Objects of Collaboration: Roles of Objects in Spanning Knowledge Boundaries in a Design Company

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OBJECTS OF COLLABORATION: ROLES OF OBJECTS IN SPANNING KNOWLEDGE BOUNDARIES IN A DESIGN COMPANY

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ABSTRACT

Engineering designers often span knowledge boundaries when developing complex systems but doing so poses challenges because members of different knowledge groups must bridge their language, cognitions, and "thought worlds" to effectively broker, resituate, and make use of each other's ideas. Objects—ranging from prototypes to kanban boards to value stream maps—are frequently used in cross-functional design practice, but the outcomes associated with such objects appear varied and dependent not only the objects' characteristics but on how, when, and by whom they are used. This paper describes a two-year inductive ethnographic study within a turbomachinery design company to understand how cross-functional design teams span their knowledge boundaries to advance their designs and design processes. We collected observations of 70 cross-functional meetings and 52 interviews across functional groups during the development of complex turbomachinery products. Our findings include three roles of objects of collaboration: routinizing cross-boundary interaction, translating information across boundaries, and motivating joint negotiation or discovery. We found two prominent outcomes—co-discovery of a design risk, opportunity, or workflow bottleneck and co-design of a joint integrated solution— that appeared to follow from the latter two roles, respectively. These findings are significant because they clarify the roles of objects in cross-boundary design work and suggest ways for designers to more effectively use objects to span knowledge boundaries.

INTRODUCTION

In the 1990s Pratt & Whitney developed a new high-thrust jet engine for Boeing 777 airplanes, the PW4098. The engine is complex with over 600 sub-system interfaces. As cross-functional design teams developed these sub-systems, two interfaces were missed which, by the time they were discovered and addressed, resulted in an estimated increase of at least 6-months in development time and 2-4 percent (likely >$1M) in the total program budget [1,2]. When developing complex products and systems, design interfaces and functional dependencies are not always apparent up front, and even when they are, shifting external conditions can create a moving target of design requirements, interfaces, and dependencies. As such, complex system design involves uncovering and addressing a potentially shifting set of unknown unknowns, many of which reside in the boundaries between knowledge groups.

Spanning knowledge boundaries has been described as both a source of and barrier to innovation [3]. Boundary spanning poses challenges because members of different knowledge groups must bridge their respective status and interests [4], language (jargon and communication rules [5,6]), "thought worlds" (interpretive systems of meaning [7]), schemas (mental representations [8]), scripts (patterned ways of acting [9]), and mental models (ways of "playing out" scenarios in one's head [10]) to effectively broker, resituate, and make use of each other's ideas. While focusing work *within* a knowledge group has advantages, working *across* knowledge groups has been found to improve product performance [11-14], innovation [15,16], product development speed [15], and optimize system-level design decisions, e.g., [17-19]. However, these boundary spanning benefits are not always realized due to between-group differences in language, cognitions, thought worlds, etc. which can lead to missed communications, such as the Pratt & Whitney example above, or miscommunications, such as excess or biased

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design margins or uncertainty in parameter estimates [20-22]. Such miscommunications can result in expensive rework cycles and decreased design quality.

Objects have been found to play a consequential role in structuring the thoughts and actions of designers [23,24], particularly when spanning knowledge and occupational boundaries [25,26]. In the present study, we define "objects of collaboration" as collaboratively developed physical or digital representations of designs (e.g., prototypes, sketches, engineering drawings), representations of design risks, tradeoffs, or problems (e.g., failed parts, FMEAs, tradeoff curves, A3s), and representations of design processes or workflows (e.g., value stream maps, obeya andons, kanban boards, sprint backlogs). Design research has contributed many cross-functional design methods (that often take the form of objects, e.g., [28-30]), but currently offers little theory [31] on how designers engage with such objects, and one another, to span knowledge boundaries.

To address this gap, we conducted a two-year (2019-2021) inductive ethnographic study within a large turbomachinery design company, "Turbo" (pseudonym). Our data include ethnographic observations of 70 cross-functional meetings and 52 interviews across seven functional groups (Advanced Technologies, Aerodynamics, Mechanical Design, Rotordynamics, Structural Analysis, Supply Chain, and Quality) during the ongoing development of Turbo's complex turbomachinery products. We analyzed these data using an inductive grounded theory approach drawing from theories in design science (e.g., [22,24,32]) and organization studies (e.g., [3, 33-35]) and guided by the question: *How do cross-functional design teams span their knowledge boundaries to advance their designs and design processes?* As our inductive process progressed, the roles of objects emerged as prominent themes, and we developed more specific research questions:

1. What roles do objects play in structuring cross-functional interactions in design practice?
2. What outcomes seem to follow from these object roles?

BACKGROUND

We draw upon research streams in engineering design and organization studies to examine how designers use objects to help bridge knowledge boundaries during product development. This section offers an orienting framework for understanding cross-boundary design work and summarizes background on types of knowledge boundaries and how these connect to prototypes and other objects of collaboration.

Cross-Boundary Work: An Orienting Framework

Multiple terms refer to people working together across knowledge boundaries in a design process, including "collaboration," "coordination," "cooperation," and "integration" [36]. We refer to these collectively as "cross-boundary design work." Edmondson and Harvey [37] offer a model of "cross-boundary teaming" that provides an orienting theoretical framework for our study (Figure 1). While their model was developed to understand cross-boundary work in innovation teams with more temporary and unstable membership, we have found the model to be applicable in our setting. It centers cross-boundary behaviors (e.g., experimenting, discussing errors, seeking feedback), objects used during interactions (e.g., prototypes, drawings, process maps), participants' individual states (e.g., role clarity, self-efficacy, belonging), and collective states (e.g., psychological safety, shared mental models, transactive memory). These constructs are affected by the languages, interpretations, and interests of each group and contextual factors like the environment, leadership, task, and time. The combination of all these variables influence the outcomes of cross-boundary work. Acknowledging the complex nature of cross-boundary design work, the focus of our study is to better understand the roles that objects play in influencing cross-boundary interactions and, ultimately, cross-boundary outcomes (as highlighted in grey in Figure 1).

