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DESIGN AS A SOCIO-CULTURAL COGNITIVE SYSTEM

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1. Introduction

Today, teams of people design products. (NB: To clarify the terminology in this paper, the word "design" refers to the activity only.) The reciprocal transference of group knowledge to individual knowledge construction influences individual and distributed cognitive processes. This article proposes a framework for describing design as a socio-cultural cognitive system. In this framework, design performance is seen as a property of the social organisation of individual cognitive capabilities. Technical design tools and methods are a "cultural medium"; they provide the structure for the transmission and propagation of cognitive states and encode patterns of behaviour. How information is cognitively and socially encoded and transmitted through the designers' cultural medium affects the mapping of individual "object worlds" [Bucciarelli 1994] to a "shared world." Observations on research in shared understanding in light of this framework examine shared understanding as a formalism for modelling design emergence as a socio-cultural cognitive phenomenon. Based on this framework, the article presents a computational model of design using cybernetics.

1.1 Background

In many disciplines, situated activity is a prominent analytic construct for studying and developing complex human-machine systems. The concept of the socio-technical system in design [e.g., Lu and Cai 2001; Boujut and Tiger 2002] stresses the reciprocal interrelationship between humans and machines. Essentially, technical and the social conditions of work operate such that mechanical efficiency and humanity are not contradictory. Rather than making a normative statement on design, the perspective is intended to elucidate the design process as a spectrum of social and technical realities. One could express this socio-technical view on design by extending (as shown in **bold face**) a commonly accepted descriptive definition of design as:

> *The transformation of natural processes and the "given world" through a systematic technical methodology to create an artefact that achieves a set of goals.*

to

> *The transformation of natural processes and the "given world" through a systematic technical methodology* ***mediated by social processes*** *to create an artefact that achieves a set of goals* ***established as a result of designers' shared understanding of the artefact's function, behaviour and structure within a context defined by both the natural environment and human interests.***

While the socio-technical perspective is a "good start" to the problem of describing design, the perspective leaves unanswered the cognitive aspects of design. Underlying the socio-technical perspective rests a layer of assumptions about how designers engage in a shared cognitive system. Three levels of cognitive processes must be understood. The first level refers to the cognitive behaviour of individual designers. This is the level of analysis that has been well researched in the literature on "how designers think." [Lawson 1997] Factors such as competency with technical design methods and tools, domain knowledge, and availability of information resources figure into individual designer's mental processes. When we turn to a consideration of the behaviour of design teams and individuals' behaviour within them, second and third levels of analysis are relevant. The second level characterises the observable events that occur when groups of designers meet to design [e.g., Stempfle and Badke-Schaub 2002]. The third level is an analysis of the cognitive processes of individual designers in the context of the group design processes. Very little research, at least at the empirical level, is available on this level. The commonality between these levels of analysis on designers' cognitive processes is the link between the technical tools of design and mental processes because the tools are devices that allow designers to acquire, manipulate, and realise their ideas. The commonality also suggests the inseparability of technical design tools and methods and the social context in which they are applied. The contribution of social transference of knowledge versus individual knowledge construction must be considered [McComb et al. 1999] because the tools are also devices for externalising and communicating mental representations. There is a wide-body of design research which describes individual and distributed cognitive processes, how cognitive processes are mediated by artefacts, how design activity grows out of the particular situation, and the influence of the social sphere. What is needed is a richer framework for describing, evaluating and analysing design, which is the aim of describing design as a socio-cultural cognitive system.

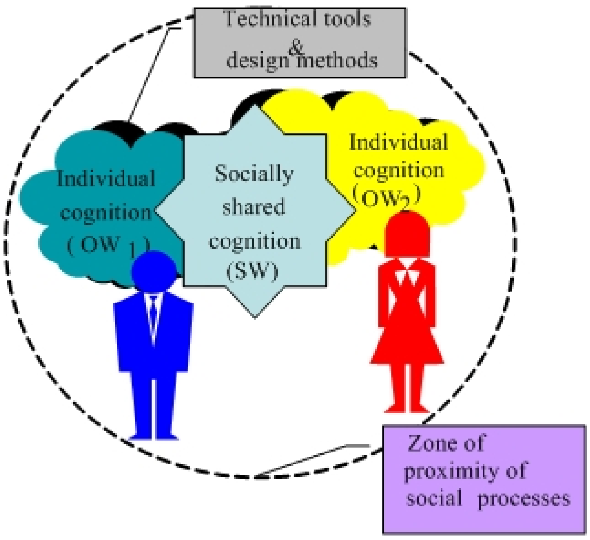

Figure 1. The socio-cultural cognitive framework

The socio-cultural cognitive framework for design connects three fundamental constructs: Suchman's [1987] *situated action model* which emphasises the emergent behaviour of human activity, Hutchins's [1995] *distributed cognition approach* which promotes the need to look at individuals and the artefacts and tools they use and at the social organisation factors that influence cognition, and Wertsch's [1991] *theory of mediated action* which delineates the reciprocity of agents (actions) and tools. Design is broadly interpreted in terms of four coupled variable groups: design stages, technical tools and methods, social processes and cognitive processes:

Design stages: a period of time when a class of design activities occurs such as conceptual design

Technical tools and design methods: tools (e.g., CAD) and methods (e.g., DFx) for synthesising design artefacts; are often specific to certain design stages

Social processes: methods and types of group interactions (e.g., negotiation, cooperation, meeting)

Cognitive processes: mental processes at the individual and group level (e.g., exploration, selection, reflection, transactive memory, shared memory)

The idea is to characterise design and how people design in terms of these four variable groups. Figure 1 illustrates some basic ideas in the framework: cognitive processes are afforded by a cultural medium comprised of technical tools and design methods; the mapping to a socially shared "object world" occurs within a zone of proximity for social processes. To further illustrate how the framework can be used to describe design, Table 1 shows the framework applied to describing mechanical design. Because cognitive processes are not necessarily distinguished by design stage, the final column describes cognitive outcomes. The list of tools and methods is representative rather than exhaustive and excludes communication tools.

On *prima facie*, the framework may appear to confound the problem of understanding design. On the contrary, the variable groups provide a way of explaining the articulation of iterative and successive cycles of individual and distributed cognition whose externalised representations (i.e., cognitive artefacts such as linguistic and diagrammatic representations) depend upon social processes [Mathieu et al. 2002], and are mediated by technical tools and methods over time (a design stage). To summarise, the framework ties together what is already known about design: that design tools, design methods, cognitive capabilities, and work organisation are proximate factors which affect design outcome. Viewing design as a socio-cultural cognitive system seeks to develop an ultimate explanation for the chain of events that lead to successful design outcomes. With respect to the latter, there is a need for more empirical evidence, beyond the managerial and financially based studies in the product development literature, to measure the interrelation of the four variable groups.

1.2 Shared understanding in design

A useful outcome of the framework is to re-think the theoretical foundations of research on design teams. One area of interest within this field is shared understanding in design. The general thesis is that team effectiveness will improve if team members have an adequate shared understanding of the team's objectives, processes, and situation, and that knowledge about tasks (i.e., who's doing what and how) should be distributed among team members. Shared understanding in design can be said to exist when the team members acknowledge the existence of and have general congruent thinking as to the function, behaviour and structure (FBS) of the product. Also, there should exist a level of awareness by and among team members of how others would interpret the FBS of the artefact and the similarities and differences among their interpretations. This latter requirement suggests that explicit negotiation and reconciliation is procedurally linked to shared understanding in design. To the extent that individual members are ignorant of the existence of shared understanding or disagree on the FBS of the product, we would not classify this group as having shared understanding. Industrial psychologists have proposed the following categories for what team members might share in order to achieve shared understanding [Cannon-Bowers and Salas 2001]: task-specific knowledge (e.g., how to use finite element modelling to compute the von Mises stress of a structural component), task-related knowledge (e.g., selecting the appropriate type of finite element analysis technique depending upon the material, environment and expected loading situations), knowledge of team mates (e.g., who knows how to do finite element analysis), and knowledge of team mates' attitudes and beliefs (e.g., if a team mate might be loath to accept the results of computer simulation compared to physical testing).

Empirical research of shared understanding in design has attempted to measure levels of shared understanding [Dong, Hill and Agogino 2004]. The aim of their research was to discover the terminological patterns in design text as a basis for characterizing a shared understanding in design. Sociological theories of communication and studies in design communication provided the theoretical underpinnings for their methodology, while the implementation drew upon the computational linguistic techniques of natural language processing and latent semantic analysis. Based on a study of textual communication over 15 week design period, they found quantitative support to suggest that a high level of shared understanding and cohesiveness among the design team lead to a better process and artefact quality. Valkenburg [1998] described design teams based on Schön's reflective design practice; the coding protocol described team activities as *naming*, *framing*, *moving* and *reflecting*. The descriptions based on the four activities provided a view of the team's strategies and group behaviour

