Rocket Science
Shared Representation in a High Performance Design Environment

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Abstract: While a great deal of design thinking research has focused on individuals and/or ad-hoc brainstorming groups, most commercially-significant design activity is played out in real-world teams situated in organizational and professional contexts where work encompasses far more than just the generation of ideas. To understand design thinking in these settings, we must direct our attention as well to phenomena of inter-subjective engagement, co-construction and the consolidation of commitment amongst members of groups to courses of action aimed at realizing preferred futures. Real-life design tends to be spread out over time and place and to involve many different actors, all of which make it difficult to study these processes in a fine grained way. Emerging practices of radical co-location and real-time design, however, offer new opportunities. These practices utilize profound spatial and temporal constraints to help teams boost productivity and move designs rapidly forward. While their performance makes them intrinsically interesting, the concentration and intensification of design activity inherent in these practices also affords fine-grained study of the dynamics enabling productivity gains. This paper reports an exploratory study undertaken into an exemplary case of high-performance concurrent design practice at NASA's Jet Propulsion Laboratory, focusing particularly on the roles played by persistent, shared representations. In this setting, teams of experts design next generation exploratory vehicles and science missions, working together in a war-room environment to achieve high quality outcomes in 1/4 to 1/10th the time required by conventional processes. The research involved on-site observation, interviews and coding of participants' interactions with one another as well as with various forms of shared visual representation. The outcomes of the study include a hybrid social-semantic (actor-discourse) network formalization for design reasoning in which persistent, shared representations are treated as actors on a par with human participants, and a framework for understanding representational support for design activity across different timescales. This suggests indicators and group-level measures with which to assess interaction in similar contexts, as well as ways of thinking about how representational support for various types of collective knowledge work might be improved.

Keywords: Collaborative Design, Actor-network Theory, Activity Theory, Visual Representation.

1. Introduction

The locus of design activity has often been taken to be the individual (creative) mind and/or divergent modes of thought embodied in practices like brainstorming. Important as these may be, in many real-world settings design happens in groups, where distributed teams, multiple disciplines and diverse communities of stakeholders with differing agendas conspire to make success problematic—even as execution under intense time pressure is increasingly a feature of the competitive landscape. Value realization enabled by groups working in these types of socio-technical and organizational contexts is key to most of the commercially significant innovation impacting our lives, and competitiveness is likely to be enhanced to the extent we master the underlying dynamics. In essence, this requires understanding not just where ideas come from, but how they are transformed (and contested), completed and made manifest within groups, and how the results are integrated in networks of commitment and flows of resources in organizations. Making this more effective will require appropriate use of technologies and environments, novel organizational forms and innovative collaborative practices. This paper reports results of an exploratory case study inquiring into such an exemplary practice: high-performance design collaboration in a setting featuring high levels of interaction between individuals and sophisticated shared representations arrayed in a warroom environment. While a number of the ways in which this practice functions within its particular ecology are discussed, the focus of the work recounted here is on illuminating the roles played by persistent, shared external representations in these types of environments.

1.1 Design as Collective Process

Fostering creative and effective collaboration across diverse knowledge domains is a central challenge in today's complex design projects. Though a great deal of fundamental research on design and design thinking focuses on the individual, it is clear that design involves group and collective processes on many levels. The organizational milieu is characterized by different "thought worlds" and organizational routines that are not necessarily (indeed, are perhaps *necessarily not*) fully aligned or commensurable with one another [6]. To solve problems and develop innovative product and service offerings, diverse perspectives and expertise must nevertheless be brought into constructive engagement. This is frequently accomplished with the aid of various types of boundary object to assist in the synthesis and transformation of the requisite bodies of knowledge [5]. Ethnographic studies of engineering design, for example, highlight a number of social and interactional aspects of practice along these lines, portraying a richer picture of what outsiders might otherwise assume to be a dry, technical and deterministic process of bringing technological artifacts into existence [4][5][8][17]. This type of design work involves not only theory and calculation, but ongoing negotiation between designer-advocates who employ a range of communicative skills, representational tools and practices to make points and ground knowledge, argue cases, enlist allies and persuade (or neutralize) skeptics [17][8]. As Bucciarelli compellingly describes it, the process of engineering design is one of "collective story-making" within a world constituted by, within and amongst all manner of objects and representations [4]. And the range of representations employed is quite broad—ranging from spreadsheets, to sketches, models and prototypes—all of which serve to *make present* the designed object itself, the context of use and the process by which the end result will be achieved. Some representations operate primarily within and amongst designers, while others must cross boundaries and travel beyond to users, managers and other stakeholders [3]. Design as a collective process, therefore, involves synthesizing perspectives, reconciling differences and consolidating commitment to courses of action intended to bring about a preferred future. In this process, design *representations* embody salient aspects of the designed intervention in that future. Understanding how this process unfolds between people, and how it is both scaffolded and propelled by the co-construction of persistent, shared representations, requires fine-grained attention to the interweaving of collective design reasoning and representational activity in interaction.

