DESIGNING: INSIGHTS FROM WEAVING THEORIES OF COGNITION AND DESIGN THEORIES

Eswaran Subrahmanian[1], Yoram Reich[2], Frido Smulders[3], Sebastiaan Meijer[3]
(1) Carnegie Mellon University and Center for Study of Science Technology and Policy (2) Tel Aviv University (3) Delft University of Technology

ABSTRACT
This paper addresses the issue of 'What is designing?' from an unconventional perspective and aims to advance our understanding of what design really is. Designing has been studied from different perspectives but the underlying theoretical basis of studying the act has often been dispersed and not clear. To address these shortcomings, the paper proposes a new topological structure that consists of two 3-dimensional spaces: Product-space and Social-space. The P-space is constructed by the complexity of the artifact, the number of disciplines involved and the availability of knowledge. The S-space consists of the number of disciplinary languages, number of different perspectives and the amount of openness and closeness of the social system that encapsulates the design activity. The two spaces are connected by means of theories on cognition, like: individual and distributed cognition, socio-linguistics, situated cognition, etc. Two examples serve to illustrate the proposed model and show that the act of designing involves the evolution of the artifact, social system, language and information embedded in the social and societal context.

Keywords: Cognition, design theory, empirical studies, designing

1 INTRODUCTION
The primary motivation for this paper comes from our own evolution in thinking about designing or design acting as well as partly historical evolution of design theories and methods that purport to support the act of designing. Design methods such as those of Paul and Beitz's [31] have been traced back to the origin of design methods at the beginning of the Industrial revolution in Europe [28]. A new life for studying design as a human activity came with the rise of cognitive science in the late sixties. While early studies of cognition were limited to the study of memory and retention in cognitive psychology, the shift to the act of designing as individual human problem solving was a significant one. Since that time, different theories of cognition arose or revived to address different concerns; yet, we are still pondering about what does the act of designing in engineering design mean? After decades of research, we are still puzzled. Why are we puzzled? And how can we advance our understanding forward, and with it our design practice, is a major question for the community. One place to look for an answer is through the use of a framework to describe the spaces in which design takes place to view them from the lens of theories of cognition that underlie researchers attempt to explain the act of designing.

How do we understand this act of designing in terms of individual and social theories of cognitive processes? What characteristics of the act of designing do theories of cognition explain? What aspect of designing do design theories attempt to address? We recall the story on the elephant and the blind men who tried to understand what an elephant is from touching it. We understand that each theory tries to "feel" the designing "elephant," but each one fails to give us the view we need and they all create frustration. In view of the story, can we weave these efforts in a quilt that tells us more about all aspects of the act of designing including innovation and creative acts?

Even as the theories of cognition may be limited by their methodological stance at times, their potential for explaining the pieces of the puzzle of designing to the extent possible provides interesting insights. We explore what this quilt looks like using approaches in design to corroborate aspects of these theories to make the quilt as coherent as possible. This study leads to insight about how we can relate individual and social cognitive theories to what has been observed in the act of designing in two specific design studies as exemplars. We invite others to both challenge and augment what we have put together as part of a continuing conversation on the basic of all human acts – to design.

The next section provides a framework within which we synthesize both cognitive theories and the empirical studies. Section 3 provides a short history of studies in engineering design that attempted to test the current theories of cognition and language. Section 4 discusses two examples to illustrate our framework. These case studies are used to test the explanatory ability of the framework presented below. The final section is a summary and future work in this attempt at synthesis of multiple theories of cognition and language.

2 THE P-S FRAMEWORK FOR SYNTHESIS OF COGNITIVE THEORIES AND EMPIRICAL DESIGN STUDIES

The origin of this framework is from the effort at the former Engineering Design Research Center at Carnegie Mellon University. In their attempt, they described engineering design using the dimensions of modularity, process type (routine / creative), information flow, activity magnitude (small to large), diversity (single to multiple disciplines), role of geometry, and degree of regulation. While a starting point, these dimensions appear to be a mix of product characteristics, representations and process but did not include the social dimensions (individual to collective) directly in the dimensions. The social dimensions could be inferred indirectly from the magnitude of the activity. From the social perspective, our case studies [14][39][44] show how information flows are affected by the social organization of the company and hence, its ability to be effective. These efforts together led us to hypothesize the framework presented in this paper to go beyond previous dimensions to include the social aspects explicitly.

