Exploring the boundaries: Language, roles, and structures in cross-disciplinary design teams

Chapter · January 2009

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1. Motivation

Many complex problems facing society today require cross-disciplinary approaches. For example, the core of the engineering profession lies in integrating broad knowledge toward some purpose (Bordogna et al 1993). Engineering involves working between technical and non-technical considerations, negotiating among different social worlds (Bucciarelli 1996), and managing trade-offs where solutions are judged by interdisciplinary criteria (Jonassen et al 2006). Reports on the future of engineering education emphasize the importance of preparing engineers to become "emerging professionals" who can deal with complexity, innovate on demand, and bridge disciplinary boundaries (NAE 2004).

Cross-disciplinary practice is quickly gaining momentum as an important topic for empirical investigation (Bromme 2000, Klein 1996, Lattuca 2001). Where disciplinary approaches to design are situated in specific bodies of knowledge, cross-disciplinary approaches focus on the nature of the problem, integrating several perspectives to synthesize a collective whole. In this way, cross-disciplinary interactions can enable innovation and amplify creative potential (Petre 2004).

The two engineering meetings provided good examples of cross-disciplinary practice and boundary work in design teams based on definitions from scholarly literature and our own experiences. This is a cross-disciplinary boundary work situation because: 1) multiple disciplines or perspectives are represented; 2) the nature of the problem is a joint disciplinary problem and not simply confined to a single perspective; 3) there are efforts to broaden and limit "boundaries" around the problem and the design process; and 4) there appears to be a focus on innovation by the inclusion of team members with diverse disciplinary backgrounds. We identified distinct ways of characterizing cross-disciplinary boundary work in engineering design teams in terms of language, roles, and structures. These characterizations enabled us to frame our research by exploring the following questions:

1. What are characteristics of cross-disciplinary boundary work in engineering design teams?
2. What is the nature of these boundaries and how are they navigated?
3. What are factors that affect or support cross-disciplinary practice?

2. Lenses for Investigation

Cross-disciplinary practice involves transgressing into and across other disciplines. Where the term *disciplinary* signifies a particular set of tools, methods, exempla, concepts and theories, the term *cross-disciplinary* characterizes a collection of practices associated with thinking and working across disciplinary perspectives. These include multidisciplinary, interdisciplinary, and transdisciplinary practices. Movements between and across disciplinary boundaries are marked by clashing paradigms, or ways of seeing the world, as well as challenges in borrowing and integrating concepts in new contexts. A literature review (see Table 1) reveals important differences in cross-disciplinary practices regarding an orientation to the problem, mode and outcome of knowledge production, and social interaction structures and discourse practices (Aligica 2004, Balsiger 2004, Klein 2004). Although some of the ideas presented in Table 1 have not been empirically grounded, they provide useful lenses for investigating cross-disciplinary practice.

Table 1. Synthesis of cross-disciplinary practices

	MULTIDISCIPLINARY	INTERDISCIPLINARY	TRANSDISCIPLINARY
Definition	Joining together of disciplines to work on common problems; split apart when work is done	Joining together of disciplines to work or identify common problems; interaction may form new knowledge	Beyond interdisciplinary combinations to new understanding of relationships between science and society
Problem orientation	Not a problem solving orientation but rather thematically oriented projects where several disciplines contribute to a theme	Problem solving orientation in which solution focus is either instrumental (pragmatic problem solving) or conceptual (philosophical enterprise)	Problem solving orientation in which solution focus explicitly includes experiences of affected persons
Mode of knowledge production	Additive, juxtaposition of perspective as separate voices.	Integrative synthesis, holistic mixing of perspectives	Integrative and action-oriented transformation that transcends disciplinary views
Outcome of knowledge production	No new cross-disciplinary knowledge	New interdisciplinary knowledge	Knowledge fusion characterized by critical reflection
Interaction and discourse structures	Divide and conquer approaches Collaborate as disciplinarians with different perspectives; no shared home	Beyond academic disciplinary structures Close collaboration; development of common ground	Participatory – science and society Close and continuous collaboration; elaboration of new language, logic, and concepts

In the context of cross-disciplinary practice, being inside, outside, or somewhere in between disciplinary zones suggests the existence of "boundaries" between different knowledge practices. For this study we draw on Gieryn's (1983) definition of boundary work as the cooperative pursuit of tasks in spite of boundaries that could prevent separate social worlds from achieving goals. Here, boundary work involves interaction among multiple worlds and competing world views (some of which may be disciplinary). In this way, the concept of boundary work lends a new eye to understanding interaction structures and social processes in heterogeneous cross-disciplinary design teams (Bucciarelli 1996). One way of investigating boundary work involves attending to the nature of boundaries and how they are maintained, navigated, reformulated, policed, or negotiated. For example, boundaries could be areas of expertise (i.e., disciplinary knowledge), epistemological differences (i.e., views on the nature of knowledge and knowing), cultural differences (i.e., language, values, norms), and organizational structures (i.e., how work environments are structured). The process of navigating boundaries highlights the role of intermediaries: people and objects that can mediate social processes, translate the unfamiliar into the familiar, and fluidly taking on different roles in relation to different situations (Bowker and Star 1999, Nersessian 2006, Star and Griesemer 1999). In these situations groups create new languages, professional roles, and forms of knowledge (Galison 1997; Klein 1996). Similarly, Newstetter and Kurz-Milcke (2004) describe successful cross-disciplinary work environments in which typical boundaries seem to no longer be active. These "agentive environments" are non-hierarchical such that no one person is expert, involve distributed expertise, and cultivate a culture of failure and impasse to foster resiliency.