1.2 Methodological Precedents

Studies in the traditions of situated action [7][18] and distributed cognition [9] offer methodological precedents for fine-grained study of work involving interactions between individuals and technological artifacts. These perspectives have a number of features in common—among these is an essentially triadic communication model that portrays interactions as occurring between people as well as with, and *over* technological artifacts. They attend closely to participants' actions, utterances and gestures in moment-by-moment detail. This level of analysis is frequently referred to as "micro" because it focuses on the processes by which individuals make sense of their joint activities based on situational awareness, knowledge they possess and resources available in the environment at the time. (By contrast, "macro" analyses are more likely to invoke longer-term patterns and rely on interpretations based on fore-knowledge and abstract theorizing to enhance their explanatory power.) Micro-level analysis requires a stable record of interaction data, frequently employing techniques of video interaction analysis [11]. These approaches reveal subtle processes of coordination and the modalities by which parties in tightly coupled work maintain their mutual awareness—which may be heavily impacted by the presence of technology. However, making broader claims about task performance usually requires additional knowledge about the context of work; for this reason micro-level analyses are often applied to highly-structured task environments, such as command and control centers, where this is more easily inferred. Design situations are, however, inherently less structured (from a task standpoint) and profoundly contingent. Fine-grained study of organically constituted and organizationally situated design processes therefore remains problematic, and a blend of micro and macro analytic techniques is likely to be necessary.

1.3 Emerging Practices

Recent developments in several domains have begun to profoundly alter the way we think about collaboration and collective designing—in terms of the work individuals have traditionally done by themselves (in isolation) vs. that which is done together. A number of practices are now emerging that employ some combination of high visibility, close proximity and spatial bounding (usually involving co-location or co-presence), and the imposition of profound temporal constraints to help groups move designs rapidly forward. Examples include "radical co-location" [19], "extreme collaboration" [16], "deep dives"[12] and pair or "extreme" programming [10]. In contrast to conventional meetings, wherein a great deal of time may be spent updating others on past accomplishments or discussing work to be carried out (individually) in the future, emphasis in these settings is placed on actually *doing* the necessary work together—making the term "real-time design" an apt description. Though creative generation of ideas figures prominently, work in these settings is also about much more than conventional brainstorming, because the emphasis is on production of tangibly realizable outcomes that will "really work" in whatever the relevant context may be. In terms of the potential for micro-analysis, this type of setting presents both opportunities and challenges. Because design activity occurs in concentrated working sessions oriented toward tangible outcomes, a greater proportion of the relevant interaction occurs within manageable bounds of space and time. The fact that so much of interest may be happening at once can, however, create conditions of overload for both analysts and participants alike.