A product can be characterized by a parameterized three-dimensional space called *the product space* (P-space) and equally another parameterized three-dimensional space that describes the locale in which the act designing takes place, the *social space* (S-space). The dimensions of these spaces were determined from our understanding of the locale of the act of design in a range of social contexts and realization of the range of products and services[45]. We claim in this paper that these two spaces are sufficient to synthesize theories of cognition and relate them to empirical studies in design.

The P-space is where the functional needs and the characteristics of the product are determined. Here, a product cannot be seen just as individual piece by itself. A product such as an electric bulb creates a need for an entire system to operate for it to function. The P-space of light bulb is part of another product, a system for delivering electricity. The iPod was not just a music player but part of a system of distribution of music that was exploiting the knowledge of use of a new network: an information network – the Internet – as opposed to the physical distribution network of yesteryears.

This P-space has three dimensions (Figure 1): a) the complexity of the product; b) the disciplines both formal and informal that need to participate in the specification and development of the product; and c) the availability of knowledge to create the product. These three dimensions do not represent a completely defined space for a product but are sufficient to our purpose. Over time, a product positioned in this space could change its location along all three dimensions. For example, knowledge that was once at the cutting edge and scarce become common practice and product once innovative becomes obsolete. In addition, as time passes, products tend to involve many disciplines, and become more complex to reflect the changes in social needs and requirements that are imposed on the product. Each of these dimensions themselves also trigger change in the other dimensions. Today's aircrafts are very different from the aircrafts of 50 years ago while the basic function has remained the same but they operate in a very different system (Social) space and technology (knowledge) availability space.

The social space (Figure 2) is influenced by the P-space and vice versa. We characterize the S-space by three dimensions: a) context in which the product is conceived ranging from open to closed world contexts (i.e., known-unknown collaborating actors); b) the number of languages (including sub-languages) characterizing the knowledge in the disciplines that are needed in the P-space; and c) the number of people that participate in the design ranging from a lone designer to a collective of hundreds of people. The S-space describes the space in which the requirements are generated for the product described in the P-space. The Cartesian product of the P-space and the S-space $P \times S$ will determine the scope and methods that characterize the processes that constitute the design as enacted. The tuple [1,1] represents a simple product requiring known knowledge from a single discipline that is performed by an individual (obviously using a single language) in a closed world situation. While we cannot imagine a real product of that nature, there are many empirical studies in design, whose setup involved precisely studying such lab situations. This gap may cast doubt on the ability to project insight from such experiments to understanding real design acts. The tuple [9,9] represents a simple robotic product designed as a class project involving 3 disciplines (mechanical, electrical, and software engineering), of simple to medium complexity, requiring available knowledge, performed by a small group of students, sharing related values and languages in a partially closed world. Finally, the tuple [8,8] represents a real complex infrastructure product, involving many disciplines where knowledge is partially unknown, performed by large team speaking different disciplinary and potentially mother tongue languages, in an open world.

