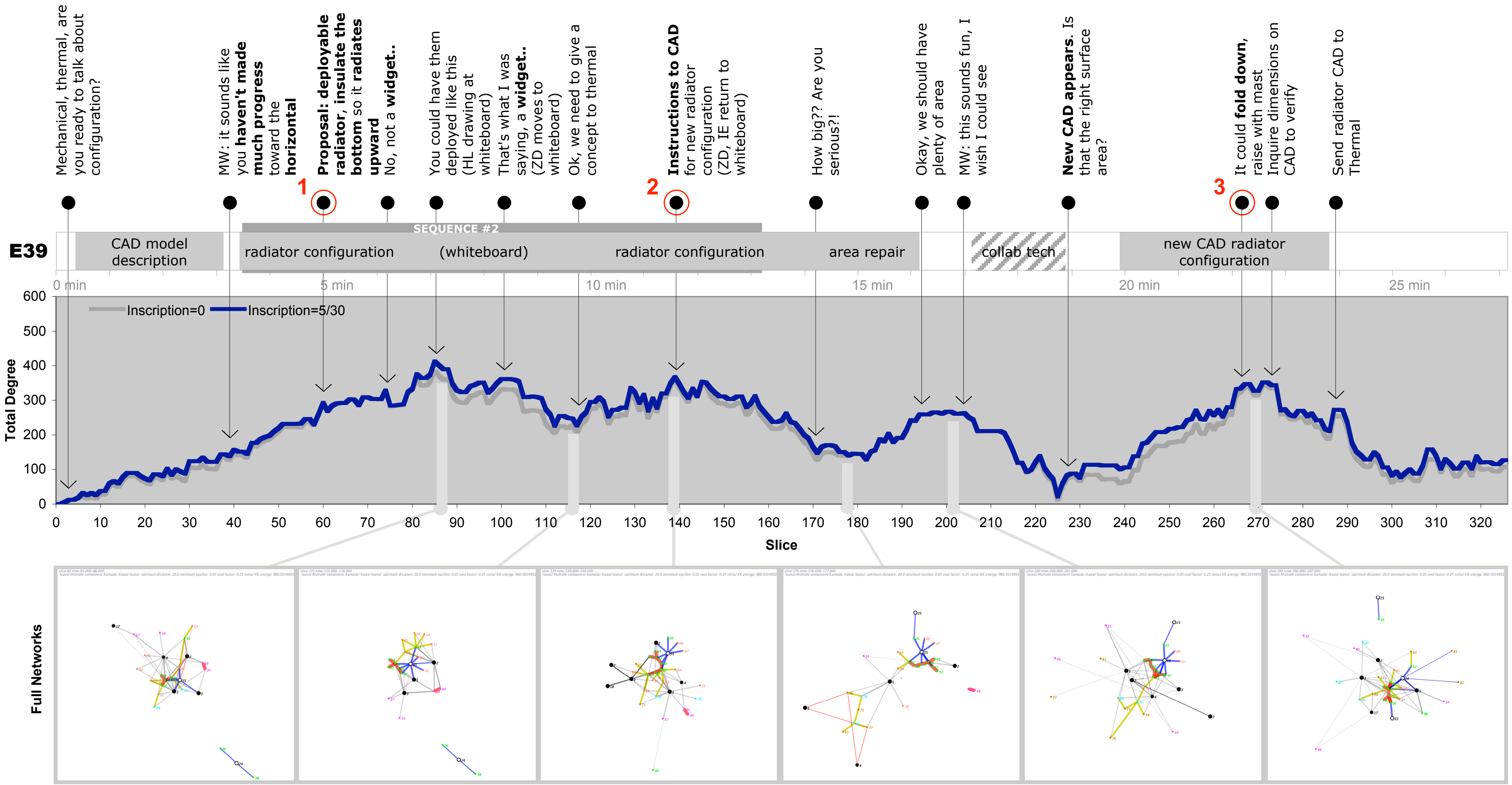


Figure 6-16 Episode 39: Timeline, Total Degree Graph and Selected Full Network Slices
Selected based on positive indicators. This episode saw the reintroduction of the horizontal radiator proposal (1), followed by an energetic period of whiteboard drawing during which a disagreement over the mechanical implementation was resolved. Instructions were issued to the CAD operator to implement the horizontal design (2). When the updated CAD representation was displayed, participants noticed the possibility of a different deployment means (3) than what they discussed at the whiteboard. The feasibility of this approach was confirmed by inquiring dimensions on the CAD model.

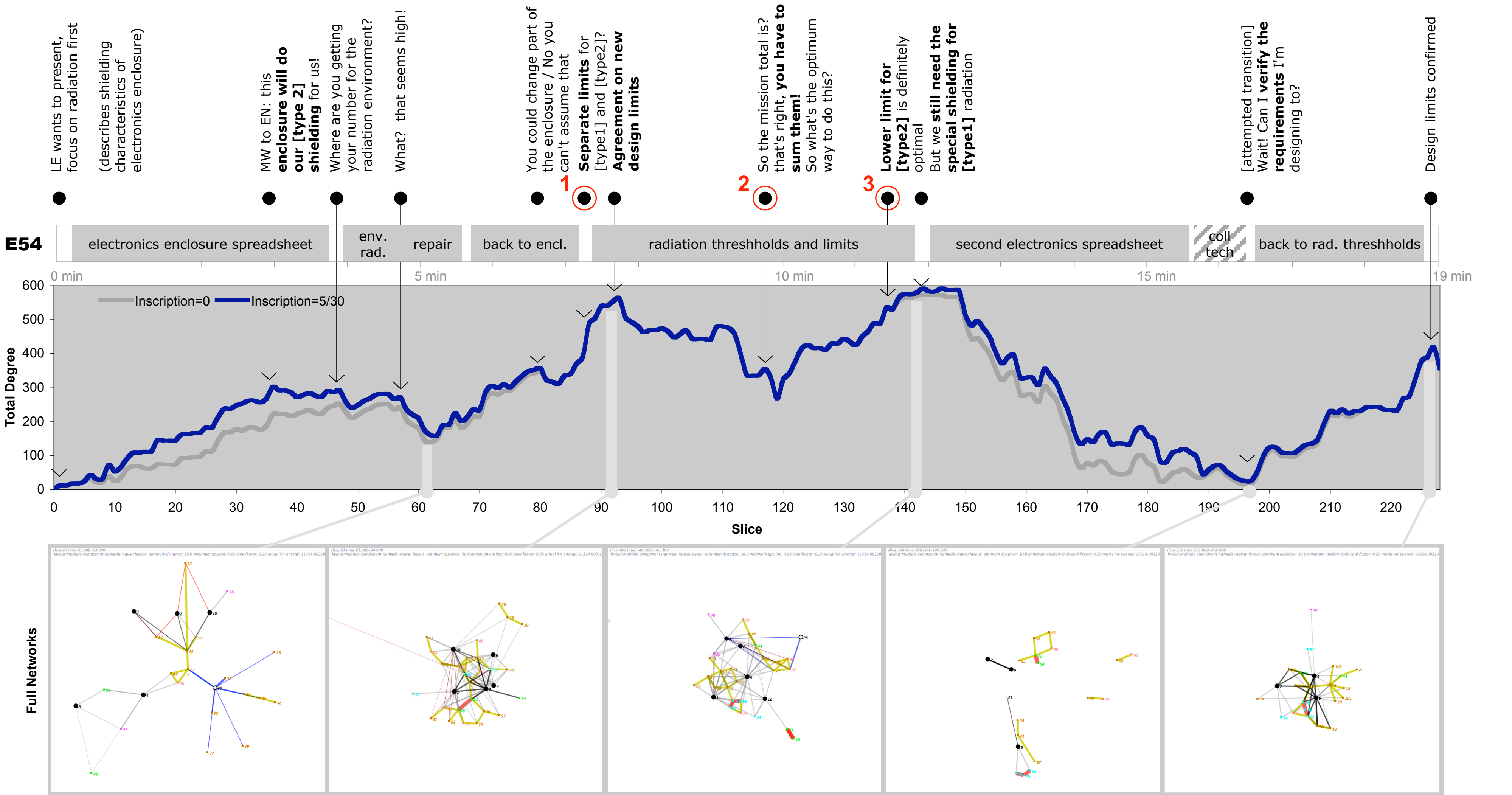


Figure 6-17 Episode 54: Timeline, Total Degree Graph and Selected Full Network Slices

Selection based on both positive and negative indicators. A narrated spreadsheet presentation sparked a discussion of radiation thresholds that led first to the recognition that separate thresholds were necessary for two types of radiation **(1)**. Following the realization these values would need to be summed **(2)**, a shielding approach was chosen **(3)**.

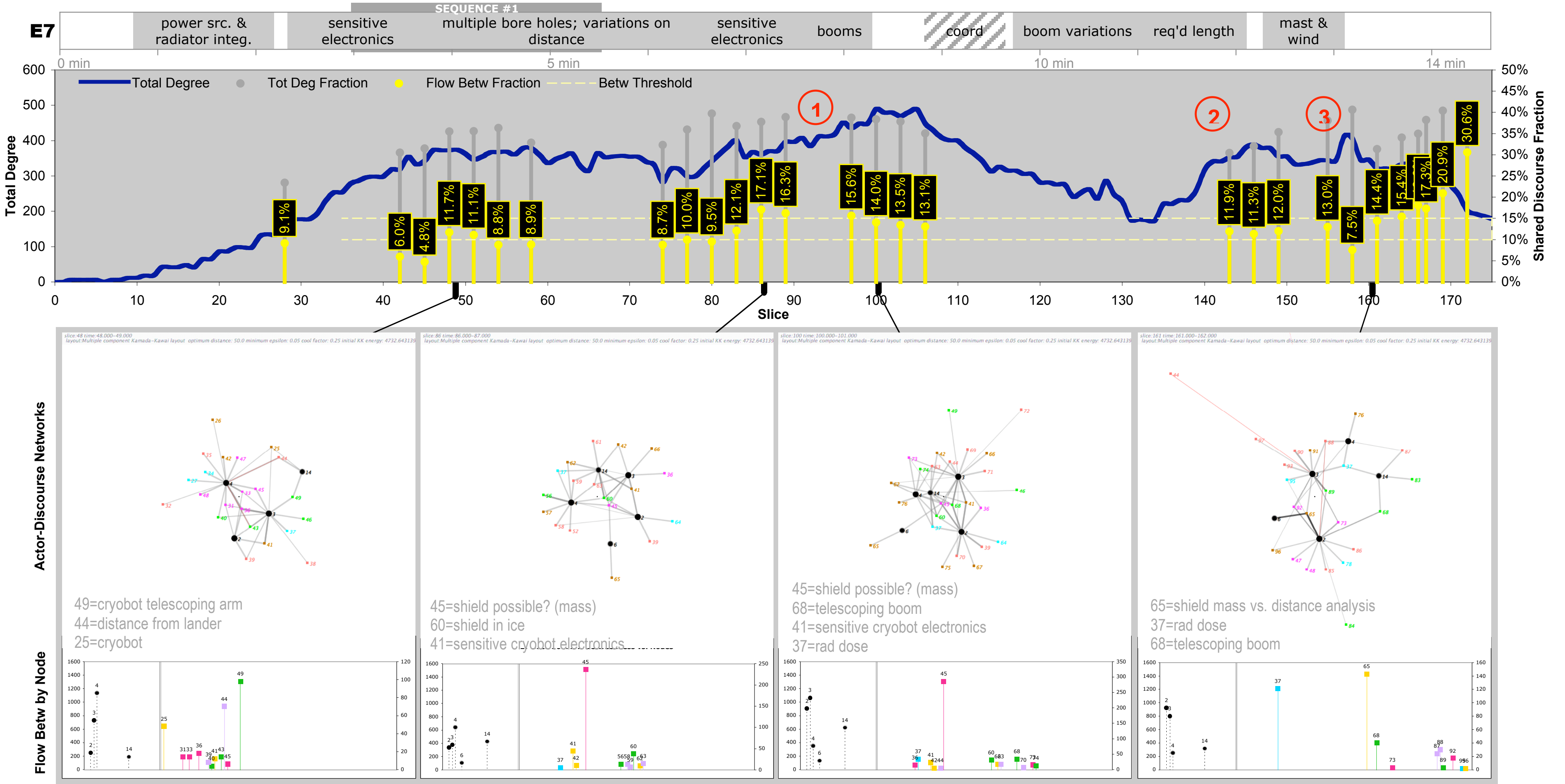


Figure 6-18 Episode 7: Timeline and Discourse Betweenness for Selected Actor-Discourse Network Slices

Peaks in total degree reflect strong overall alignment and high mutual engagement around the proposal to place sensitive electronics on a telescoping boom **(1)**. A peak with slightly lower alignment and mutual engagement is associated with the idea of going vertical rather than horizontal **(2)**, reflecting some disagreement over boom length and whether wind would be an issue. There is consensus on the information required to make a decision **(3)** and a commitment is obtained to perform the analysis. Flow betweenness values for individual nodes reflect the participation of actors and the discourse elements with high mutual engagement in selected network slices.

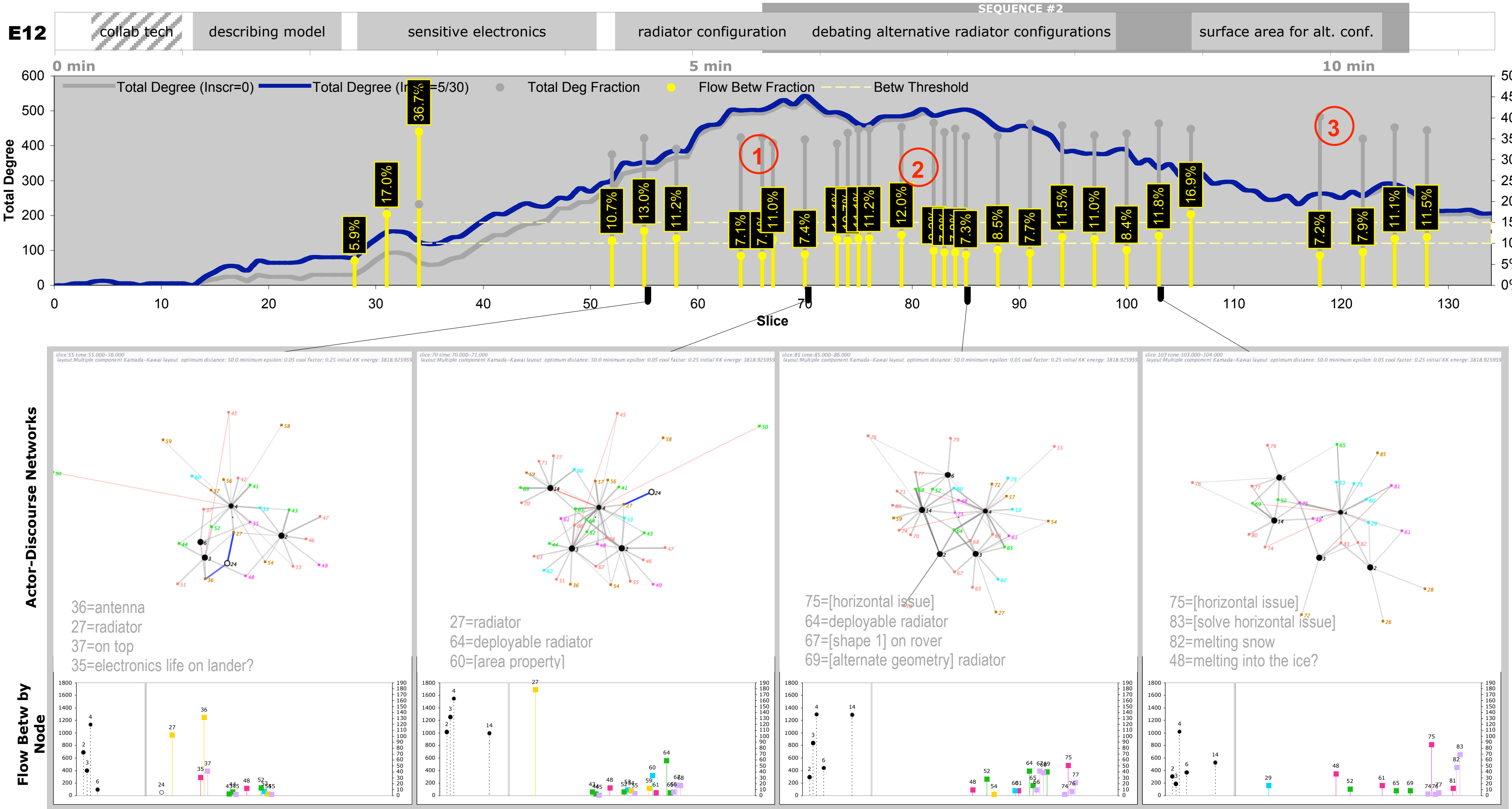


Figure 6-19 Episode 12: Timeline and Discourse Betweenness for Selected Actor-Discourse Network Slices

A peak in total degree corresponds to proposals for two alternate radiator configurations **(1)**. Relatively low discourse betweenness (the index for mutual engagement) reflects disagreement between experts over the merits of the two proposals in the ensuing debate, with some confusion resulting from the lack of an effective shared external representation **(2)**. Apparent consensus on the second proposal **(3)** unravelled in a subsequent session. Flow betweenness values for individual nodes reflect the participation of actors and the discourse elements with high mutual engagement in selected network slices.

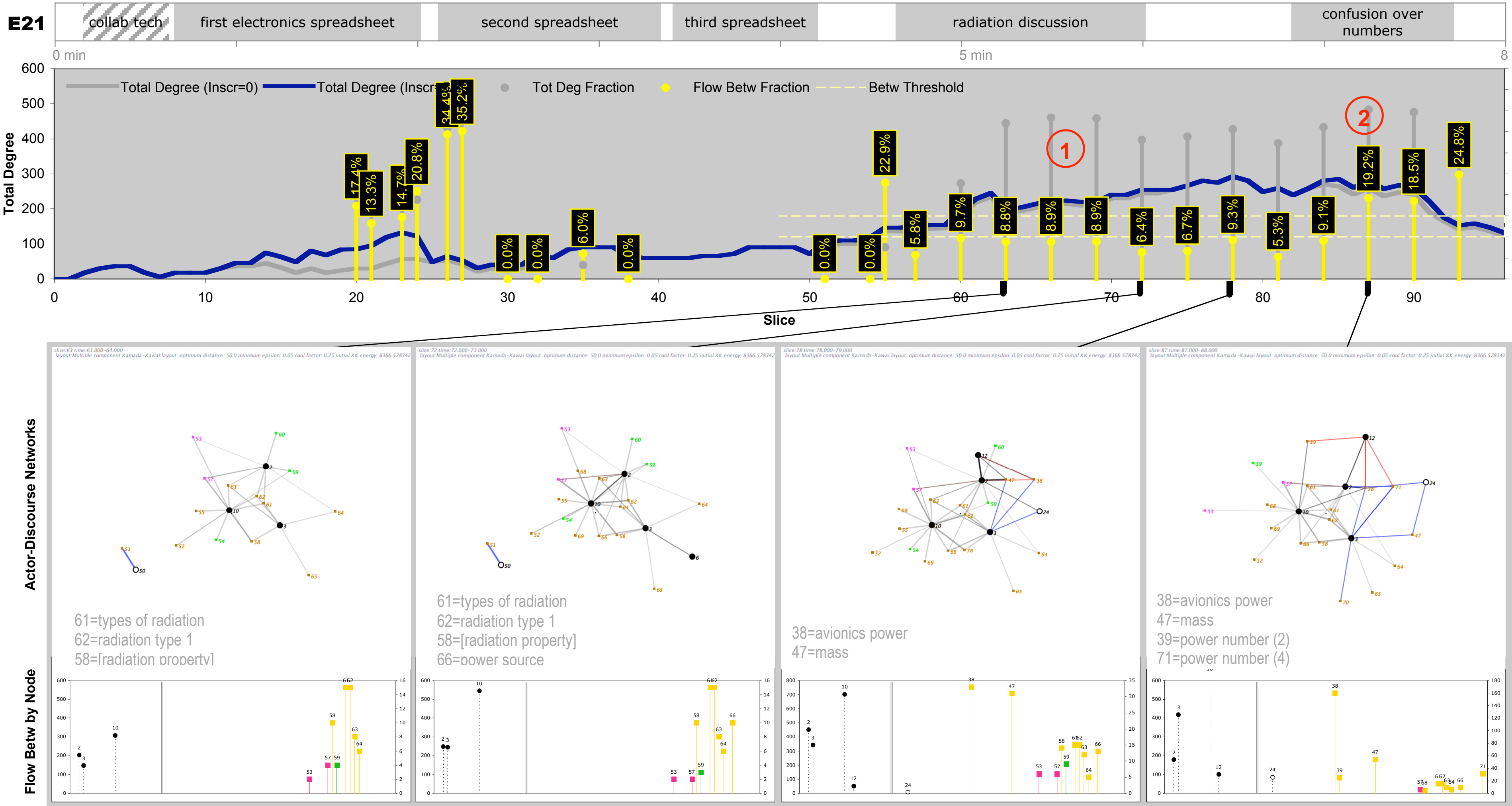


Figure 6-20 Episode 21: Timeline and Discourse Betweenness for Selected Actor-Discourse Network Slices

A narrated spreadsheet presentation evolved into a discussion of radiation types and their effects on sensitive electronics. Relatively low alignment and mutual engagement reflect disagreement over the nature of the issues and matters of fact during which participants appeared to have some difficulty using consistent terms **(1)**. High mutual engagement was finally achieved in repairing confusion over specific numbers to be recorded from a spreadsheet **(2)**. Flow betweenness values for individual nodes reflect the participation of actors and the discourse elements with high mutual engagement in selected network slices.