Knowledge Boundaries

Knowledge boundaries demarcate functional, disciplinary, and other knowledge groups [38]. Such boundaries are spanned when information is *transferred*, *translated*, and/or *transformed* between knowledge groups [33]. Scholars have identified three kinds of knowledge boundaries, in order of increasing complexity: syntactic, semantic, and pragmatic [3,39,40]. Spanning a syntactic boundary involves establishing a "shared and stable syntax" by which information can be accurately transferred between groups [41]. *Syntactic* boundaries are

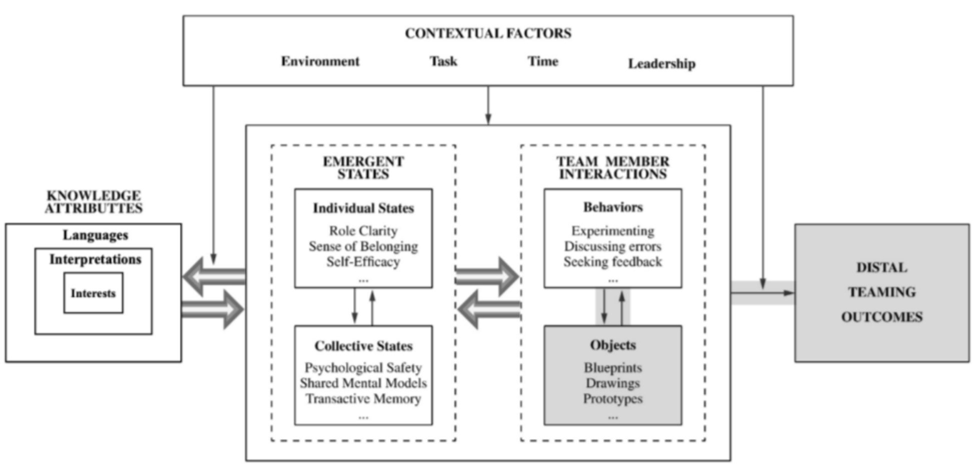

Figure 1. An orienting theoretical model of "cross-boundary teaming for innovation," taken from Edmondson and Harvey's model [37]. Our focus is highlighted in grey.

foundational in that spanning any knowledge boundary, by definition, minimally involves a transfer of information. For example, in developing a new automobile, engineers from the Engine/Powertrain and Climate Control functional groups might both offer parameters values related to the size of a vehicle's front grill. Such parameter values need to be understood using the same parameter syntax in order for the different values to be properly compared.

Semantic boundaries involve not just the transfer but also translation of information. Even when two knowledge groups share a common syntax (e.g., a shared understanding of variables related to a vehicle's grill), information transferred between them may be interpreted differently unless a shared interpretative scheme is used. Shared interpretive schemes can make visible the novel differences and dependencies between groups' "thought worlds" [7]. Imagine that the Engine/Powertrain group advocates for a higher horsepower engine. This information would need to be translated to show its meaning for other groups, otherwise the Styling group might not see how the new engine affects vehicle hood slope and the Safety group might not see the implications for vehicle weight, bumper position, etc.

Pragmatic boundaries add a final layer of complexity. These acknowledge that spanning a knowledge boundary is not just about challenges in transferring and translating information but about addressing groups' different and potentially competing interests and agendas. Spanning a pragmatic boundary involves making one's knowledge, skills, and designs—hard-won within one's own knowledge group—vulnerable to being transformed as a result of interactions with other groups [3]. Consider how a vehicle Engine/Powertrain group might aim to maximize engine power whereas Styling, Climate Control, and Safety groups might aim to achieve a certain look and feel, heat flux, and safety rating. Including a higher horsepower engine could advance the goals of the Engine/Powertrain group but not necessarily the goals of other groups. Table 1 provides a summary of these three types of knowledge boundaries. Understanding which kind of knowledge boundary(s) is being spanned can help designers to improve their boundary spanning efforts.

Table 1: A typology of knowledge group boundaries [3]

Knowledge Boundaries of Increasing Complexity →

	"Syntactic" Boundary	"Semantic" Boundary	"Pragmatic" Boundary
Signs of this Boundary	• Unshared language, variables, symbols, representations, etc. • Using different words to mean the same thing or the same word to mean different things	• Poorly understood group differences or dependencies • Little visibility into how the work of one group specially affects the work of another	• Different and potentially competing group interests or agendas • Conflict, resentment, or mistrust stemming from unaligned group goals
Spanning Involves	Spanning involves establishing a shared and stable syntax by which information can be *transferred* between groups' lexicons [40].	Spanning involves establishing a shared interpretive scheme by which information can be *translated* between groups' "thought worlds" [7].	Spanning involves establishing shared goals that motivate information and designs to be *transformed* through cross-group work [3].

Objects of Collaboration in Design

Objects play a central role in the cross-functional collaborative work of product development [23,42-45]. We refer to "objects" broadly to include representations of designs, risks, opportunities, tradeoffs, processes, workflows, etc. In the field of organization studies, scholars refer to such artifacts as "objects of collaboration" [34]. The following paragraphs summarize background from the engineering design literature on prototypes, a prevalent category of objects involved in cross-functional design collaboration and coordination. We then summarize theories and findings from organization studies on objects of collaboration more broadly, their different roles, and how these roles help to span syntactic, semantic, and pragmatic knowledge boundaries.

Prototypes. Prototypes play prevalent roles in design practice and are key objects of study in design research. Foundational studies of prototypes describe how they provide both material and cognitive representations of design ideas [46], are used at different fidelity and stages to increase design quality and reduce development time [47], and vary depending on the type of questions being answered (e.g., "works-like," "looks-like," or integration prototypes) [48]. A study with students found that simpler prototypes (those with fewer parts and fewer parts added over time) were correlated with better design outcomes [49]. Ethnographic studies in design firms found that prototypes—whether physical or digital—provided "small wins" [50] that fueled a sense of progress, reframed failure as an opportunity for learning, and strengthened designers' creative confidence [51] in addition to enabling communication and informing decision-making [24]. Other design scholars have developed a "prototyping for X" framework that structures prototyping for novice designers [52] and heuristics that support designers to better tradeoff resources spent on and design information gained from a prototype [53]. While many studies have been based in Europe and North America, some have examined prototyping in East Africa [54] and India [55] and found that prototypes remain relevant collaborative objects but operate with different constraints and opportunities (e.g., the availability of materials or software, regulatory flexibility, etc.). For a more extensive review of design prototyping strategies and techniques, see [56].