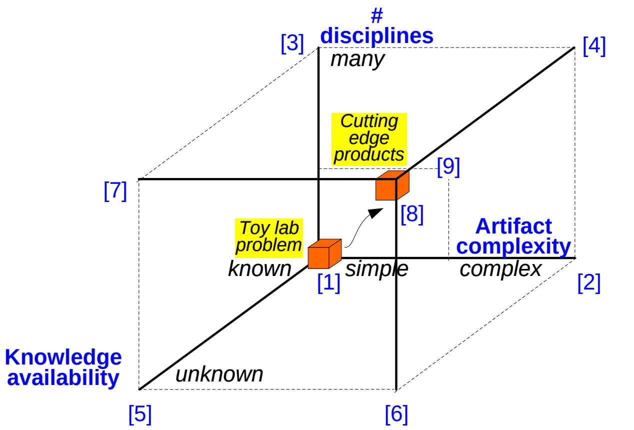

Figure 1: The product space (P-space) characteristics

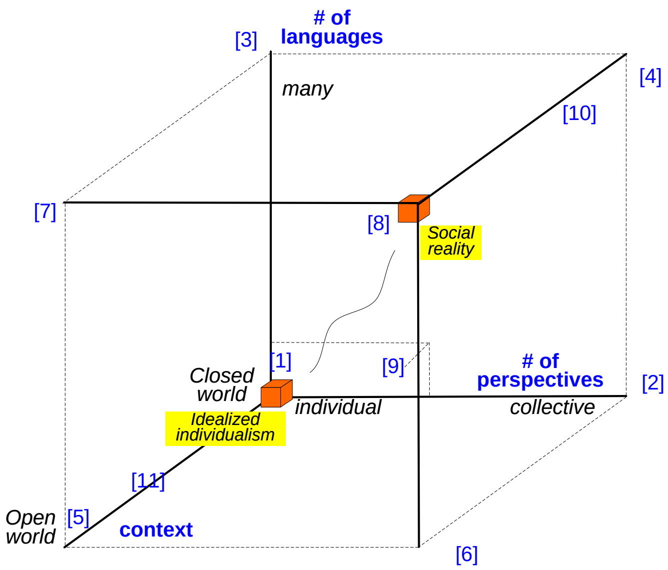

Figure 2: The social space (S-space) characteristics

What is the role of this framework in understanding the act of designing and existing theories of design? The framework attempts to capture the spectrum of contexts in which the artifact is conceived and act of designing takes place. The spectrum spans the context of a lone designer to a collective and simple to very complex products, infusion of new disciplines that impinge on the ability to conceive products, for example, computing technology has radically changed what can be done with products. Further, the dimensions of availability or non-availability of knowledge at the time of product design could lead to choices of additional explorations (i.e., actors available in the open world) or restricting oneself to a given closed world within which the design is done. Within this framework, we can get a more elaborated understanding of the act of designing and the relationship between studies in design and theories of cognition.

3. DESIGN STUDIES AND THEORIES OF COGNITION

The study of designing is immemorial from the days of Vitruvius, the German design method, and the rise of operations research and systems engineering during and after World War II. Two major thrusts of design studies started in the 1960's, one is derived from the *prescriptive* models for designing that emerged from Systems engineering, the normative model that came out of economics and operations research and the second, the *descriptive* model of designing has origins in cognitive studies of individual designer. As other theories of cognition and language have emerged, this section walks through the history of design studies and their relation to these theories.

Prescriptive models of design

For our reference point, we will stake the German model of design as a starting point for prescriptive models of design. The famous Pahl & Beitz [31] model is a derivative of the German approaches to a prescriptive formalized set of steps along with representational structures and documentation during the design process. These methods had their roots in educating a large number of people in machine design, and to ensure systematic work, and the need to work together. This design approach did not distinguish the individual designer from the collective explicitly but was focused on systematization irrespective of the number of designers.

In 1962, Post World War II design conference brought together systems designers and others who devised complex systems such as radars to move towards formalizing the "analysis, synthesis, evaluation (ASE)" [11] model of design. The rise of complexity of the product and the need to integrate disciplines that now included electrical, electronic and mechanical systems led to these new prescriptive methods. The prescriptive tone of these methods was addressed to overcome the limitations of human memory and the need for collective representational structures to mediate design. These methods did not directly use any cognitive theoretical basis for such prescription; rather, they were driven by some clear notion of pragmatics and the desire to create a formal science of design with the idea of a design method similar to the scientific methods [24]. This desire was motivated by the rise of scientism [12] in the middle of last century in all disciplines including economics and other social studies to move toward formal models rooted in mathematics. This approach led to a number of formal representations for use in requirements definition, conceptual design, design and in other steps of designing. As we shall see later, this view of design while normative and prescriptive was directed at creating shared representations within the community of practice; in effect, implicit acknowledgement of social aspect of cognition.

Design Cognition: a description of Individual as the designer

The study of individual cognition in psychology in its early days was restricted to understanding memory and retention as their focus. Meanwhile, the study of human problem solving at the individual level had gained attention. This move primarily came from Herbert Simon, who was battling the "homo economicus" view dominant in economics to make the case that cognitive limitations of the human being would prevent any human to achieve substantive rationality posited by the idealized human assumed by neo-classical economics. He proposed the alternate notion of procedural rationality that gave rise to the idea of *satisficing* instead of *maximizing* and the use of heuristics to deal with complexity of the process of computation of the solution by an individual. With this, the concept of bounded rationality was born.

Meanwhile, in the architecture community, in the early 1960's, Christopher Alexander's work on "Notes on Synthesis of Form" was a call for adoption of formal models of design. As Alexander put it, architects needed to become more formal otherwise less gifted engineers will do the designs (pg 10, [1]). Subsequently, Manheim's thesis on "Hierarchical decomposition" as integral to designing added to the formalization and rationalization of design. This work was predicated on the individual designer at the core of designing without any direct reference to the work in cognition that was emerging.