The concepts of cross-disciplinary practices and boundary work extend and allow deeper investigation into current theories in design research, in particular those on social processes in design. For example, cognitive artifacts such as representations and prototypes (e.g., Visser 1997) may serve as boundary objects that mediate social interaction. A boundary work lens may provide a way of understanding co-evolutionary (Dorst and Cross 2001) and transformative design practices (Adams et al 2003) in cross-disciplinary design teams. A focus on cross-disciplinary practice may reveal how interdisciplinary interactions influence innovation in engineering design teams (Petre 2004), how storytelling promotes common ground (Lloyd 2000), and how the nature of design tasks influences design processes and thinking (Goel and Pirolli 1992, Jonassen 2000). Points of synergy in this volume include practices of negotiation among territories of expertise (McDonnell), the intersection between social order and brainstorming (Matthews), understanding problem "scope" (Atman et al), how intermediary design objects may regulate and legitimate design moves (Luck), and the role of analogies and metaphors as language tools that elaborate mental representations (Stacey et al) and reduce uncertainty (Ball and Christensen).

2. Methods

We analyzed engineering meetings 1 and 2, hereby notated E1 and E2, focusing on the interactions among people with different perspectives and disciplinary knowledge. This includes what participants did, what they said and how they said it, as well as the context of their actions. The analysis followed a grounded theory approach (Glaser and Strauss 1967) where characterizations of the data emerged inductively from the participants' words and actions. In the first pass through the data, we watched the videos of the meetings and used the meeting layout diagram to immerse ourselves in the workings of the meetings. We did not assume that disciplinary identifiers provided in the meeting layout represented how participants might identify themselves (see Table 2). In the first pass through the data, we identified language, roles, and structure as possible descriptive dimensions of cross-disciplinary boundary work. In the second pass, we created personas of the participants to further distinguish aspects of these themes. The personas included a description of the language that the participant used and their actions over the course of the meeting.

Table 2. Participant descriptions (*italics* denote presence in both meetings)

Meeting E1	Meeting E2
AJ	*Jack (Mechanical Engineering)*
Chad (Mechanical Engineering)	Patrick (Electrical Engineering, Software)
Jack (Mechanical Engineering)	*Rodney (Industrial Design)*
Rodney (Industrial Design)	Roman (Electrical Engineering, Software)
Sandra (Ergonomics)	*Sandra (Ergonomics)*
Todd (Mechanical Engineering)	Stuart (Electrical Engineering)
Tommy (Electrical Engineering, Business)	*Tommy (Electrical Engineering, Business)*

In the final pass, we created a narrative timeline of E1 and E2 meeting processes by "living" the data – reading the transcripts as if they were the script of a play with characters, episodes, and climaxes. This resulted in the identification of narrative episodes or passages in the transcript that marked different stages and topics in the meetings. This process of creating episodes is similar to the work of Reyman et al (this volume) who defined episodes in terms of problem and solution shifts, and McDonnell (this volume) who defined episodes in terms of feature, function, and detail phases. The outcome of this process was robust characterizations around **language**, **roles** and **structures** and how they interact to illuminate aspects of cross-disciplinary boundary work.

Language classifications describe what participants talked about from a disciplinary perspective, and how it was communicated. This is similar to Luck's focus on language as a linguistic marker and boundary object (this volume). Six language types were identified (see Table 3): computer science, electrical engineering, mechanical engineering, business, technology, and printer company. Printer company language is environmentally situated and appeared to have a unique meaning within this professional setting (i.e., a printer company) and may have served as a common language in the group. For example, "firing the dots" was a way of talking about how the printer head worked in relation to the media and would likely be unfamiliar when used outside this situation. We did not include a specific language code for discussions related to the user, which might be an ergonomic disciplinary language, because it was too difficult to delineate from everyday conversational aspects of talking about the use of the product or its users.

We also characterized how the participants communicated with each other: their use of metaphors and analogies, humor (see also Dong and Lloyd in this volume), gestures, representations, imprecision related to technical details, and mixing of languages. Where others in this volume provide a more detailed account of the nature and use of metaphors (Stacey et al, Ball and Christensen), we focused on how metaphors and analogies triggered different kinds of cross-disciplinary practices. We also noted the role of gestures in which participants used their bodies to communicate a particular idea (e.g., various participants pounding the table to evaluate the maximum force that could be applied to the pen under design). Visser provides a richer characterization of gestures in this volume. Representations (e.g., flip charts, prototypes, sketches, presentation slides) served as tools for communicating design ideas and providing common reference points (see also McDonnell and Luck this volume). "Imprecise" language distinguished a type of everyday language that lacked technical precision or specificity (e.g., "wobbly bits" when referring to the part of the pen design that holds the print head) or hedging words about project goals (see also Ball and Christensen this volume). Finally, mixing of languages refers to linking together different kinds of language (see Table 3) in uninterrupted talk and may signify efforts to translate, bridge, or integrate multiple perspectives.

Table 3. Language Classification Scheme

LANGUAGE	DESCRIPTION
Computer science	Language associated with the computer science profession and/or ideas associated with programming, writing software and protocols, but not at a hardware level (e.g., digital format, digital signatures, binary, and prestore).
Electrical engineering	Language associated with the electrical engineering profession and/or ideas that are electromechanical, related to power, design architecture and interface, involve electronic technologies that are not specifically computer-related (e.g., architecture, sensor, energy per dot, CCD, just a peak, shifthead register, and sinusoidal pattern).
Mechanical engineering	Language associated with the mechanical engineering profession and/or refers to ideas related to forces, angles, temperature, mass, friction, etc. (e.g., controlling the forces, thermal mass, grammage, compressed, and angle control).
Technology	Language associated with using computers, but not designing or programming them (e.g. upload to laptop, download, Wifi, and USB).
Business	Language associated with the business profession and/or ideas associated with

	market issues (e.g., risk adverse, demonstrator stage, engineer the cost, profit from the media, on the cheap, and market for it).
Management	Language associated with managing the meeting (e.g., first thing to do, what we already know, moving it to the side, keep brainstorming going, and it's going well).
Printer company	Language associated with the printing profession (e.g., heat it up, dpi, fire the dots, and laid down in stripes).