Objects Used in Spanning Knowledge Boundaries. We now turn to the literature in organization studies to summarize theories and findings on how objects of collaboration, including prototypes, help designers to address the challenge of spanning knowledge boundaries. Knowledge boundaries are challenging to span because members of different groups use different language, interpretive schemes, and hold different goals and interests thus making it difficult to communicate and design together. Objects of collaboration can help, and we review how objects have been found to play different roles when spanning syntactic, semantic, and pragmatic knowledge boundaries. This literature categorizes objects not by their inherent qualities but by how they are used, thus the same object can be categorized differently when it plays a different role in a different situation. To make this concrete, we use an example from Carlile [33] of a computational fluid dynamics (CFD) model that served as an early-stage integration prototype of a new vehicle at a major global automotive firm. The CFD prototype augmented traditional clay models that Vehicle Styling designers also created at that stage. The clay models did little to help the firm's four major functional groups—Vehicle Styling, Engine/Powertrain, Climate Control, and Safety—to foresee how the designs of one group would affect the designs of another. For example, a higher horsepower engine might affect the Vehicle Styling group by requiring a steeper front hood slope or the Climate Control group by requiring a bigger front grill. The CFD model is an illustrative object of collaboration in that it played multiple roles in helping these groups to span multiple kinds of knowledge boundaries. Let us begin with the CFD's use as an infrastructure object to span syntactic boundaries.

Infrastructure Objects. "Infrastructure" objects scaffold the transfer of cross-functional information [57,58], such as images, plots, charts, or other visuals used at cross-functional meetings. Such objects help groups to develop a shared, stable syntax that facilitates accurate information transfer across group boundaries. For example, in co-developing a CFD model for a new automobile, designers from the Styling, Engine/Powertrain, Climate Control, and Safety groups "were able to establish a base common language that they could use to specify critical differences (e.g., size, geometry, weight, functionality, etc.)" in their designs [33, pp. 562]. To "specific critical differences" in, for example, the size of a vehicle's front grill, designers from each functional group needed to understand grill parameters in the same way so that their parameter values could be compared. The CFD model helped the designers to develop a shared syntax and thereby effectively transfer pertinent information across their syntactic boundaries. Many objects can play an infrastructure role in engineering design, including part libraries, Gantt charts, obeya walls [59], sprint task lists [60], FMEAs [61], and other standardized forms and methods. While such objects can facilitate a shared syntax for information transfer across a syntactic boundary, this does not guarantee a shared translation across a semantic boundary — that is the work of boundary objects.

Boundary Objects. "Boundary" objects translate information across group boundaries thereby allowing members of different groups to see and communicate different meaning from the same information. This can make visible consequential group differences and dependencies [3,25,62-64]. Boundary objects facilitate shared meaning by providing "interpretive flexibility" — being "plastic enough to allow polysemy across knowledge boundaries and rigid enough to support particular meanings within them" [65, pp. 281]. The automotive CFD model acted as a boundary object when it was used to represent the cross-functional consequences of potential design decisions, such as integrating a more powerful engine into the vehicle [33]. This design information was translated into new engine block dimensions, heat flux values, and vehicle weight so that the Styling group could see how it would affect hood slope, the Climate Control group could see how it would affect grill size, and the Safety group could see how it would affect bumper location. Each group saw both different meanings (implications for their group's specific design goals) in addition to common meanings about what was of consequence. Many design artifacts can play the role of a boundary object, including prototypes, sketches, engineering drawings, bills of materials, value stream maps, and others. While boundary objects support translation across a semantic knowledge boundary and improved visibility of differences and interdependencies across groups, they do not necessarily establish shared goals and transform knowledge or designs across a pragmatic boundary. Here we turn to activity and epistemic objects.

Activity and Epistemic Objects. These two types of objects build shared interest across pragmatic knowledge boundaries, though they do so in different ways. An "activity" object is used to identify contradictions between group interests and motivate negotiations across groups [66,67]. Activity objects show how the knowledge, goals, outputs, etc. of one group have consequences for the knowledge, goals, outputs, etc. of another and, importantly, motivate cross-group negotiations that address these interdependencies and potential contradictions. While activity objects act as sources of contradiction and negotiation, "epistemic" objects act as sources of attraction and discovery [68]. Epistemic objects stimulate joint interest in collaborating to solve a problem or generate new knowledge. They represent the "thrill of potential discovery" and offer a "not-yet-completeness" that stimulates energy and emotional investment [34] and rallies otherwise weakly connected individuals to build solidarity and form a provisional community to address the joint challenge or opportunity [68]. Both activity and epistemic objects facilitate not only cross-boundary transfer and translation but also the transformation of multiple groups' knowledge, designs, workflows, etc.

To illustrate, the CFD model act as an activity object in that "each group could first represent their various concerns, data points, and requirements, then engage each other to identify, negotiate, transform, and verify the knowledge that they would then use to design the vehicle" [33, pp. 563]. In this way, the CFD model not only transferred and translated but also transformed within-group knowledge and associated design parameters across the four functions. For example, when considering the use of a higher horsepower engine, Engine/Powertrain, Styling, Climate Control, and Safety each transferred their desired design parameters into the shared infrastructure of the CFD model. This helped them to transfer, translate, and see the consequences of their design parameters on other groups' designs, but it also helped them to transform their designs by seeing and negotiating tradeoffs at an early stage when design changes were relatively inexpensive to make. This resulted in a vehicle development program that "avoided major rework costs and launch delays" [33, pp. 562]. While CFD models are one example, a variety of engineering objects act as activity objects, including tradeoff curves [69], decision matrices [70], and value stream maps [71]. Others act as epistemic objects, including failed parts, novel prototypes, and A3 reports [72]. Both kinds of objects develop shared interest and motivate negotiation or discovery thus transforming knowledge, designs, and workflows across pragmatic boundaries.