Table 1. Socio-Cultural Cognitive Framework for Mechanical Design

Design Stage	Design Activities	Technical Tools and Methods	Social Processes	Cognitive Outcomes
Idea Validation	Determine customer and market needs	Customer interviews, surveys, and focus groups; Ethnographic studies; Patent search; Affinity diagrams; TRIZ/ARIZ	Formation of core product development team; Assign team roles; Create "social network" (i.e., who including external suppliers should be involved)	
	Determine broad product and business objectives	Product portfolio planning	Define and order product objectives (e.g., must-have features and nice-to-have features)	Team mental model (who will do what, how, when, why)
Conceptual Design	Identify essential problems	Design freedom and uncertainty	Development of team jargon and vocabulary; Decide how to handle ambiguity, uncertainty and imprecision; Distinguish specifications from constraints	
	Propose function structures	Bond graphs; Design structure matrix; Mechanical design compiler	Division of design tasks among team members; Division of larger design teams into smaller teams by product sub-system	
	Search for and propose solution principles	Case-based information retrieval; Method of imprecision	Consultation with experts within company, communities of practice	
	Select, combine and refine into concepts	Pugh charts, pairwise comparison charts, Borda charts		
	Evaluate concepts against design criteria	QFD; Design Compatibility Analysis; Compromise Decision Support Problem	Agreement on method(s) for evaluating and selecting concepts against criteria; Establish norms for critiquing designs	Shared agreement of design process (task mental model)
Specification and Design	Develop preliminary configurations	Shape annealing; evolutionary and co-evolutionary design	Establish accepted design procedure (e.g., adopt appropriate design codes); Communication and sharing of technical design issues to all team members (distributed cognition)	
	Select best preliminary design(s)	Multi-objective concept selection	Reconciliation of design objective conflicts	
	Refine designs and configurations and evaluate against technical and economic criteria	Design and system configuration optimization	Team learning of design trade-offs, potentials of new technologies, incorrect assumptions, etc.	
	Detailed analysis of refined design(s)	Finite element modeling and analysis; Design-rule checking	Acceptance of testing methodologies, test environments, lead customers, etc.	
	Review for errors, manufacturability, and cost	DFM/DFA/DFx		
	Prepare a preliminary parts list and manufacturing and assembly drawings			
	Final design analysis and verification	Finite element modelling and analysis	"Sign-off" by all team members	
	Complete detailed drawings and production documents	Computer-aided drafting and visualization (e.g., solid modelling; surface modelling; rendering; animation)	Team post-mortem	Shared understanding of the function, behaviour and structure
Prototype production and testing	Prototype	Rapid prototype; "desktop machining"		
	Test and evaluate	Taguchi quality		
Manufacturing	Design solution		Transfer of design knowledge to manufacturing	Socially shared narrative

in decision-making that lead the teams through the conceptual design stage. Valkenburg proposed that these descriptions could be useful in framing the teams' levels of shared understanding of design objectives and design processes.

The common thread that links these two bodies of research is the assertion that conflicting mental models on the design processes and the FBS of the artefact may stall further activities. More noteworthy, the design teams within each of the studies essentially utilised the same design tools and methods, and the participants within each study were of equivalent technical competency and expertise in design. While expertise level may have contributed to individual differences in cognitive strategies [Ahmed et al. 2003] during specific design activities, the overall differences in the teams' performance *over the course of the entire design process* were instead likely to have arisen from their socio-cultural orientation. That is, the cognitive properties of design teams may have depended on their social organisation, how communication was structured over time, and the facility by which the design teams manipulated the cultural medium to suit the conduct of their design activities.

These researches in shared understanding in design, then, are really identifying emergent cognitive processes that transformed the design team from individual "object worlds" to a "shared world." Ultimately, the conclusions of the research in measuring shared understanding in design are that a socially shared understanding of what was designed *must be* reached to effectively attain technical satisfaction of the design requirements, and that design tools and methods play a transitive role in the formation of the shared understanding. Design teams do not necessarily start out with a shared understanding. In fact, it is often the contrary. Two justifications are generally cited for the use of cross-functional teams in design. First, there is the assumption that pooling disciplinary expertise will result in addressing and solving design problems early in the process, which ultimately leads to a reduction in costs associated with re-design and shorter cycle times. Second, there is the assumption that that group design decisions lend credibility given that the relevant experts have given a "stamp of approval." The shared consensus after the group decision may also result in higher levels of individual (or departmental) commitment to the selected artefact and course of action for completion of the design process. Shared understanding is an emergent property from the process of design when design is viewed as a socio-cultural cognitive system. A full account of design must describe activities at the various bands of human action [Newell 1990]. Whereas cognitive theories of design operate at the rational and cognitive bands, framing design as a socio-cultural cognitive system characterises design at the social band. We might regard design as the social experiences, situations, and tools and methods designers use to construct artefacts from present versions of past experiences.