2. The Case

Real-time design practices work by bringing individuals with relevant expertise together in a high-awareness, task-oriented and outcome-focused environment to move designs rapidly forward. But how does this occur? What is the nature of the interactional work taking place, and how are shared representations implicated in the process? Aerospace design is a particularly complex, technical domain involving highly interdependent, often high-stakes decision-making, in which success requires effectively bridging distinct domains of expertise, knowledge and experience. Mark [16] in her account of "extreme collaboration" describes "Team-X" at NASA's Jet Propulsion Laboratory (JPL) in which a standing team of experts, working in a warroom environment with a system of networked spreadsheets, completes complex space mission proposals, hitting tight schedule and budget targets with impressive productivity gains. In April 2002, an opportunity arose to work with another of the standing concurrent design and proposal development teams at JPL, the Next-generation Payload Development Team (NPDT). Like Team-X, NPDT convenes a standing design team in a warroom environment, together with program managers and scientific investigators who are in essence the champions and customers for a particular project—to flesh out a detailed and robust proposal in a fraction of the time required by more conventional processes. Whereas Team-X is concerned with the logistics of an entire mission, NPDT is more focused on producing an integrated hardware design for instrument payloads and landing vehicles. Rather than the networked spreadsheets of Team-X, NPDT incorporates a range of representational tools specific to engineering design, including mechanical CAD, structural and thermal analysis packages. And, because it is somewhat smaller than Team-X, NPDT is also applied to more open-ended projects and speculative proposals. Together, these factors make NPDT an attractive setting to address the particular focus of this study, namely, the representational and interactional dynamics of innovative, collective and collaborative design activity.[1]

2.1 Background

JPL is a federally-funded research and development center operated by the California Institute of Technology under contract to the U.S. National Aeronautics and Space Administration (NASA). Primarily, work at JPL involves the design, construction and operation of robotic scientific probes for the study of Earth from space as well as for exploratory missions throughout the solar system and beyond. Concurrent design and proposal development teams at JPL have taken shape over the last decade in response to NASA's "faster-better-cheaper" imperative, imposed during the mid-nineties, which charged the agency and its contractors to refocus their efforts on smaller, less costly missions more effectively targeted at specific scientific objectives. These teams, each comprising 10-20 core participants, are key to JPL's strategy to produce more and better proposals, more quickly, while carefully managing risk and reusing knowledge more effectively. Members of NPDT devote approximately 20% of their time to participate in proposal development projects—referred to as "design studies"

[1] More details on the nature of the setting, in terms of the backgrounds, time commitments of various participants, physical description of the infrastructure and the process of mission design at JPL are contained in Shaw, B. (2007). *More than the Sum of the Parts: Shared Representations in Collaborative Design Interaction*. PhD Dissertation, Royal College of Art, London.

Figure 1. The NPDT in Action at JPL. Team leader and customer seated at central table with domain experts around perimeter; remote participants join via conference phone (central table) and screen-sharing application.

[2]—with the balance devoted to fully-funded projects in advanced stages of development, launch or operation. The result of these teams' efforts (approximately 9 3-hour sessions over a 3-4 week period) are highly-detailed technical proposals which, to the extent they compete successfully in NASA's funding environment, ensure a continued flow of work to sustain the lab as a whole. Though the intense atmosphere of the warroom is not for everyone, membership on these teams conveys benefits to participants as well. These include a certain prestige and visibility for skills and expertise which, to the extent their contributions are valuable, make participants more likely to be offered work on funded projects as they go forward. The practice allows a small group of champions pursuing an idea to be augmented in concentrated, targeted doses with a deep pool of knowledge, experience and specialized technical expertise, without burdening early-stage projects with large headcounts. By leveraging skills and building a strong core of expertise to execute projects quickly, at the same time preserving the ability to have many lightly-staffed exploratory efforts, JPL's practice is a novel and effective response to the dilemma organizations face in allocating resources between exploration and exploitation activities [15].

2.2 Preliminary Observations, Case Method and Units of Analysis

Observations at JPL were conducted over a 9-week period in Spring and early Summer of 2002, during which time the NPDT completed two related projects to explore the applicability of a new, high-power source to energy-intensive scientific explorations on Mars. During early observations, a number of features of the practice were identified to help address methodological issues in case study design. The approach taken for this research was to discern multiple, embedded units of analysis within the single case as a basis from which to make analytical comparisons. Key methodological challenges in this regard included arriving at ways of parsing the organic activity into distinctly analyzable units, and making comparisons so as to highlight the most analytically-informative contrasts [20].