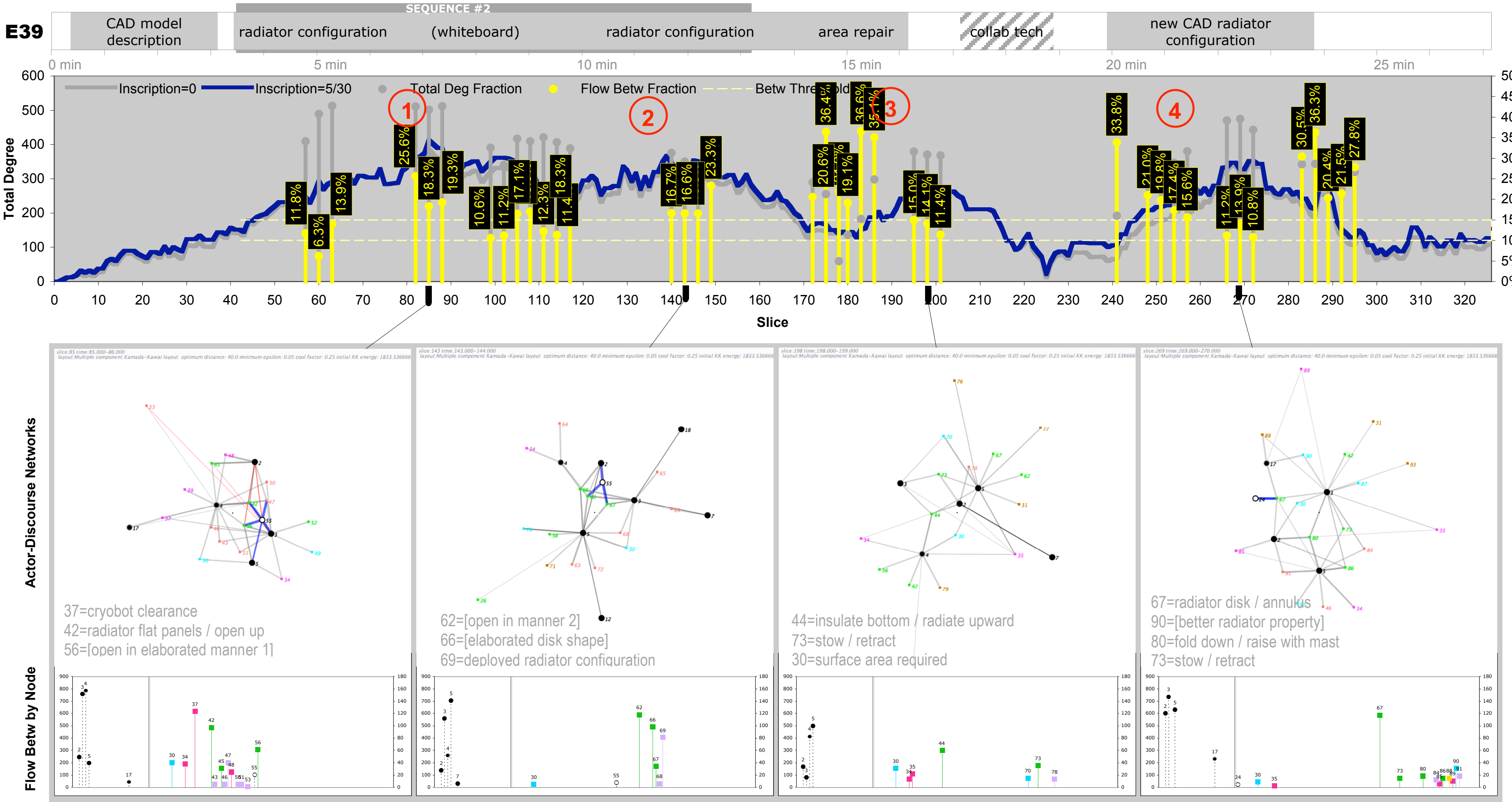


Figure 6-21 Episode 39: Timeline and Discourse Betweenness for Selected Actor-Discourse Network Slices

A reintroduced proposal for a horizontal radiator triggers an energetic period of whiteboard drawing **(1)** characterized by strong alignment and mutual engagement that also reflected when the CAD operator is instructed to implement the change **(2)**. Confusion over the surface area is resolved **(3)**, and a different deployment means is proposed once the updated CAD representation is displayed **(4)**. Flow betweenness values for individual nodes reflect the participation of actors and the discourse elements with high mutual engagement in selected network slices.

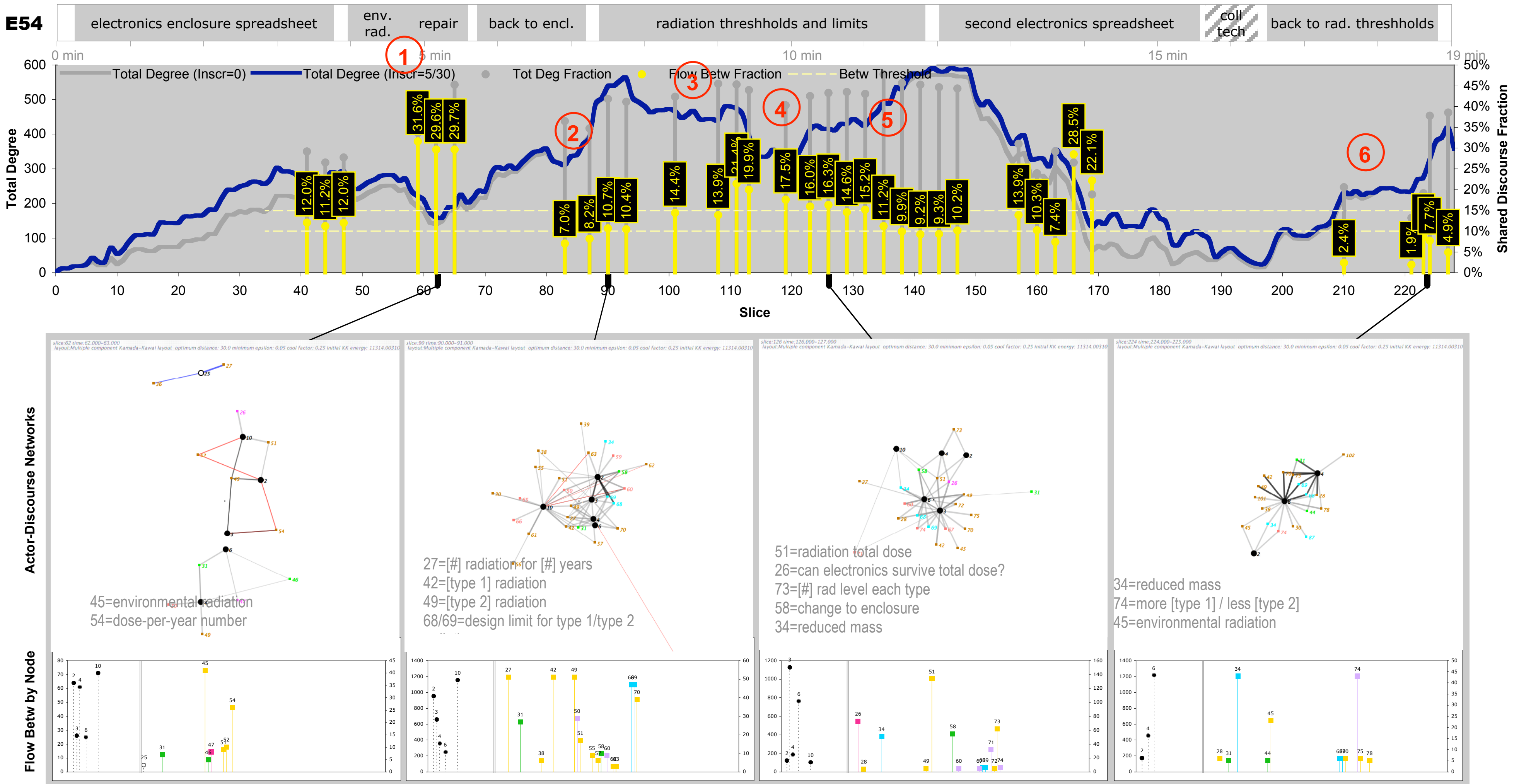


Figure 6-22 Episode 54: Timeline and Discourse Betweenness for Selected Actor-Discourse Network Slices

A narrated spreadsheet presentation on the electronics enclosure elicits repair over the level of environmental radiation on Mars **(1)**, followed by insight into the need for distinct thresholds for two types of radiation **(2 & 3)** and strong alignment on a new shielding approach **(4 & 5)**. This consensus is not fully shared by one expert, resulting in slightly lower mutual engagement **(2 & 5)**. Two experts reiterate the shield design direction with relatively less involvement of the others **(6)**. Flow betweenness values for individual nodes reflect the participation of actors and the discourse elements with high mutual engagement in selected network slices.

7. MACRO-ANALYTIC RESULTS

In the previous chapter, I presented the results of the micro-analysis I applied to several episodes specifically selected to offer the most informative contrasts. Through this analysis, I characterized productivity differences between these episodes in terms of four characteristics of network structure: overall alignment, mutual engagement, participation of the appropriate human actors and integration of shared representations. I also identified two additional factors on the basis of categorical coding: the development of design discourse and closure with an enhanced degree of specificity and commitment.

While I believe these factors are generally applicable to real-time design conversation, additional insight can be obtained by considering more of the data set. Analytically interesting events occurred during some episodes that were excluded from micro-analysis after refined parsing (described in Chapter 4) revealed them to have a complex internal structure or to be direct continuations of other episodes. It also appears that some phenomena involving shared representations, such as those manifest in major design changes and process breakdowns, inherently require consideration over longer time frames and across multiple episodes.

In this chapter I will review a number of these developments, making use of the macro-analytic threads as alternate units of analysis. In the following chapter I will synthesize results from both micro and macro-analyses to formulate conclusions about the constructive involvement of persistent shared representations in collaborative design over a range of time scales.

Threads

As complementary units of analysis, episodes and threads reflect different approaches to parsing interaction. While episodes are distinct and temporally-bounded periods of continuous interaction, threads draw together discrete instances based on thematic content relationships. Each thread tended to involve a consistent subset of the team (i.e. key participants plus certain domain experts), a recurring, high-level design issue, and the same or a closely-related set of representations. Thus, in addition to commonalities in thematic content, threads reflect regularized participation structures (one of the analytic foci identified by Jordan & Henderson, 1995).

All the major threads (discussed in Chapter 4) comprise parts of multiple episodes, and some episodes involved discussion that pertained to more than one thread—particularly when issues were "organically" interwoven and the impact of decisions cut across domains. Because threads are not mutually exclusive units, they cannot be compared quantitatively; rather, each is best seen as telling a particular story. Because they involve different problems and different representations, these stories convey insight into different facets of representational activity in real-time design. Over shorter time frames, these relate to shared reference and the resolution ambiguity, as well as the recognition of unanticipated opportunities and suggestions. Over longer time frames, they underscore the involvement of representations in capturing and holding progress, in drawing participants together and in fostering convergence between disparate viewpoints.

I proceed to describe analytically noteworthy developments on five threads:

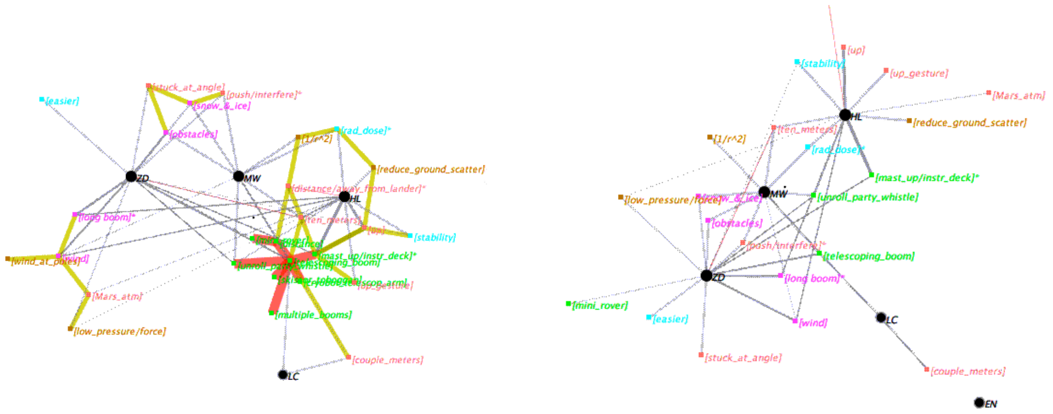
- Sensitive Electronics (persistent ambiguity in the absence of a shared representation, emergent insight from an unintended reading)
- Radiator Configuration (persistent ambiguity of reference, confusion and a disadvantaged remote participant, resolution of ambiguity through shared drawing, insight suggesting a refinement of the design)
- Start-up Sequence Timeline (stabilized complex and lengthy interaction, mismatch of representational tools to task at hand, process breakdown when results not effectively captured)
- Data Rate and Telecom Architecture (significant development triggered by collective failure to remember, task with cross-domain implications and overall schematization not supported by any tool)
- Landing Site Selection (non-convergence and impasse regarding an important decision, resolved with the aid of external experts and a cascade of credible representations)

Note that specific transcript extracts referred to below are contained in Appendix D. The landing site selection thread proved particularly interesting with regard to the roles of shared representations. I offer an account of the resolution of this thread, employing constructs from activity theory as well as the actor-discourse network formalization I have developed, that I hope usefully illustrates some aspects of how representations can help mediate a convergence of perspectives under such circumstances.

Sensitive Electronics

The sensitive electronics thread comprises recurring discussion of aspects of the design strategy to mitigate the deleterious effects of radiation from the compact high-power source (CHPS) on scientific instrumentation and sensitive electronics. It includes essentially all of Episode 7, which was subjected to micro-analysis and described in detail above. Considered over a time-scale longer than that of the micro-analysis, developments on this thread also illustrate a relatively minor but interesting instance of persistent ambiguity. The absence of a shared representation may have allowed two key participants to retain differing perspectives on the outcome of a discussion that were carried over into the next discussion several days later. More interestingly perhaps, this thread later witnessed an unintended (even mistaken) reading of a CAD representation that actually gave rise to a significant insight that was incorporated as a feature in the final design.

Episode 7 did not involve the use of any persistent shared representation; this was nonetheless a very productive discussion during which one of the most noteworthy features of the final design first emerged. Essentially, this involved the use of a mast or boom to introduce distance between sensitive electronics and the intense radiation environment near the CHPS. At the conclusion of Episode 7, the team leader ZD favoured the initial proposal for a horizontal boom, while the internal customer HL had become quite enthusiastic about a vertical mast.



(a) (b)

Figure 7-1 E7 Slice 156 (a) Full and (b) Actor-Discourse Networks
ZD shows greater alignment with horizontal boom option and wind-related issues, compared to HL who clearly favours a vertical mast as more stable.

These two key participants appear to have retained their differing ideas about which solution was most promising when discussion resumed, in Episode 12, even though their explicit conclusion called for a specific analysis to decide the issue. When recalling the idea in Episode 12, HL's clear elaboration of a vertical, a "tall mast", contrasts with ZD's immediate reassertion of the horizontal approach, a 4-5 m. boom "out to the side."[156] As it happened, the vertical approach eventually held sway without any explicit decision between the two options; the results obtained from EN's radiation model—presented graphically in a later session, clearly showed a more favourable radiation environment in the vertical direction, and ZD never reintroduced the wind issue.

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[156] Transcript extracts of the exchanges cited are included in Appendix D. This exchange is extract D-1.

The later development (during Episode 18) involved a shared CAD model that, by this time, had been created to portray the vertical mast/platform idea. The CAD operator, responding to a request for an update, described his progress in positioning volumes for different electronic subsystems on a platform in the model, in order to decide what size was necessary. Upon seeing the CAD in this transitional state, HL appears to have recognized the possibility of a physical rearrangement that would make significantly more effective utilization of the shielding. Had it been subjected to micro-analysis, this would have been coded as an instance of HL's "noticing" the possibility of an advantageous design change even though that particular configuration was not inscribed in the representation. Conceiving of both HL and the representation as actors, it appears that the representation *suggested* an opportunity to HL, who then voiced the idea to the group. The advantageous rearrangement garnered enthusiastic support from ZD, was further developed in subsequent episodes and clearly embodied in the final design.[157] [158]

Radiator Configuration

This thread comprises recurring discussion regarding how best to accommodate a radiator with the necessary surface area within the volume constraints presented by the spacecraft's aeroshell. In addition to mechanical aspects of deployment, a key consideration was a configuration that would minimize the possibility of waste heat from the operation of the CHPS melting the Martian ice beneath the spacecraft. This thread, which includes the majority of Episodes 12 and 39, and parts of several others, saw a proposal for a horizontal radiator made twice by one expert before other alternatives were rejected and it was finally adopted the third time around in Episode 39. At several key points, in the absence of an effective shared representation, imagistic language provided by one or another of the participants seemed to have decisively shaped the reception of different proposals. Once the horizontal proposal was finally accepted, an accurately-scaled rendition in CAD appears to have suggested— to two participants independently—the possibility of an alternate deployment approach that was adopted and embodied in the final design.

The horizontal radiator was first proposed in Episode 12 by an off-site expert, MW, participating by audio-only teleconference. The team leader, ZD responded by voicing some confusion; before MW could reply, the on-site agency customer HL volunteered a description referring to an unrelated rover design the entire team had seen displayed during an introductory session. During the earlier session, a CAD model with prominent solar

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[157] See extract D-2 in Appendix D.

[158] Casual observations of the CAD model also resulted in identification of redundant electronics boxes in Episodes 57, 59 and 61. In these cases, participants' suggestions corresponded to actual features present in CAD.

panels from an unrelated design study was briefly displayed. One of the agency participants mistakenly interpreted the panels as a deployable thermal radiator—a suggestion greeted with humour by other members of the group.[159]) In the absence of any contradiction by MW or a more specific visual representation, this formal description ("[shape 1]" in excerpt D-3, Appendix D) appears to have taken hold.[160]

As we saw in the micro-analysis of Episode 12, LC almost immediately proposed an alternative configuration (excerpts D-3 & D-4) and a debate over the relative merits ensued, with LC's counter-proposal garnering the support of another remote expert EN. MW's request for an image to clarify his understanding was deflected and he was entrained in a discussion of the required area (excerpt D-5). Instructions were eventually issued by ZD to implement the alternative configuration. The fact that MW had lost track at this point of precisely what the alternative proposal embodied is evident, later, in his perfunctory response when the updated CAD model is unequivocally described to him in Episode 18: "so, *that's* dumb." When MW proposes the horizontal idea for a third time, in Episode 39 (excerpt D-6), he is prepared to offer an elaborate verbal description of his own. Referring to a different familiar object with no relationship either to the [shape 1] of the initial description or the familiar object of LC's alternate proposal, MW details the form he has in mind and how it will work.[161] This time, as we saw in the microanalysis of Episode 39, the proposal is enthusiastically accepted. When it appears, the updated CAD model seems to suggest an alternate means of deployment to both HL and IE, who make similar proposals independently.[162] All key participants voice strong support for the approach (excerpts D-7 & D-8), with MW saying, "I'm really sorry I don't have the communications set up so I can watch you... this sounds like a lot of fun."

In the dynamic exchanges that comprise this thread, remote participants attempt to remedy confusion and ambiguity in the various verbal proposals by using imagistic language and making recourse to analogies with familiar objects. MW's horizontal proposal appears to have been saddled early on with a formal description that others may have found awkward; in any case structural and functional issues were suggested. Over time, MW is able to refute

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[159] This session occurred prior to video data collection

[160] Specific descriptions of alternatives to the final, published design were redacted by a JPL reviewer on the basis of export control concerns. In transcripts and network diagrams I use substitute descriptions enclosed in [square brackets].

[161] The fact that MW refers to a PowerPoint image he has prepared indicates he has devoted significant energy to be sure he can adequately convey his idea to the others.

[162] In Episode 39, upon seeing the disk radiator in CAD, HL mentions the possibility of folding it down with reference to a third familiar object (transcript para. 3558). Later, approaching the screen and gesturing over the CAD model, IE elaborates the same fold-down idea (transcript para. 3624), apparently having not heard HL's earlier verbal proposal.

most of these issues with reference to physical properties and functional differences between thermal radiators and solar panels (exemplifying the techno-scientific "object-world" discourse described by Bucciarelli (1994)). However the most significant difference in the actual content of his final, successful proposal, compared to the two previous occasions, is a compact and clear formal description with an inherent structural logic that had been absent in the initial description.[163]

By contrast, the physically co-present participants were able to rely on shared drawing and animating gestures to convey and elaborate their proposals. When the accurately-scaled CAD representation appeared, participants who could see it were able to mentally animate it, with the result that an alternative deployment means became obviously preferable. The details of this approach are worked out and implemented in CAD in relatively short order.

Start-up Sequence Timeline

This thread comprises recurrent discussion of the sequence of events and tasks to be performed by the spacecraft, after landing on Mars and leading up to the activation of the CHPS. With regard to the use of shared representations, this thread is notable for the way a simple list provided an effective scaffold for an extended period of interaction. However, the absence of a shared representation to hold the results of this discussion led to a breakdown and substantial loss of work between sessions.

A key constraint in Mars exploratory missions is usually the availability of sufficient power (from solar cells and batteries) to allow the spacecraft to position itself, take scientific measurements and maintain its own temperature within operating limits. As an essential step in determining power requirements, the team leader ZD initiated a discussion to construct a timeline. This led to an unusually long and complex interaction of one hour and five minutes, comprising Episodes 17, 18 and 19.[164] In addition to power requirements, this conversation encompassed tangential topics as diverse as the rearrangement of components on the elevated platform, the acquisition of photographic images, possible chemical effects of radiation on materials, and rejection of one radiator geometry in favour of another.

A pre-existing task list, created by the agency developers of the CHPS, provided a scaffold for much of the discussion in Episodes 18 and 19. Visual availability of this list on a shared

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[163] It is also true that, at this point, other participants had worked through two alternatives to the horizontal approach and found them lacking. However, no mention of structural issues was made in response to MW's third proposal, unlike on the two previous occasions.

[164] As discussed in Chapter 4 above, the initial parsing of episodes was revisited using Clark's (1996) typology of conversational sub-projects. The transitions that initiated Episodes 18 and 19 were seen to be sub-project returns to the project initiated for Episode 17.

screen oriented participants toward the shared purpose of the discussion and facilitated frequent returns from these disparate topics to the main thread (as evident in the parsing diagram for these episodes, in Chapter 4 and Appendix A). Having instructed one participant to take notes, the team leader assumed the results of this conversation were being captured in a new timeline; unfortunately, this was not the case. Moreover, because no new timeline was ever effectively shared, the team did not became aware of this fact until it was too late.

The story of this particular interaction is more complex than one participant's failure to carry out an assignment. Presumably, the team leader ZD intended that a new timeline would be shared and assumed this would be most easily done electronically. The difficulty of the task—and the resistance offered by the tools the participant was asked to use, were all too easy for the others to overlook. When ZD instructs team member KR to create a timeline using PowerPoint, early in Episode 17, he switches KR's computer to a shared screen; a slide eventually appears with a horizontal band and several numbered divisions. Shortly after the timeline discussion begins, KR asks if the scale is appropriate and is advised to give himself "more scale on days." KR begins to remove information from the slide—presumably to recreate it with a different scale.

Before any new timeline is completed however, KR is taken off the shared screen to allow the newly-located agency task list to be displayed. As the discussion continues, KR is again advised to change his scale—this time from days to hours. Given the assignment of capturing the discussion in real time, and evidently struggling, KR is visible in the background switching to paper. When asked to read back what he has captured, KR approaches the speakerphone with a sheaf of paper notes from which he reads back haphazardly. Subsequent difficulty with the collaboration technology prevents KR from sharing any form of electronic timeline he might have managed to prepare.

Three days later, during the next session, when a review of the power budget revealed missing information, it was discovered that key information from the start-up sequence timeline discussion had not been captured and/or had not been relayed to the power engineer, LA. As ZD expresses surprised consternation, "we put that all together, didn't we?" HL chimes in, "yeah, well, we sure talked about it."[165] KR, the team member given this task in the previous session, was not present that day. HY, asked to capture the info when trouble became apparent late in the game, had only written down day-by-day totals and could not retrieve the specific information.

[165] Session S-041502, Episode 41, transcript paras. 4562-4564.

Let us try to imagine how difficult it would be to use either PowerPoint or Excel to track such a conversation. Any new timeline would require that actions be tabulated in order, with the proper duration and appropriate units to enable individual power requirements to be totalled. The actual conversation moved fluidly back and forth between the preliminary list and detailed (sometimes tangential) discussion of various tasks and activities. The temporal scale of these activities ranged from days to half-hours. There were frequent decisions to renumber and reorder activities, moving them from one day to another. In the midst of all this, KR was expected to keep track of specific power numbers mentioned by different experts. Both PowerPoint and Excel are strongly schematized to facilitate particular operations.[166] Frequent changes to essential parameters demanded by these tools would make them cumbersome—if not actively hostile to the demands of the timeline task.

It is probable that KR was asked to use PowerPoint or Excel because these applications are ubiquitous, and an electronic document could be more readily displayed and shared. It is easy to see, however, how the resistance these tools would offer might prompt someone acting under time pressure to jettison them and attempt to keep up with pencil and paper. Once KR's note taking was removed from the shared display, it was easy for others simply to assume that the details of their conversation were being captured. KR struggled as the group was relieved of any collective responsibility to ensure that this important work was preserved, or that the pace of conversation wasn't exceeding his—or anyone's capacity to keep up.

This thread highlights the importance of a match between the inherent schematization of a tool and the demands of the task it is intended to facilitate that should be instructive to the developers of tools to support this type of collaboration. The problem in this case involved the difficulty of tracking task specifics, precedence and sequence over a dynamic range of time scales.[167] On a more collective level, this thread also illustrates the effect shared representations can have to instil a *shared* sense of responsibility for the successful completion of such a task, which may be an equally important consideration.