These developments had come to the attention of Herbert Simon who with his focus on human problem solving became interested in design as a human activity. Simon even before he wrote his book on the "Sciences of the Artificial" [38] had encouraged his colleagues Charles Eastman and Omar Akin to examine the cognitive process of designing by Architects. An architect, the quintessential lone ranger designer, symbolized the act of designing as a supremely individual and an embodiment of intelligence in a single being. The influence of the newly minted individual-focused cognitive science was to best realized in the activities of the architect. In his recent paper on design cognition Omar Akin claims that Architects in contrast to engineers think outside the confines of the specification and assume a stance that makes the problem ill-defined even when well-defined, to envision new alternatives [2]. Further, he claims that the difference may be due to the different socialization of the architect in contrast to the engineer; an acknowledgment of the social in the individual. In spite of these observations, the individual centric model of design has dominated the study of designing for the longest time and still does implicitly in numerous studies in architecture, industrial design, and in the area of automated designing and computational support for designing. The models of design that were rooted in individual cognition gave rise to numerous studies that were directed at creating algorithms that incorporated heuristics and illuminated certain modes of behavior such as tunnel vision and the use of memory aids in the form of symbolic structures for representations of the process and the artifact being designed.

The other individual oriented design characterization was the work coming out of the optimization paradigm that have the model of a human as one who maximizes utility, profit and other measures. These methods following the idea of substantive rationality from economics did not worry about the problem solving limitations that were identified by the cognitive scientists. Decision based design, a derivative of individual centric view, has maximization of utility by an individual at the heart of designing. These methods still had the problem of assigning utility, as it is not clear as to how one would assign utilities across multiple perspectives and needs that are required to use these methods. For more on the debate on this issue refer to [18][33]. In summary, work on individual designers across different approaches (normative or descriptive) can be placed in the (1,1) to (1,5) coordinates in $P \times S$ space, trying to extend towards more open world context.

Redefining Cognition – individual in social and interacting social and individual

Challenges to the individual view of cognition and alternate conceptualization came from other cognitive scientists who found the methodological individualism wanting. These new perspectives acknowledged the social but in slightly different ways[1]. One strand of work that argues for situated cognition [25], accepts the idea that the individual designer is working in a given social context (situated). In this model, it is still the individual designer with the social context as input to the individual. The tuple (1,1) with the social collapsed *to* the individual, thus serving as an input to the individual work but not altering or interacting with him. Within situated cognition, another stream of work makes the case that individual ability to solve problems is totally determined by the social context. In this second strand, the individual is collapsed *with* the social [26]. The third model argues that the social and the individual mutually influence and contribute to each other [20]. The difference between the second strand and the third strand is that all knowledge (representation and semantics) in the second strand is socially determined through communities of practice [26]; while in the third strand, the knowledge and semantics can arise out of an individual situated in the social and the social providing the acceptance and institutionalization (inclusion in the community of practice) that in turn is embodied and interpreted in the individual [20].

Representations and nature of engineering work: A sociological perspective

The common theme that goes through all of the above studies reported show the importance of representations in both individual and social aspects of designing. How specific representational objects arise and get used while interesting is not our focus; however, the role of representations is very critical in both sense making and concurrence in understanding engineering work that is necessarily at once individual and social.

Representations go beyond the use of sketches and their likes; designers also use physical models, mockups and prototypes for communication and discussion purposes. All these representations of the product and processes under development are to be considered as boundary objects as introduced in bio-history by Star & Giesemer [43], suggested for design by Bucciarelli [5] and empirically described in design by Carlile [6], Subrahmanian et al. [44], and Smulders [39]. Based on the recent literature, we see an increasing interest among academics in boundary objects as tools that enable spanning social boundaries in multidisciplinary settings. Boundary objects form a common representation that can be interpreted by the different stakeholders along their particular line of reasoning and knowledge. In the design discussion, the paradoxes across perspectives become apparent and the need for them to

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[1]Cole and Engestrom [10] argues that distributed cognition incorporating the social is not new but has been rediscovered in that last 20 years and that historical psychology as conceived by William Wundt (1914) acknowledged and incorporated the social as integral to individual cognition. For a more detailed discussion on distributed cognition, see Solomon [42].

be resolved. The use of boundary objects clearly indicates the changes in the view of cognition as connector between the two spaces: product and social.