Role classifications describe participants' actions in the engineering meetings in terms of the project, processes, and experiences. They do not represent participants' areas of expertise. We observed eight role types (see Table 4). Two characterized how the project was managed (Facilitator) and how information was brought into the meeting (Informer). Four characterized design process activities: Evaluator, Idea Generator, Interpreter, and Questioner. Two characterized users or experiences of use: Storyteller and User Contextualizer. In terms of cross-disciplinary boundary work, we might anticipate how acting as a Facilitator involves managing the boundaries of the project and the group process. Similarly, the other roles provide different ways for bringing in multiple perspectives such as translating ideas (e.g., Interpreter), advocating the needs of users (e.g., User Contextualizer), challenging perspectives (e.g., Questioner and Evaluator), or providing information to the group that may not be common across the group (e.g., Informer, Idea Generator, and Storyteller).

Table 4. Role Classification Scheme

ROLE	DESCRIPTION
Facilitator	Directs the meeting by (1) *managing* – directing the flow of the meeting, providing structure, and keeping people on task (e.g., AJ's activities in E1); (2) *encouraging* – encouraging others to be involved and affirming inputs (e.g., Tommy positively affirmed people's brainstorming ideas in E2); and (3) being a *historian* – recording the meeting outcomes (e.g., AJ and Tommy captured ideas on the flip chart, and Rodney gathered sketches in E1).
Informer	Brings outside information into the meeting such as (1) *project information* that already exists (e.g., Tommy provided information regarding the client (E2, 7)); (2) *company information* gained through experience within the printer company (e.g., Patrick provided information about drivers he had used in the past (E2, 1611)); and (3) *disciplinary information* that is unique to a particular discipline (e.g., Patrick provided disciplinary expertise regarding PCs and power supplies (E2, 1334)).
Evaluator	Makes judgments regarding the ideas discussed in the meeting and identifies a need to conduct an evaluation (e.g., Patrick compared the pen to a simple pencil (E2, 981) or the idea of having a PC connection for the pen was evaluated (E2, 1325)).
Idea Generator	Presents new ideas about the topic being discussed. Ideas can be technical or non technical, and range from very specific to quite abstract (e.g., Chad proposed a new idea on how to keep the print head on the paper using a rolling ball (E1, 224)).
Interpreter	Involves translating information such as (1) *clarifying* a concept or idea presented to the group (e.g., Rodney suggested an application for the thermal pen and Tommy giving an analogy (E2, 645)); (2) *building* on information or ideas on the table by providing additional details (e.g., Patrick suggesting having all of the user interface for the thermal pen on a PC (E2, 1007) and Sandra building onto this by suggesting a library of patterns (E2, 1024)); and (3) *manipulating* an idea or concept or connecting it to another idea (e.g., Stuart manipulated a previous idea of lottery tickets to one of pin codes (E2, 193) and Jack manipulated that by linking it to private letters (E2, 212-213)).
Questioner	Asks for information that has not already been brought into the conversation (e.g., Patrick solicited technical information about the product (E2, 113;169; 354-355; 507) and Sandra asked about the plan for the product (E2, 371-372)).
Storyteller	Contextualizes an idea or clarifies an idea by telling a story of a personal experience (e.g., Todd presented his idea about controlling the placement of the thermal pen on the paper as a story about his son (E1, 397-416)).
User Contextualizer	Provides a "voice of the user" to the discussions both (1) *internally* – by picturing themselves as users (e.g., Todd described how hard it is to draw a picture with a mouse (E1, 633)) and (2) *externally* – by projecting or advocating the view of the user (e.g., Sandra raised the idea that older children may want to use the pen to create something to keep (E2, 758)).

While other classifications exist (e.g., Stempfle and Badke-Schaube 2002, Redström 2006, Kelley and Littman 2005, Lloyd 2000), these classifications emerged inductively as a way to characterize the *combination* of design and social process issues that collectively characterize cross-disciplinary boundary work. These role classifications share similarities with other analyses of the engineering meetings in this volume in terms of design processes (Atman et al) and ways of prescribing use (Lloyd). They also parallel analyses of the architecture meetings. For example, Goldschmidt and Eshel (in this volume) observed a role of someone who initiates and brings up topics, asks questions, expresses confirmation, and plays the role of absent clients. Their observations map to our classifications of Idea Generator, Questioner, Evaluator, and User Contextualizer. McDonnell (in this volume) observed the role of asking questions to defer and assert expertise (often disciplinary) which triggered conversations. It is interesting to note that McDonnell did not observe tactics to control the conversation in the architecture meetings.

Structure classifications describe the action context: the structure of the design space and the organizational structure of the meetings. The design space classifications are illustrated in Figure 1. Here, the problem-solution space boundaries include the proof-of-concept design space (dashed box) and the future market design space, which includes the proof-of-concept space. Each of these classifications relate to the goals of the two meetings: to produce a proof-of-concept demonstration of a thermal pen for young children, and to develop new product ideas that utilize the novel print head and media technologies. These proof-of-concept and future market design space classifications are similar to the brainstorming topic codes developed by Atman et al in this volume (i.e., aspects of the proof-of-concept pen (features, interface, and architecture) and applications (future market)). The interface boundaries in Figure 1 include the media, thermal print head, electronics, casework, and user interface. Many of these interface boundaries relate to the disciplinary backgrounds of the engineering team meeting participants (e.g., mechanical engineering, electrical engineering, industrial design, business, and ergonomics). These map to the conversation focus codes developed by Atman et al in this volume (i.e. the pen, paper, users, and interactions between them).