[166] Excel has a strong row-column schematization to facilitate the repetitive application of mathematical operations to tabular patterns of data in spreadsheets. PowerPoint is strongly schematized according to a particular paradigm of presentation-making. As Tufte (2003) describes, this enforces a relentless chunking of information onto lines and slides and is positively "medieval in its preoccupation with hierarchical distinctions." (p. 10)

[167] Useful models for solutions might be found, for example, in project management software (for dynamic and readily modifiable representations of task sequence and precedence relationships) and sound or video editing software (which have developed extremely flexible and expandable timelines).

Data Rate and Telecom Architecture

This thread includes discussions of the rate and volume of science data to be collected and the telecommunications strategy for relaying that data back to Earth. A significant development—the adoption of a new telecommunication system—was triggered by the team's collective failure to remember an agreed-upon number from one session to the next. Though the outcome was positive for the mission, the dynamics were somewhat similar to those seen in the start-up timeline thread. Specifically, the absence of a persistent shared representation for this task left the team vulnerable to the vagaries of individuals' memories and key participants' attendance of both sessions (which, in this instance, proved unreliable). This is thread also illustrates an opportunity in which a shared tool, with a schematization consistent with the nature of the task, might have improved the team's collective performance.

As the landing site selection was finalized, it became clear that the constraints of telecommunication links to the polar site were severely limiting the amount of data that could be sent back to Earth. The science representative agreed to formulate a scaled-back data collection plan. A specific data collection constraint was discussed and agreed upon in one session; however, the data collection protocol circulated by the cryobot expert (GG) prior to the next session inexplicably did not take this agreement into account.[168] The situation was complicated by a lower than usual overlap in attendance between the two sessions; several key participants including the team leader were absent, and those in attendance evidently did not remember the agreement to reduce the volume of data collected.

In the next session four days later (Episode 62), the telecom chair pointed out the glaring mismatch between the amount of science data and the capacity of the telecommunications channel, emphasizing at one point, "there's not a prayer of getting, you know, 5% of that back."[169] At this experts' suggestion, the team considered a different technology which, though it required a more complex antenna, afforded much higher bandwidth during the limited transmission windows. In an extremely interactive period (Episodes 69&70) after the team leader returned, the old antenna was jettisoned in favour of a new one with a greatly improved data rate. Despite the team leader's chagrin at the failure of the system to hold key information (the previously-agreed constraint), no one was disappointed in the new telecommunications architecture since the mission objectives were clearly better served.

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[168] The cryobot scientists' agreement to scaled-back data collection occurred in Episode 60, near the conclusion of the 04-22-02 session. The revised plan was circulated by Email prior to the following session on 04-26-02.
[169] S-042602, Episode 69, transcript para. 3464.

Why was this proposal not made earlier? Participants' retrospective accounts differ; the proposal clearly depended upon specific knowledge possessed by the telecom expert who, for whatever reason, had not been prompted to mention or seriously consider this option before. Equally clearly, real-time design places competing demands on participants' attention such that vagaries of awareness will always be an issue. This thread presents an opportunity for a shared representation to better support the collective performance of human actors. In addition to mutual visibility and awareness, this again raises issues of a task-appropriate schematization.

Determining data rate and telecommunications architecture involves a complex, distributed calculation that, overall, can be seen as an end-to-end flow problem. Discrete subsystems are essentially links in a chain, from the point of data collection through processing, storage, and transmission in stages back to Earth. Each domain has its own particular representations, and only a single number is routinely shared: the data volume. In real-time interaction however, tradeoffs between domains require continuous recalculation on the basis of domain-specific parameters and assumptions that are largely invisible to the group—except when they are verbalized in periodic flurries of activity. The overall data collection-storage-telecom chain has no *persistent* representation—consistent with the flow nature of the problem—that would allow simultaneous, cross-domain awareness of specific limitations at any point. This, again, is indicative of a direction for tool development to better support this type of collaborative activity. As this research was underway, the team leader reported that JPL was developing just such a tool to visualize the end-to-end telecommunications flow for use in real-time design sessions.

Landing Site Selection

This thread comprises discussions leading to the determination of a specific landing site, launch and arrival dates for the cryobot lander mission. These decisions have a decisive impact a number of other important constraints, including the allowable spacecraft mass, availability of solar energy and telecommunications options. Accordingly, the issue was taken up early on. Even so, this thread was marked by a prolonged period of non-convergence during which two key participants, team leader ZD and internal customer HL, had difficulty reconciling their positions and the landing site oscillated from north, to south and back again.

In this instance, both ZD and HL made recourse to credible evidence and marshalled plausible arguments. Neither rejected the other's position entirely, but both gave weight to differing and seemingly incompatible evidence that made agreement elusive. A convergence was ultimately reached, involving a confluence of scientific evidence, external expertise and the recollection of a prior study. As the pieces fell into place, they were accompanied by a series of credible and persuasive representations that anchored—and ultimately reconciled the two participants' distinct concerns. I will briefly describe these concerns before relating the events and associated representations. Finally, in resolving events on this thread, I will reintroduce aspects of activity theory that appear to be helpful.

From a scientific standpoint, thick ice is preferable for a cryobot mission since it allows more of Mars' climactic history to be reconstructed. The capability of the CHPS to generate large amounts of power make it a good fit for such a mission. Orbital observations have revealed Mars to have ice caps at both poles. The southern one shows substantial seasonal fluctuation and is probably composed largely of carbon dioxide. The northern one appears to be significantly thicker, more stable, and to consist substantially of water ice. The possibility of obtaining evidence of past life on Mars is also an overall priority that favours water ice over frozen carbon dioxide.

Key constraints for any interplanetary mission include orbital and trajectory considerations. The relative positions of Earth and Mars in their respective orbits dictate periodic opportunities during which transit between the two planets is energetically favourable—that is, missions can be accomplished with a reasonable payload mass on top of the propellant required. These opportunities, known as "launch windows" occur roughly every two years. For each launch window, the orientation of the planet means different latitudes of Mars' surface are more easily reached; some latitudes may be effectively inaccessible because of the prohibitive amount of energy required to get there.

Discussion of an appropriate landing site began with the first session, during Episode 5. Over the course of several episodes and sessions an impasse was reached (recounted in transcript excerpts D-9 to D-11). ZD favouring a southern latitude based on orbital considerations, and HL becoming adamant that a northern polar latitude was necessary to achieve the mission's scientific objectives. While HL refers to published articles and word coming from climate experts, ZD relies on graphical solutions, known as "porkchops," routinely employed at JPL as proxies for complex orbital calculations. (An example porkchop is shown in Figure 7-2.) HL emphatically states at one point, "there's no point in sending a multi-year drilling mission if it [the ice] is only a few metres deep." In response, pointing to negative numbers on the porkchop diagrams, ZD is equally emphatic: "that means negative is south, and if it's south, you really can not get to the north."[170]

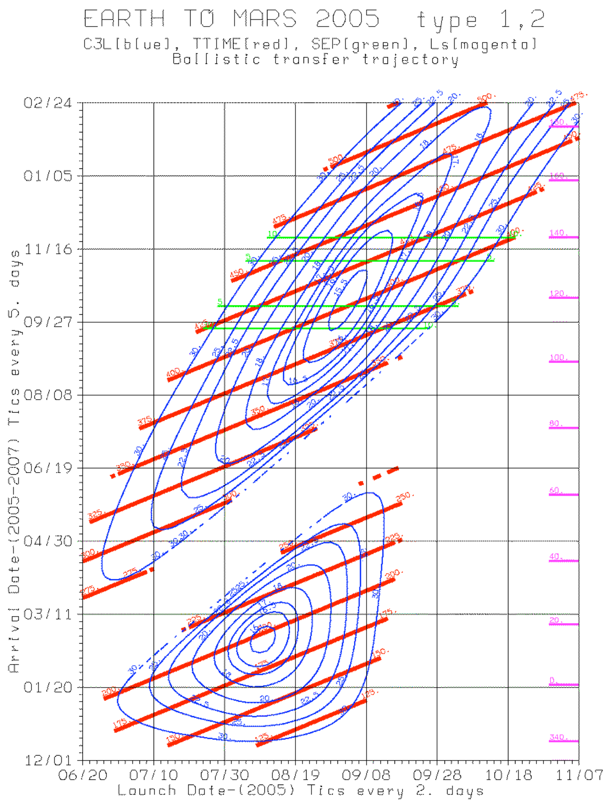

Figure 7-2 Example Porkchop Plot for 2005
This plot shows launch "windows", arrival dates and accessible latitudes for ballistic trajectories. It is representative of, but is not the actual chart used by the team in this study. Source: JPL "'Porkchop' is the First Menu Item on a Trip to Mars." <http://mars.jpl.nasa.gov/spotlight/porkchopAll.html>

Whereas ZD seems to take the porkchops as definitive evidence, HL is convinced they do not preclude all possibilities; in any case his determination to go north is buttressed by input from an expert and a journal article he obtains, describing the presence of thick, water ice only at the northern pole. To support his position, he directs ZD's attention to illustrations in a hard copy of a journal article (shown in Figure 7-3

[170] S-041502, Episode 28, transcript paras. 623 and 773 respectively. See excerpt D-11.

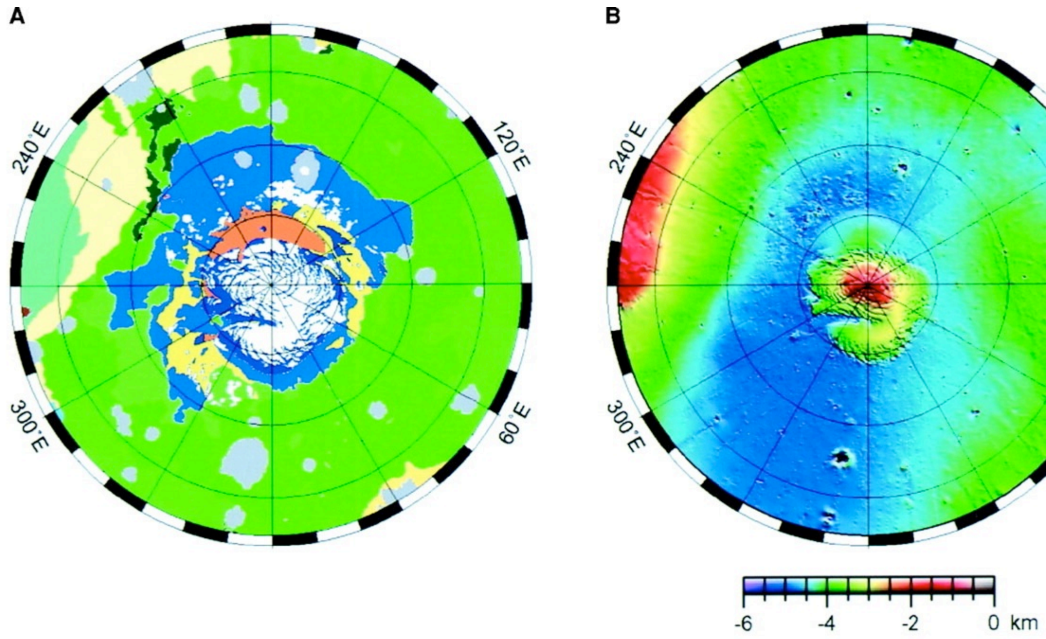

Figure 7-3 HL's Journal Article Illustrations
"Polar Stereographic Projections from 55˚North to the Martian North Pole" (A) classification of surface geology, (B) indication of surface elevation. Source: Science Magazine, Zuber et al. 1998. <http://www.sciencemag.org/cgi/content/full/282/5396/2053>

A shift begins in Episode 29, when an external orbital expert, contacted by HL—and evidently respected by ZD as well, enters the session. This expert is able to interpret the porkchop diagrams to suggest that a high northern latitude might be reached at a particular point in time with a more complex mid-course manoeuvre—a possibility he promises to verify with his own more sophisticated analysis tools (see excerpt D-12).[171]

At this point, apparently prompted by another illustration in HL's journal article, ZD recalls an earlier study that also selected a high northern site and instructs a team member to retrieve the study report.[172] When an electronic image from this report is displayed on a shared screen, ZD's tone changes from provisionally favourable to quite supportive of the idea of a northern polar site. The image is clearly based on the same data as the journal hardcopy to which HL had been referring; it identifies a specific latitude and longitude and bears a landing "ellipse"—a graphical indication that an orbital calculation has been performed.

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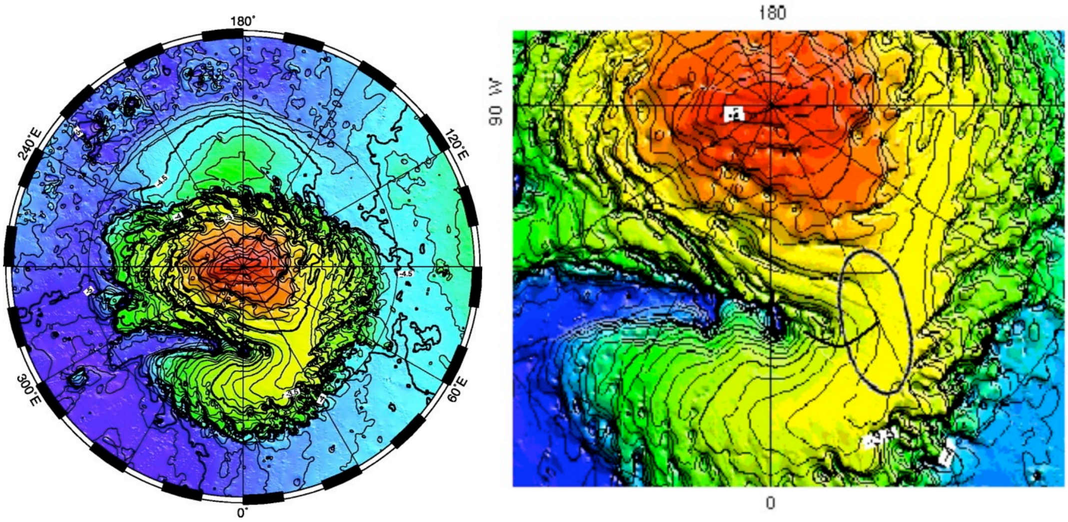
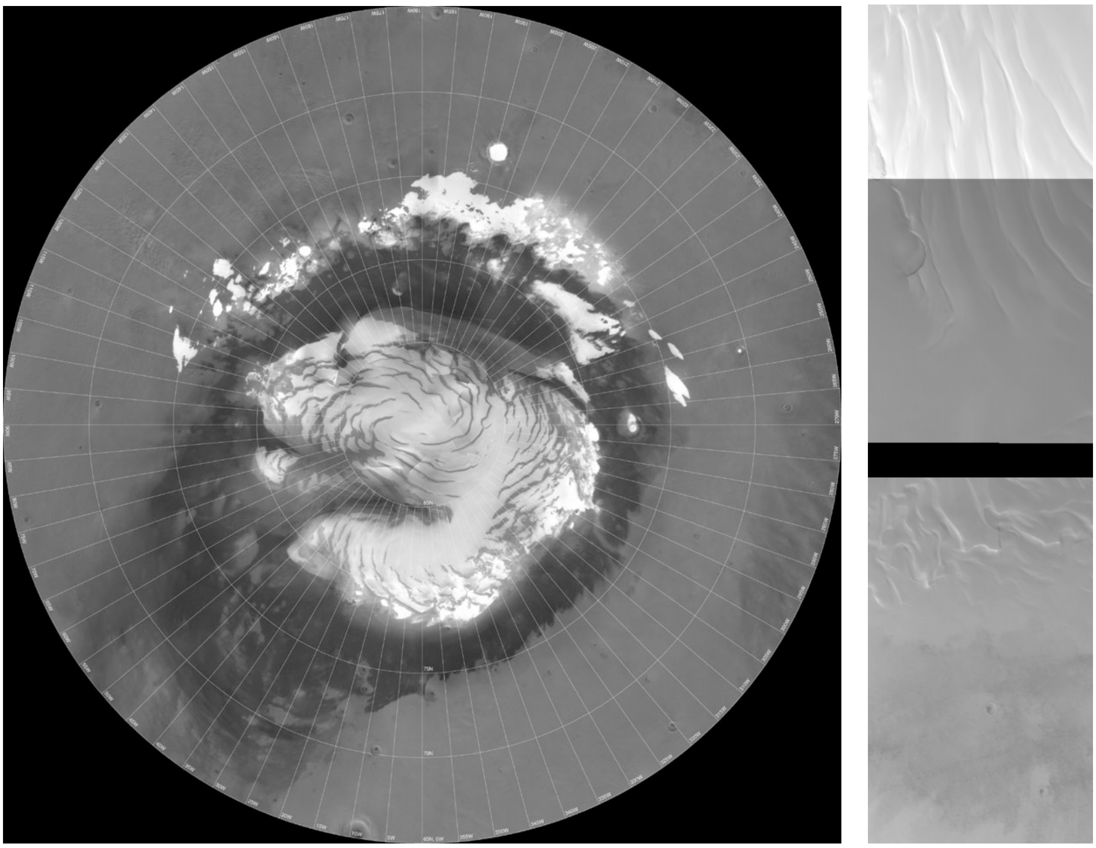
[171] A second orbital expert came in later and corroborated the opinion of this expert.
[172] This study had been conducted by students working with ZD a year and a half earlier. Referring to them as "my students," he emphasized they had involved JPL experts and that he considered their results credible.



(a) (b)

Figure 7-4 (a) Journal Article Illustration (b) Landing Site from Previous Report
The landing ellipse evident in (b) reflects the envelope of uncertainty of the orbital calculations. Sources: (a) Science Magazine, Zuber et al. 1998. (b) JPL

With specific coordinates in hand, another team member, IE, sets about retrieving high-resolution satellite imagery of Mars' north pole. When such an image is found, bearing precisely ruled latitude and longitude lines, it is so large on screen that the labels are not immediately visible. There is palpable suspense as IE scrolls to locate numbers on the perimeter of the image. Team members exclaim, "exactly!" as the labels reveal a promisingly smooth, snowy arm near the pole to be the same spot indicated by the student report.



(a) (b)

Figure 7-5 Mars Orbiter Camera[173] (a) Composite Image of North Polar Region; (b) High-Resolution Image of Final Landing Site
Source: NASA/JPL/Malin Space Science Systems. <http://www.msss.com>

On one level this is the story of how expedient tools and patterns validated by past experience (in case, the use of the porkchop diagrams) present what appear to be hard constraints that, in fact, can be relaxed by additional expertise and technical capability. It is also a story of how such patterns involve more than just pure reason. Concepts drawn from activity theory prove helpful in making sense of developments in the landing site selection thread. By emphasizing the way external representations were involved, I hope to suggest ways of bridging the disparity between activity theory and actor-network theory in this respect that I identified in Chapter 2.

Mediated Convergence of the Landing Site Impasse

The landing site thread involved a gradual convergence between ZD and HL who initially based their alignments on different criteria and constraints. In following distinct lines of reasoning, each marshalled his own array of facts, experts and credible representations. Rather than boiling down to a difference of opinion over a particular issue, ZD's and HL's respective concerns are embedded in different activity systems. As they interacted with

[173] The Mars Orbiter Camera is an instrument also aboard the Mars Global Surveyor spacecraft.

external experts to soften some constraints, their convergence was mediated by a succession of representation that were increasingly able to hold and credibly reconcile their proximal concerns.

Recalling the activity theory concept of an objectified motive, let us compare the orientations of ZD's and HL's activities, respectively. As a leader of one of JPL's standing design teams, ZD has a central interest in the productivity of the team and efficient use of time in the completion of a design. For ZD, a completed design is exemplified by a 3D CAD model of the spacecraft with features that are fully justified and determined through comprehensive engineering analysis. On the other hand, as a JPL proposal manager, HL has a central interest in formulating a mission with compelling science objectives that can be achieved with reasonable investment and risk. For HL, such an outcome is exemplified by a convincing proposal, one likely to garner funding commitments in the competitive NASA environment.

ZD has developed an understanding of the patterns governing different decisions and the sequence in which issues must be resolved to complete a spacecraft design. His experience has prepared him to expect the availability of solar energy at the landing site to be a key factor, making resolution of this issue a priority for him. He is also a proponent of bringing sophisticated modelling tools into the real-time design environment, taking some pride in this as a point of difference between his and other JPL standing teams. These tools include a commercial 3D-solids modelling system and a proprietary solar power simulation developed in-house at JPL. The latter is a relatively recent addition and ZD has repeatedly touted its advantages over previous methods in comments during the sessions.

In activity theory terms, a key function of representations is mediation. This is the process by which the object-motive is made present, or proximal to the actor. ZD's object, a completed design, involves satisfying the needs of a cascade of representations: the CAD model needs solar panels and batteries, the dimensions of which depend upon the spacecraft's energy requirements (determined from the start-up timeline) and the panel area the power simulation tool indicates will be necessary to achieve them. The power simulation in turn requires specified landing coordinates and date; thus it is these that became ZD's proximal items of concern. And it is precisely these things that are conveniently available and inscribed (in the form of accessible latitudes) in the porkchop diagram which, at this moment, was his proximal representation.

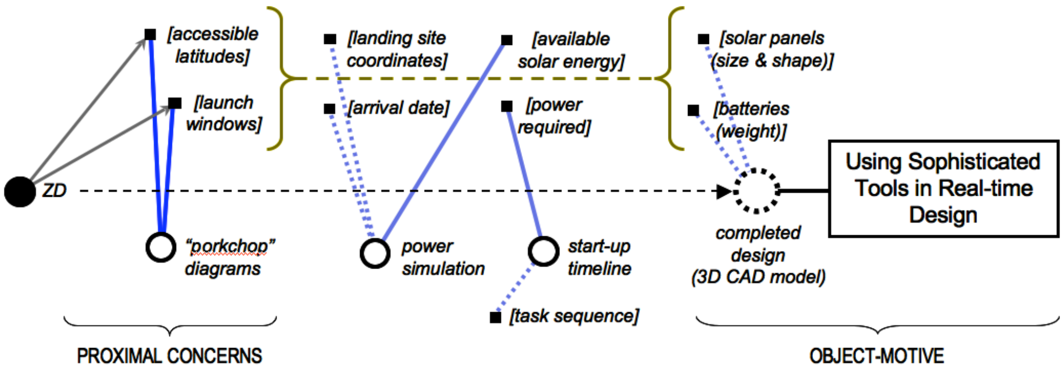


Figure 7-6 ZD's Objectified-motive and Proximal Concerns

HL's object, a successful proposal, requires a compelling science mission that effectively showcases the CHPS.[174] For HL, inability to reach thick, water ice would undermine an essential aspect of the coherence of the proposal. He has identified certain constraints to be of proximal concern, namely finding a site with year-round, surface water ice at least a kilometre in depth. These items are inscribed in scientific papers and journal articles, such as the one he has brought into the session; thus, it is these that are HL's proximal representations.

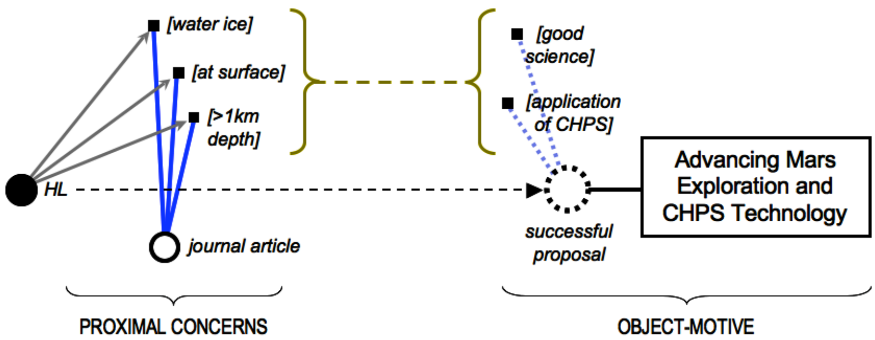


Figure 7-7 HL's Objectified-motive and Proximal Concerns

Because ZD is satisfied that ice in some form will be present at the southern latitudes dictated by his porkchop plots, he is ready (indeed eager) to move forward. (He also noted with satisfaction that arrival in southern spring, as indicated by the plots, would offer the best scenario for solar energy; at this time the north pole would be about to enter into an extended period of total darkness.) HL, however, refuses to acquiesce to a landing site in

[174] In an individual interview, HL described his broader JPL role in charting the future of manned Mars exploration. He explained his conviction that power systems like the CHPS would ultimately be required, and mentioned his previous industrial experience working with the underlying technology. Rather than an incidental concern, successfully showcasing the CHPS is therefore central to HL's professional role and career identity, in much the same way that sophisticated modelling tools in real-time design are important to ZD.

the south, maintaining on the basis of his articles that a northern polar site is necessary for a scientifically valid mission.