Prescriptive methods such as Pugh's method, ASE, Pahl and Beitz, House of quality and others have created representations that serve as boundary objects in the discourse of design. These cognitive artifacts serve as scaffolds for changing the course of action in the act of designing without losing the threads and inter-relationship across the different disciplinary knowledge spaces. Implicit in these methods were not a prescription for an individual designer but really one of co-coordinating work in a collective and creating a standards of documentation, economy of transmission and record. From a sociological view, the use of representational structures in collaborative work, operates to create meaning within and across disciplines. This view can be explained by the theoretical perspective of distributed cognition that places the representational structures within the individual and within a community. The different cognitive interpretations of the representation overlap between and across communities of practice.

Ethnography and Design as Initiator for a New Language

Ethnographic studies of engineering design work in groups and across disciplines have taken the position in our framework that all engineering work is social and the processes are necessarily social. This work is exemplified by Buccirealli's [4] work that characterizes design as a social process that involves the creation and use of representational objects and the discourses that take place during the design. These discourses are about deciding on naming, articulating, negotiating and making decisions. The use of language and creation of new language during the act of design is understandable and has been empirically observed at different levels: engineering design being a creative act has to create new languages to describe the artifacts being conceived and produced. The work of Dutoit and Brugge [17], Mabogunje and Leifer [29], and the study of designers such as Gordon Murray and Edison show that new language is created and used to describe the artifacts being designed out of known and newly created functional devices [13][41].

A language based understanding the evolution of physics illustrating the creation of new languages to accommodate changing world views (Copernican, Newtonian and Einsteinian) and their incremental evolution, is described by Bruce Gregory [19] in his book "Inventing reality: Physics as Language." These sources illustrate the fundamental role of language and the attendant symbolic representations in the collective acts of inquiry and designing.

Designing any artifact requires the creation and negotiation of meaning of the product including in use. The importance of meaning creation is apparent in Verganti's [47] work where successful companies employed culture and social interpreters that direct development towards products that create new meanings for customers, meanings that customers will tend to adopt.

Designing as language creation and use leads us to look at theories in linguistics. Traditional theories of linguistics that emphasize universal grammar for languages and evolution [8][32] have been argued to be inadequate in the use and eveolution of language. The work of Herbert Clark [9] argues for a contextual meaning of symbolic language and that language is sensitive to the context of use (common ground) in determining the semantics of the terms. A more cognitive linguistic account of language generation, variation, evolution and use presented by Chater and Christianson [7] is in line with Clark's use of language. The fundamental argument is that there exist no single universal grammar but there are cognitive modules in the brain that allow for the composition of syntactic and semantic structures that are geared toward the ease of learning of the language in a community.

Chater and Christianson, to make this model of cognitive linguistics operational, propose two types of induction that characterize language acquisition, evolution and use. The two types of induction are n-induction and c-induction. N-induction is induction of observations in nature and the environment (both physical and social) and c-induction, termed as co-operative induction, is the induction on the use of language in the community to enable co-operation and communication. C-induction is the mechanism by which the semantics of the language is co-coordinated in a community to be able to understand and to act in the social world. N-induction feeds into the c-induction and c-induction in turn, allows for the development of semantics within a community of practice. Without a c-induction in the social context of human acts such as designing, societies could not have possibly maintained a shared memory of its practices and the ability to transfer it across generations. Further, this account of generation and use of language describes well the observation that even in material science, the terms used for the same phenomena or artifact by different sub-disciplines is often different [30][37] pointing to the social context of origin of the language.

Coming back to designing, Dorst's [14] view of the underlying phenomenon of designing brings us close to the socio-interactive dimension of design. He proposes to describe the design problem and process as multiple discourses that initiate conflicting and paradoxical situations in need of resolution. Discourses, according to Dorst span "the *complete* breadth of human thinking" (p.15, italics in original) and human activity within a certain domain. This resembles the notion of disciplinary object worlds [4] and disciplinary thought worlds [16]. Thus for discourses to become paradoxical more than one domain must be involved, that is, it requires more than one actor representing another domain. While Dorst's view is interesting, we see his description of design as "the resolution of paradoxes between discourses in a design situation" ([14], p.17) in contrast to the rational models of product design [40]. The use and creation of language then mediates between the product in status nascendi and the social actors representing the variety of discourses.