First, it was noted that different subsets of the team tended to concentrate in parallel on different design issues, using different sets of representations, with the team leader raising particular subjects to the attention of key participants and customers at different times. Furthermore, in sessions, the team leader rather actively managed transitions between these topics of discussion according to a plan loosely formulated in advance, based upon his understanding of precedence relationships and dependencies between major decisions generally required in mission design (such as regarding launch and arrival dates, telecommunication architectures, and tradeoffs

[2] The work the JPL team performed during the period of observation will henceforth be referred to as "the design study" to differentiate it from the research activity reported in this paper.

between various sources of on-board power). The actual design project the team was engaged in manifest its own segmentation in terms of a set of interdependent, but distinct design challenges posed by the specific mission under consideration. Both of these features of practice—management of process through announced topic transitions, and distinct design challenges involving different subsystems and portions of the team—formed the basis for two distinct and complementary units of analysis, summarized below in Table 1. Both proved essential to understand the roles played by shared representations in this context.

Table 1. Complementary Levels and Corresponding Units of Analysis

level of analysis	*unit of analysis*	*description of units*	*analytic activity*
micro	episodes	continuous periods of coherent design conversation bounded by announced, process-governed topic transitions.	• parsing and selecting episodes • coding communicative acts and utterances
macro	threads	discrete instances of thematically-related discussion pertaining to one of the major mission challenges or other high-level issues in aerospace design	• qualitative comparisons highlighting genesis of innovative features, sudden or dramatic changes, breakdowns and loss of work

3. Analysis and Results

These units of analysis were separately tracked with respect to indicators relating to criterion variables of productive interaction and innovative design outcomes.[3] These were triangulated on the basis of in-session observations and video review, post-session interviews with the team lead (and follow-up interviews with team members) as well as technical papers and management presentations authored by key participants. These units of analysis, episodes and threads, were employed in micro and macro-level analyses respectively.

3.1 Development of Coding Scheme

Micro-analysis was undertaken first, on episodes selected on the basis of high density of positive and/or negative indicators. Initial, exploratory coding was carried out with a number of categories culled from the design thinking and design rationale literatures. Attempting to register each participants' contributions with respect to the team's design reasoning as it evolved over time, a decisive realization was that a network-based analytic representation was vastly superior to more conventional, categorical coding. This was informed by actor-network theory (ANT), which attends to the dynamics of conscription and shifting allegiances between actors.[4] Networks generated from this coding embody a spatial metaphor wherein network proximity corresponds to affinity, in terms of participants' expressed support or "alignment" with particular elements of design reasoning (principally comprising issues, options and criteria). A network-based coding scheme was iteratively developed over a subset of selected episodes coded in an order determined to introduce complexity in stages, with each

[3] In-session positive indicators included evident excitement and participants' expressions of satisfaction, with evident frustration and expressions of dissatisfaction tabulated conversely. On the outcome side, interaction directly related to the genesis of demonstrably innovative features in the final design, or to dramatic changes in major subsystem configurations were positively highlighted, while instances of substantial miscommunication, lost work or work performed in error were highlighted negatively. The terms positive and negative in this context do not ultimately reflect judgments about the value of any particular instance of interaction—rather, they were used, as Yin [20] suggests, to enable the most analytically informative contrasts.

[4] ANT was initially formulated through sociological studies of science but has since been applied to better understand innovation in other fields of endeavor [1][14]

episode re-coded after major changes to ensure consistency. Also consistent with ANT, the coding scheme was configured to treat human participants and representations as actants on a par with one another.

3.2 Micro-analytic Results

A combination of graphical pattern matching and numerical measures applied to networks generated from interaction coding was used to discern six distinct factors to account for variation across the positively and negatively-selected episodes, summarized below in Table 2. These were taken to constitute a reasonable proxy for the quality of design conversation in this context. In the case of numerical measures, two group-level metrics were found to adequately discriminate between episodes selected for positive vs. negative indicators. Qualitative assessment of cumulative network layouts for each episode provided additional information about the level of participation of different experts and the extent to which tokens of discourse—in particular collaborative productions co-constructed by multiple participants—were inscribed in persistent shared representations. Finally, in terms of categorical composition and temporal development of discourse coding, productive episodes could be seen to manifest a collective reasoning cycle through which the designs advanced. After an opening was initiated (in one of a number of ways), reasoning progressed through discussion with contributions offered by various participants, moving toward a mode in which positions were consolidated with increasing commitment, until a process-sanctioned closure was reached with enhanced specificity in the design.