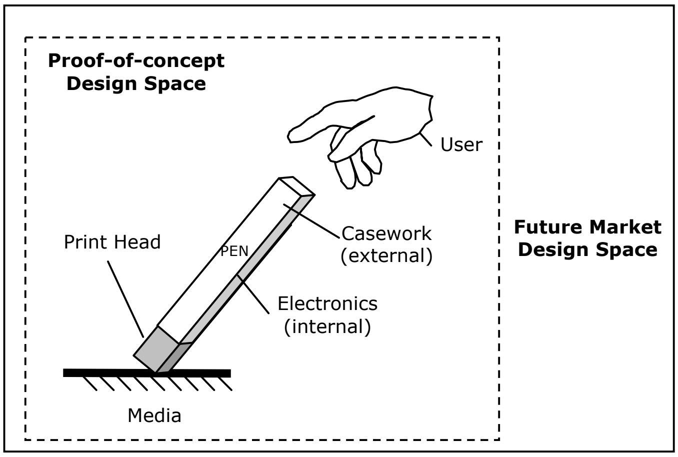

Figure 1. Engineering Meeting Design Space

The organizational structure includes both the meeting goals and the presence of different participants in different meetings (see Table 2, italics). The goals of both engineering meetings were clearly stated in an agenda. This differed from what was observed in the architecture meeting where the client and architect came with their own agenda (McDonnell, this volume). Participants in the meetings were different for potentially intentional reasons. For example, a goal of the E1 meeting was to have a "mechanical brainstorm" on the casework of the proof-of-concept pen, and as such many of the participants had a mechanical engineering background. Similarly, goals of the E2 meeting were to have an "electrical brainstorm" for the proof-of-concept pen and to brainstorm future applications for the print head and media technologies. Most of the participants in the E2 meeting had an electrical or electronics background. Perhaps to facilitate cross-talk, some participants were present in both meetings (Tommy, Jack, Rodney, and Sandra).

3. Observations

We observed two consecutive engineering meetings occurring in the early stages of the design of a new thermal pen. As such there was a major effort to brainstorm new and novel ideas for both how the design would function and how it would be used.

Almost everyone in both meetings used every type of language identified, regardless of how frequently they talked. Printer language was predominant throughout both meetings, suggesting that it was a common language for the group. There was substantial language mixing, with some participants such as AJ and Tommy mixing four or more language types in a single utterance. This suggests some level of multilingual capability amongst the participants (an ability to link or integrate multiple perspectives) and of people borrowing concepts from outside of their expertise. The mixing of language is often seen linking technical issues to user or business issues, which is similar to McDonnell's observation (this volume) of switching "territories of expertise" in the architecture meeting. While meetings were marked by considerable mixing of language, there were times when only a few disciplinary languages were evident. We also observed the evolution of new printer language: phrases around "ducks" (E2; 146-157) (e.g., fat ducks, skinny ducks, a line of ducks) that appeared to help participants create a common understanding of how the printer head interacted with the thermal media. Also, language (via gestures, representations, metaphors and analogies) was often used as a boundary object that helped create conversational spaces or relay user experiences around the pen. As Ball and Christensen (this volume) observed, most of the analogies and metaphors were non-disciplinary in nature, referencing everyday objects and lived experiences.

Participants switched among a variety of roles, with some engaging in particular roles more often than others. Everyone engaged in an Interpreter role, which often involved efforts to understand the context of the problem such as user and client issues (see also McDonnell in this volume). The prevalence of the Interpreter, User Contextualizer, and Storyteller roles suggests that understanding the user and the new technology became places for team members to build a shared understanding of the problem. Disciplinary expertise was most often relayed through the Informer role (e.g., providing details about the technology or the existing proof-of-concept prototype). The Facilitator role often involved managing the meeting flow, including determining which aspects of the design space could be discussed. This is similar to an observation by Matthews (this volume) on how the meeting facilitators (AJ and Tommy) mediated the social dynamics and brainstorming rules. Overall, participants fluidly enacted different roles which suggest that roles were flexible, impromptu, and not assigned to any one person based on disciplinary expertise. A similar finding was observed for the architect meetings (Goldschmidt and Eshel in this volume).

An analysis of structure classifications revealed boundaries that limited or enabled opportunities to interact across disciplines and aspects of the design space, including potentially co-evolutionary interactions between the proof-of-concept and future market applications. The meeting structure decomposed the proof-of-concept space into areas of disciplinary expertise – providing opportunities for some disciplinary interactions (i.e., Electronic, Industrial Design, and Ergonomics) and potentially limiting others (i.e., Electronic and Mechanical). In some situations participants transgressed boundaries (this was particularly the case when goals were ambiguous); in other situations boundaries were strongly policed (e.g., what could be talked about or negotiated in the different meetings). Examples of these observations are provided later in this section.

While language, roles, and structures characterizations were insightful as separate analyses, a more comprehensive picture emerged when they were viewed in combination. This allowed characterizations of cross-disciplinary boundary work as revealed through conversational and social interactions in reference to different work environment situations (i.e., the design space and the structure of the meeting). Five examples of cross-disciplinary boundary work are presented below in relative chronological order. Collectively these examples characterize social processes in cross-disciplinary teams as signified by shifts: 1) in topic or language associated with aspects of the design space (see Figure 1), 2) in focus between proof-of-concept and future market design spaces, 3) in phases of the design process, and 4) in disciplinary, multidisciplinary, and interdisciplinary practices. In presenting these examples, we will highlight the influence of language, roles, and structures in triggering and navigating these "shifts" as well as describing the situational context in which they occur.