4. WEAVING THEORIES OF COGNITION AND EMPIRICAL STUDIES OF DESIGN: SOME OBSERVATIONS AND SUMMARY

The above journey into designing and theories of language and cognition shows us that the act of designing encompasses the entire gamut of human thinking and action at the individual and social levels. It would be unwise for design researchers to be wedded to a single particular perspective in design but embrace a broader perspective. The elephant, the act of designing, mentioned in the introduction has so many different features, of which design research has seen various pieces of its body, often without regard to the underlying methodological stance. Design research has not been able to figure out the whole 'elephant' yet, nor is it a tenable goal.

The Quilt of Theories of Cognition

Just as Newton's law works for most part until we need relativity for a particular case. The same way we believe, while not being dogmatic, the position that the social and individual cognition mutually reinforce and challenge each other, could be a more fruitful approach to understanding the act of designing. If so, how do we deal with reconciling these perspectives without getting into the primacy of any of these received methodological stances of design studies? Rather, we use them to create the quilt that would provide a more coherent but incomplete understanding of design. Within this understating, we see the role of numerous theories, methods and representational variations to articulate, negotiate, and mediate the act of designing or design acting.

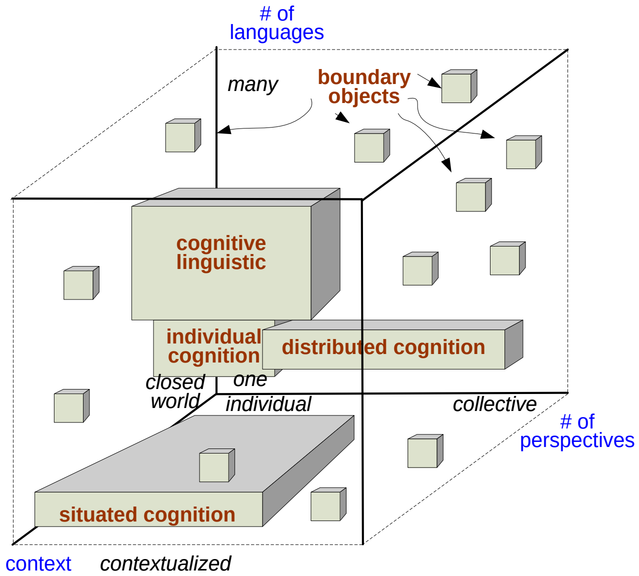

Figure 3: The quilt of cognitive theories

The quilt we see so far has (Figure 3):

a. individual cognition, the study of individual problem solving provides us a means to understand the manipulation and use of representations;
b. situated cognition allows us to examine the strategies for problem solving in changing contexts;
c. distributed cognition allows to understand the role of artifacts as cognitive artifact that mediate the semantics among the participants in the design act and across generations;
d. boundary objects from sociological theories of work provide us with the role that boundary crossing representations play in mediation; and
e. cognitive linguistic theories account for the evolution and variation in language structures in the context of a community, culture and social settings.

Without this quilt, one cannot account for the individual contribution to the social in terms of symbolic representational structures that get proposed for ease of computation, or the needs for communication to the social. Without distributed cognition, co-operative sense making would be impossible in problem solving contexts, and without boundary objects, serving as mediators it would be impossible to bridge disciplines. Finally, without the ability to create, transmit and evolve languages it would not be possible to create a cognitive continuity from the past to the future in the individual or the community.

Examples Showing the Necessity for Weaving the Theories Together

Example 1: Designing autonomous robots in a robotics course

In a robotics course program for high school students in Israel, small groups of students developed autonomous robots for competing in an international competition. All the students come from the same class and supposedly have much knowledge and values in common; nevertheless, even with such baseline context, students have multiple perspectives and speak different “languages.”

It was observed that the performance of these robots was not reliable in these contests. Artifact complexity and number of disciplines, while manageable, was too much for high school students to manage without proper shared representations and boundary objects. This prompted a re-examination of the course curriculum and teaching strategies [36][35][36]. A careful design process of the course started from high level goals such as: acquiring system thinking approach; improving skills of problem solving, decision making, and learning; developing critical and creative thinking abilities; developing social and teamwork skills; strengthening useful personality traits; and experiencing development of a product, with time and budget restrictions. It was also clear that good performance at the national and international contest was a major driver for students learning.