Several things had to fall into place for this impasse to be resolved. First, for ZD, the hard constraint presented by the porkchop plot (validated by previous project leaders) had to be softened. This was accomplished by two respected experts with their own authoritative (albeit invisible) representations[175] who were able to offer a credible alternative in the form of a mid-course manoeuvre. Though ZD became provisionally supportive of a northern site, he still requested an "actual image,"[176] not willing to accord that status to the illustrations in the journal articles.

A second trigger for the confluence was ZD's recollection of the previous student report that had selected a northern polar site. This seemed to allow ZD to connect the northern alternative to his past experience *and* his design process, and also provided a precise specification *in the terms required by his next proximal representation*: the power simulation tool. From this point there is rapid progression to a representation simultaneously inscribed with *both* ZD's proximal parameters of latitude and longitude (plus landing date supplied by the external orbital expert[177]) *and* the evidence HL required of ice coverage (in conjunction with the journal paper). The image from the student report was an important bridge, eventually reinforced by the satellite photography—the high resolution of which conveyed a visceral conviction that this *was* a real place, smooth, white and covered with snow, to which it would be possible to go.

[175] These representations were never introduced in the design session, but their use was referred to by several participants as "running codes."
[176] Session 041502, Episode 29, transcript para. 1268, at which time IE undertook to find the satellite imagery.
[177] The orbital expert's return triggers Episode 42. He reviews specific dates with no evidence of doubt they can be achieved. These dates are entered into the power tool which indicates a reasonable amount of solar power will be available.

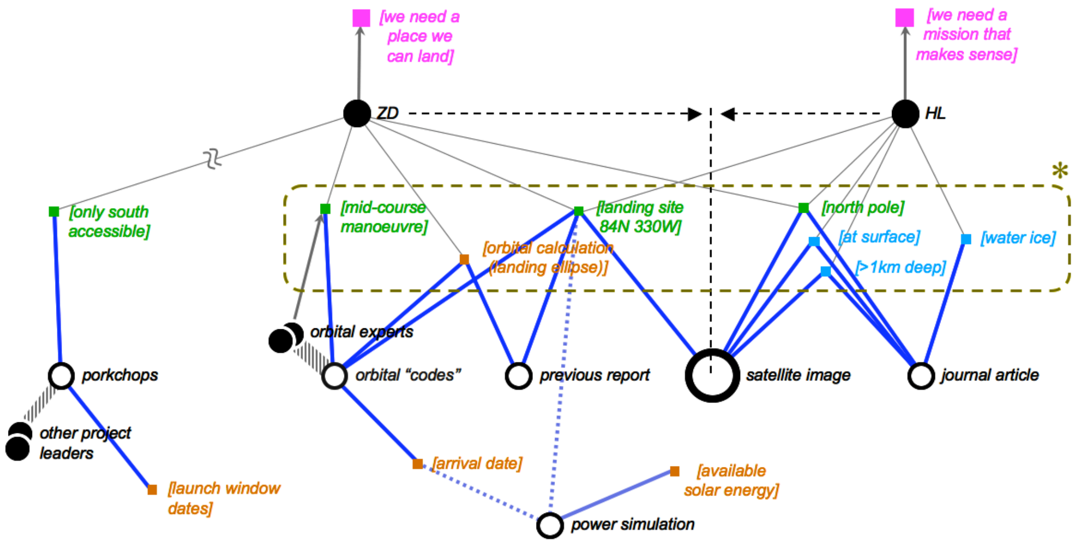


Figure 7-8 Mediated Convergence of ZD and HL on a Northern Polar Landing Site
Convergence was achieved with the aid of a cascade of credible experts and representations, leading to a single representation (the satellite image) that was able to simultaneously anchor the proximal concerns of both ZD and HL. This required ZD to relax his initial alignment with the southern latitudes suggested by the porkchop plots. (The box with asterisk encloses the discourse nodes over which convergence was achieved.)

The convergence eventually reached in the landing site selection thread can be understood, at least in part, in terms of interaction with external experts and with shared representations carrying inscriptions corresponding to the proximal concerns of different actors. Through interaction these were coordinated and brought into alignment to resolve the landing site impasse. I propose this description as indicative of an approach to reconcile a number of the disparities and questions I highlighted in Chapter 2.

In actor-network terms, commitment to the final decision in this case was stabilized by a constellation of human actors and credible representations. Referring to Engeström & Escalante's (1996) objection to actor network theory, the necessary interactional work was precisely that required to forge a coherent and robust constellation, drawing together the nodes over which ZD and HL converged (enclosed in the area marked with an asterisk in Figure 7-8). The effect of this convergence is essentially the conscription to which Henderson (1999) refers. This was accomplished in part, by a representation with inscriptions able to satisfy the proximal concerns of the key actors, allowing each to move toward realization of their respective objectified motives. The convergence involved the reconciliation of options with key constraints and criteria, bolstered by numerical calculations and credible representations. In the composition of these nodes (as well as the paths to the participants' respective objectified motives) we can see the residue of Bucciarelli's (1994) object-world discourse and collective story-making.

We also see, in activity theory terms, how representations and tools that are closely identified with an objectified motive, validated by past experience and consonant with professional identity, may create patterns that are difficult for participants to re-evaluate in new situations. While ZD's concerns about reaching the north were by no means unfounded, it may be that his desire to move the process efficiently forward made him less open than he might otherwise have been to HL's concerns.

As Carlile (2002) points out, innovation requires transformation of knowledge. Certainly, in this case, participants developed a deeper understanding of the constraints presented by the porkchop diagrams, and had to "un-learn" some of the patterns established by their past work. As it turned out, because the spacecraft's start-up power requirements were relatively modest and could be satisfied with batteries alone, it was eventually determined that solar panels were unnecessary—hence the power simulation was superfluous! HL greeted this result enthusiastically, since the absence of solar panels (which would be obvious to those accustomed to looking at models of exploratory spacecraft) further underscored the novelty of the CHPS application.

8. SYNTHESIS AND INTERPRETATION OF FINDINGS

What are the roles of persistent shared external representations in collaborative, real-time design? This chapter presents a synthesis of findings, based on results obtained from both micro and macro analyses, to answer this question. First, primarily based on the results of the micro-analysis, I summarize the factors I found associated with productive interaction in the selected episodes. These include structural properties of actor-discourse networks, the engagement of actors and shared representations, and the composition and temporal development of design discourse. Because of the breadth of the original selection criteria, I argue that these factors are generally indicative of the quality of design conversation in the real-time context.

Then, considering both micro and macro results, I describe a more complete set of roles persistent shared representations appear to have played in productive interaction. On this basis I present a framework of situational attributes, operating over different time scales, that constitutes a comprehensive notion of representational support for design interaction. This framework provides a language with which to describe the state of support in any given situation, as well as a way of imagining how support might be improved. Considering the overall effects of these attributes, I characterize the involvement of shared representations in real-time design and in collaboration more generally, in terms of competing dynamics of generativity and stabilization.

The various factors and attributes I propose are all conceived in terms that make them operational within the actor-discourse network formalization. This coherence facilitates elaboration and follow-on hypothesis testing in a number of areas. I will discuss these and other aspects of further work, including methodological issues, technical elaborations and theoretical implications, in the following chapter.

Quality of Design Conversation

I initially began this research with an exaggerated hypothesis in mind: that design collaboration was not possible without the creation of persistent shared representations. Of course, this was not supported; Episode 7, a productive design conversation without the use of any such representation, provides direct counter-evidence. It is therefore necessary to articulate more precisely what roles persistent shared representations do play in productive design interaction. As a first step I will summarize the constituent factors I found associated with productive conversation based on comparison of the selected episodes.

The process of triangulating and selecting episodes for micro-analysis took into account a range of indicators, both positive and negative. These included participants' evident excitement, the tone and energy of their interaction, expressions of satisfaction, dissatisfaction or frustration, as well as key developments and major design changes related to important or demonstrably innovative outcomes. Assessments of these were based on in-session observations and video review, post-session interviews, retrospective evaluation and participants' own presentations and published accounts. I propose that, taken together, these indicators serve as a reasonable proxy for the quality of design interaction in this context.

Through the micro-analysis I identified four *structural network properties* to account for differences between the episodes that were selected on the basis of positive and negative indicators. As discussed above (in Chapter 6), these structural properties include quantitative measures of the overall alignment and mutual engagement in actor-discourse networks, and more qualitative judgements about the participation of human actors and the extent to which shared representations were integrated in conversations.

Based on *categorical* content coding, I identify two additional factors relating to the composition and temporal development of discourse in interaction. These include the development of design discourse (that pertaining to the proposed intervention in an imagined future) and the degree to which explicit closure was reached, with enhanced specificity (regarding requirements, design directions, or more refined questions) and commitment on the part of team members to enact further work. I will summarize each of these factors below.

Quantitative Measures: Overall Alignment and Mutual Engagement

Through microanalysis I discerned two attributes of actor-discourse networks, indexed by structural metrics, that were associated with positive interaction in the selected episodes: a high degree of overall alignment and the mutual engagement of actors with common elements of the design discourse.[178] These properties have a commonsense relationship to productivity in design conversations. Collaborative design involves synthesizing perspectives and reconciling differences to envision a preferred future, and forging collective commitment to a course of action calculated to bring this future about.

Total degree is the sum of the strengths of all arcs in the actor-discourse network. It is therefore a direct index of the overall level of alignment expressed in discourse. This notion

[178] These measures were based on conventional network metrics of degree centrality and flow betweenness centrality. Because these assess the centrality of individual nodes, I used sums and ratios to yield overall, group-level metrics (total degree and discourse betweenness).

of alignment goes beyond simple agreement; it reflects a degree of personal investment and commitment expressed by an individual with regard to particular elements of design discourse. This aspect of commitment is essential to achieving outcomes in design, and it stands to reason that peaks in total degree generally corresponded to important outcomes in interaction.

However, it is possible for individuals to express strong alignment with respect to entirely different things. Productive designing requires some level of agreement amongst participants, manifest in their mutual engagement with the same elements of discourse. As an index of mutual engagement, I developed a measure of discourse betweenness (based on flow betweenness centrality) to reflect the extent to which discourse nodes acted as bridges between actors.

While I identified problematic aspects of the discourse betweenness metric under certain circumstances (discussed in Chapter 6, detailed in Appendix C), in conjunction with total degree it does appear to usefully discriminate between the positively and negatively-selected episodes. Peaks in total degree occurring in conjunction with relatively high discourse betweenness were associated with strong consensus around key design developments. Low levels of both total degree and discourse betweenness characterized lulls and lacklustre or unfocused interaction. Low points in total degree accompanied by very high discourse betweenness characterized periods dominated by communicative repair. Periods of relatively high total degree accompanied by low discourse betweenness were seen as indicative of flawed consensus and systematic disagreement.

This last situation is perhaps the most interesting, as it appeared to account for two of the more subtle features of the selected episodes: the unstable consensus in the positively-selected Episode 12, and the dual nature of Episode 54—selected on the basis of negative indicators but which also saw a significant emergent insight embodied in the final radiation shielding approach. Both of these developments involved peaks of high overall alignment accompanied by anomalously low mutual engagement. Both cases were instances wherein the analysis displayed the ability to surprise me—drawing attention to a richer picture rather than simply reinforcing a characterization of one episode as positive or negative, or overall alignment as uniformly indicative of productivity. Indeed, to more fully understand the implications of these quantitative measures the remaining two, more qualitative factors must be taken into account.

Qualitative Judgements: Participation and Integration

In terms of network structure, the participation of the human actors is reflected primarily by their engagement with various elements of discourse and representations. Integration refers to the manner in which representations are brought into participation by the human actors, and the extent to which elements of shared discourse—particularly collaborative productions—are inscribed upon them. In the results I have presented, these network attributes were assessed primarily through qualitative evaluation of cumulative actor-discourse and semantic network diagrams. Though quantitative metrics could be developed in further work, I wish to emphasize two distinctions that make these factors complementary to those I have just discussed. The first is that these are not synchronic or real-time assessments intended to characterize interaction at any particular point in time; they are cumulative evaluations made retrospectively over a period of time corresponding to some sort of meaningful progress in the design. The second is that they necessarily involve some level of subjective judgement with regard to what may be necessary and appropriate in a particular situation.

Returning to the results above, cumulative network diagrams of positively-selected episodes, 7, 12 & 39, reveal a generally strong engagement of key participants in discussion and with the important collaborative productions. Weaker or more lopsided engagement is visible in the negatively-selected episodes, 21 & 54, with a complete absence of collaborative productions in Episode 21. Episodes 12 and 54 present a more complex picture, underscoring the importance of judging participation in terms of relevant expertise and requirements of the task at hand. Both Episodes involved peaks in total degree associated with relatively low mutual engagement. Both involved at least one actor who dissented or objected to proposals receiving collaborative support from other participants. However, the outcomes were distinctly different.

Episode 54 was selected on the basis of negative indicators, primarily a result of substantial communicative repair and the inability of two experts to see eye to eye about radiation and its effects—which produced a certain amount of impatience and frustration. The collaborative outcome of this episode was, however, robust in that a significant insight (tangential to the nominal focus of the episode) led to a substantial refinement of the shielding approach that was embodied in the final design. Episode 12 on the other hand involved adoption of a design direction that was later rejected in favour of the dissenter's proposal, which became the basis for the final design. The dissenter in this case, remote participant MW, was principally responsible for the design of the radiator, so the subject of the disagreement was central to his expertise. That none of the principal advocates of the competing proposals had access to a shared display or representation—along with the general level of uncertainty and confusion expressed at various times—might well have raised flags. The fact that neither the team leader nor I noticed this state of affairs at the time attests to how difficult it can be for participants to monitor each others' attention and arguments in the midst of a complex discussion.

While I have not explicitly taken participants' specific expertise into account in this micro-analysis, it seems clear that assessing the quality of design conversation would have to take appropriate levels of participation by actors with centrally-relevant expertise into account. Disagreement is not inherently negative in design interaction. However it requires careful attention when key voices on a particular issue (either by virtue of their expertise, their stake, or the necessity of their commitment) are disadvantaged by being remote, or "disenfranchised" by lack of access to shared representations.[179]

Similarly, it is difficult to definitively state the importance of engagement with representations and inscription apart from the specifics of a given situation. However in this case, the overall results (including events detailed in the macro-analysis) make clear that, at least in this type of real-time design, appropriate shared representations play a number of important roles. Shared representations lend structure and focus to interaction, and provide resources for detection of error and resolution of ambiguity. Their absence may allow ambiguity to persist or may result in the loss of work accomplished through interaction that remains un-inscribed. Accordingly, in conjunction with quality of design conversation, I propose to recognize two distinct facets of representational integration: the engagement of actors and the creation of inscriptions.

Cumulative episode aggregate diagrams make differences between the selected episodes relatively clear. Episode 7 was a productive brainstorm in which no persistent shared representations were employed. Problematic discussion in Episode 21 took place on an issue that was completely disassociated from the shared representation that had been the focus of interaction up to that point. Representations in Episodes 12 and 54 served as points of departure, but new proposals and collaborative productions were not captured or inscribed in any way. Episode 39 was unique in that the human actors engaged strongly in design reasoning *and* in changing representations. This highlights the difference between relatively

[179] I have also not addressed the social processes by which a group determines whose expertise is relevant because, as noted earlier (in Chapter 2), the structure of the concurrent design practice at JPL largely relieves teams of the need to deal with these issues in-session. Accordingly, in this research I have undertaken the development of a method to make the dynamics of task processes (vs. socio-emotional processes) particularly visible. I discuss ways in which other social and relational processes might be investigated in future work, in conjunction with this method, in the following chapter.

passive engagement and neutral description of features already represented and the creation of new inscriptions corresponding to emergent collaborative products.

I hesitate to evaluate the quality of conversation in Episode 7 negatively because shared representations were not involved—particularly because there were no demonstrably negative effects of the ambiguity that lingered between HL and ZD.[180] As Minneman (1991) notes, skilful management of ambiguity around points of disagreement—particularly in early stages—may be an essential aspect of effective design interaction. It may also be that the *specific* outcome of this episode—an agreement and commitment to decide between the two options on the basis of additional analysis—made a shared representation less important at this point in time.

Composition and Temporal Development of Discourse

The selected episodes differed with respect to the degree of development of design discourse, and the extent to which closure was reached with specific commitments that advanced the state of the design. These attributes were most visible in the categorical coding overview diagrams presented in Chapter 6.

Design discourse is that which is organized around elements of design reasoning. It is characterized by two principal distinctions: first, it addresses an aspect of the design situation that has been recognized as problematic in some way by the group; second, it is temporally located in the imagined future context of the design (as opposed to being a time-independent statement of a physical property or a matter of fact). It must also embody some element of alignment, apart from a question or neutral movement of information. Thus, design discourse pertains to things as they *should* or *could* be, rather than simply as they are. Interaction dominated by discussion of a point of factual information—without participants' taking a position on a design issue, criterion or solution—was not coded as design discourse.

The positively-selected episodes all showed well-developed design discourse, evidenced by a large number of strongly-aligned contributions with respect to elements of design discourse, and an overall balance of the constituent elements of design reasoning (e.g. issues, options and criteria). This was also true of the negatively-selected Episode 54, accounting for the significant outcomes generated during this episode, in spite of a significant amount of repair and disagreement. In the episodes that significantly advanced the state of the design, a recognized issue or opportunity led into discussion which

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[180] I will propose (below) that participants' discussion of alternatives might have progressed differently had some form of persistent shared representation been involved, but this will be an issue for future work.

constructed the problematic situation. Options were identified and relative merits discussed until some sort of convergence was reached. The trajectory from initial recognition of an issue or opportunity, through to closure constitutes an *essential cycle* in the advancement of collective design reasoning.

This cycle is not strictly tied to the temporal bounding of episodes, which is one reason complementary units of analysis were useful in this project. Referring to the coding overview diagrams, Episodes 7, 39 and 54 appear to have witnessed *two* such cycles, wherein the state of the design was distinctly advanced; these were associated with peaks in network metrics and marked by closure in meta-process acts. Conversely, the landing site thread can be seen in some ways as one long cycle that spanned several episodes and different days. Flexibility to suspend work on an issue that has stalled in order to delve into something else—until the time is right to take the issue up again—is essential to the productivity of real-time design interaction. It is this that gives rise to the type of intricately-woven thread structure revealed by the refined episode parsing diagrams in Chapter 4. The ability to accomplish these transitions successfully is enhanced by the use of shared representations—part of what I describe in the next section as “representational support.”

The factors indicative of quality in design conversation I have identified above are summarized below, across the five selected episodes, in Table 8-1.

Table 8-1 Factors of Quality of Design Conversation
Summary of basis of episode selection and factors identified through microanalysis

	triangulation			network metrics		discourse composition		participation and integration		
episode	**selection**	pos > average	neg > average	overall alignment	mutual engagement	design discourse development	closure w/ incr. specific. commitment	participation of human actors	engagement with SERs	inscription of outcomes
E7	**+**	+		•	•	•	•	•	n/a*	...
E12	**+**	+		•	∘	•	•	•		∘
E21	**-**		-	∘	∘	∘	∘		∘	∘
E39	**+**	+		•	•	•	•	•	•	•
E54	**-**	+	-	•	∘		•	•		∘

Factors of quality: (•) notably present / (∘) notably absent / (blank) not notable in either regard
(*)Episode 7 did not involve persistent shared external representations; this did not negatively impact the quality of design conversation in this instance.

Representational Support

Having articulated the factors I found indicative of quality in design conversation, I now turn to address the roles played by persistent shared representations more generally across the data set. I have chosen the phrase "representational support" to convey an overall sense of the breadth of constructive involvement. I develop this notion first by recounting the roles played by various representations in the various episodes and threads. I then reformulate these roles in terms of paired sets of situational attributes—that is, attributes of representations that are not necessarily intrinsic, but arise in situations of use. It is these attributes—arrayed across different time scales and participating at different points in the essential cycle of collective design reasoning—that together constitute representational support.

The diagram shown below in Figure 8-1 was a relatively early attempt to depict how persistent, shared representations might co-evolve in conjunction with both the cyclical and progressive aspects of design activity (i.e. facets characterized by the various coding schemes reviewed in Chapter 3). This diagram depicts representations directing and stabilizing interaction revolving around them, much like the central column of a spiral stair.

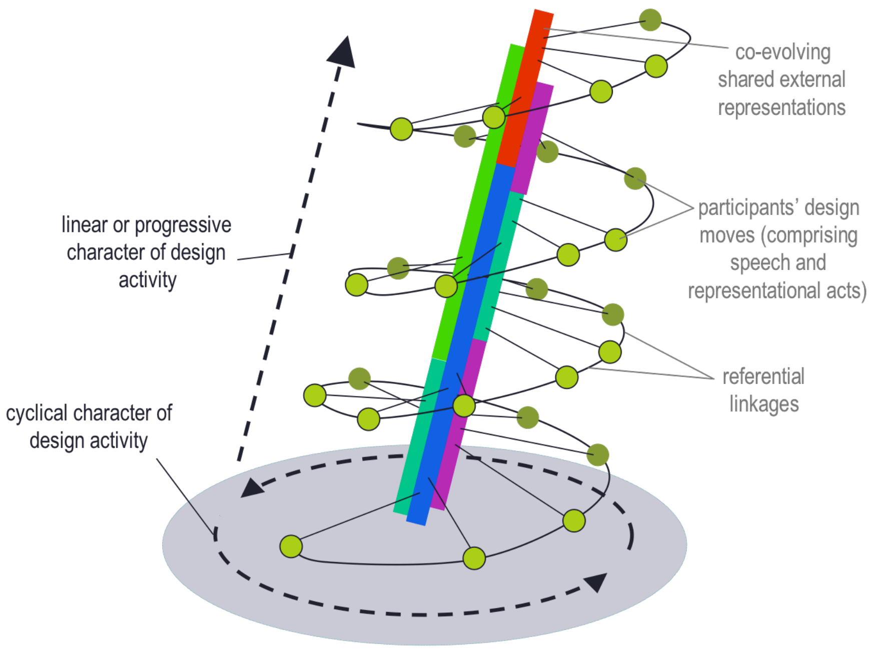

Figure 8-1 Spiral Depiction of Representational Stabilization
This diagram was an early attempt to represent both the cyclical and progressive aspects of design activity, showing how these revolve around and are stabilized by the co-evolution of persistent, shared external representations.

As a point of departure, this diagram remains useful, though actual analysis reveals the cycles to be highly nested and irregular, and the network around the representations to be far more complex than a simple spiral. The diagram still conveys a sense of how an activity might be advanced through the completion of cycles in a direction that, at least to some extent, is imparted or scaffolded by shared representations. In this section I take up more specifically a number of ways in which representations accomplish both: helping to propel the cyclical as well as directing the progressive aspects of design activity.