3.1 Towards Interdisciplinarity: Todd's Ghost Story (E1)

During engineering meeting E1, AJ facilitated a brainstorming session to have participants take turns presenting their ideas. This conversation was often characteristic of a multidisciplinary "divide and conquer" approach since the design space was limited to brainstorming only mechanical engineering solutions and efforts to consider other features of the design space in Figure 1 were often curtailed. However, these organizational and design space boundaries were transgressed as illustrated in the episode of "Todd's Ghost Story," which resulted in a push towards interdisciplinary practices and the emergence of a novel concept.

After Rodney suggested a mechanism analogous to the way a razor works (E1, 307) and Sandra initiated a short conversation by asking about different options for the media (E1, 378), AJ asked for additional thoughts (E1, 391). Todd began his idea by suggesting that he: "only brought a magic marker… cos I didn't think there's a problem" (E1, 392-394) which prompted laughter in the group. He then put forward his idea by means of a story about a toy ghost his son found in a cereal box. By adopting a Storyteller role, Todd helped the group develop a common understanding of the product and situated his example in a familiar context others might understand. Sketches and gestures served as a means of communication between participants, and supported the push toward interdisciplinarity. Todd explained how the toy worked by using a gesture of moving his pen around the paper in front of him, and Rodney asked him to draw it (E1, 400). Everyone engaged the role of Interpreter, by clarifying and building upon Todd's idea, using analogies and metaphors that served as bridges between the idea and a group understanding: "pastry brush" (E1, 419), "white line machines" (E1, 422), and "wide like a caravan" (E1, 432). While the focus was on brainstorming mechanical solutions to the pen casework problem, mechanical language did not dominate the conversation. Instead, there was a considerable amount of language mixing, particularly among mechanical, user, and printer languages.

The earlier controlled turn-taking structure of previous episodes was relaxed during Todd's episode, allowing for all participants to freely contribute without AJ's interruption as Facilitator. This provided opportunity for a common understanding to emerge, which is characteristic of interdisciplinary practices. Participants actively contributed to the discussion, sought clarification verbally and in the forms of drawings or gestures, and built on each others' ideas. Humor appeared to soften the managerial and social structure of this episode. Todd began his idea with a humorous comment, and others added humor throughout the meeting. For example, Tommy clarified the idea Todd was explaining by saying: "blimey does that go all over the walls and everything" (E1, 413). AJ ended this episode by returning to a facilitated turn-based process and asked the group for additional ideas (E1, 465).

Our observations around "Todd's Ghost Story" parallel others in this volume. For example, Ball and Christensen described Todd's ghost story as a non-printer based analogy that helped create a common space. Matthews observed that this brainstorming episode did not clearly fit the rules of social order because the idea lacked relevance and went "off topic"; however, it triggered a conversation that resulted in a novel idea. While it may be true that the idea had limited technical relevance, a different kind of relevance was established through the introduction of a personal story *as a user*.

3.2 Towards Interdisciplinarity: Sandra's Choice (E2)

In the second engineering meeting, E2, Sandra posed a question that triggered a move towards interdisciplinary practices. Prior to the question, the previous episode was marked predominantly by electrical engineering language and revolved around the printing resolution of the print head and the paper (E2, 343 – 365). Sandra initiated this move by asking if patterns would be stored in the pen (E2, 371), shifting the conversation from detailing the proof-of-concept solution to opening up a new market consideration regarding using external technologies. Patrick and Tommy then initiated a predominantly disciplinary conversation by suggesting ways of interfacing the pen with external technologies (e.g., incorporating a USB port (E2, 378 – 384)), in the process shifting the conversation back to detailing solutions. This was followed by Roman asking about the business issue of the price of paper (E2, 385), which again triggered a disciplinarily-oriented conversation about the proof-of-concept solution: "you may energise the dots for about two milliseconds … and during that period the centre of the dot might go to more than two hundred degrees" (E2, 408-411).

Sandra redirected this conversation back to the future market design space by asking: "There's actually quite different applications aren't they? The one where you're printing a pattern and the one where you're just uncovering things?" (E2, 424-426). Here, Sandra clarified two forms of future market opportunities, writing with the pen and revealing with the pen (uncovering hidden text in the print media). This option of "revealing" text was a novel idea for how the pen could be used. Then the group shifted to a more general conversation about possible uses of the pen based on the options introduced by Sandra.

Overall, the structure of "Sandra's choice" resembled a ping pong game where the discussion bounced back and forth between the problem and solution spaces, as well as the proof-of-concept and future market design spaces. This had a co-evolutionary quality in which shifts were triggered by asking questions about use of the product or its users. These shifts (which were each on the order of several minutes) marked moves between disciplinary and interdisciplinary practices, where disciplinary practices were often associated with detailing a proof-of-concept solution and interdisciplinary practices were associated with understanding user and media issues. As such, the participants often enacted a User Contextualizer role to understand issues about how users might interact with the pen (E2, 457-472). This was signified by language that had an everyday, imprecise character to it in which everyone was involved in the conversation: "you could have a story about I don't know a teddy bear or a snowman" (E2, 448). In contrast, the pushes towards disciplinarity involved predominantly one or two types of language, most often being mechanical or electrical.