Table 2. Summary of Micro-analytic Process and Outcomes

level of analysis	*indicators of conversation quality*
numerical structural metrics applied to real-time actor-discourse networks generated from coding	• overall alignment (reflecting participants' expressed support for particular elements of design reasoning) • mutual engagement (reflecting the extent to which actors are connected through their shared discourse)
qualitative assessment of cumulative network layouts	• engagement of participants with topically-relevant expertise • integration of shared representations via inscription of shared discourse
categorical composition of coding and temporal development of discourse	• development of design discourse (that addressing a problematized aspect of the design, with locus of discourse in a preferred future) • explicit closure with enhanced specificity in the design and/or commitment to perform specified follow-on work

Table 3. Summary of Roles of Shared Representations Based upon Synthesis Micro & Macro Analyses

time frame of enactment *longer <------------------------> shorter*	provide shared reference:	• convening groups • drawing individuals into discussion • serving as resources for resolution of ambiguity
	afford noticing:	• initiating topics and managing returns • suggesting issues and/or alternatives
	accept contributions:	• providing a locus for expression (i.e. participants directing remarks toward the representation rather than other people) • receiving opinions and elaboration • registering participants' acts through perceptible changes
	foster decision:	• providing answers • stabilizing consensus
	carry inscription:	• preserving accomplishments over time • carrying results beyond the bounds of the group

3.3 Macro-analytic Results

A number of important phenomena pertaining to the roles of shared representations (evident in the broader data set) were obscured by the micro-analytic parsing because they played out over longer time scales and across multiple episodes. For this reason, a secondary, macro-analysis was undertaken to compare, in more qualitative terms, events that transpired over longer time scales. These included dramatic convergences and co-constructed solutions to resolve stubborn problems, serendipitous—sometimes accidental—insights as well as instances of confusion and miscommunication resulting in loss of work. The full set of roles played by shared representations discerned through a combination of micro and macro-analysis is summarized above in Table 3.

4. Discussion

It is clear that a number of factors enable the extraordinary performance achieved by the concurrent design teams at JPL. Decades of experience in space mission design provide a foundation of shared understanding with regard to the ways in which projects like these unfold and how various domains of expertise contribute to forging solutions to the challenges they entail. Furthermore, as scientists and engineers, members of these teams have access to a common language around technical issues and—though they might not always see eye-to-eye—are perhaps more likely to agree on the nature of evidence and what constitutes a compelling argument in this context than groups drawn from more disparate backgrounds or dissimilar professional traditions. The standing nature of concurrent design teams at JPL, situated as they are in an organizational ecology that supports and encourages participation, may allow them to concentrate relatively more time and energy on accomplishing task work and less on group organization and conflict resolution in maintaining working relationships.[5]

Bearing these factors in mind, it is clear that the synchronous interaction afforded by co-location and access to shared representations in the warroom environment contribute substantially to the impressive gains in productivity over methods previously employed at the lab. So, how do persistent, shared representations contribute to performance in real-time design? Because of the nature of the units of analysis, the roles summarized in Table 3 above in most cases reflect the involvement of *multiple* representations on any given thread or episode. These are recast and depicted diagrammatically below in Figure 2 as a set of *situational attributes* that might be exhibited to varying degrees by particular representations in their contexts of use. These are positioned in relation to the collective design reasoning cycle identified through micro-analysis. Attributes in Figure 2 are arrayed horizontally such that those on the left are associated with opening and those on the right with closure, and vertically in progression to reflect the increasing timescales over which associated processes are operating. That the attributes of representational support have more precise meanings and specific interpretations in the context of the network formalization opens the possibility of making quantitative statements about each. Figure 2 also depicts a pair of orthogonal *representational dynamics* to account for the contribution of shared representations to performance in real-time design environments. The first of these, "acceleration," denotes the ability of powerful representations to raise issues, frame questions and provide specific answers quickly, thereby reducing latency and in essence driving the reasoning cycle more rapidly.

[5] The method described here is therefore particularly suited to rendering the accomplishment of task work in design; it can be used in conjunction with other methods to understand how productivity is influenced by these types of socio-emotional small group processes [2] in other settings.