Roles and Situational Attributes of Representations

The last two columns of Table 8-1 above suggest some of the roles shared representations played in relation to the quality of design conversation. Some of these roles were directly visible in the microanalysis since they tended to operate within the time frame of a single episode. Other roles were not fully apparent until longer time frames or multiple episodes were considered. Thus, taking the macro-analysis into account enriches the picture and conveys a deeper understanding. Table 8-2 below summarizes the roles of representations seen across the full data set (i.e. encompassing both micro and macro-analyses). The roles are grouped into the following categories, with the latter building upon the former:

- provide shared reference: serving to convene or draw groups into discussion, and as resources in resolving ambiguity
- afford noticing: initiating topics and managing returns, suggesting alternatives
- accept contributions: providing a locus for expression (i.e. directed toward the representation, not necessarily other people), receiving opinions and elaboration; registering participants' acts through perceptible changes
- foster decision: providing answers and stabilizing consensus
- carry inscription: preserving accomplishments over time and carrying them beyond the bounds of the group

The roles in Table 8-2 represent a variety of processes operating at different levels and over different temporal scales. Taken together, they convey an idea of the level of representational support enjoyed by various episodes and threads. While outline bullets denote where actual problems occurred, blanks in the table may also suggest missed opportunities or new possibilities.[181] This framework can provide a comparative picture of representational support in other settings of design interaction. In conjunction with the factors for conversation quality described in Table 8-1, these can be used as the basis for more specific predictor and criterion variables in future research.[182]

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[181] For example, one can imagine how a CAD model might be animated to assume different configurations corresponding to the timeline, thereby using temporal task structure to help initiate topics and manage returns. Similarly, the Data Rate and Telecom Architecture thread could have been better supported by a representation with the end-to-end flow schema discussed in Chapter 7.
[182] For future research aimed at testing specific hypotheses (i.e. in an explanatory vs. exploratory case study), some adjustments would be in order. To keep criterion variables distinct from predictor variables, it might be preferable to evaluate mutual engagement without taking inscription arcs into

Table 8-2 Roles of Shared Representations in Design Interaction
Summary of roles identified through micro and macro-analysis. Horizontal overlapping bars denote roles that build upon one another.

										carry inscr.	
								foster decision			
						accept contributions					
			afford noticing								
	provide shared reference										
micro: episode	resolve ambiguity	gather, convene make proximal	initiate topics manage returns	draw questions	suggest alternatives	provide a locus for expression	respond to changes	provide answers	stabilize consensus	preserve accomplishments	travel beyond the group
E7	n/a*	...	...	...	...	...	...	...	...	n/a**	
E12	∘		•						∘		
E21	∘	∘									
E39	•	•		•	•	•	•	•	•		
E54	∘		•	•							
macro: thread											
Sensitive Electronics	∘/•	•		•	•	•	•	•	•	•	•
Radiator Configuration	∘/•	•		•	•	•	•	•	•	•	•
Start-up Timeline		•	•			•		•	∘	∘	
Data Rate & Telecom Arch.		∘				•	∘/•		∘/•	∘	
Landing Site		•				•		•	•		•

Roles of representations: (•) notably present / (∘) notably absent / (blank) not notable in either regard
(*)Episode 7 did not involve persistent shared external representations.
(**)These roles operate between episodes and were therefore not readily visible in micro-analysis.

For a given thread, the roles depicted in Table 8-2 above may have been shared across several representations. To understand the nature of the support provided by a particular representation in any given instance, I reformulate these roles in terms of nested pairs of situational attributes operating over different timescales.[183] These are summarized in Table 8-3 below.

account. It would also be necessary to add criterion variables for key design developments and process breakdowns, thereby extending the conversation quality matrix to longer time frames.

[183] By "situational," I intend for these attributes to refer to the way representations are *used* more than any particular characteristics of the representations themselves. Thus these attributes reflect network effects more than intrinsic properties.

Table 8-3 Situational Attributes, Associated Roles and Actor-Network Manifestations

time scale	*attribute*	*description*	*associated roles*	*actor-network manifestations*
long time scale	span	the extent to which the representation simultaneously holds items of proximal concern to different participants. (evident in a rep. that becomes "shared property")	• gathering, convening by making proximal • initiating topics, managing returns	• engagement of diverse actors around a representation. • association of a representation with a broad range of issues and "organic" transitions
	robustness	the extent to which inscriptions are stable, recoverable (at a later date) and credible (to participants and others)	• holding accomplishments • carrying inscriptions	• shared reference to previously inscribed discourse • credulity of information; general absence of repair
intermediate time scale	evocativity	the extent to which the representation assists in the initiation of topics[184] and suggestion of issues, options or criteria. (evident in a representation's ability to surprise)	• initiating topics • drawing questions • suggesting alternatives	• noticing, or raising questions • implication by participants proposing issues, options or criteria
	authority	the extent to which the representation is seen to present credible evidence. (for CAD, includes attributes like scale and accuracy)	• providing answers • stabilizing consensus • fostering decisions	• actors engaged with inscriptions conveying results • general absence of calling-into-question
short time scale	availability	salience and accessibility; the extent to which the representation can be perceived, approached, indicated by participants	• providing shared reference • resolving ambiguity	• implicate or explain-describe acts between human participant and representation
	responsiveness	the extent to which the representation responds to participants' change acts. (depends upon interface technology and inherent schematization)	• accepting contributions • stabilizing consensus	• create/add/change acts giving rise to new inscriptions

To make the temporal relationships between these attributes more clear, they are depicted diagrammatically in Figure 8-2, with each attribute positioned to reflect its involvement in collective design reasoning (i.e. initiating, sustaining and/or bringing closure) over different time scales.

[184] While these acts were carried out by human actors in this setting, it is possible to imagine more autonomous representations that could make such proposals directly.

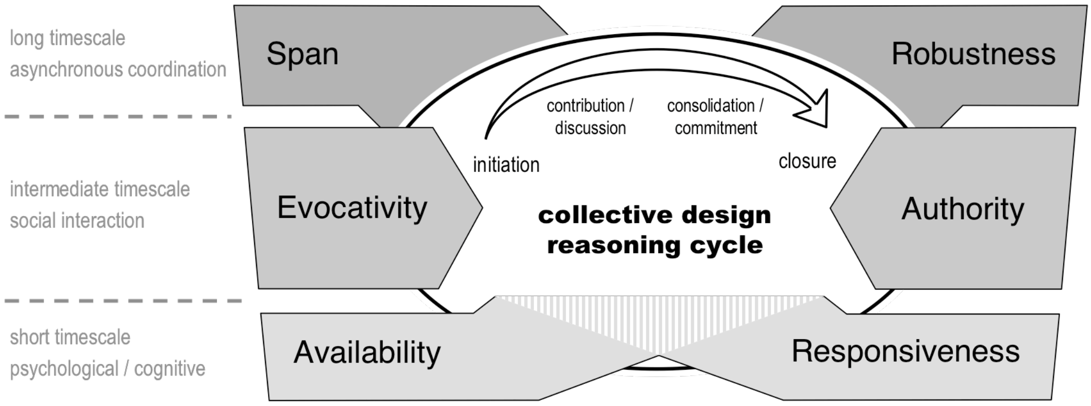

Figure 8-2 Framework for Representational Support
Situational attributes of representations are depicted with respect to an essential cycle of design reasoning. Attributes are arrayed vertically according to the time scale over which they operate, and the processes principally associated with each. Attributes identified primarily with initiation of collective design reasoning are to the left, those associated with closure are to the right.

The focus of this research is on the intermediate time-scale, at a level corresponding to the cycle of collective design reasoning. Here, the cycle is initiated by participants' recognition of an issue or opportunity. Representations' roles are evident in instances of noticing and implication in participants' proposals. The associated situational attribute is *evocativity*, because representations evoke contributions from participants—who in a sense lend their voices to the representation. In bringing closure to the cycle, representations' roles include offering conclusive answers and credible evidence; the associated situational attribute is one of *authority*. These are in turn dependent upon two lower level situational attributes, acting over shorter time scales: *availability* and *responsiveness*. A representation cannot be evocative for those that cannot perceive it, nor can it provide shared reference. At the other end of the cycle, a representation is unlikely to provide authoritative evidence without having made some response to the problematic situation, i.e. changing or allowing itself to be configured to represent a particular idea or address a specific question.[185]

These properties are interdependent. The interplay between evocativity, authority, availability and responsiveness is clearly illustrated in the dynamic use the CAD model and whiteboard in the radiator configuration discussion of Episode 39, initiated after ZD noticed a minor issue in the CAD model. As MW's proposal for a design change gained momentum, ZD and HL disagreed over the need for a "widget." HL's move to the whiteboard was a reflection of the fact that the CAD model was no longer helpful, since it embodied nothing of the proposal at hand. At this moment—though both had visual access to the CAD—HL's need to clarify precisely what he thought they were discussing caused

[185] Minneman (1991) highlighted facility with mundane representations as a central competence in collective engineering design practice. "By facility, I mean first that designers exhibit the ability to manipulate representations in a manner that is responsive to the opportunities and troubles that arise in the moment, and second that they are adept at relating those activities to the work at hand." (Minneman 1991, p. 145)

him to opt for the more responsive whiteboard representation. Eventually, to avoid being marginalised, ZD was compelled to join the interaction at the whiteboard to clarify his suggestion. With satisfactory agreement on the proposal, further progress required a scale representation to judge the actual size that would be required; at this point the responsiveness of the whiteboard gave way to the authority of the CAD model. When the updated model *was* displayed, it promptly evoked a proposal for an alternate deployment approach—an option not mentioned during the previous interaction around the whiteboard.

The higher-level situational attributes, span and robustness operate over longer time scales. *Span* refers to the breadth of a representations' relevance across various issues and alternatives making up the design space. Just as some human participants are able to speak authoritatively over a broader range of issues than others, span accounts for a representation's ability to draw a range of participants into proximal interaction. This was exemplified in the Landing Site Selection thread, recounted in Chapter 7. In this instance, resolution of an impasse took place in conjunction with a sequence of representations increasingly able to anchor the proximal concerns of both key participants HJ and ZD (regarding ice coverage and trajectory accessibility, respectively). Similarly, the CAD model figured in a large number of organic transitions between threads because it simultaneously represented many components and subsystems, thereby making issues between them available for noticing.

The start-up timeline also figured in a large number of effective transitions and returns. However, breakdown on this thread resulted from complete absence of the corresponding closure property, *robustness*. Robustness entails material stability and a reliable physical presence, as well as semantic recoverability and credibility (over time and across different individuals). Span and robustness allow a representation to move beyond the boundaries of a group and to speak to those not involved in its creation. They are also reflected in the extent to which a given representation comes to be regarded as group property. These attributes account for the decision by HJ and ZD to incorporate the CAD model in their presentation to higher level management, and the use of similar representations in journal publications.

Representational Dynamics in Real-time Design

Considered together, what effects do persistent shared representations have in real-time design? I propose two paired sets of dynamics are at work. The first two, compression and acceleration, operate semi-independently but, in tandem, account for the productivity of real-time design environments. [186] The second two, generativity and stabilization, may be considered more of an opposition. While representational generativity contributes to the emergence of novelty in design interaction, representational stabilization imposes a certain coherence with past work and conventional practice.

Compression and Acceleration

First, to understand the productivity of real-time design environments, I propose two distinct dynamics that are related to the horizontal and vertical axes implicit in Figure 8-2 above. I describe these as “acceleration” and “compression,” respectively, superimposing them on the attribute diagram in Figure 8-3 below.

Acceleration is an overall shortening of cycle times and corresponding increase in productivity, primarily the result of reduced process latency (Chachere et al. 2004). In real-time design, the rapid communication afforded by close proximity and electronic data sharing means instrumental inquiries are rapidly addressed, with answers and decisions disseminated quickly. In practice this reduces waiting, coordination overhead, and the likelihood of work being performed in error. I depict it primarily operating in the horizontal dimension, to reflect a quickening of the pace of the design reasoning cycle.

Compression, on the other hand, is a focus on outcomes driven by the incorporation of advanced representational forms, typical of more mature design stages, as objects of collective work in real-time design environments. Such representations, evident in practices like rapid prototyping and the use of comprehensive, high-fidelity modelling, are able to more fully embody the envisioned design or outcome. They are also likely to provide more direct input to various downstream “consumers” of design information. Essentially, in Figure 8-3, compression is manifest by representations with a comparatively greater span and robustness appearing in interactional situations with greater availability and responsiveness. In actor-network terms, these representations help to draw the team together, and facilitate the conscription of allies, making adoption by essential constellations of stakeholders more likely. [187]

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[186] I am indebted to Syed Shariq for applying the term “compression” to real-time design. Though he did so without referring to representations or the effects I describe here, Dr. Shariq’s insistence that the real-time environment involved phenomena distinct from what might otherwise be termed “process acceleration” was an important inspiration.

[187] The NPDT team leader reported working with CAD vendors to simplify the interfaces of “high-end” (analytically sophisticated, high fidelity) modelling tools to make them more suitable for use in the real-time environment. A program manager who was a recent customer of NPDT reported that as a result of using advanced tools in early-stage design, the team’s results were more likely to be accepted and incorporated by designers working on later stages of development and implementation.

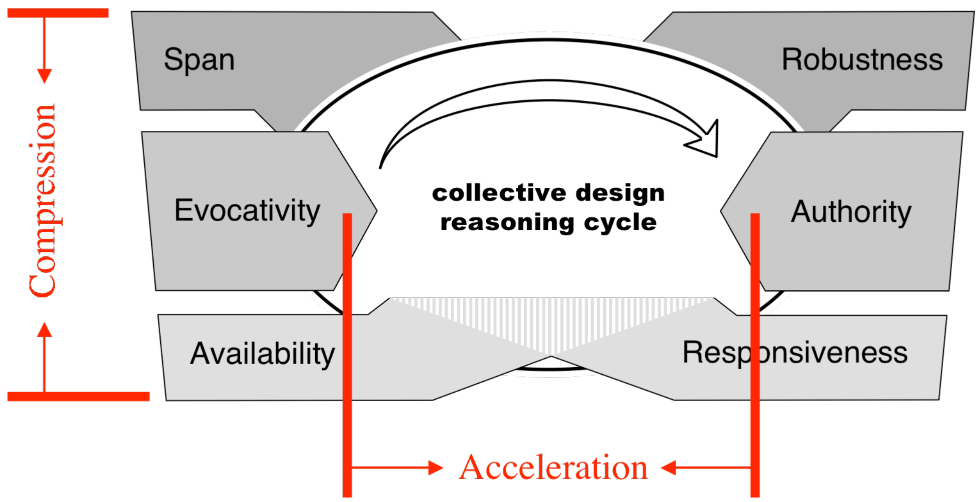

Figure 8-3 Acceleration and Compression in Real-time Design
Operating in tandem, these two representationally-mediated dynamics help account for the productivity of real-time design environments.

Participants may experience compression as a need to make decisions, fix specifications and develop more mature aspects of the design at earlier stages than they are used to doing—a pressure some may find uncomfortable. In fact, rushing to final representational forms without the ability to answer essential questions may not be productive in the long run. This is why it is important that expertise and tools keep pace—in essence, that compression and acceleration occur in tandem.

By making the distinction however, I wish to underscore that the full benefit of a real-time design environment involves more than just reducing latency and speeding information movement. To promote innovation in real-time design, it is important to recognize a difference between doing the *same* things one would previously have done separately—albeit faster and more accurately—and doing something *new and different* as a result of interaction. This contrast is the subject of the second pair of dynamics I will discuss.

<u>Generativity and Stabilization</u>

Through this study, it has also been a goal of mine to better understand how interaction over persistent shared representations may be involved in emergent and novel products of collaboration. What several JPL respondents referred to as "serendipitous insights" arise when the distinct voices of customers, stakeholders, and experts are brought into proximal interaction so that a novel reframing becomes possible. These outcomes are not the result of focusing exclusively on achieving an initially-intended outcome more rapidly.

Generativity in the real-time environment arises from individual action and collective construction. Recall Sawyer's (2002, 2003a, 2000b) conception of "collaborative emergence" as a dynamic balance between coherence and inventiveness, an interplay between upward causation and downward constraint (discussed above in Chapter 2). Participants engage in selective and constructive appropriation, their contributions shaping—and at the same time constrained by an emerging interactional frame. This layering produces an outcome with an overall or total character that, though it is dependent only upon individuals' contributions, is fully-determined by no *one* individual and is not predictable in advance. Representations contribute to the generativity of the real-time environment, as a result of whom they involve as well as the issues and opportunities they suggest. By virtue of their span, availability, responsiveness and evocativity, representations broaden the range of experience and perspectives drawn into engagement and facilitate constructive appropriation.

Conversely, stabilization begins with the need to fix and preserve outcomes to ensure productivity. Tools have a tendency to enforce coherence with prior work and the established practices of communities within which the design activity is situated. Past experience and precedent, embodied in such artefacts, tends to determine the types of representation and evidence likely to be credible in subsequent interactions. Thus stabilization comes into play first with representational authority and robustness. It is also reflected in the span of conventional representations, like boundary objects, which tend to conform to—and thus to propagate organizational routines. It is natural that teams tend to avoid departures from these as a matter of cognitive economy.

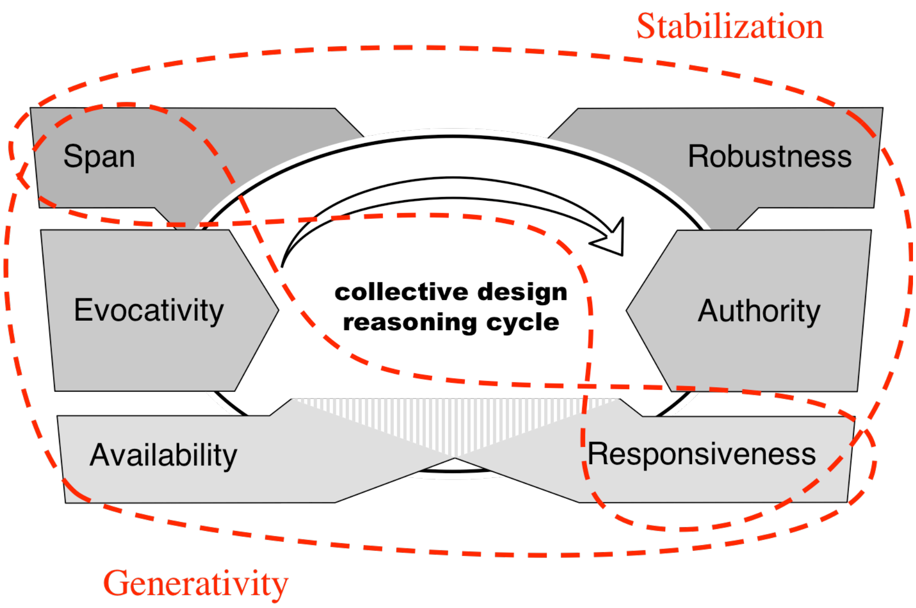

Figure 8-4 Representational Generativity vs. Stabilization
These reciprocal dynamics account for the contribution of representations, both to the emergence of novelty in interaction and to the propagation of conventional forms and practices.

Stabilization may also arise more locally. As we have seen, useful tools may develop a certain momentum of their own. Consider the power simulation that anchored the intersection of the Start-up Timeline and Landing Site Selection threads. The need to "feed" this representation the information it required was an explicitly stated purpose of interaction even though, as it turned out, the issue was rendered moot by the incorporation of the CHPS—the essential innovation at the heart of the mission.

In the actor-discourse network formalization, stabilization will be manifest as a pattern of recurring proximity between representations, actors and issues across successive projects. The findings of this research suggest directions and elaborations, to be developed in further work, to deepen our understanding of the dynamics between generativity and stabilization in innovation, and ways in which these may be grounded in interaction over representations. This, along with critical reflection on methodology, is the subject of the following chapter.

9. REFLECTION AND ELABORATION

In the previous chapter I synthesized the results of micro and macro-analyses to develop several findings with regard to various ways in which persistent shared representations take part in productive design activity. I proposed a comprehensive framework for representational support, and several dynamics through which it was possible to characterize the work performed by representations in real-time design interaction.

In this chapter I take stock of how successfully the research has met its objectives, and discuss possible directions for further work. Critical reflection on methodology provides a starting point from which to consider more refined questions, enhancements, limitations and theoretical implications of the perspective I have developed.

Methodological Issues and Reflection

The purpose of this research has been to deepen our understanding of the involvement of persistent shared representations in situated, collaborative design. The approach involved fine-grained analysis of communicative acts and representational activity associated with collective design reasoning. This sheds light on the essential interactional work of collaborative design: a process of synthesizing perspectives, reconciling differences and consolidating commitment to action intended to bring about a preferred future.

The specific objective was a perspective and an analytic method to highlight the work performed by shared representations in design with the potential to inform other settings and contexts. The results have included a comprehensive framework for representational support and a way of looking at design interaction that is integrative and addresses gaps between prominent theoretical perspectives regarding this type of activity. The framework provides a way of understanding the state of support in any situation and ways in which it might be improved. The perspective suggests more refined questions, provides a method that will be useful in subsequent hypothesis testing, and has implications for extant theorizing on several levels of analysis.

On this basis I believe the study has met its objectives. In keeping with its exploratory nature however, a number of issues have arisen that provide impetus for improvement and further work. As a starting point, I will now shift to more critical reflection on methodology, first by revisiting other aspects of study quality as raised earlier in Chapter 3.

Study Quality Revisited

Yin (1994) presents several criteria for evaluating case study quality, including construct validity, internal validity, external validity and reliability. I will summarize each below, and then elaborate on problematic areas that suggest issues, opportunities and potential limitations.

Construct validity requires that the analytic constructs are appropriate and adequate to address the phenomena present in the data. In developing the micro-analytic approach, I reviewed a range of previous observational coding schemes and employed exploratory coding of a large number of episodes to determine which distinctions were most applicable to my data. I introduced additional categories and refinements as required by a micro-analysis of episodes selected to offer the most informative contrasts. These were ordered to introduce complexity in stages, with iterative re-coding to ensure consistency. I found certain features of network structure and discourse composition provided an effective means of identifying productive patterns of interaction across the selected episodes. Combining this with macro-analysis of developments over longer time scales yielded a set of coherent constructs regarding representational support across a range of time scales, within the overall formalization of an actor-discourse network. On this basis I believe adequate construct validity has been demonstrated.

Internal validity reflects the robustness of causal assertions made on the basis of correlations in the data. Because of the exploratory stance of this research, testing of causal hypotheses was not an objective, hence the criterion of internal validity is not strictly applicable (Yin 1994). [188] It is still appropriate to consider the validity of the relationships I proposed between network metrics and favourable aspects of interaction (and hence the implications for conversation quality). In this regard I found one metric to be robust; the second was informative but problematic in some respects. To address this weakness, I proposed a new metric as a more appropriate index for mutual engagement.[189] I also offer a number of suggestions for subsequent, hypothesis-testing research below.

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[188] Exploratory case studies are designed to provide more useful insight in situations where relevant phenomena are not yet well-enough understood to warrant the testing of specific hypotheses with regard to causal relationships. Exploratory studies should meet clearly-defined objectives and give rise to better, more refined and potentially testable questions—as this study has done. (The latter are detailed below).

[189] Some difficulties with discourse betweenness as an index of mutual engagement stem from behaviour of the flow betweenness centrality metric under certain circumstances, described in Chapter 6 and detailed in Appendix C. An alternate approach to assessing mutual engagement is described in Appendix E. Overall, discourse betweenness did appear to usefully discriminate between the positively and negatively selected episodes.

External validity reflects the likelihood that findings can be generalised and usefully applied in other cases. I argue it is positively indicated by three aspects of this work: (1) general applicability of the perspective and the utility of the roles and attributes framework to evaluate representational support in collaborative design interaction; (2) at the level of collective design reasoning, an integrative extension of theory and method that conveys the ability to ask more refined questions; (3) at other levels of analysis, consistency with the boundary conditions presented by extant theorizing. As I discuss in more detail below, while I believe this perspective has broad applicability, by no means does it encompass all phenomena that may be important in collaborative design.[190] Accordingly I anticipate several issues with regard to analytic generalization, and discuss these in terms of opportunities for further work and potential limitations of the approach.