3.3 Towards Multidisciplinarity: Hitting the Boundaries (E1 & E2)

After the group from the first meeting had identified a number of "mechanical brainstorm" ideas, Tommy stated that they had at least three ideas for the pen casework and reminded the group about the importance of controlling the movement of the pen (E1, 550-555). This sparked a nearly half-hour conversation in which efforts (often by Tommy and AJ) to direct the group toward generating ideas about details of the mechanical aspects of the proof-of-concept solution were sidetracked by efforts to evaluate how children might actually use the pen. This evolved into an iterative process of concurrent development of ideas for the final solution and future market opportunities, while generating greater clarity into the requirements for the proof-of-concept. Prominent roles throughout this episode include Interpreter, Idea Generator, Evaluator, and User Contextualizer.

During this conversation, the group continually hit boundaries related to the goals of the meeting. The meeting facilitator pushed the group to focus on the mechanical aspects of the pen while redirecting discussion of future market scenarios and user issues to the second meeting. AJ, Tommy, and sometimes Jamie took on the role of Facilitator in order to manage these boundaries. The first contact with an E1 meeting boundary began with Sandra:

622	Sandra	what do we sorry what do we actually envisage kids doing with this pen I mean
623		are they drawing pictures or making invitations and Christmas cards or-
624	Tommy	erm ( ) we're going to try to deal with that a fair bit on Monday
625	Sandra	oh alright
626	Tommy	as well as electronics and some of the control and user interface features
627		and things whereas erm this is the kind of functional end of the mechanics and
628		keeping the head on
629	Sandra	it does affect a little bit-
630	Tommy	it does yeah you're right

This sparked a brief interdisciplinary conversation about user issues which was then redirected back to the multidisciplinary space of the "mechanical brainstorm" where mechanical and electrical language was predominant. User issues returned to the foreground when Rodney contextualized issues by talking about his own preferences regarding pens (E1, 685): "I think if I was in their shoes using this I'd prefer there'd be something where I decide whether it's in the right position or not…" Participants responded to Rodney's comments by considering how to train people to use the pen properly through the use of various feedback mechanisms (E1, 714). This sparked another interdisciplinary conversation where participants connected their own perspectives on how they use pens (E1, 716) with ways to design the shape of the pen so that it would be held in a particular orientation. This shift was marked by the mixing of language types and analogies (e.g., graphic art, calligraphy, paintbrush, and roller).

Sandra continued to take a role in critiquing and clarifying user issues, including asking questions about whether the pen was to be a training aid or a toy (E1, 893). These moves towards interdisciplinary practices were cut short by managerial redirections to table the discussion for another time (e.g., Tommy's response that the purpose of the pen is "for fun" (E1, 894) which effectively ended this initiated switch). This switching back and forth between interdisciplinary phases of activity around user issues and multidisciplinary phases of activity around designing the casework continued until Tommy redirected the group to consider issues about protecting the print head from user abuse (E1, 1070). This unveiled a crucial design issue at the intersection of the user-casework interface that could have seriously impacted the functionality of the pen (E1, 830). However, the group was directed away from spending too much time on this issue that would be discussed during the second meeting. This resulted in a push back toward multidisciplinary "divide and conquer" practices.

Overall, this example illustrates a continuous push-pull of multidisciplinary-interdisciplinary practices marked by shifts between the proof-of-concept and future market design spaces and triggered by issues surrounding the user. Boundaries regarding which meeting would discuss issues surrounding the user were policed by Facilitators (primarily Tommy and AJ) and were challenged by participants asking questions about the use of the pen. These observations parallel other analyses in this volume. For example Matthews observed how social action was facilitated by Tommy and AJ and how this created boundaries that limited activity. Similarly, Lloyd observed boundaries associated with use and issues related to the user. Also, the process of "hitting a boundary" was not unique to the first meeting. An example of a similar scenario in E2 was when

Patrick said: "we probably ought to go through this list and look at which ones you can actually do with a pencil" (E2, 981), to which Tommy replied: "that's the screening stage yea… lets move on" (E2, 985) cutting off further discussions on this topic.

3.4 Towards Disciplinarity: Jack's Sketches (E1)

Near the end of the first meeting Jack tried to focus the conversation on detailing the design of the casework. This initiated a move towards disciplinary practices.

After a short discussion on whether or not ways to clean the print head should be a design requirement (E1, 1361 – 1393), Jack took on a Facilitator role by requesting that the group move towards detailing the design of the casework: "OK want to do some more detail a bit more the mechanism" (E1, 1395). However, AJ first checked to see if the group had covered everything in the agenda (E1, 1396) and then started a brief interdisciplinary discussion on the issue of children using the thermal pen on something other than the provided media (e.g., their skin or clothes). Tommy tabled this user-safety discussion to the second meeting (E1, 1416), creating a boundary around the allowed topics for discussion. However, questions about the heat generated and how quickly the heat dissipates continued until AJ directed attention back towards Jack (E1, 1478). At this point, Jack asked the group to identify details of the casework and produce sketches (E1, 1479), marking a move to a disciplinary discussion. This also marked a shift from brainstorming to detailing a solution, as well as a shift from discussing user issues to discussing technical functionality issues.

Jack started this disciplinary conversation by sketching the proof-of-concept, which focused the group's attention on the sketch. Unlike the sketches earlier in the meeting, which helped develop a common understanding of the functional issues within the group, these sketches were used to develop and record design details. AJ sat down for the first time in the meeting (E1, 1498), which potentially signaled a switch of the Facilitator role between AJ and Jack. The language used from this point on was predominantly mechanical, with the concepts discussed revolving around the sketches Jack drew: "you'd need an additional part of the mechanism… you could have contacts on top and bottom of that piston" (E1, 1504), "this stays at a fixed angle in that way it can move up and down and it can move side to side it's fixed that way" (E1, 1521). This marked a change from a potpourri of language types to the predominant use of one type of language (mechanical engineering). During this time, AJ, Todd, and Tommy took on the role of Interpreter by clarifying, manipulating and building on the design ideas on the table. This focus on disciplinary issues continued until the end of the meeting.