Objects can play multiple roles and transition between roles depending on the context of their use, as is evident in the CFD model example. So, we do not ask *which* type of object a collaborative artifact is, but *when* it is a certain type. This matters because how an object is used (the role(s) it plays) appears consequential for the outcomes of its use (e.g., uncovering a cross-functional design risk, co-designing a joint solution, etc.).

METHODS AND EMPIRICAL CONTEXT

The lead author underwent a 24-month ethnography focused on cross-functional work during the development of complex hardware products within a global turbomachinery company. Focused ethnography directs a researcher's inquiry toward a particular phenomenon or situation—i.e., cross-functional collaborative design work—instead of exploring an entire organizational and cultural system [73]. We used ethnographic methods and paid particular attention to cross-functional interactions that occurred in the presence of objects. Data collection and analysis happened in parallel, as described below.

Field Site: Turbo

"Turbo" designs, manufactures, and services turbomachinery internationally as part of a large corporation. Their campus in the United States houses thousands of employees. Compressor Engineering (CE), one of Turbo's product development divisions, consists of roughly 60 engineers who contribute to developing industrial gas compressors (see a representative example in Figure 2). Turbo CE engineers ranged in age from just-graduated to near-retirement with many who had been with the division for decades. Turbo CE was formally arranged as a matrix organization with seven functional groups: Advanced Technologies, Aerodynamics, Mechanical Design, Rotordynamics, Structural Analysis, Supply Chain, and Quality. A Products Management group consisted of program managers who oversaw each product development program, managed budgets and timelines, and helped to coordinate work across the functional groups. Beyond CE, other divisions like Marketing, Manufacturing, and Packaging Engineering were also involved in new product development programs. For about a decade, leaders of Turbo CE had been experimenting with using tools like kanban boards (a workflow management system), obeya walls (a system to visualize work status and identify deviations from expected conditions), and other tools from lean process and product development, e.g., [69]. Their advanced use of these tools in developing a complex hardware product, and an apparent culture of learning and continuous improvement, was what initially attracted the lead author to this organization.

Data Collection: Ethnographic Methods

Qualitative data were collected from December 2019 through December 2021 in the form of ethnographic observations and interviews [74]. From December 2019 to February 2020, the lead author spent about one week per month fulltime within Turbo CE. He was given a desk, building access, introductions, and invitations to attend meetings and conduct interviews. In March 2020, as the Covid-19 virus spread throughout the United States, Turbo moved to primarily remote work. From May 2020 to December 2021, the lead author conducted virtual observations and interviews for roughly 1-5 hours per week. The methods used for data collection included: (1) in-person and virtual observations in the workplace, (2) fieldnotes of workplace observations, written and logged daily, (3) audio recordings of semi-structured interviews, (4) audio recordings (or fieldnotes when recordings were not preferred) of informal ethnographic interviews to debrief prior observations and validate emergent findings, (5) images or sketches (when images were not permissible) of documents, prototypes, and other artifacts resulting from cross-functional collaborative work. As the study progressed and theoretical categories emerged, data were "theoretically sampled" [75,76] by observing targeted social situations that helped to elaborate emergent findings. We aimed to collect not only data that validated our emergent understanding but also "negative cases" that led to revision or expansion of our coding scheme. The total dataset collected and analyzed in the present study consists of 70 cross-functional meetings observed (in-person and virtually), 52 interviews conducted (ethnographic and semi-structured), and 84 objects observed in use the context of cross-functional meetings or retrospectively in the context of interviews. This came to a total of roughly 130 hours of data spanning a two-year period, as summarized in Table 2.

Figure 2: An industrial gas compressor representative of the products being developed at "Turbo." Credit: Baker Hughes (not the actual product or company observed).

Table 2: Summary of data

Data	#	hours
Semi-structured interviews	25	21.8
Ethnographic interviews	27	27.5
Cross-functional meetings observed (in-person)	24	~30
Cross-functional meetings observed (virtually)	46	~50
Objects of collaboration observed	84	

Data Analysis: Grounded Theory Approach

We took an inductive grounded theory approach [75,76] in analyzing our ethnographic data. This involved open coding of fieldnotes and interview transcripts, building a codebook by iteratively moving between emergent codes and theoretical concepts from the literature, writing and discussing memos among the research team, axially coding to form links between concepts, and constantly comparing and refining codes until theoretical saturation was reached. Our unit of analysis was observed or described instances of cross-functional interaction in the presence of an object (a digital or physical artifact). Open coding resulted in codes such as "low/high cross-group engagement," "translating," "problem solving," "co-developing a joint integrated solution," etc. which were further refined by reviewing the literature on prototyping, lean product and process development, boundary objects, and team learning. The concept of "objects of collaboration" and subtypes of infrastructure, boundary, activity, and epistemic objects as described by Nicolini, Mengis, and Swan [34] were particularly fruitful for our understanding. Our final codebook is provided in Table 3.

Addressing Validity

Our study, like other in-depth ethnographic studies, strives for internal validity not generalizability. Future research may examine the generalizability of the findings from this single company by testing them across multiple organizations and contexts. To establish internal validity, we followed recommended practices for analyzing qualitative data e.g., [77,78]. Our process included intensive long-term involvement in our field site (24 months), strong theoretical foundations from the engineering design and organization science literatures, theoretical sampling and triangulation using multiple data sources (i.e., interviews, observations, objects images or sketches, etc.), *clearly reporting* how data were collected and analyzed, debating the results among a team of multiple researchers, examining "negative cases," and validating the findings with key informants (staff at Turbo). To protect privacy, pseudonyms are used for all informants in the following text.

FINDINGS

Our findings identify a typology of objects of collaboration that draws attention not to the qualities of objects themselves but to the roles that they play—how they are used—in cross-functional design work. These findings support and translate existing theories from organization studies, e.g., [34], into engineering design. We also identify a typology of cross-functional design outcomes that appear to follow from certain object roles.