Finally, *reliability* requires confidence that errors and bias have been minimized. As a concept, reliability is distinct from replication.[191] In research involving coding schemes, reliability is often framed in terms of the consistency with which a coding scheme can be applied by other researchers—though there are differences of opinion about the importance of this criterion (cf. Nyerges et al. 1998 and Morse 1997). In case research, since literal replication is seldom an option, reliability more often rests upon straightforwardness of method and clarity of description (Yin 1994). Would the coding scheme have benefited from having a second researcher attempt to deploy it on the same data? On balance I think it would have, had this been practical.[192] The essential question is whether the distinctions are analytically appropriate, adequately articulated and sufficiently non-arbitrary to be usefully applied by others. Toward that end I have tried to be as explicit as possible and have provided abundant detail in appendices. I hope this work exhibits the necessary thoroughness, clarity of method and quality of documentation to afford analytic generalization and theoretical replication by others.

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[190] On the whole, I argue that the method usefully highlights the involvement of representations in task processes, and allows correlation with other (e.g. socio-emotional) processes assessed orthogonally or in conjunction with other means.

[191] Though literal replication is an indication of reliability, the two are distinct concepts. As Yin (1994) makes clear, the primary mode of replication in case research should be theoretical rather than statistical. Theoretical replication is achieved when the results of subsequent cases are shown to be consistent with a particular perspective and not consistent with others.

[192] As discussed below, interpreting utterances as referring to or being about the same thing is an essential analytic judgement. For real world interaction in a complex technical domain, these determinations would be difficult for an analyst to make without benefit of the many hours of observation, follow-up and contextual interviews that comprised the data collection. In this research, one other investigator took part in observations and participated in the early qualitative analysis. Because this researcher's objectives were substantially different from mine, it would not have been possible for her to expend the redundant effort required to learn and apply the coding scheme I developed.

I will now elaborate on issues of analytic generalization, including opportunities, possible extensions, and limitations of the approach I have developed. To address potential reliability issues, I will also reflect on problems I encountered in coding and analysis and improvements that may be undertaken in further work.

Issues and Limitations on Analytic Generalization from this Setting

How likely is it that the approach I have described can be generalized, and what issues may be encountered in applying the analysis to other settings? Though the data I used in this research are drawn from a particular setting, I have endeavoured to formulate concepts in terms that will allow them to be applicable and relevant to design activity more generally. I believe the notion of alignment (the basis of the spatial metaphor PROXIMITY=AFFINITY in the network formalization), reflects an essential aspect of collaborative design interaction in many situations, wherein success depends upon achieving collective commitment and coordinated action.[193] I believe the categorical distinctions embodied in the coding scheme are sufficiently general to be usefully applied—if not comprehensive—in other settings and contexts. I recognize that particular characteristics of the setting may, however, have an impact on analytic generalization. These include:

- a relatively structured and patterned process with a leader and team members with clearly defined roles and agreed-upon boundaries of expertise
- a highly technical domain involving complex but deterministic phenomena amenable to modelling
- an engineering design discourse emphasizing rational argument within a problem solving paradigm
- primarily conceptual design activity excluding a number of non-design functions (e.g. manufacturing, sales, marketing)—and the attendant diversity of "thought worlds" (cf. Dougherty, 1992)—that might be encountered in other settings[194]

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[193] The coding scheme is essentially based on alignment as an index of an individual's expression of commitment to particular solutions and other aspects of design reasoning. The spatial metaphor is therefore a meaningful interpretation of network distance in a mathematical sense, apart from any particular visualization. Structural network metrics were used as a way of transcending the limited reliability of visual interpretation of 2D layout diagrams alone, as I have discussed in Chapter 5 and detailed in Appendix E. My conclusions about the relationship between network structure and aspects of design interaction are based upon a combination of these numerical metrics and visualizations constructed to minimize layout problems, bearing limitations of the latter in mind. I use the overall correspondence between network structure (assessed in this manner) and relevant aspects of interaction to validate the coding scheme and network formalization for design activity. While the precise details of network structure depend upon certain decisions, such as regarding the relative duration of arcs, I have articulated my reasoning and the relevant considerations, endeavoured to be consistent, and undertaken sensitivity analyses where appropriate to ensure the results are not unduly dependent upon arbitrary decisions.

[194] This is the type of situation likely to make the actor-network processes of *translation* more visible and problematic. Bringing such diverse perspectives into real-time interaction will, however, create opportunities for mediated convergence along the lines I describe in Chapter 7.

I will briefly qualify each of these characteristics before elaborating on the issues and limitations I foresee. With regard to deterministic phenomena and the use of modelling, other design fields also have their own distinct, persuasive representational practices. Many practitioners now employ computer-based tools alongside more traditional media. I have attempted to formulate my conception of representational support in terms of roles and attributes that are relevant and sufficiently general to encompass this diversity of practices.

It is also true that decades of experience in aerospace design at JPL establish a basis for substantial common ground amongst participants with regard to the ways in which design projects unfold. This is an environment, however, in which every project involves a significantly novel undertaking, continually introducing new voices and new knowledge.[195] In addition to the leader and standing team, the design process involves the differing perspectives of scientists, technology developers, other agency customers and program managers. While this diversity is perhaps not the same as one might encounter elsewhere, it does allow for significant differences of opinion and conflict to arise. All participants can, however, be expected to engage in and respect the terms of an engineering/scientific “object-world” discourse (Bucciarelli 1994).

As I discussed above (in Chapter 2) the JPL setting foregrounds task work processes over other, more socio-emotional processes. I argue that this has presented an opportunity to make representations’ involvement in task work processes particularly visible. (Indeed, rather than being incidental, this may be an essential contributory factor to the outstanding performance of these teams.) However, socio-emotional work may be equally important—even decisive—in other settings of collaborative design. This has implications for generalization and applicability which I will now review, identifying the characteristics of situations I believe will render the method more or less useful.[196]

<u>Direct Application</u>

Based on characteristics of interaction in the setting and the data I was able to collect, the observational method I present here is likely to be directly applicable to design situations with the following characteristics:

- interaction that is substantially verbalized, as opposed to predominantly implicit or relying on non-verbal communication

[195] JPL’s charter within NASA involves addressing the risks and challenges of one-of-a-kind exploratory space missions; the environment is therefore one in which profound uncertainty and innovation are essential aspects of routine (O’Donnell 2002, NASA undated JPL fact sheet).

[196] As I will discuss in a later section, the theoretical perspective may still have useful implications even in situations where the observational method is not directly applicable.

- design discourse that emphasizes explicit reasoning over more purely affective responses
- conversational contributions that, on the whole, are specifically directed and clearly pertain to particular discourse elements or features of representations

Overall, such interaction can be characterized as predominantly *rational* and *lexical*. More generally, it will be important to take socio-emotional processes, individual and collective affect, other discourses and communicative modalities into account, since these may play essential or decisive roles in other settings.[197]

Use in Conjunction with Other Methods

Essentially, the approach I have described constitutes a lens. It can be used to analytically represent the accomplishment of *task* work that is enacted through individuals' expression of differential alignment in discourse, accompanied by some form of negotiation to obtain consensus and commitment. By employing orthogonal observational methods and coding schemes for socio-emotional processes and affective expression,[198] the relationships between these and task accomplishment can be analytically investigated. Along these lines, I propose several follow-on questions that can be addressed in further work in the following section.

Different conceptions of collective reasoning may also be accommodated by reformulating categories for discourse nodes within the overall formalization. In general, the observational method I have presented can be analytically useful and should provide complementary insight in conjunction with other methods for the following types of research questions and design situations:

- questions concerning status or group dynamics, situations of actively contested status or group formation
- questions concerning tone or group affect, situations in which contributions are more overtly affective in nature
- questions concerning tension or conflict, situations in which responses are more personally directed or involve strong feelings, such as enmity or evident antipathy, between actors

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[197] I have not excluded affect and non-verbal interaction entirely; excitement, enthusiasm and expressions of satisfaction or frustration were among the criteria for episode selection. Certain gestures and physical movements in the space were coded to reflect increased levels of engagement, though these were generally in categories assigned a shorter duration in the coding scheme.

[198] Regarding coding of socio-emotional processes in groups, cf. SYMLOG (System for Multiple Level Observation of Groups), Bales 1970, 1999, as well as the system for coding enacted status presented by Owens (1998); regarding affective coding cf. FACS (Facial Action Coding Scheme), Ekman & Friesen 1978, SPAFF (Specific Affect Coding System), Gottman et al. 1996, Giese-Davis et al. 2000.

Limited Applicability

Some basic assumptions may impose more fundamental limitations on the applicability of the observational approach. First, I assume a basically constructive orientation on the part of participants, with a relative transparency of their intentions and motivation. While strong disagreements may occur, I assume participants are not engaging in intentional deception or antagonistic to the point of formulating their arguments solely to undermine each others' positions. As a reflection of the quality of design conversation, alignment expressed in communicative acts becomes irrelevant if what participants say bears no relationship to what they believe or what they intend to do.

An additional limitation on the network formalization arises from the basic assumption that shared experience of interaction can reliably be taken as knowledge in common. The network representation primarily on the basis of observable behaviour, not as a reflection of what any member of a group might be thinking.[199] The notion of distance between actors in a singular network space (albeit one of high dimensionality) are only significant when all key actors, at least arguably, have access to the same interactional events. This is justifiable in a synchronous, real-time design environment (though as we saw, vagaries of attendance and attention will remain an issue).[200] As interactions become more distributed and asynchronous, representing collective reasoning with a singular network will be increasingly problematic.[201]

Another basic assumption in the actor-discourse formalization is that participants' substantive contributions can be localized to elements of discourse. I discuss below the possibility of elaborating the formalization in areas of non-verbal and affective communication (in conjunction with the salience and impact of contributions). However, non-specific affective responses or behaviour, such as might reflect the overall tone of participants' engagement, are probably best assessed by other means. Similarly, the network representation becomes cumbersome and inappropriate when communications are

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[199] It was not possible to interview participants immediately following interactions to query what they might have meant by any particular utterance. Some inference beyond strictly what was said was necessary in order to construct networks that adequately reflected the coherence and connectedness of conversation; this was conservatively limited to what interlocutors might infer under normal circumstances based on actual behaviour (as discussed in Chapter 5). Numerical assessments of network structure were made so as to exclude some of the more speculative judgments, such as those regarding semantic associations.

[200] At least in closely coupled, synchronous interaction, significant misperceptions are more likely to be detected and remedied by participants, as compared to decoupled, predominantly asynchronous interaction.

[201] Though it is potentially a combinatorial problem, this does not preclude the possibility of maintaining separate networks for every significant subset of closely-coupled interactants.

essentially "broadcast" and/or in situations where individuals acquire an attribute or have a certain type of experience primarily as a result of their physical location.[202]

In summary, the utility of the observational approach I have presented may be more limited in situations characterized by:

- adversarial relationships in which participants lack a fundamentally collaborative orientation and/or are likely to engage in intentional deception
- predominantly asynchronous, distributed settings in which key participants' interactions with each other cannot reliably be taken as a basis for common ground for the larger group
- interaction that is predominantly non-specific, non-verbal, non-lexical, or which relies very heavily on participants' tacit understandings[203]
- interaction in which the essential notion of task work described above is not relevant

Problematic Aspects of Coding and Analysis

In carrying out coding and developing the micro-analytic approach, I found certain judgements continued to be more subjective and/or more complex than others; accordingly, it seems the following are points at which reliability issues seem most likely to arise:

- *parsing of episodes with overlapping and interwoven topics* Though all the roles and attributes of representational support I describe have manifestations in the actor-discourse network formalization, they were not entirely visible through microanalysis alone. For this reason it will be necessary to consider how longer and discontinuous periods of interaction might be analyzed, striking a balance or synthesizing aspects of micro and macro-analyses.
- *coding instances of talk as referring to "the same" thing* This is the essential analytic judgement necessary to construct an actor-discourse network. While some theorists would say we can never truly speak about the same thing, as a practical matter I relied on background knowledge and participants' behaviour to indicate when they undertook to speak about the same thing, and felt they were doing so to a degree adequate for their purposes at hand. The fact remains however, that people sometimes act as though they are speaking about the same thing when they are aware that, perhaps to a significant extent, they are not; conversely, people who share a great deal of common ground may use different lexical forms to refer to "the same" thing in ways that could escape the analyst.

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[202] This situation could arise with regard to physical spaces that tend, on the whole, to foster creative or productive interactions (cf. Hillier 1996, Hillier & Hanson 1984, Penn et al. 1999) or "cultural" knowledge transmission that is diffuse and difficult to observe. The latter might more accurately be represented as a *field* rather than a network, wherein entities acquire an attribute by virtue of their position in space.

[203] Entirely non-verbal drawing interaction could nonetheless be analyzed in terms of an affinity network so long as the drawing surface itself provided a means of localizing contributions.

- *incompleteness of reference and indexicality of ordinary talk* People communicate effectively without explicitly spelling out the full extent of the references they intend.[204] Participants with substantial common ground in close collaboration use truncated utterances with a great deal of implicit deixis. In coding, I invoked the minimum number of nodes I felt were necessary to account for the "connectedness" of discourse between adjacent contributions, limiting carryover of implicit references to a single turn. Because these judgements have a direct impact on network metrics however, consistency is essential for comparisons to be meaningful.
- *complexity of tracking and updating semantic network relationships* Participants' contributions often embody different semantic relationships between overlapping discourse elements—particularly when they are disagreeing. Registering multiple actors' contributions—which may be at odds with one another—in a singular semantic network proved difficult within the logic of the SoNIA representation. It also significantly increased the number of decisions required (and hence opportunities for inconsistency) in coding.
- *coding of inscription* Within a rather limited logic to govern arc behaviour, a number of arbitrary decisions were required to determine the strength, duration and timing of inscription codes, distinguishing between acts that ranged from casual reference to active drawing. I made these decisions to preserve an overall parity between human and representational actors. Parity, however, does not denote equality. Besides desiring a better empirical grounding for these decisions, a more complex logic may be necessary to adequately reflect representational "speech" (as discussed below).
- *inappropriate root metaphor of flow betweenness metric* The flow betweenness centrality metric is based on a conception of nodes as potential control points for information flow in homogeneous networks (i.e. networks having only one type of actor). This metaphor is inconsistent with my conception of shared discourse elements as bridges between participants. Rather than engage in a lengthy process to characterize the behaviour of this metric more fully, I proposed a new metric that I feel more directly assesses mutual engagement, with the additional benefit of optionally utilizing the semantic network in structural assessments.

These problematic aspects encountered during coding and analysis suggest a number of possible technical developments that could be undertaken for further work, including:

- changes to enhance the content and reliable interpretation of 2D layout diagrams
- a more complex logic to govern arc aggregation and temporal behaviour of arc strength
- a layout procedure to minimize artefactual movement in animations
- a metric for mutual engagement based on an electrical conductance analogy

These are described in more detail Appendix E.

[204] This is an essential insight of ethnomethodology, cf. Garfinkel 1964, 1967 and in Suchman 1987

Elaboration for Further Work

To be judged a success, an exploratory case study should meet its objectives *and* give rise to more refined and potentially testable questions (Yin, 1994). Based upon the issues and problematic aspects identified above, I propose the following directions for elaboration in further work. These include testing of follow-on hypotheses that can be addressed through the method I have developed, either alone or in conjunction with other methods, as well as certain extensions of the formalization that may be required to make the method more useful and do justice to other settings.

Refined Questions and Follow-on Hypotheses

As I outlined above, with appropriate data collection[205] and complementary observational methods, the approach I have presented can be used to explore more refined questions and to test follow-on hypotheses. Essentially, the method allows the accomplishment of task work to become a criterion variable in studies investigating hypothetical relationships with various other (e.g. socio-emotional) processes.[206] The network-based approach provides an inherent consistency with a number of other constructs amenable to social network analysis, including status, expertise and social capital.

The following are types of research questions for which specific hypotheses could be formulated and tested:

- In terms of role, status, expertise and credibility, how do formal designations compare with enacted behaviour in different situations? What behaviours appear to impact participants' assessments most decisively?
- In what ways are remote participants potentially disadvantaged? How does the composition of discourse and the character of interaction change as more participants are remote?
- With regard to the composition of discourse, engagement of expertise and use of representations, what decision quality constructs are appropriate for design reasoning in different situations?

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[205] This includes sufficiently detailed observational (i.e. video) data and adequate access to interview participants in detail about their perceptions, thinking and subjective experience of interaction.
[206] In this exploration, I utilised concepts from actor-network theory. This generally argues for a balanced treatment of human and non-human (i.e. representational) actors; accordingly, I performed my analyses on networks that included inscription and representational acts, to maintain parity with communication directly between human participants. For subsequent hypothesis testing however, if representational acts and mutual engagement are employed as predictor and criterion variables, it may be advisable to define mutual engagement only between human actors. This would eliminate a potential circularity whereby inscription can directly increase mutual engagement in the analyses I have presented.

- Under what circumstances are disagreements and tension productive? How do participants regard those with whom they disagree, as related to the substance or form of the disagreements?
- What is the relationship between participants' engagement and co-construction of representations, and their commitment to the outcomes the representations are understood to embody? What are the social effects of successful joint action in a representational domain, compared to other forms of joint action?

Extension of the Formalization

The network formalization allows for the creation of a record of observable behaviour that can be visualized and queried using numerical techniques. Construction of these representations has been a form of modelling.[207] In this spirit, working within the formalization has raised certain questions that, if better understood, will convey additional insight and facilitate further elaboration.

Registering the Impact of Contributions and Dimensions of Representational "Speech"

In the network model, arcs correspond to communicative acts of various types, and relationships between actors are primarily mediated by elements of discourse. The coding scheme was adjusted to foreground what I identified as design discourse, de-emphasizing other acts and neutral exchanges of information. In this admittedly lexical view of interaction, the parity suggested by actor-network theory essentially requires that representations are endowed with a capacity analogous to human actors' speech. How might this metaphor be taken further?

Arc behaviour is currently governed by a rather straightforward logic, wherein each arc has a fixed strength and duration, and multiple arcs between the same nodes are either summed or averaged; otherwise, arcs are completely independent of one another. As I mentioned above, more elaborate coding for non-verbal communication, and/or affectively-laden acts directly between participants may be required to reflect the impact of their contributions.

More generally, what determines the salience, impact and memorability of any particular contribution, and how important is subsequent social acceptance (and by whom)? Specifically, how should this translate into *inscription*, in terms of the parameters of the network representation (e.g. arc strength, duration)? As a direction for technical development, I would propose a more elaborate logic to allow an inscription's strength to respond to more than just the initial act that created it. It seems reasonable that a variety of

[207] Snodgrass & Coyne (1992) discuss the essential utility of models (as a subset of metaphors) in terms of their ability to stimulate cycles of interpretation and re-interpretation.

factors may come into play, including the way other actors subsequently engage, who they are, their status in the group, etc.

I formulated the concept of representational support in terms of situational attributes that essentially describe the involvement of representations as network effects. An obvious next question is, what intrinsic properties may impact any particular representation's ability to afford these situational attributes? Are there properties of media or other aspects of structure or configuration that make some representations inherently more compelling and convincing, or are these situationally determined as matters of practice? What might be necessary to account for the particularly compelling nature of prototypes (highlighted in Chapter 1, and a subject to which I return briefly in the concluding chapter that follows)? I used the term "autonomy" to refer to representations, such as simulations, that when set in motion operate subject to their own internal rules as a credible proxy for reality. Are other attributes like "totality," "fidelity" or "verisimilitude" necessary to account for complexity, detail, or the way some representations leave less to the imagination? Conversely, are representations that leave *more* to the imagination particularly powerful in other ways?

I intend this discussion to pertain primarily to the collective level of design activity, since this has been the focus of this research. By no means do I intend the situational attributes I proposed at the more individual or organizational levels to be exhaustive. It may be that engagement on an essentially affective level comes into play as well, perhaps in a manner analogous to person perception. How we feel about a representation may impact how receptive we are to what it has to "say." While these may be distinct phenomena—i.e. we can believe something without liking it, and vice versa—the most powerful representations are probably those we both like *and* believe. Again, while it cannot answer these questions directly, the approach I have described can be used in conjunction with other methods to shed light on answers that could, eventually be incorporated in the network formalization.

Other Discourses

To explore other types of design activity, it will be necessary to embrace design discourses less dominated by rational argument, and that adhere less closely to a problem-solving paradigm than the activity I observed. I propose that, subject to the considerations and limitations outlined above, this principally requires developing new categories for nodes. In the approach I have taken, the actual composition of discourse—vis-à-vis the categories for reasoning (e.g. issues, options and criteria) is only of secondary importance. The most important aspects are alignment, mutual engagement, and closure with the commitment necessary to advance the state of the design. The precise manner in which this is accomplished, and the form it takes in discourse, can be accommodated in different ways within the basic approach I have described. This is best undertaken in a data-driven manner, through subsequent work in different settings; consequently I will mention only a few differences that might be anticipated.

Coyne & Snodgrass (1995) discuss the ways in which different metaphors render different aspects of design activity problematic. Focusing on issues as initiators of cycles of collective reasoning, as I have done, is consistent with a problem-solving frame for design activity. Another conception of design sees it as fundamentally driven by the recognition of opportunities to expand the scope of what is possible. The Sony Walkman, for example, was not preceded by a recognized need for such a device. The Cryobot Lander Study was arguably initiated by the opportunity created by the compact high-power source.[208] Though it was not required by this data set, I would propose a fourth discourse category for "opportunity/possibility," complementing "issue/problem," as a first step to expand the scheme beyond strictly problem-solving discourse.[209]

Beyond such an incremental change, other features of design discourse can be anticipated. Visual and linguistic metaphor may be essential to access affective dimensions of objectives and criteria.[210] Iconic objects, projects and personalities may serve as essential "reference points" for reasoning more broadly construed to include narrative, and other ways of knowing that blend both affect and reason.[211] Other design discourses are likely to have different ways of making room for surprise, unanticipated connection and the departures from routine that are essential to innovation—as well as different ways of "rationalizing" these so they may be acted upon.[212] While the specifics may require different lenses, it is these dynamics that are at the heart of the formalization I have presented, and which I argue will be broadly relevant to design activity.

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[208] This took place prior to the research observation for this study, hence it is not present in the data.
[209] Even in a hypothetical design exercise, the frame of an imagined possible future rapidly becomes real as the "joint pretence" (Clark 1996) essential to the conversational project. It is within the context of such a frame that issues and problems arise and solutions are generated. An "opportunity/possibility" would denote a proposal for an entirely different frame, simply as an exciting possibility in its own right, not as a solution predicated upon an established issue or problem.
[210] Dumas (1994) describes the use of co-constructed "totems"—shared representations utilizing visual metaphor—as part of an intervention strategy to improve communication within product development teams.
[211] Lakoff (1987) discusses metonymy in conjunction with reference point reasoning, citing Rosch (1975, 1981). Bruner (1990, 1979) reflects on the diverse ways of knowing embodied in psychology and literature, to better understand the place of myth and narrative in thought and to advocate a broader appreciation of other-than-rational discourse—even within the sciences.
[212] Snodgrass & Coyne (1992) argue that scientific models and other metaphors share an essentially hermeneutical rationality rather than a logical one. McLachlan & Coyne (2001) find that such a post-structuralist account is most in accord with the discourse of avant-garde architects. For my purposes, the most interesting question is not how such architects persuade each other, but how they collaborate across discourse boundaries.

Representational Actors

The representational actors in this case were only a subset of the canonical forms of design representation. While CAD models and spreadsheets were abundant, with the noteworthy exception of some whiteboard sketching, other types of drawings and paper media were relatively scarce, and hardware and physical prototypes were entirely absent. In more general design interaction, other forms of representation will be involved and it is necessary to consider what one might wish to include as a representational actor in such situations.