These goals led to a careful design of the curriculum including an overall design method for autonomous robots specific for a particular context showing that not only are design situations contextualized but also that the set of suitable methods is contextualized. The new design method is composed of 6 specific methods[2]: atomic requirements, conceptual design, creative design, fuzzy logic, fault tolerance, and microprogramming. This new design method helps students carefully analyze the requirements of the robot, and break them down into small atomic pieces and systematically translate them through a sequence of steps into a working robot. Each tool forces students to document their thinking. The careful selection of the tools allows smooth transfer of information between them; and consequently, a trace of design decisions is created. The tools also allow to breakdown the development task into several independent parts of designing the mechanical hardware, the electronic hardware and the software. Testing and calibration of the product are also incorporated into the documentation. While the methods provide a skeleton for documentation, each project team evolves its own language in the course of the project; and it finds its own specific way to document design decisions and organize the material.

We already see that while the design of the new method did not use explicitly the framework presented in this paper, the goals reflecting contemporary design practice clearly embed the spaces within them [36]. Further, the resulting design method was providing ample boundary objects – a living body of knowledge – for sharing design information across time and supporting the development of shared language, distributed, and situated cognition. These were observed in a careful study with four schools over two years.

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[2] It is beyond the scope of this paper to explain the nature of these methods.

One such example serves to illustrate the value of the framework [23]. At one international competition, when the team first came to Trinity College where the contest was held, they noticed that an obstacle in the contest arena was different from the one published in the official contest website, and the robot, which was designed for different obstacles, would not perform well with this modified item. Members from other international teams were overwhelmed by the situation. They were not prepared for such situation nor had they the necessary living body of knowledge to deal with it. They simply did not attempt to act upon this situation. In contrast, one team that studied the new design method was confident that it could overcome the situation in the short time available by effectively "replaying" their design process and decisions. They started with a creative thinking session to find a solution, which was to modify the location of one of the robots wheels. The team realized the risk of such change that had an impact on the robot performance and its control software; numerous parameters had to be changed including many of the navigating values.

The team was confident that it could implement this change. The software team said it would not be a difficult problem, as they have built the software according to micro-programming and fault tolerance guidelines. Therefore, it would take no more than two hours including actual calibration tests to modify the software. This was in fact true; it took twenty minutes for the hardware team to perform the change and then after one hour and thirty minutes, the robot was fully functional and handled perfectly the new obstacle. This is not a trivial matter. The solution was found and implemented smoothly due to the following key points:

1. The student skills of organizing the information and analyzing the advantages and disadvantages of the alternatives as they learned within conceptual design method enabled reuse of previous considerations.
2. The atomic requirements method simplified handling both hardware and software components.
3. The clear division between hardware and software tasks, allowed the hardware team to work in parallel with the software team, which in turn decreased substantially the time needed for fixing the problem.
4. The embedded fault tolerance design method and the microprogramming design helped the students implement the desired change.

Here we see that the P- and S-spaces are well synchronized by having the right social-cognitive elements in place facilitated by the student learning and available method. P-space: available knowledge, simple design situation, three known disciplines and in S-space: closed world, collective action, three known languages. Teams without such elaborated product, social, and tools infrastructure, could not compete well in the original competition. Once the world opened a little by introducing new objects, all teams but the one with the right infrastructure were simply unable to perform in this situation.

Example 2: Re-designing train dispatch and control for ProRail

For ProRail (the Netherlands' railway infrastructure provider), we ran a program to support the design of new train dispatching and control methods to facilitate a 50% increase in the number of train services on the Dutch railways. The design can be characterized in the product space as something for which the knowledge is available and the number of disciplines is fairly limited. The complexity of the artifact is low, as it requires only time tables and work procedures. The social space however is way more complex, as the problem is an open problem with disputed knowledge and boundaries that connects a tremendous number of different stakeholder' and actor perspectives each with their own languages. Examples of people involved are train dispatchers, network controllers and national coordinators from ProRail, materials and driver planners from the various train service providers, passenger information employees (shared between ProRail and the major service provider NS), as well as passengers, train drivers, management, maintenance, emergency response teams, and the national parliament and ministry meticulously following the consequences.