Three Roles of Objects in Cross-Functional Design Work

We observed a variety of objects during cross-functional interactions at Turbo (see examples in Figure 3) that appeared to support design coordination, exploration, specification, problem solving, decision making, and more. Across these objects, three roles emerged in how they facilitated cross-boundary design work. We found that objects of collaboration (1) *routinize* cross-functional information transfer, (2) *translate* information across functional groups, and (3) *motivate* cross-functional negotiation and discovery (see summary in Table 4). In describing each role, we show how the latter two roles appear to be connected to certain kinds of cross-boundary design outcomes. We found that objects could play multiple roles simultaneously, and while they tended toward a primary role in a given situation, the role could shift over time. This implies that an object's role does not derive from its essential qualities but from how it is used. These findings offer guidance for how design teams might employ an

Table 3: Data analysis codebook

Top Level Codes	Secondary Codes	Tertiary Codes	Definitions
Roles of Objects in Cross-Functional Design Collaboration	Routinizing	Infrastructure Objects	When an object is used to scaffold routine cross-functional information transfer. The object itself may fall into the background during such cross-group interactions [57,58].
	Translating	Boundary Objects	When an object is used to translate information between groups in ways that make it meaningful to the info-receivers, perhaps facilitating different meaning than that of the info-providers. This may result in clarified group differences and dependencies [3,25,62-64].
	Motivating	Activity Objects	When an object is used to identify contradictions between group goals and motivate negotiations between groups [66,67].
		Epistemic Objects	When an object is used to stimulate joint interest in solving a problem or generating new knowledge. The object may act as a source of attraction spurring members of different groups to come together, working closely as part of a temporary "proto-community" [68].
Cross-Functional Design Outcomes	Collaboration Outcomes	Co-Discovering a Design Risk or Tradeoff	When a new concern, risk, or tradeoff is collectively identified that could potentially degrade the performance of the product or system.
		Co-Developing a Design Solution	When a design solution is collectively identified that meets the goals of multiple functional groups.
		Collectively Reframing a Problem	When a design challenge or requirement is reconceptualized and collectively viewed in a new way.
	Coordination Outcomes	Co-Discovering a Workflow Bottleneck	When a task bottleneck or pattern of rework is collectively identified in a cross-functional workflow.
		Co-Developing a Workflow Solution	When a solution is collectively developed to a workflow bottleneck or other resource constraint.
		Collectively Revising the Critical Path	When the expected critical path—the sequence of tasks that determine the minimum time to develop a product or system—is collectively rerevised.

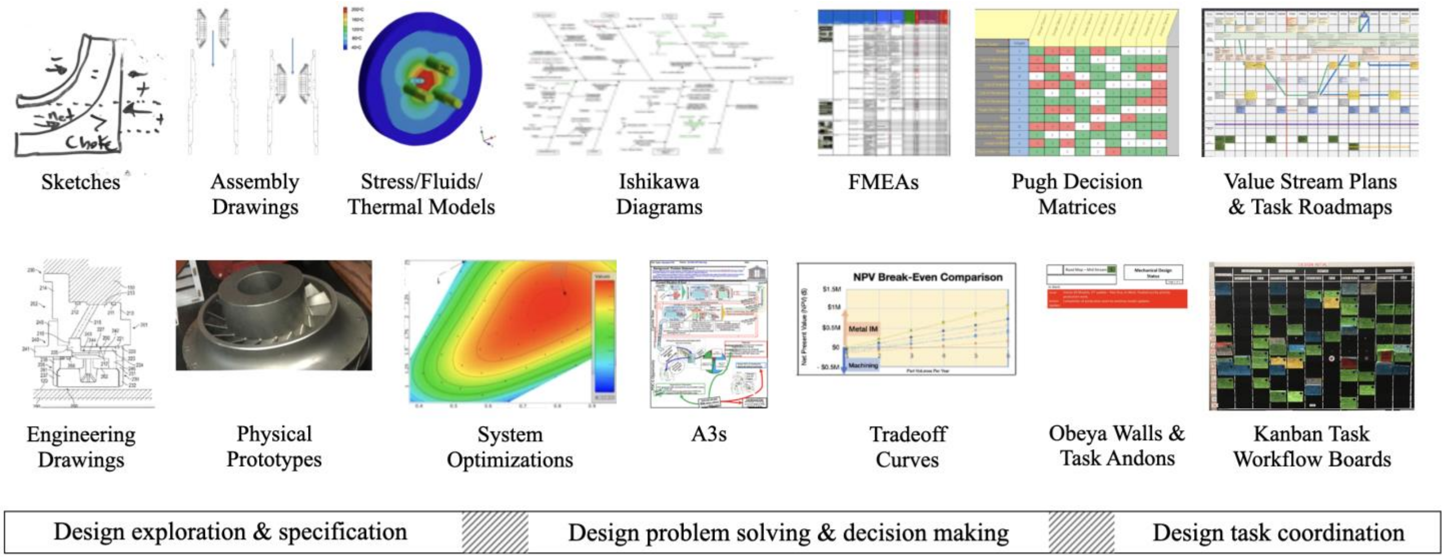

Figure 3: Examples of objects of collaboration observed at Turbo Compressors Engineering (CE). Some objects have been blurred or reproduced with modification to protect confidentiality.

appropriate range of objects during cross-functional interactions, use objects in ways that encourage desired cross-functional outcomes, and align team members' expectations of an object's role in any given situation. We begin with the first role — how objects routinize interactions between knowledge groups.

Role 1: Objects Routinize Cross-Boundary Interactions. In our observations, objects played a *routinizing* role when they acted as infrastructure scaffolding routine cross-functional interactions. Objects acting as routinizing infrastructure were not sources of attraction or contradiction like epistemic and activity objects, nor were they a means of cross-functional translation like boundary objects. They were scaffolds that routinized cross-functional engagements and, in the process, could fade into the background. At Turbo, objects playing a routinizing infrastructure role included artifacts such as kanban boards (a workflow management system), obeya wall "andons" (flags that indicated deviation from expected conditions or progress), and "NIC charts" (an individual designer's upcoming work plan). Development teams used such objects to structure their discussions in weekly cross-functional meetings.