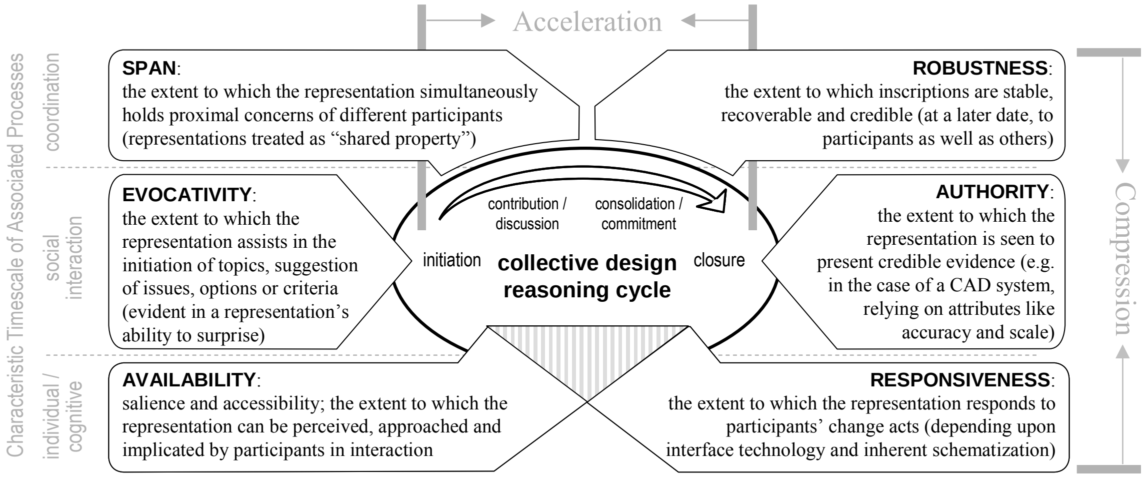

Figure 2. Situational Attributes of Representational Support and Dynamics in Real-Time Design

Acceleration is, however, only part of the picture. Participants and analysts alike also highlight the importance of flexible and opportunistic teaming afforded by the environment to understand issues, address problems, and respond to emergent insights. Representationally, this corresponds to a dynamic of "compression," whereby integrative and comprehensive representations (typical of mature designs and later stages of development by virtue of their span and robustness) are brought into a space of enhanced interactivity (in terms of availability and responsiveness) with a broad cross-section of team members and customers. Engagement over such representations draws participants who might not have crossed paths in more conventional settings into proximal interaction, enabling what team members referred to as "serendipitous insight." Thus, real-time design involves *working smarter together*, rather than simply doing more rapidly what individuals might otherwise have done by themselves (as might be inferred from acceleration alone).

5. Conclusion

The results of this study portray a number of ways in which persistent, shared representations contribute to enhanced productivity and performance in real-time design environments. Consistent with actor-network theory, the network formalization employed for micro-analysis of participants' interactions with each other and with shared representations foregrounds the interactional work of design reasoning in terms of alignment and commitment. This elaborates notions of collective story-making [4] and knowledge transformation [5] in the construction of compelling deterministic accounts able to attract adherents and garner resources in organizations, and enhances understanding of the functions of representations as boundary objects [5] and conscription devices [8] at the heart of engineering design. The conception of representational support, utilizing concepts drawn from activity theory, illustrates how co-constructed shared representations attract participants on the basis of proximal concerns and entrain them in focused and constructive conversations. Coherence between the network formalization and conception of representational support facilitates the use of quantifiable network distance and other structural concepts from social network theory to understand participants' respective positions vis-à-vis important topics of conversation, and the extent to which these are anchored in persistent, shared representations. Methodologically, while the study made use of some relatively unique features of the design practice in question, it is also illustrative of strategies and techniques, particularly with regard to the complementarity of micro and macro-level analyses, that may be useful to others seeking to develop a fine-grained understanding of authentic, organizationally situated design activity. These have the potential to enhance our understanding of the ways in which design representations act to suggest possibilities, consolidate consensus and stabilize networks of commitments to help design teams realize preferred futures.

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