The state in which we got involved was where two schemes to handle major disruptions had been developed by specialists in timetabling and traffic flow. They handled the 'product space' of design but experienced problems in the validation of the design and the translation to design of work methods in the organization. Simply said, they had no idea what the emergent outcome would be of the two schemes once rolled out. Every person they spoke to had a different language and therefore perceived the design differently. C-induced learning could not take place because this requires a discourse that is shared.

To facilitate the social space of the design we developed a gaming simulation in which most of the actors mentioned above were asked to plan their real-world role in a simulated environment of railway networks and trains. The design of the gaming simulation was lead by an interdisciplinary team of people with a proven track record of work across (disciplinary) discourses. They built a test environment that was their joint understanding of the environment, to have participants play out their own roles in their discourse to be able to confront the different discourses and through debriefing come up with a joint discourse for evaluation of the product space in the social space of the design. The result was a rejection of one of the scenarios and a tremendous list of actions, points of attention and constraints for bringing the new scheme into a fully working organizational design. The value of this exercise proved itself in reality when ProRail and NS experimented in real life with the new timetabling. In the large scheme of the project, the handling of major disturbances was specifically noted as designed best in advance.

Here we see that in addition to a (simple) product a new social space needs to be developed in order to finalize the design of the product. Prototyping this social space in combination with the possible versions of the product by means of gaming enhanced the further development of the product.

As we can see from these limited set of examples, all of the phenomena explained by these theories are observable in design but some questions remain unanswered. Where do the new representations for a given domain arise from and how are they accepted within a community of practice? What are the criteria for acceptance or rejection of these representations? What are the conditions under which these representations, their interpretations and their cognitive power get corrupted? What are the conditions under which, the potential for creativity is enhanced? Given all of these, how would one create a team of disciplines to design a given artifact in a given context? How will you determine the processes required to conduct design in various points in the Cartesian product social space of the framework we have presented? We ask other design researchers to examine the combined use of these theories and the framework in examining the acts of designing that they encounter

5. DESIGN THEORIES AND THEIR RELATIONSHIP TO THEORIES OF COGNITION

Most design theories are not explicit about their methodological stance. Prescriptive theories tend to assume some need for co-ordination and co-operation in the act of designing. Other theories of design such as the General Design Theory (GDT) [35][46][48] again do not comment on complexity, dimensions of number of actors and knowledge availability. Braha& Reich's topological spaces [3] or the C-K theory [21][22] do not make specific whether their theories are applicable to the individual and/or the collective but implicitly claim that they work across $P \times S$ space. Further, these theories are primarily addressing representations and operations needed in the Product space. They both allows for expanding the product space by allowing for the expansion of knowledge availability dimension in the product space. C-K theory has by virtue of well-defined operators to expand the C-Space in C-K theory and the knowledge dimension (K-Space in C-K theory), is able to explain creative episodes and able to create a method for use. However, the KCP method [27]emphasizes the assemblage of K-Space for the method to be effective. In essence, it acknowledges the need for the social space. In that sense, C-K theory if augmented with the points in the S-space could potentially examine variations in creative products produced by the KCP method by varying the dimensions in the product space.

Nevertheless, all of these theories while creating abstract models of designing still lack the kind of explanation of behavior that we observe in act of designing. Our exposition on weaving different theories of cognitions leads us to believe that while these abstract theories of the product space are useful to an extent, without the augmentation of these theories with their interaction in the social space, in which the design takes place, their use will be limited. In essence, GDT and C-K theory themselves are a boundary objects in the design theory and research community. Their explanatory power needs to be tested in different design contexts and in design over time. In light of these discussions, we contend that the crux of the act of designing is best described by multi-attributed activity as below:

> "***Designing*** is a cognitive (both formal and informal structures, symbolic and perceptual) and a social activity (negotiation, creation and evolution of language, and validation) for sense making that is emergent over time at the individual and social levels, punctuated by temporary closures for the requirements of the artifact being designed. Designing involves

the evolution of the artifact, the social system, language and the information embedded in the social context."

Any comprehensive theory of design has to be able to explain all of these activities. Our contention is that with the framework provided in this paper, and the theories of cognition that we have enumerated, we have a better understanding of the needs for the act of designing for any point in the space of the Cartesian product between the social space and the product space.

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Contact: Prof Eswaran Subrahmanian
Center for Study of Science Technology and Policy
Raja Ramanna Complex, Aksar Ali road, Raj bhavan Circle, Bangalore, 560001
Phone: +91804090535
Email: sub@cmu.edu