An example of an infrastructure object at Turbo CE was obeya wall andons. Pre-pandemic, staff members routinely met in a centrally located physical obeya room with walls covered from floor to ceiling in text, plots, charts, and images that depicted program milestones, progress to date, and countermeasures to address technical, timeline, or other challenges. Each section of the room was allocated to a different product development program or improvement project. All team members within a program maintained a "NIC chart" (a task chart) in a clear plastic sleeve pinned to the wall. These had a standard cover page that included highly visible green or red boxes with text called "andons." The intent of a red andon was to call attention to a deviation from an expected state (a slip in timeline, change in scope, poor technical performance, etc.).

Table 4: Three roles of objects in cross-boundary design work

Role 1: Objects Routinize Cross-Boundary Interactions			
Playing an *Infrastructure* Object Role	Develop *common syntax* to span syntactic boundaries	*Routinize* and scaffold interactions across group boundaries, thus facilitating information transfer	e.g., A CFD model used largely for one-way updates or parameter value sharing
Role 2: Objects Translate Information Across Boundaries			
Playing a *Boundary* Object Role	Develop *common meanings* to span semantic boundaries	*Translate* group-specific information by identifying novel differences and dependencies, thus facilitating shared interpretations	e.g., A CFD model used to see the effects of a proposed design change across multiple groups/domains
Role 3: Objects Motivate Cross-Boundary Negotiation and Discovery			
Playing an *Activity* Object Role	Develop *common interest* to span pragmatic boundaries	*Motivate* cross-boundary negotiation by identifying group contradictions and tradeoffs, thus facilitating design and/or knowledge transformation	e.g., A CFD model used to expose contradictory goals and facilitate negotiations across groups
Playing an *Epistemic* Object Role		*Motivate* cross-boundary discovery by rallying groups around a collective opportunity or problem, thus facilitating design and/or knowledge transformation	e.g., A CFD model used to understand the cause of a problem or explore a joint opportunity and develop a joint solution

Spanning Knowledge Boundaries of Increasing Complexity

As the pandemic took hold, the physical obeya was converted into a virtual one using a set of internal online webpages with embedded documents, and andons were migrated into green and red rectangles on web-based presentation slides. Obeya meetings typically involved routine status updates and coordination of expected handoffs of information or materials. In a weekly virtual obeya meeting for a large product development program, Geoff (pseudonym), the program manager thanked the previous speaker from the Mechanical Design group and asked, "*Is Arnold [an engineer in the Advanced Technologies group] on?*" Arnold's voice appeared and stated, "*Yes, I'm here. I finished the system efficiency calculation, and I passed it to Tatsuo [another Advanced Technologies engineer] for review. As soon as Tatsuo and I get a thumbs-up from Han [the Advanced Technologies group manager], I'll send it to everyone [other functional groups].*" As Arnold was speaking, Geoff scrolled to Arnold's virtual obeya wall using his virtually shared screen and displayed Arnold's single red andon. This was a red rectangle on a slide with text that mentioned the efficiency calculation task and expected completion date (see Figure 4). Han confirmed this, and Geoff alongside Arup and Ellis, the managers of the Rotordynamics and Aerodynamics groups, thanked Arnold for the update.

In this example, Arnold's red andon routinized a cross-functional interaction during which information on the status of the efficiency calculation was transferred from Arnold and Han (Advanced Technologies) to Geoff (Products Management), Arup (Rotordynamics), and Ellis (Aerodynamics) who depended on this information. In this case, the information being shared needed only to be transferred (not translated or transformed) because each group held aligned interests around achieving a high system efficiency and already understood how they depended on the efficiency calculation and each other. This made the andon's routinizing role sufficient in this situation. In other situations, such as when more complex (semantic or pragmatic) boundaries were present, objects were called to play other roles.

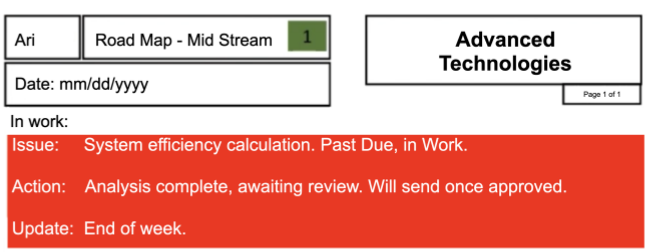

Figure 4: An example object playing a routinizing role: Arnold's obeya andon. Modified to protect confidentiality.

Role 2: Objects Translate Information Across Boundaries. The objects we observed played a *translating* role when they acted as a shared interpretive scheme thereby facilitating information translation rather than just routinizing information transfer. Like boundary objects, objects playing a translating role served as flexible lenses through which information was situated and meaningfully interpreted by members of different groups. At Turbo, artifacts that played a translating role included value stream plans/maps, prototypes, FEA analyses, engineering drawings, and more. In one example, designers built a scaled prototype of a compressor to perform rotordynamic "drop tests" that involved "dropping" the rotor off its main bearings to validate that its backup bearings did not produce "whirl" or other negative consequences. This prototype acted as a shared interpretive scheme between designers in the Advanced Technologies group who used the prototype to perform the empirical tests and designers in the Rotordynamics group who built and calibrated a predictive analytical model based on the prototype's results.