3.5 Towards Disciplinarity: Tommy's Technical Time (E2)

Late in the second engineering meeting, E2, the group discussed possible features and uses for the proof-of-concept pen. Tommy changed the direction of the meeting by asking for detailed clarification on one of the ideas presented, which moved the discussion towards a disciplinary discussion about electrical issues.

The prior conversation was marked by mixing multiple kinds of language: electrical engineering (e.g., watts, charging, power supply, electrics), mechanical engineering (e.g., spacing, drag, longish), and printer (e.g., "you could have one character per line per line or something" (E2, 1266-1267), "pre-printed or just a grid that you colour in" (E2, 1294)). After a discussion of potential features of the pen, Tommy interrupted the conversation flow with a key question: "You can probably just get electrics for that stuff can't you?" (E2, 1354). Tommy's question marked the beginning of a shift to detailed design, since he asked for clarification on how the ideas previously discussed could be implemented. Jack then reinforced the move Tommy initiated by asking: "how would you want to select the different features on the pen then" (E2, 1360). The level of technical electrical language is maintained for the duration of the disciplinary episode. They talk about LCD panels, buttons, scrolling, and ideas including: "a lot of controllers microcontrollers have got LCD drivers wired in" (E2, 1398). The role of Disciplinary Informer is prevalent in this episode, such as when Patrick said: "just say that on the paper built in LCD driver" (E2, 1400). However, some mixing of language occurred, such as discussions about business issues and cost as a way to evaluate technical electrical ideas (e.g., a discussion about the cost versus benefits of adding wireless capabilities to the pen design (E2, 1409-1455)). These divergences reinforce the disciplinarity of the primary conversation by allowing them to evaluate ideas and generate or modify ideas based on these evaluations.

This disciplinary conversation ended when Tommy facilitated a change of discussion: "right erm OK we've done the other ones erm I'd like to talk a bit about erm the choice of architecture" (E2, 1479-1480). This signaled the beginning of a new disciplinary conversation about a different technical issue.

3.6 Comparison of Examples

These five examples of cross-disciplinary boundary work all provide lenses for revealing social processes in cross-disciplinary design teams. They illuminate different cross-disciplinary practices and how movements among these practices are initiated. They also suggest that cross-disciplinary boundary work is less about crossing disciplines and more about crossing perspectives (where disciplines are one of many perspectives).

The examples are also different in important ways. Sandra's Choice (3.2) differs from Todd's Ghost Story (3.1) in the kinds of interdisciplinary shifts; the first is situated in the problem space, the second in the solution space. This suggests that the context of what is being discussed doesn't guarantee an interdisciplinary shift since interdisciplinary practices were observed in both problem formulation and detail design phases of activity. The multidisciplinary example (3.3) emphasized how boundaries, often imposed by a facilitator, can trigger multidisciplinary-interdisciplinary shifts. The two disciplinary examples were both situated in the detailed design space; however Jack's (3.4) was a facilitated shift, whereas Tommy's (3.5) shift was in response to a general question.

4. Interpretation and Discussion

An analysis of language, roles, and structures revealed (1) characteristics of cross-disciplinary boundary work in engineering design teams, (2) the kinds of boundaries encountered and how they were navigated at an individual and group level, and (3) actions that limited or enabled different cross-disciplinary and disciplinary practices. Each of these addresses our original research questions.

As summarized in Table 5, language classifications revealed what perspectives were included (and in some cases excluded) and marked cross-disciplinary and disciplinary conversational shifts. Role classifications revealed actions to police, maintain, reformulate, or modify boundaries associated with the design space, the way the meetings were organized, and the design process followed in the two meetings. In this way, roles triggered shifts among cross-disciplinary and disciplinary conversations. Structure classifications provided a means for describing participatory boundaries, conversational topic boundaries, and problem-solution boundaries as well as their evolution in relation to participants' actions. These boundaries impacted the kinds of cross-disciplinary and disciplinary interactions possible within the two engineering meetings. When boundaries were relaxed, important conversations occurred that resulted in pushes towards interdisciplinary practices and the generation of novel ideas. For example, Sandra's push on user issues opened up new avenues for future markets (episode 3.2); Tom's humorous story of a "ghost" provided a new way of configuring the proof-of-concept pen design (episode 3.1).

Table 5. Language, Roles, and Structure in Cross-Disciplinary Boundary Work

LENS	NATURE OF BOUNDARIES AND CHARACTERISTICS OF CROSS-DISCIPLINARY BOUNDARY WORK
Language	• Language marked cross-disciplinary and disciplinary conversational shifts • Predominance of printer language suggests a history of cross-disciplinary collaboration in this group • Language served as boundary object to enable common ground and synthesis via (1) language mixing and people using disciplinary language outside of their training, (2) use of analogies and metaphors, (3) sketches, (4) imprecision and hedging words around project goals, (5) using gestures to communicate issue about using the pen, and (6) generating new language (e.g., "ducks" as new printer company language)
Roles	• Roles triggered shifts among cross-disciplinary and disciplinary conversations or practices, and therefore triggered different modes of knowledge production and social interactions • High level of role switching suggests the meeting environment was non-hierarchical where access to roles was unlimited • Roles illuminated how people and actions mediated and facilitated cross-disciplinary practices by (1) bridging and synthesizing multiple perspectives (particularly issues of use and users), (2) encouraging discussion, (3) stretching and stimulating imaginations, and (4) negotiating ideas. For example: o Facilitator enabled or limited participation in a conversation, policed and reformulated what could be discussed o Informer enabled bringing knowledge into the conversation and was only specific disciplinary role observed o User Contextualizer and Storyteller enabled including knowledge about use and users o Questioner challenged problem-solution ideas, what could be discussed (or not), when ideas could be discussed, and how ideas could be discussed. Often these actions were associated with questions about user issues (e.g., sections 3.1, 3.2, 3.3)
Structures	• Structures impacted social interactions by creating participatory boundaries, conversational topic boundaries, and problem-solution boundaries • Structural boundaries created an exclusion-inclusion dynamic that prompted participants to enact roles that pushed on boundaries or brought outside information into the design space • Participation and process structures revealed multidisciplinary practices (e.g., divide and conquer approaches), interdisciplinary practices (e.g., creating common ground), and disciplinary practices (e.g., focusing on technical specificity)