By definition, actor-networks are heterogeneous. That is, they can include many things, ranging from individuals, to technologies, to organizations and institutions. Going forward, the question arises, how shall we bound the notion of a *representational actor*—particularly with regard to artefacts that share superficial attributes with common design representations? For example, in what sense might shared video monitors of real-time events (cf. Goodwin & Goodwin 1996) be considered representations? What about the simple computational artefacts and techniques that Hutchins (2005) describes as material anchors for conceptual blends, or the paper charts Goodwin (2000) describes for standardizing archaeological descriptions?[213] Conversely, artefacts like advanced prototypes may look far more like "the real thing" than any representation, yet still serve important representational functions.[214]

For my purposes, whether a particular artefact should be classed as a representation depends upon the way it is used more than any intrinsic property or attribute. Overall I have chosen to emphasize the aspect of *making present* (to the eye or to the mind) and *standing for* (in the manner of a proxy) to characterize something as a representation. Determining something to be a representational actor also depends upon the purpose of the analysis. If the intention is to understand the continuity of situated action or distributed cognition, then things like real-time displays and standards charts might properly be included as actors.

My central interest, however, has been understanding the ways in which persistent shared representations figure in *design interaction*. This involves more than coordination and computation; it requires commitment to bringing about a fictive future reality. I consider design representations to be those artefacts that stand for and make present the object of a group's collective work—a calculated intervention intended to bring about a preferred future. This would include representations of the designed artefact itself, as well as shared objects like profiles and scenarios that make present users and their behaviour. Procedural

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[213] Goodwin (2000) refers to these reference charts as graphical or semiotic fields, saying they are more properly seen as spaces for the production of action rather than as representations. Of course, I am arguing that design representations can also be seen in these terms.

[214] Even production prototypes—virtually indistinguishable from final products—are experimental in that they involve anticipations or approximations of "real" processes.

artefacts, like schedules and process descriptions could also take on the roles of design representations if they have a substantive impact on design reasoning.

Other questions are likely to arise with regard to more typical design representations under different circumstances. For my purposes, for example, multiple copies or instances of "the same" representation (such as a particular CAD model or document) would be treated as the *same* representational actor (particularly if participants are engaged in closely coupled interaction)—unless substantive, perceptible changes were durably inscribed on one vs. another.[215] Conversely, one might ask, at what point would an evolving CAD model become a *new* representation? I would argue that looking at the commonality of inscribed features from one instance to the next provides the most reasonable way of making such a distinction.[216] However, when representations—even those sharing substantial features—are made present simultaneously to embody a choice between mutually exclusive alternatives, these must be treated as distinct representational actors.

<u>Parsing, Conjoining, Collapsing and Expanding</u>

To expand the scope of the method I have presented, it will be necessary to encompass interaction over longer time frames and across temporal discontinuities. For further work I propose two developments that will be required to make this possible. One is a less fine-grained approach to coding, so that the analysis of longer periods is not inordinately time-consuming; the other is a less-subjective basis upon which to parse interaction and conjoin related but temporally distinct episodes.

For a less-fine grained approach to coding, I propose returning to the essential cycle of collective design reasoning, discussed in Chapter 8 (and in Appendix C), that was evident in the positively-triangulated episodes. This involved some form of initiation or opening, followed by subsequent development of a problematic situation and potential solutions, leading eventually to some form of closure with enhanced design specificity and commitment. I propose that a more streamlined coding approach could be developed at the level of this cycle, with individual actors' engagement normalized in some way to reflect their alignment with respect to key outcomes.

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[215] For example, annotations on one copy of a document that became a shared referent for a subset of people in a meeting could become a distinct representational actor.

[216] Note that the process of inscription I have outlined allows a representation to assume different figurations in different contexts, by virtue of what features are identified by different actors. Over longer time frames, distinct representations sharing a substantial number of features will remain close to each other in network space, so the question of whether something should be a distinct representational actor becomes one of degree rather than kind.

This type of analysis will always require some sort of bounding, and it may be that only a fraction of the interaction in a particular setting pertains to a feature of interest. Since real-time design interaction involves a fluid shifts between topics and participants, the issue of parsing remains complex. For further work I propose that a proximity threshold for network distance can be used as a more reliable basis for many of the decisions required to analyze longer episodes and discontinuous periods, including:

- distinguishing threads on the basis of clustering of issues and actors in network space
- distinguishing between actors (both participants and representations) who participate broadly across many issues vs. those that are more narrowly focussed
- parsing on the basis of discontinuities in the temporal evolution of the network (jumps between disparate parts of the issue-actor space in the absence of any content-logic connection)
- conjoining temporally discontinuous sequences of interaction on the basis of their proximity in the issue-actor space

Another issue is how one might reconcile and merge the effects of interaction across discrete episodes and from analyses performed at different levels of granularity. For this, an approach to collapse the level of network detail to a uniform consistency may be useful. As I illustrate in Appendix E, a pair-wise closeness metric allows conversion of an actor-discourse network to one consisting only of actors.

To understand the temporal evolution of design reasoning, however, I argue that discourse should not be excluded entirely. The most productive simplification is likely to be one which retains key relationships between actors and the discourse principally associated with initiation and closure. Such a network could be obtained from the type of coding I performed by driving the strength of all semantic arcs to be very high. This would have the effect of collapsing all the discourse that pertained to a particular issue into a single node.[217] Participants' proximity to this node would reflect their overall engagement in the discussion and their alignment with the approach embodied therein.[218]

This notion of collapsing the elements of a confirmed agreement onto a singular node is essentially comparable to the actor-network processes of "punctualisation" (Latour 1986, 2005) or "black-boxing" (Latour 2005). This is one way in which the effects of jointly-accomplished work and consolidated agreement—particularly when robustly inscribed in

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[217] This could provide a network formalization corresponding to Dorst & Cross' (2001) co-evolution of problem and solution spaces.

[218] This might obscure subtle defects of consensus, such as we saw in Episode 12, unless these were registered in other ways.

representations—might stabilize constellations of actors around a particular design approach. Understanding design in terms of the temporal evolution of such networks leads us to some explicit theoretical elaborations which I will now discuss.

Theoretical Implications

The review in Chapter 2 highlighted several discrepancies between the prominent theoretical perspectives that address situated work interaction around shared external artefacts and representations. The situated action perspective is characterized by close attention to artefacts and fine-grained interaction analysis. Its focus, however, tends to be on relatively low-level coordination processes and behaviours which, despite their importance, are somewhat removed from practitioners' consciously-formulated instrumental concerns. Along with a certain scepticism toward the notion of representation, this remove makes it difficult to relate situated action analyses to a relevant theory of performance for design. Distributed cognition also devotes close attention to artefacts in interaction. Out of a desire to speak authoritatively about internal mental processes however, it tends to focus on highly structured interaction and essentially computational tasks that bear little resemblance to design.

Activity theory delves into the relationships between subjective awareness, motivation, and the socio-cultural-historical patterns embedded in tools and artefacts. By emphasizing the constituent structure of each activity system however, the framework becomes somewhat cumbersome when it comes to interaction at the *intersection* of activity systems. An explicit stance to disregard any distinction between that which is internal vs. external to individuals also makes the perspective problematic for design interaction, where external representations are of obvious and undeniable importance.

Actor-network theory (ANT) addresses precisely this intersection of activities, but focuses on points of contention, coordination and the dynamics of allegiance to delineate the relevant structure of the systems involved. This makes it a useful perspective with which to understand change and technological innovation. However it offers no detailed account of how essential processes (i.e. translation, conscription, punctualisation) are actually manifest at the level of interaction, or how they are accomplished through interactional work. Whereas activity theory accounts for innovation as a result of internal contradiction *within* systems, actor-network theory depicts it as a result of tension and competition *between* systems. In design, innovation involves both competition and creative collaboration, so it seems reasonable to attempt some sort of synthesis.

Constellations of Issues and Actors

In my conception of representational support I have tried to account more explicitly for the essential involvement of design representations in this range of processes. By making actor-network concepts operational at the level of interaction, in terms of alignment—and by treating representations as actors, I have synthesized a triadic communication model comparable to that embodied by the situated action and distributed cognition approaches. Drawing upon aspects of activity theory that better account for individuals' motivations, I have offered an account of how conscription operates through individual actors' proximal concerns, their collective reasoning, inscription, and attributes of representational credibility and robustness.

Essentially, this leads to a view of design activity in terms of temporally evolving constellations of issues and actors, in which representations act to mobilize and anchor networks of commitment. Ultimately, this approach provides an answer to what it is that is *created* through design collaboration—particularly in the case of commercially meaningful innovation. I argue that it is these constellations—their order, stability and robustness—that is the essential product of collaboration. Achieving the necessary alignment of actors and a configuration of representations that will enable such a constellation to enlist an expanding network of allies *is* the interactional work of collaborative design.

With regard to collaboration, this framing helps us avoid difficulties with treating *ideas* as outputs, and getting mired in questions about whether one outcome is *more creative* than another.[219] Instead, we can characterize outputs in terms of the span of the networks that are created, and the resources they are able to marshal. This maintains a fundamental consistency with both actor-network and activity-theoretic accounts of innovation, allowing their respective dynamics to be explored. Finally, this notion gives a specific and concrete meaning to the commonly-used phrase "more than the sum of the parts" that I have chosen to incorporate in the title of this thesis.

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[219] Tang 1989 (pp. 105-109) describes an early analytic focus on "idea careers" which he abandoned as it became clear that tracking ideas as robust units was problematic. An advantage of the approach I have taken is that it presents no particular problem if options are modified, blended with alternatives or discarded. Productive interaction can be manifest in an increasingly robust network structure of actors aligned with discourse, even if no single proposal survives uniformly intact throughout. Sawyer 2003b (pp. 170-175) similarly brings up difficulties associated with focusing on ideas in conjunction with group creativity. Sawyer's answer to what it is that is created in creative collaboration (in the context of improvisational performance) is the performance itself—including relatively intact sequences that serve as "ready-mades" incorporated in subsequent performances. While Sawyer notes significant differences between performance-based art and collaborative work in organizations, his notion of ready-mades as products of collaboration is compatible with the actor-network concept of punctualisation, or the creation of durable network objects.

Certain criticisms of the approach I have described might nonetheless arise from a canonical ANT perspective. Whereas Latour (2005) admonishes the ANT-analyst to follow controversies, an objection might be raised that my approach overly favours consensus and agreement. I argue that the conception of spatiality I employ, based on a notion of alignment as an interactional "building block" of commitment, is essential to the purposeful nature of small group design activity. The heterogeneous and dynamic nature of actor-networks means, however, that associations always involve translation and that instability, rather than stability, will be the norm. "Design by committee," it seems, is invariably a pejorative term with regard to design, and emphasizing consensus above all else is not a road to success or innovation. As I mentioned above, the method I have described enables more refined questions about potentially constructive aspects of tension and conflict to be answered in further work.

An additional objection may be raised to the network formalization I have adopted. Both Latour (2005) and Law (Law & Hassard 1999) argue against overly static interpretations of spatiality in actor-network accounts.[220] Indeed, Latour (2005) argues for text as the medium best suited for analytic portrayal. I have made a tradeoff here: opting for a more singular conception of spatiality enables an internally consistent representation that is particularly effective at "summing up" analytically-distinct judgements of actors' moves. I justify encompassing my actors in this homogeneous spatial representation by virtue of the fact they share significant common ground[221] and their interaction is sufficiently closely-coupled to ensure that conflicts between viewpoints are reliably surfaced. As I mentioned above, as we depart from these conditions, a singular spatial representation becomes increasingly problematic.

Compared to the heterogeneity present in other actor-network analyses, it may be that the process of translation was less in evidence (compared to those of conscription and punctualisation) in this setting.[222] However, insofar as a collaborative effort involves closely-coupled, face-to-face exchanges with the necessary outcome being some form of consensus and commitment, I believe the network formalization I have described is relevant and potentially useful.

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[220] Latour (in Law & Hassard 1999) particularly objects to the notion of a network that entails an instantaneous, faithful transport and relocation of information which is, in fact, antithetical to the conception of translation in actor-network theory.

[221] This includes respect for the fundamental terms and norms of techno-scientific discourse, (cf. Bucciarelli's (1994) "object world").

[222] Indeed it may be that the problematic communication I identified in Episodes 21 and 54, when experts had difficulty seeing eye to eye and using consistent terms to describe radiation and its effects, exposed a point at which a successful translation (in the ANT sense) had yet to be accomplished.

Implications for Extant Theorizing

The focus of this research has been on the collective accomplishment of design reasoning through interaction; however, the resulting view has specific implications for extant theorizing at more individual and organizational levels. I will touch upon these briefly by returning to the dynamics of generativity and stabilization, discussed above in Chapter 8.

Toward shorter analytic time scales, I have illustrated how connectedness in discourse involved image-schemas—both verbalized and in gesture—that can be incorporated in network structure. Though the mechanisms are probably different, these schemas appear to have played a role in emergent developments arising both in talk and interaction with shared representations. Oxman (2002) asserts that domain-specific knowledge, in addition to more basic perceptual processes, are involved in visually-mediated conceptual emergence at the individual, psychological level. I propose the possibility of extending this view of emergence to include the effects of contributions made *by other participants* in social interaction. Focusing on the schema transformations embodied in participants' contributions may be a way of extending theorizing about perceptual and cognitive emergence to take social interaction into account.

Conceptual blending theory (Fauconnier & Turner 2002) proposes another potential mechanism for generativity, by describing how conceptual blends give rise to mental spaces with emergent properties. We can ask, what mental spaces may be anchored by the features of shared representations? I propose that, based on the interaction I observed, design representations may invoke some or all of the following:

- embodied and kinaesthetic knowledge pertaining to three-dimensional shapes, material properties, movement and other behaviours
- knowledge of abstract principles and mathematical relationships that govern aspects of form and function
- environmental and experiential knowledge about context and the conditions into which the design object will be placed
- process and procedural knowledge of the collective and organizational work required to realize a particular design
- personal experience necessary to estimate the effort required on the part of the individual, along with consequences and benefits likely to result from commitments they make to the team
- awareness of the points at which a successful outcome depends upon the commitments and skills of other members of the team

When someone else reads something unexpected into a representation and voices this to the group, how is one's own interpretation impacted? By looking at the adjacency and content of contributions, it may be possible to understand in more detail the ways in which these spaces are associated with each other, and how these associations are mediated—both by features of representations and by interaction with other participants.

We can also direct attention to the ways in which representations are implicated in longer-term organizational processes and persistent features of practice. The view I have developed is consistent with the boundary conditions presented by the theoretically-informed ethnographic studies I discussed in Chapter 2. Specifically with regard to collective, organizationally-situated design practice, Henderson (1999) formulated a conception of meta-indexicality as a property of design representations, and articulated a role for prototypes as conscription devices. Meta-indexicality is an unwieldy concept however, perhaps because it encompasses such a great deal.

For Henderson, the concept denotes the drawing together of participants, the holding multiple forms of knowledge (tacit and explicit), as well as an ability to support flexible use in different situations. The framework of situational attributes I have proposed can be used to unpack this property of meta-indexicality to reveal distinct functions, and also to account for the effects of conscription and representations as "carriers of practice" and "social glue" (Henderson 1999). In my view, these functions resolve across the distinct attributes of *responsiveness* (as a matter of co-construction and joint action), *authority* (as a matter of collective reasoning and storytelling), *span* and *robustness* (as matters of continuity with practice). Because each concept is more specific, and because each can be related to distinct actor-network manifestations, the performance of different representations can be understood in terms of distinct features and more meaningfully compared.

Bucciarelli (1994) describes the interactional work of collaborative engineering design as collective "story-making"—the production of a jointly-constructed account with the right kinds of discourse characteristics. I have elaborated this production as a matter of design reasoning, coupled with the alignment of key actors. In essence, by looking at discourse composition, the degree of convergence and closure in an actor-discourse network, we are able to say *when* a good story has been told, *what* it has involved (including how it relies upon any number of technological and representational actors) as well as *who else* considers it to be a good story.[223]

[223] Equally interesting from an actor-network point of view is how the same representation might anchor *different* good stories for different constituencies, by anchoring their respective proximal concerns or otherwise enabling them to accomplish their objectives. Whereas I have provided an account of *conscription* above, this would correspond to the actor-network process of *translation*.

Finally, where Carlile (2002) refers, rather generically, to “knowledge transformation,” we can now see a distinct process whereby participants layer their discrete contributions and weave them together, integrating them to create new knowledge and inscribing this in new representations. We can also see how, over time, collaborating participants may need to “un-learn” things they *thought* were essential, as they distance themselves from reasoning, conclusions and representations with which they were once closely aligned.

These theoretical considerations are balanced by a number of more practical implications for collaborating teams and organizational groups. These, and some of the other issues and motivations I identified in Chapter 1, are the subjects to which I return in the following, concluding chapter.

10. CONCLUSION

In this final chapter, I briefly review the contributions of the research in light of the study's broader aims and motivations more generally. Putting the work in context frames a final discussion of practical implications, what may come next, and how I or others might build upon the work I have described.

Objectives and Motivations

Through the work I have reported in this dissertation, my aim has been to advance our understanding of design collaboration over persistent, shared external representations. The representations employed in design commonly include drawings, models and prototypes—but I have extended the category to include any persistent, material artefact that can, in some way *stand for* or *make present* the object of a group's collective work effort. An essential property common to all such design representations is their instrumental association with a fictive, preferred future and/or with a course of action aimed at bringing this future about.

Essentially, collaborative design involves synthesizing perspectives and identifying alternatives, reconciling differences and consolidating commitment to collective action. My motivation in undertaking this research has been a keen interest in creative collaboration, and a belief that expanding our repertoire of shared representational objects could potentially improve the productivity and effectiveness of many purposeful, small group interactions. Consequently, I set out to understand the roles played by shared representations in collaborative design interaction, particularly with regard to the emergence of novel outcomes associated with innovation. My specific objective has been to develop an analytic perspective, grounded in an observational method, to make visible the work performed by shared representations in this context.

I approached this objective empirically, through an exploratory study of an exemplary case: a leading "real-time" concurrent design practice noted for accelerated performance and prominent use of advanced shared representations.[224] This setting presented a unique opportunity for research. While the high degree of temporal and spatial bounding inherent in the practice afforded fine-grained analysis of interaction, the activity remained situated within an authentic organizational context with real-world performance imperatives.[225] This

[224] I discussed objectives and outcome criteria appropriate for exploratory studies, and the validity and potential utility of single-case studies, in Chapter 3. These considerations were revisited in Chapter 9.
[225] I discussed the nature of the concurrent design practice at JPL as both essential to the work of the laboratory and professionally beneficial to the participants involved, in Chapter 4.

allowed relatively close observation of practicing designers, collectively engaged in real work, to be combined with meaningful assessment of process and outcomes.[226]

The setting provided an opportunity to focus particularly on the accomplishment of task work in conjunction with shared representational activity. I believe the approach will be applicable in other contexts, and has the potential of doing justice to novel forms of representation as well as more conventional media. I also recognize that particular characteristics of the setting entail certain limitations for the approach I have described, particularly with regard to more socio-emotional small group processes and affectively-laden modes of expression. Accordingly I have proposed a number of refined questions and potential elaborations that may be undertaken in further work.

Contributions of the Study

I have described an observational method and an analytic technique for the assessment of design interaction based on a novel actor-discourse network formalization. Using this technique, I portrayed a number of ways in which shared representations are involved in accomplishing the essential work of real-time, collaborative design. At a micro level, useful information about the nature of interaction taking place can be extracted from aspects of network structure. By selecting and comparing episodes on the basis of indicators of productivity, I was able to associate patterns of interaction with the quality of conversation in the context of real-time design.[227]

Synthesizing these results with a more macro-level analysis, I described specific roles and situational attributes of representations that foster advances in a cycle of collective design reasoning. These roles and attributes, operating over different time scales, inform a comprehensive notion of representational support for design interaction. By negation, they

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[226] These included criteria based on observation of design sessions, participant interviews regarding noteworthy developments and demonstrably innovative outcomes (supported by participants' internal presentations and professional publications). The situated nature of the activity meant that participants' behaviour and representational activity were authentic responses to a legitimate range of demands and constraints. It also enabled the analysis to relate participants' immediate behaviour to their longer-term objectives and professional considerations (illustrated by the analysis of the landing site selection thread in Chapter 7).

[227] This involved qualitative assessment of network structure on the basis of network visualizations, quantitative evaluation of numerical metrics (not subject to the distortions inevitable in layout diagrams), and additional insights obtained from the categorical composition and temporal evolution of discourse (detailed in Chapters 5 and 6, summarized in Chapter 8). Qualitative agreement was sought for the purpose of validating the adequacy and internal consistency of the coding scheme; this was reinforced by the correlation between session observations and numerical metrics. Utility of the analysis was further demonstrated by its ability to surprise and reveal subtle aspects of interaction in the data (specifically with regard to Episodes 12 and 54 in Chapter 6).

call attention to problems that may arise in under-supported situations, or with disparities of access or participation.

This work has both theoretical and practical dimensions. On a theoretical level, the overall contribution of the perspective I have developed lies in making concepts derived from actor-network theory operational at the level of design interaction. It invokes aspects of activity theory to better account for individuals' motivations in this context, while preserving a focus on the group as the primary level of analysis. The result is a conception of design activity in terms of the temporal evolution of constellations of issues and actors, in which representations act to mobilize and stabilize networks of commitment.

The network formalization of design activity is useful because of its consistency with other forms of relational analysis involving social networks. It enables a connection between phenomena in interaction and essential processes (e.g. interessement, conscription and punctualisation) in actor-network theoretic accounts of innovation (cf. Akrich et al. 2002).[228] It also provides an answer to what is *created* through creative collaboration that is directly meaningful in the context of innovation, characterizing *collective* outputs that are clearly distinct from individual constructs related to creativity and ideas (cf. Sawyer 2003b).

With this method, the dynamics of collective design reasoning can be documented, in conjunction with other observations, to enable testing of follow-on hypotheses regarding a number of other relational constructs and more socio-emotional group processes. The concept of representational support can be used to distinguish the effectiveness of different representations in fulfilling certain roles, as well as a way of conceiving how any given interaction might be better supported.[229] While the method could be used to provide feedback on the quality of conversation in real-time design, a greater value may be in the portrayal of the nature of collaboration in this context. This view emphasizes mutual engagement and appropriation, for example, over argument. It provides an understanding of the ways in which representations mediate dynamics of acceleration and compression essential to real-time design environments, as well as the need for both generativity and stabilization.

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[228] Akrich et al. (2002) also foreground a process of "accusation," whereby nascent socio-technical configurations are challenged by actors with competing or conflicting interests, as another essential constituent process in innovation.

[229] This is facilitated by the table summarizing roles of representations in Chapter 8. Examples relating to representational responsiveness and task schematization are mentioned in conjunction with problems the team encountered in the start-up timeline and telecommunication architecture threads discussed in Chapter 7. The landing site selection analysis, also presented in Chapter 7, provides a useful illustration of the way in which a mediated convergence of perspectives may be achieving through a simultaneous and credible representation of proximal concerns.

Certain developments, as I have discussed, will make the method more useful and will be required to meaningfully analyze longer and discontinuous periods of interaction. Despite these limitations, the view I have presented describes a number of useful and essential roles for representations in design interaction. These include how representations can be used to convene groups by carrying inscriptions of proximal importance and facilitate the engagement of stakeholders. It addresses how they can respond to change acts and carry inscriptions to preserve key outcomes of interaction. Finally, it draws attention to the way in which representations can "stand for" consensus and agreement, and provide a field for successful joint action. On this basis, I would like to explore how these roles might have broader implications for team performance, subsequent research and technological development.

Broader Implications

I now return to discuss some of the issues I raised in my introduction in Chapter 1. These topics are more open-ended and speculative than the specific aspects of follow-on work and theoretical implications I discussed in the preceding chapter. (They also bear a less direct relationship to what I was actually able to accomplish.) Nonetheless, these questions have been important for me in the research process and I hope some aspects of this discussion might prove useful for further work.