In another example of the translating role, functional groups engaged each other in creating what they called Value Stream Plans ("VSPs"). These were physical or virtual workflow diagrams of interdependent design tasks. A row could be a single engineer, functional group, or some other group of contributors, and the columns were segments of time, such as weeks or days. Consider the example of a relatively simple VSP conducted to plan a product test. The VSP was developed because the test involved an out of the ordinary gearbox swap midway through. Beth, a product manager in the Products Management group, called a meeting to co-create the VSP with Max, an engineer from Rotordynamics, and Justin and Dave, a manager and technician from the Test Cell. Beth hung a long white piece of paper on a wall. The paper was printed with a grid that had days listed along the columns and "*Test*," *Aerodynamics*," and "*Rotordynamics*" listed along the rows (see top of Figure 5). She offered a few introductory remarks, then Max, Justin, and Dave started to populate the grid as described in the following fieldnote excerpt:

> Dave places the post-its he has written in Day 1, Day 2… all the way to Day 5 then announces that he's done. "It will take roughly 4.5 days." Now Max is at the chart adding his post-its in the Rotordynamics row, starting at Day 6, just after Dave's tasks have ended. As he does so, Beth moves around the room, looks over to Justin and asks: "*How long does it take to swap the gearbox?*" He replies: "*Four shifts*." Beth asks: "*Can you work through the night?*" "*You bet,*" Justin says. Max finishes his post-its, then Justin adds his following Max's but in the "*Test*" row. His tasks include swapping the gearbox. Beth is standing with Justin at the chart and asks how many shifts are represented by each of his post-its. Justin says four. Max jumps in and asks: "*Do you need low vibes for this?*" Beth replies: "*Yes, that's the whole point.*" Max confirms: "*So we need to trim balance?*" and Beth nods affirmative. Justin finishes his line of post-its, and Dave adds a few final post-its ending with Day 16. Beth walks over to the chart and reads each post-it in order (see top of Figure 5). She asks several questions to ensure that each task will have what it needs.

This VSP translated information from Justin and Dave (Test Cell) into a form that was interpretable by Max (Rotordynamics). The information shared by Justin and Dave sparked Max to ask clarifying questions to Beth (*"Do we need low vibes for this?"* and *"So we need to trim balance?"*) which helped Max to learn which rotordynamic tasks he needed to perform. Justin and Dave learned from Max when he would finish his tasks and they could start their second round of work (Day 11), and Beth learned that

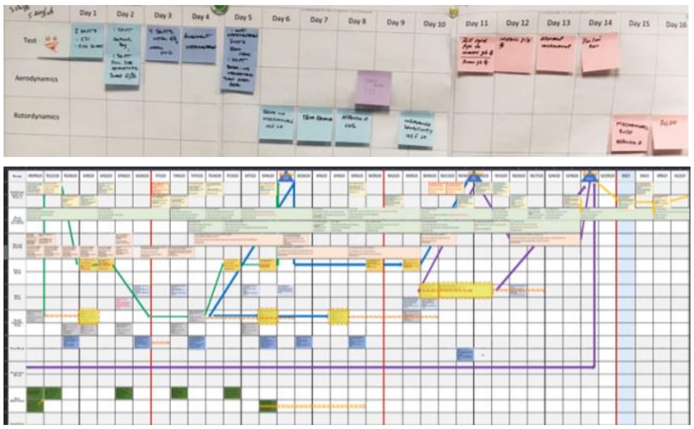

Figure 5: Example objects playing a translating role: Two Value Stream Plans (VSPs) showing expected sequencing and dependencies between tasks for a product test (top) and complex product development program (bottom). Blurred to protect confidentiality.

the entire test would require 16 days. The process of developing the VSP clarified handoffs and dependencies between the Test Cell and Rotordynamics groups. We observed that this kind of translation was even more important when creating a VSP for a more complex product development effort. In another example, eight different functional groups similarly came together to co-develop a VSP (see bottom of Figure 5). This process again helped to translate the sequencing and dependencies between each group's expected design tasks and allowed them to provisionally map the development program's "critical path" (the green, blue, and purple arrows). Taken together, these example VSPs and "drop test" prototypes made visible interdependencies between different group's design parameters or design workflows which allowed pertinent information to be re-situated and thereby translated across their group boundaries. We now turn to a final role of objects observed in our data that helped to not just transfer and translate information but to transform it and associated designs and design processes.

Role 3: Objects Motivate Cross-Boundary Negotiation and Discovery. The third major role that objects played in our observations was *motivating* cross-boundary negotiation and discovery. Some objects motivated cross-boundary negotiation by acting as sources of contradiction, whereas others motivated cross-boundary discovery by acting as sources of attraction – akin to activity and epistemic objects, respectively. When compared to routinizing and translating roles, objects played a motivating role when they facilitated shared interest, not just shared syntax and meaning, and supported transformation, not just transfer and translation of knowledge, designs, etc. At Turbo, objects that played a motivating negotiation role included tradeoff curves, Pugh decision matrices, prototypes, etc. and those that played a motivating discovery role included failed parts, finite element analyses, "A3" reports [72], etc. For brevity in this paper, an example of only the motivating negotiation—not motivating discovery—role will be provided.

To illustrate an object that played a motivating negotiation role at Turbo, consider the "cost knockdown" spreadsheet and manufacturing cost-volume tradeoff curves (see Figure 6) that were jointly created by Jimmy, a manager from Products Management, Armando, a manager from Supply Chains, and other stakeholders. Jimmy and Armando had been tasked with transitioning several hundred existing impeller parts to a new manufacturing supplier. They worked closely together on this effort but were frustrated by little progress over many months. At the time, Jimmy described their efforts as having devolved into a *"whack-a-mole game"* of *"what-about"* scenarios that had stymied decision making. To illustrate the situation, consider the following excerpt from an observed meeting between three members of Products Management and three members of Supply Chains, including Jimmy and Armando:

> Jimmy invites the group to discuss their feedback on a proposal to forge a number of components. He says: *"The first thing I want to start with is your comments on the forging envelopes."* Carlos, a Supply Chains staff member jumps in, *"Jimmy, so when you're talking about the forging envelopes, are we talking about minimizing the amount of metal that we get for each one of the stages?"* Jimmy responds, *"Well, so Carlos, I think you're referring to some of the shape requests that we [Products Management] made throughout there?"* Carlos says, *"yes"* and explains that this will *"multiply the amount of work that we [Supply Chains] are going to have."* Jimmy describes what he sees as a tradeoff between adding individual forgings for each stage versus a forging that can capture multiple stages. Carlos responds, *"Well, what you're pushing, though, is to push our [supplier] to make different dies, because I don't think those are managed as rings."* Carlos describes how different dies would be needed to reduce the amount of metal that is used for the first press in the forge, and *"then you will still have to machine some off. So you either machine it off [in-house] or machine it off at the supplier. Last time [our in-house capability] went down, and we were down for a about two months, so we better be careful what we decide."*

This excerpt illustrates potential tension between the two groups and one *"what-about"* scenario (what if our in-house machining capability goes down again?). Such *"what-abouts"* were offered by members of both Products Management and Supply Chains with a conclusion similar to *"so we better be careful what we decide"* that made it difficult for the cross-functional team to move forward. This suggests that a pragmatic knowledge boundary was present in that the groups' interests and agendas appeared contradictory and conflictual. For example, Product Management had interests and goals around achieving particular costs, geometries, tolerances, and other aspects of quality that affected product performances whereas Supply Chains had their own goals around working with suppliers that already had large volume contracts with Turbo, were easy to work with, offered good pricing and lead times, etc.