Through a combined lens of language, roles, and structures we characterized different outcomes of boundary work in this setting. These outcomes describe different cross-disciplinary and disciplinary practices in terms of modes of knowledge production, and social interaction and discourse structures (see Table 1). These are summarized below:

- In **disciplinary boundary work** practices, a single discipline dominates the language, roles, and representations within the group. Disciplinary practices were often strongly mediated by a facilitator who encouraged the group to focus on a specific subset of issues. It is important to note that in this situation this occurred even though people from multiple disciplines were present and participating in a group environment. We observed how disciplinary boundaries limited the group from considering ideas or practices outside of the dominant disciplinary space.
- In **multidisciplinary boundary work** practices, individuals retain disciplinary identities while working with others with different disciplinary backgrounds. In this situation the group had a history and a common language around a shared topic (i.e., electronic printer technologies). Participants engaged in the group conversation through roles where they brought their disciplinary expertise into the design space. Managerial structures and the Facilitator role played a crucial role in defining multidisciplinary environments in three ways: divide and conquer approaches, juxtaposition rather than integrating two or more perspectives, and creating artificial disciplinary boundaries.

- In **interdisciplinary boundary work** practices, individuals from multiple disciplines work together in a way that is not specific to a single discipline. Part of the process includes creating common ground to overcome challenges due to differences in disciplinary languages and world views. In this situation, group processes and culture involved active participation, collaborative building around ideas, language mixing and other efforts such as using everyday and imprecise language to enable conversation and the creation of common ground. Creating opportunities to question issues at the user-product interface relaxed work boundaries and triggered the development of novel ideas.

This study illustrates how a lens focused on cross-disciplinary boundary work can help interpret events, actions, and social processes in design settings. Here, language, roles, and structures classifications illuminated (1) different boundary work practices regarding the nature of boundaries, how boundaries emerged, and how boundaries were navigated, and (2) different cross-disciplinary and disciplinary practices regarding modes of knowledge production and social interactions.

We feel this research has important implications for engineering design research and education. First, it provides another way to understand design as a social process (Bucciarelli 1996). Here, social processes are revealed by exploring how people interact within a design work environment: the boundaries they experience, the way individuals and groups navigate these boundaries, and the outcomes of this boundary work. In this way, this study complements other studies in this volume such as McDonnell's work that illustrates the subtleties of collaboration and negotiation of progress with a design. Second, this study emphasizes the importance of considering use and users and how these considerations can trigger innovative outcomes and pushes towards interdisciplinary practices. This supports Lloyd's (this volume) observation about how considering "unethical" user behaviors sparked creative imagination. It also provides a complementary framework for Reyman et al's (this volume) observation of how "use" was a bridging concept in the engineering meetings that linked problems and solutions in a functional way (see also Atman et al, this volume). This is similar to McDonnell's (this volume) observation in the architecture meeting on how appealing to use or user created conversational openings.

Third, this study provided another framework for considering co-evolutionary and transformative processes in design (Dorst and Cross 2001, Adams et al 2003). Efforts that challenged "boundaries" often triggered abstract-concrete cycles around problem requirements and solution alternatives, which is one way of describing co-evolution in design. These often involved shifts toward interdisciplinary practices. However, problem-solution cycles were not the only kinds of co-evolution observed. There were also co-evolutionary cycles between the proof-of-concept space and the future market space. In other words, conversations around future market applications sparked a dialogue by linking to an issue regarding the proof-of-concept design, and vice versa. This is an observation of co-evolution in design that may be novel. Fourth, a cross-disciplinary boundary work lens illuminated features of innovation environments and innovation social practices (see also Lloyd this volume, Petre 2004, Newstetter and Kurz-Milcke 2004). These were often associated with shifts toward interdisciplinary practices triggered by considerations of use and users.

This study also provides insights for supporting cross-disciplinary work environments and facilitating cross-disciplinary practices. Because we observed many pushes and pulls towards different disciplinary and cross-disciplinary practices, facilitating cross-disciplinarity may be less about enabling a particular practice and more about enabling multiple practices and switching among these practices. This makes sense since different practices may be appropriate for different phases of the design process or facilitating different kinds of outcomes (i.e., novel solutions or applications). Similarly, this study illustrates that boundaries (participatory, conversational, and structural) can be transgressed as well as policed. Individuals can trigger a shift through their actions (e.g., User Contextualizer and Facilitator roles) as well as their use of language. This suggests that enabling cross-disciplinary environments involves fluid access to roles and promoting multilingual capability as a precursor to developing common ground. Finally, structures appeared to have the greatest impact on facilitating cross-disciplinary shifts. Cultures that support cross-disciplinary work should provide opportunities for individuals or groups to challenge and reformulate existing structures or boundaries.

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