Team Performance

In Chapter 1, I mentioned a number of factors, suggested by a confluence of management literature and empirical organizational research, that appear to promote successful collaboration and enable the performance of teams in organizations. I would like to return to these subjects to see what insights this research might convey. These factors related broadly to shared task focus, substantive participation, and the creation of an appropriately supportive yet challenging environment. Specific constructs for further empirical research included shared mental models, collective cognition and group affect. In what ways might the interactional phenomena highlighted by the method I have developed relate to these processes?

A shared representation, closely identified with the object of collective work and the focus of strong mutual engagement, would seem to be a very good way of instilling (and analytically assessing) a shared task focus. When such a representation makes present participants' proximal concerns, and is able to respond to register their contributions in interaction, substantive participation would also seem a likely result. Attending to the *distribution* of actors' contributions to collective design reasoning seems as good a way as any of talking about shared mental models. By providing an observational basis upon which to make statements about models that are otherwise "mental," it also becomes possible to make more precise and meaningful statements about which aspects are shared—and which are not.

The ability to identify, and perhaps quantify distinct effects in the network formalization suggests this method may provide a useful means with which to explore these phenomena. It also has implications for the actor-network process of *translation*, which might relate to the ways in which disparities and inconsistencies between such models and interpretive frameworks are negotiated. If not reconciled, these must be at least neutralized or sequestered in some way, so as not to present obstacles to collective action. This suggests that, beyond shared mental models, understanding successful performance may require equal attention to the management of what is un-shared as well.[230]

With regard to team performance, it is also appropriate to return to the question of prototypes as representations. What is necessary to account for the particular motivating power of a prototype? This is an important question that should be the focus of specific inquiry in its own right. The compelling nature of the reality embodied and portrayed by a prototype seems as likely to involve issues of affect and identity as of a particularly powerful and credible form of representational talk-back. In the view I have developed, it is possible to understand ways in which prototypes might be particularly effective network organizing devices.

In addition to conveying a compelling sense of reality, prototypes embody a particular kind of stabilization that stems from the fact that, unlike representations such as drawings, technological artefacts are not arbitrarily malleable. As a representation becomes more like a prototype, it incorporates—by virtue of the decisions it embodies—durable technological actors that are increasingly resistant to change because of the network of dependent decisions and the commitments of other actors. While it remains in some sense experimental, a prototype at the heart of a design effort represents an aggregation or black box that actively resists being cracked open—unless a successful "accusation" (Akrich et al. 2002) can be mounted against it. As actor-network accounts make clear, innovation is very likely to involve contention, distancing or breaking away from some part of an existing

[230] Some of the other factors identified in Chapter 1, including group affect and what might constitute an appropriately supportive yet challenging environment, seem to be among the factors that are off-loaded onto the system at JPL. More a part of the background than the processes I could easily observe empirically, these are likely to be more directly assessed by other methods.

constellation, in order to make room for novelty. At some point it becomes necessary to resolve competing claims and determine who and what will be listened to and incorporated, and conversely which perspectives will be excluded or rejected.

Social Cognition

Some of the factors the JPL setting allowed me to bracket out of my analysis can, I think, shed light on a number of dimensions of truly *social* cognition taking place within design teams.[231] Design groups enact their collective reasoning on the basis of their members' expertise and some pre-determined or emergent division of labour. Such groups need to ascertain what expertise and experience are relevant to the task at hand, and with whom they reside. They also need to ensure that their work can enlist support and withstand potential challenges from outside. These imperatives are inevitable in modern organizations with internal competition for resources and commitments. These seem not only to relate to design, but to be essential characteristics of collective human action (perhaps having been so for millennia) that rely upon processes that are inherently social.

It may be possible to understand the effectiveness of JPL's concurrent design teams in terms of social cognition and the allocation of collective cognitive resources. At JPL, domain specialization and agreed-upon roles mean teams generally don't need to expend a great deal of time or energy deciding how to approach a project, what skills are necessary, where to find them, or determining who will be in or out of the group. These processes are therefore not particularly visible to the analyst, because the work has essentially already been done—off-loaded onto the system and larger organizational context. Even at JPL however, a successful proposal must generate interest, excitement, confidence and allegiance—both within and beyond the group engaged in design.

These processes involve more than collective reasoning and sound argument, and they are likely to involve representational activity to some extent. In addition to the more specific questions pertaining to socio-emotional processes in design groups I raised in the preceding chapter, broader questions can be raised about the interweaving of social cognition and representational activity. How is the credibility of an individual or a representation determined; how does one enhance the other? How do representations become "group property" and what essentially collective functions do they support?

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[231] While distributed cognition has generally focused on highly-structured, essentially computational tasks that involve multiple individuals, some cognitive scientists have undertaken to understand cognition as a unique phenomenon at a social level as well (cf. Resnick et al. 1991, Nye & Brower 1996).

These questions are far broader than what I could hope to address in this study. I simply raise them in hopes that research into social cognition may be able to shed light on the involvement of representations in inherently-social processes that go beyond what are essentially computational tasks. In the manner Donald (1991) has portrayed external symbolic support systems as essential enablers of more complex forms of human living, I hope we will develop greater insight into additional dimensions of shared representations' involvement in collective action. In this vein, I would like to briefly revisit a few ways in which the perspective I have sought to develop through this research may bear upon the opportunities rapid technological developments now present.

Technologies for Engagement and Co-construction

The potential for computer-based representations to aid design thinking goes beyond the high-fidelity and geometrically accurate renderings produced by today's sophisticated 3D CAD systems. Technologies under development will allow for increasingly immersive experience of imagined and artificial environments, gestural modes of input, tactile and other rich sensory feedback, as well as integration of high-fidelity physical modelling. Increasingly, agent-based and dynamic systems models and simulations will be used to make natural and social phenomena *present* to participants in design processes. Communications technologies will enable broader ranges of stakeholders to make themselves present to each other, and to *re-present* their interests and perspectives.

As these representations become more comprehensive and credible, they will take on a measure of autonomy that will require us to see them as actors in their own right. Moving toward a conception of interaction with the potential of doing justice to these kinds of behaviours has been an objective in the work I have undertaken. Another important objective has been to emphasize the importance of co-construction. To illustrate the nature of the change I see this entails, consider the following examples.

A recent film, "Minority Report," includes a detailed portrayal of sophisticated computer interface technology projected to exist in the year 2054.[232] In the film, the protagonist appears surrounded by a large, wrap-around display, nimbly sifting sorting and connecting kaleidoscopic fragments of visual information—under great time pressure—to identify the

[232] "Minority Report," directed by Steven Spielberg, premiered in 2002. It is based on a short story of the same name by Philip K. Dick. To develop visuals and the depiction of specific technologies, Spielberg convened a group of respected technologists and futurists to envision settings for the film, and obtained ongoing advice regarding specifics of computer interface technology (Clark 2002, Kennedy 2002).

perpetrators of crimes *before* they act.[233] The futuristic policeman, part of an elite "pre-crime" unit, assumes the stance of a conductor with imagery flashing before him, responding fluidly to his head, arm and hand movements. Yet, he is a conductor without an orchestra; other individuals stand by only as observers, their presence irrelevant—other than as witnesses to an act of deception around which the plot revolves.

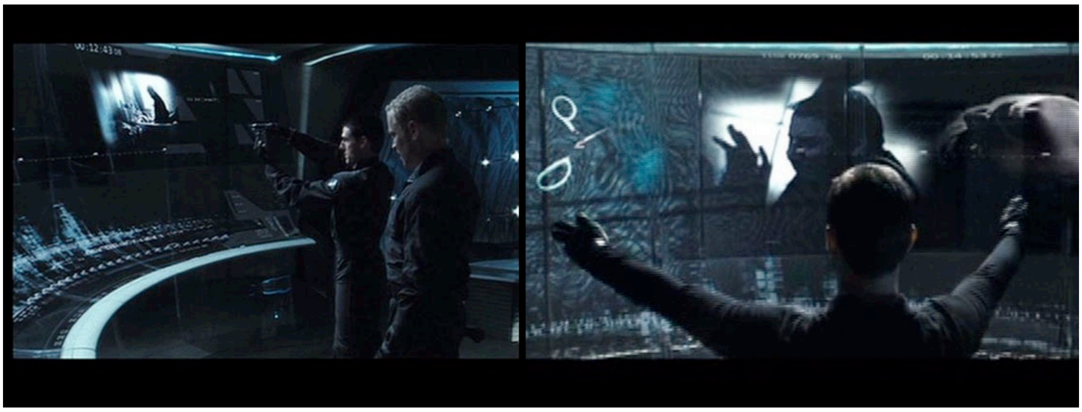

Figure 10-1 Still Images from the Film "Minority Report"
(2002) directed by Steven Spielberg, distributed by DreamWorks SKG Twentieth Century Fox. Prominent futurists and technologists in the field of human-computer interaction were consulted for this depiction of computer interface technology in the year 2054. Despite advanced features, including a wraparound display and gestural interface, the portrayal primarily involves only a single individual interacting with technology.

An alternate view of the use of representation—in a decidedly non-technological but highly mediated interaction—is embodied in the practice of the architect Will Alsop. Alsop prominently incorporates drawing and painting in his practice. In particular, he describes the creation of large paintings, sometimes metres in size, as essential to his creative process.

[233] This dystopian future, with individuals banished to indefinite cryogenic suspension for crimes they were *about* to commit, is avoided when the protagonist uncovers a nefarious plot by the creator of the "pre-crime" detail, using it to obscure a murder he himself has committed.

Figure 10-2 Will Alsop's Large Paintings
(a) Powell, K. (2002). *Will Alsop, Book 2 (1990-2000)*. London, UK: Laurence King; (b) a depiction of Alsop's proposal for a canvass tunnel for public expression, submission for the Montreal Biennale 2004, <http://www.arch.mcgill.ca/prof/drummond/arch672/fall2004/alsop2.jpg> Alsop's architectural design process involves large paintings, working with his close collaborator, painter Bruce Maclean, as well as in more participatory settings to engage members of the communities where projects will be situated.

Alsop emphasizes the importance of large body movement and the sheer, environmental presence these paintings have in the visual field as necessary to make the aesthetic connection with environmental experience required for architectural design. Alsop disavows his paintings as being representations of buildings per se. Though some forms and motifs may originate in these works, he emphasizes them as vehicles for establishing more affective connections in a convivial social environment.

> It seems to me that what you build is the result of a process, and if the process is boring, the results are going to be boring. If its exciting and enjoyable, then you might end up with something optimistic. (Alsop in O'Callaghan (2004), interview for BBC Architecture Week.)

Cognitive science increasingly implicates the body and movement in processes previously thought to be purely mental in nature, and Alsop's ideas are not inconsistent with HCI researchers' interest in gestural interfaces—such as those depicted in "Minority Report." Two essential differences exist however, between Alsop's practice and the vision portrayed in the film. One is the importance of the *materiality* of paint itself, its presence as a medium, which Alsop emphasizes. The second is the fact that Alsop's works are essentially collaborative in spirit.[234] The size of these works and the accessible nature of the media allow the simultaneous involvement of multiple individuals.

Of course, the activity portrayed in Minority Report is fictional, so there is little point in talking about it as if it were a real work practice. (Nor have I observed Alsop's practice.) It is the seemingly paradigmatic portrayal in the film, of interaction with information

[234] Alsop undertakes these works with his collaborator, painter Bruce Maclean. He also describes engaging in collaborative paintings with members of the community prior to developing the design of the Peckham Library in London, awarded the Stirling Prize in 2000.

technology as an individual activity I wish to question. There is no reason to think such a sense-making task would necessarily be more effectively performed by an individual than by a group. The metaphor of a *conductor* is a desirable step away from that of a user—or worse, a mere operator. However, while immersion and fluidity are important, so are availability and responsiveness to multiple individuals. It is necessary to understand what underpins the evocativity of design representations, as well as their authority, and to configure them to support collective acts of co-construction as well as individual processes of cognition and reasoning.

Collective Wisdom

Faced with the prospect of ever more immersive, socially-engaging and persuasive representations in design process, we also must ask the question what constitutes wisdom in these settings. I have asserted that the formation of consensus and commitment to action are essential aspects of collective design reasoning (hence an important aspect of what might be seen as social cognition in the design context). Accordingly, I placed these in the foreground of my analytic method. In undertaking this project, I was motivated by a conviction that small-group interactions involving diverse thought worlds might be enhanced and made more collaborative through the use of shared representational objects. What if improved representational support, however, entrains groups in self-sealing assumptions, counter-productive patterns of thought or dangerous courses of action?[235] This question lies beyond the scope of the project I set for myself, but completeness demands a brief discussion. This requires standing for a moment outside the protective brackets holding consensus and commitment to be desirable and good.

In a broad discussion of diverse theories of decision making, March (1994) described individual, situational and organizational factors that impinge upon decision processes and lead to poor outcomes.[236] Describing the limitations of rational-choice, bounded rationality and rule-following models, March advocates an awareness of the reflexive relationship between identity and decision making. He refers to the need to augment logics of consequence and appropriateness with "a technology of foolishness." This allows decision makers to suspend prevailing expectations of logic and consistency, to experiment and creatively re-construct experience, memory, intuition and conceptions of self. "They need

[235] Small group processes leading to pitfalls in policy decision-making were first described as "groupthink" by Janis (1972).
[236] March (1994) discusses individual and structural limitations on the robustness of inference in decision making in organizations. Structural limitations relate to the paucity, redundancy, ambiguity, and the strategic (or political) nature of information.

ways to do things for which they currently have no good reason. In that sense, at least, they need sometimes to act before they think." (March, 1994, p. 262).

Representational support should augment human capabilities with respect to things people are *not* particularly good at; this may include offsetting foreseeable limitations of attention, memory and reasoning. But the expectation should not arise that wisdom could ever be off-loaded onto representations—this remains principally a matter of the careful selection of human participants and the validity, integrity and strategic diversity of their perspectives. The notions of representational span and robustness must also entail some awareness of how easy it is for new participants to enter, and the way in which dissenting voices are treated.[237]

Representations and the Research Process

The conduct of this research has, itself, been an instance of the broader project—in terms of the effects different analytic representations have had. For purposes of analysis, such a complex activity as design must be reduced and re-presented, highlighting some aspects while obscuring others. Awareness of this is particularly important as specialized, computer-based analytical tools bring their relentless efficiencies and schematization to bear. In developing an adequate portrayal of collective design reasoning, both network and categorical analytical representations have proven to be useful and necessary. Synthesizing what each has had to offer, and determining the visual form in which to present complex (albeit reduced) data has entailed its own challenges, and I hope the dissertation proves valuable to others in this regard as well.

Latour and Law (1999) advocated text and the more fluid properties of language as the appropriate vehicles with which to express the dynamic and heterogeneous nature of actor-networks. I have argued (above) that within the context of design and purposeful small-group interaction, the more singular interpretation of network spatiality and the efficient "summing up" enabled by my approach are justifiable and advantageous. The more ethnographic accounts of representations in design practice (e.g. Carlile 2002, Henderson 1999, Bucciarelli 1988, 1994), also describe connections between people and objects (both artefacts and discourse). On one level, I have simply made this network language more explicit and the representation more formal, in order to deploy it in a scheme for coding real-time interaction.

Compared with ethnographic methods and more narrative ways of developing and conveying insight, the network formalization and coding scheme I have presented here are

[237] Janis identified a reliance on dismissive stereotypes of out-groups and opponents as one of the symptoms of groupthink.

essentially ways of being explicit and consistent with regard to entities and relationships. Like any analytical representation, this entails a particular way of looking at design activity that will not encompass all phenomena of interest and therefore is not appropriate for all situations. However, along with the potential to span levels of analysis, I believe the formalization makes the approach more faithfully transportable than purely narrative methods. The ability to make quantitative comparisons, even internally within a given data set, significantly adds to the potential of the method to provide practical guidance and feedback to assist designers of tools and processes. (This also carries over into the notion of representational support, which accepts a positive instrumentality more readily than either of the conceptual notions of "boundary object" or "conscription device.")

Working within the confines of the network formalization and determining where it resisted an adequate response to the phenomena has suggested areas for elaboration and technical improvement. It has also helped focus my thinking and has indicated directions for theoretical development—particularly in terms of the processes by which representational actors are given voice and the ways their action is evident at different levels of analysis. Alongside the conception of representational support, I hope developing the observational method can provide practical feedback on the quality of interaction to inform the use of advanced representations in real-time design. As representations become more authoritative, autonomous and persuasive, we must attend carefully to the situational, social and organizational factors necessary to ensure that the wisdom of the group remains the ultimate criterion by which the quality of interaction is judged.

GLOSSARY

Actor-discourse Network (analytic representation) The term I use to distinguish the network formalization I have developed in this research from more conventional conceptions of social networks (consisting only of human actors with arcs corresponding to relations directly between them) and semantic networks (consisting only of words or other elements of discourse, with arcs corresponding to semantic relationships or co-occurrence). The formalization I developed allows for semantic network relationships to be included within actor-discourse network, though the numerical metrics I employed do not take these into account at this time.

Alignment (analytic construct) A degree of support—with implicit or explicit personal commitment—expressed on the part of the speaker with regard to particular elements of discourse. The principal basis for arc strength values used in conjunction with design discourse. The essential micro-analytic judgement that, accumulated and overlain to build up the network formalization, forms the basis of the spatial metaphor (Proximity = Affinity) of the network representation.

Betweenness (betweenness centrality) a network property reflecting the extent to which a given node lies on paths connecting other nodes.

CHPS (Compact High-Power Source) A power system developed by an external agency. Capable of supplying an order of magnitude greater power than has been available on previous Mars missions. The agency provided part of the funding for the design studies to explore possibilities of using the power system to do innovative scientific research on the surface of Mars.

Co-location (collocation) interactants sharing the same physical space (such as a room or office) but not necessarily engaged in interaction with each other

Conscription (actor-network theory; see also Interessement) The term "conscription device," applied to representations is due to Henderson (1999). In general, conscription is expressed by the following quote from Latour (1986, p.5) "Rather [than look to the history of imaging or the anthropology of writing to understand scientific and technical change], we should concentrate on those aspects that help in the mustering, the presentation, the increase, the effective alignment or ensuring the fidelity of new allies. We need, in other words, to look at the way in which someone convinces someone else to take up a statement, to pass it along, to make it more of a fact, and to recognize the first author's ownership and originality."

Criterion Variable (see also Predictor Variable) An outcome or resultant behaviour of the research system (generally a preferable one) that is of particular interest. Presumably impacted by a number of possible predictor variables. What would otherwise be termed a dependent variable in experimental research on determinant physical systems.

CSMAD (Centre for Space Mission Architecture) the JPL facility within which the concurrent design practice is situated and where sessions are conducted.

Degree (conventional network metric of degree centrality). Degree centrality is a conventional network metric, generally reflecting the importance of a node in the network. In a binary graph, it is the number of other nodes to which any node is connected; in a valued graph, it is the sum of the arc strengths.

Deixis (linguistics, also Indexicality) Deictic references are those whose meaning cannot be determined without reference to the immediate context of use (words such as here, there, now, this, that, as well as other pronominal references).

Design Discourse (coding category) Discourse pertaining to the design object in an imagined future (as opposed to simple queries, or discussion of time-independent properties or invariant physical principles), also embodying an aspect of alignment or commitment on the part of the individual (i.e. a state of affairs as it *should be*, rather than simply as it is).

Discourse Betweenness an overall network property, used as an index of Mutual Engagement. Based on the conventional network metric of Flow Betweenness Centrality.

Episode (micro-analytic unit of analysis) A temporally bounded period of continuous interaction. temporally bounded on the basis of announced process transitions and forced transitions, such as those triggered by the entry of an external expert.

Figuration (actor-network theory; see also Translation) The manner in which actors present themselves to one another in order to accomplish translation and interessement. Prior to figuration, an actor may be referred to as an "actant." Latour (2005) also distinguishes between *mediators*, which accomplish translation in heterogeneous systems, and *intermediaries*, which transport force or meaning without transformation in more homogeneous systems.

Flow Betweenness Centrality (conventional network metric) a measure of the extent to which nodes lie on maximum flow paths connecting other nodes.

Indexical (semantics, also linguistic Deixis) Meaning that is essentially a matter of pointing to something else.

Inscription (actor-network theory / coding category) In ANT, a compact, durable and readily transportable condensation of, for example, a complex natural phenomenon in science, into the form of a numerical finding published and reproduced in a scientific journal. In my coding scheme, a recognizable *feature* of a representation identified as having a particular meaning—as well as the *process* whereby such a feature is created.

Interessement (actor-network theory; see also Conscription) The enlistment of allies in an actor-network.

JPL (Jet Propulsion Laboratory). An affiliate of the California Institute of Technology, a federally-funded research facility principally under contract with the US National Aeronautics and Space Administration (NASA).

Meta-process Act (coding category) Meta-communication relating or reflecting upon progress, summarizing what has been accomplished, or stating what is required at a given point in collective designing.

Mutual Engagement (a conversational property) reflecting the extent to which discourse elements act as bridges between actors. Indexed by discourse betweenness as a structural property actor-discourse networks discourse betweenness, in turn based on the conventional network metric of Flow Betweenness Centrality

NPDT (Next Generation Payload Development Team) One of the JPL concurrent design teams which was the focus of this case study. The focus of this team is on innovative instrumentation and hardware design for exploratory space missions. See also Team-X, which focuses more on overall mission design.

Overall Alignment (a conversational property) an overall property reflecting the combined level of alignment expressed by all actors in the network. Indexed by the total degree metric, which in turn is the sum of the degree centrality all nodes.

Parsing (analysis) The method by which an otherwise continuous record of interaction is separated into discrete units for purposes of analytic comparison. Distinct from, but ideally taking into account, participants' own behaviour to segment their activity through, for example, announced starts, topic shifts, transitions and endings.

Predictor Variable (see also Criterion Variable) A presumed contributory factor or attribute present in the research system, the impact of which may be reflected in the observed behaviour of interest. What would otherwise be referred to as an independent variable in experimental research on determinant, physical systems.

Punctualisation (actor-network theory) An actor-network process whereby a particularly stable and robust set of associations comes to operate as a singular actor, sustained by agreement amongst other actors, until some sort of breakdown exposes the constituents and opens them up for potential re-association (Latour 1986, Law 1992, 2003). Also "black-boxing" (Latour 2005).

Semantic Network (see actor-discourse network) A network depicting relations only between discourse elements, not between actors or between actors and discourse.

Situated (situated action, situated learning, situated cognition) A theoretical commitment, common to several orientations, to study authentic human activity as it exists in native settings of practice, rather than as it is purported to correspond to abstractions or to synthetic processes in controlled, "laboratory" settings.

Slice (network animation, SoNIA) The temporal interval over which individual arcs (corresponding to participants communicative acts) are aggregated in order to construct a network. SoNIA offers three choices for aggregation of multiple arcs between the same nodes in a given slice: counting, summing, or averaging. I employed averaging for real-time layouts, and summing for cumulative aggregate layouts.

Team-X (JPL) The largest and longest-standing of JPL's real-time concurrent concept design and proposal development teams. Focuses on overall mission design in support of the advanced concept and proposal development activity at JPL.

Thread (macro-analytic unit of analysis) discrete, discontinuous, recurring issues or thematically related content. characterized by relationship of discussion to a particular, high level issue, also characterized by involvement of the same subset of team members and/or the same set of external representations.

Translation (actor-network theory) A process whereby inherent contradictions (in terms or objectives) and potential conflicts of interest arising from the differing agendas of actors are reconciled—or effectively sequestered—to enable their ongoing association and engagement.

Turn (conversation analysis) A relatively continuous conversational contribution by a single participant who holds the floor.

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APPENDICES

CONTENTS

FIGURES

TABLES

TRANSCRIPT EXTRACTS