These tensions began to resolve when Jimmy and Armando found ways to "build ownership," as they described, in a jointly developed "cost knockdown spreadsheet" — an object that played a motivating negotiation role. They invited stakeholders across Supply Chains, Products Management, and other functional groups such as Marketing, to add to the spreadsheet all information that each stakeholder believed was necessary to calculate net present value tradeoffs around producing each component using various manufacturing processes (e.g., forging, machining, etc.). As the group progressed, they collectively examined, debated, revised, and eventually agreed upon a manufacturing process recommendation for each component. Along the way, they generated visualizations that further clarified group tensions and tradeoffs, such as the plots showing key manufacturing process tradeoff curves in Figure 6. In this way, co-creating the spreadsheet and tradeoff curves motivated negotiations that triggered contradictions and clarified tensions between the Product Development and Supply Chains groups. This made it possible for joint decisions to be made and the groups' impeller manufacturing processes to be transformed, thus spanning their pragmatic knowledge boundary.

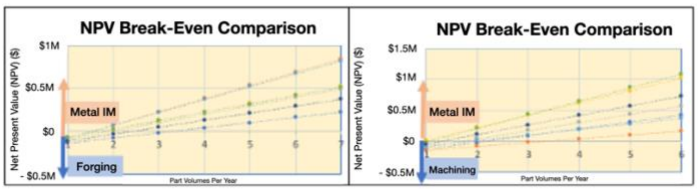

Figure 6: An example object playing a role of motivating negotiation: Manufacturing cost-volume tradeoff curves from a jointly built "cost knockdown" spreadsheet. Modified to protect confidentiality.

DISCUSSION & FUTURE WORK

Through in-depth ethnographic observations in an engineering design company, we identified a range of objects that designers used to span knowledge boundaries and make sense of or improve their designs and design processes. We built upon prior studies of prototypes in engineering design and objects of collaboration in organization studies to offer a typology of the roles that objects play in cross-functional design work — to *routinize* cross-boundary interactions, *translate* information across boundaries, and *motivate* cross-boundary negotiation or discovery. In doing so, we add support to existing theories of infrastructure, boundary, activity, and epistemic objects in organization studies, e.g., [34], and nuance to the ways that prototypes have been found to facilitate communication, learning, and decision-making in engineering design, e.g., [24].

For example, prototypes can improve cross-functional communication by facilitating translation between groups when group members might otherwise talk past one another. This can result in those involved seeing their interdependencies and co-discovering design or workflow risks or opportunities, a key cross-functional outcome in our data. When playing a motivating negotiation or discovery role, prototypes can motivate intensified cross-boundary interaction, learning, and joint interest resulting in the co-design of joint integrated solutions, another key cross-functional outcome we observed. We found that not only prototypes played such roles but many objects used in engineering design (see Figure 3). A variety of design methods may be categorized using the proposed object role typology. As an example, methods (and objects) like the Design Structure Matrix [80] might often play a translating role by identifying and clarifying the interfaces and interdependencies between groups. Understanding a given method's routinizing, translating, or motivating role could help designers to better identify when and how to use the method to help span knowledge group boundaries.

An object's *espoused role* can differ from its *role-in-use*. For example, Turbo engineers explained that the role of a red andon was to signal that a design task had deviated from its target condition thus sparking cross-group problem solving to address the issue. In other words, the *espoused role* was one of translating information and/or motivating cross-group discovery. However, in practice, we observed that the *role-in-use* of red andons was more often to routinize cross-boundary interaction in the form of one-way updates (as described in the Findings). Our study suggests that product managers might improve collaborative outcomes across functional or disciplinary groups by modeling the use of objects for their translating and motivating roles and less for their routinizing role.

This study suggests that the outcomes associated with a collaborative object cannot be reduced to essential qualities of the object itself. The role that an object plays in any given situation, and the outcomes that it facilitates, depend not just on the qualities of the object (e.g., its affordances) but on how people interact with it and each other (e.g., interaction scripts). While the ways that designers use objects of collaboration cannot always be anticipated, future research may examine the object affordances and interactions scripts associated with desirable cross-boundary outcomes when using objects. This could advance the field's understanding of how to build collaborative design tools that are likely to not just routinize interactions but to also facilitate translation and motivate negotiation and discovery.

Prior research suggests that issues may arise when members of different groups hold different views of an object's role in a joint effort e.g., [34]. We observed that members of some functional groups tended to hold static views of the role of objects like kanban boards, obeya walls, A3s, etc., as routinizing infrastructure that were unlikely to be useful in surfacing design risks or solving design problems. Such beliefs and misalignment in expectations of an object's role might limit the object's ability to be used for translating or motivating thus foreclosing its potential for joint discovery or design. Future research may examine this phenomenon, including engineers' mindsets surrounding objects of collaboration. Such studies could draw from a different part of Edmondson and Harvey's model of cross-boundary work [37], namely, how individual and/or collective states affect cross-boundary behaviors and outcomes.

This study is limited in that it is based on observations in a single design company. Future work is needed to examine the generalizability of our findings and the possibility of other roles of objects of collaboration in different organizations or industries. Taken together, the findings are significant because they clarify the roles of objects in cross-boundary design work and suggest ways for designers to more effectively use objects to span knowledge boundaries.

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