1.3 A Cybernetic System

An important question to pose, then, is how to observe this socio-cultural cognitive system "at work" in order to build tools to control the system to optimise its output, the artefact. A cybernetics viewpoint is an efficient solution for describing complex systems in which the output is realised through the creation, transformation and propagation of states and for which the system operates within a particular environment (medium). Central to the methodology of cybernetics is the consideration of a range of possible behaviours that a machine may produce. First-order cybernetics deals with systems which are observed externally; second-order cybernetics deals with systems for which observers are a constitutive part of the system. The choice of characterising design as a first-order or second-order cybernetic systems rests on the perspective of the observer. What distinguishes the characterisations is *how* the system is subject to "controlling" factors.

The problem is that there exists potentially insufficient access to the internal data (i.e., the cognitive state of the designers) required to control the system through feedback to the designers (first-order cybernetic system) or for the system to self-govern (second-order cybernetic system). That is, the system may not be fully observable externally (a first-order cybernetic system) nor is the system able to fully observe itself (a second-order cybernetic system). If it's not possible to directly measure the values to control the system, those values may be calculated. One can set up a sympathetic system alongside the real system to receive the same data as the real system and calculate the internal states based on a model of that system. The starting condition of the real system is usually unknown, but can be compared to a calculated value with the measured output vector and the difference used to correct the system. This particular form of observer is called a Luenberger observer as shown in Figure 2.

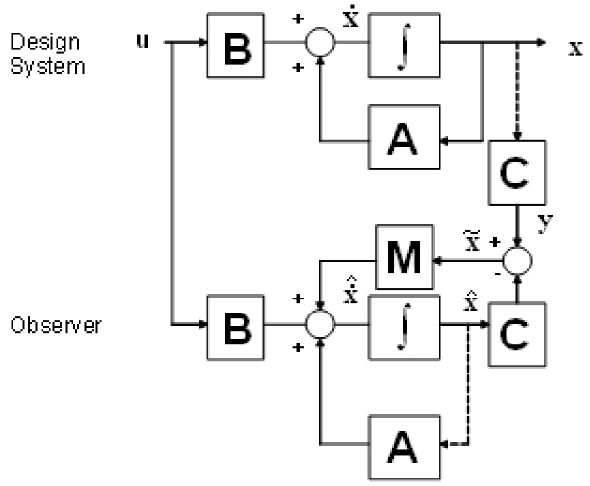

Figure 2. Design Process Observer

In Figure 2:

- the "^" represent observed states
- **x** is the cognitive state of the design team
- **A** is the design team's mental model such that **Ax** is their shared understanding
- $\dot{\mathbf{x}}$ is the change in design team cognitive state over time
- $\tilde{\mathbf{x}}$ is the error between the observed state and the actual state
- **u** are the design tools and methods (cultural medium)
- **B** represents the mediation of technical tools and methods
- **C** represents the available means to measure the design team's cognitive state
- **y** is what can be observed and measured of the design team's cognitive state
- **M** represents mechanisms to maintain "stability" of the observer

Cybernetics and the Luenberger observer characterise design as a socio-cultural cognitive system through a computational formalism. Given this formalism, we can express the concepts described above in systems terms:

- The design team's cognitive state over time is (the vector) $\dot{\mathbf{x}}$ comprised of individual cognitive states (vector components) $x_1 \ldots x_n$ but is also influenced by feedback (propagation) from other team member's cognition and external stimuli.
- The observed team cognitive state over time ($\dot{\hat{\mathbf{x}}}$) is based on a model of the team's shared understanding ($\mathbf{A}\hat{\mathbf{x}}$), the mediation of design tools and methods (**Bu**) and the corrections to the team's cognitive state ($\mathbf{M}(\mathbf{y}-\hat{\mathbf{y}})$). The fourth bullet point discusses these corrections.
- The system (design as a socio-cultural cognitive system) is "observable" in the sense that it is possible to determine cognitive states from the cognitive artefacts. This is the basis of some protocol studies employing artefact stimulus and the research in shared understanding in design which employ design documentation, verbal communication and verbalisations, sketches and drawings as signs and symbols (cognitive residua) of the cognitive states of the designer(s).
- The system is "controllable" to the extent that appropriate mechanisms (**M**) and design tools and methods (**Bu**) can be brought to bear towards steering the system towards a desirable state. In systems theory, this is known as "controllability." In the context of design, the notion of "controllability" has two interpretations. If the system (design) is considered as being externally observed as in a first-order cybernetic system, then the mechanisms **M** would be interpreted as external influences such as team management. If the system is observing itself, as in a second-order cybernetic system, then the mechanisms **M** are reflexive such as

reflection-in-action. As described previously on Valkenburg's research in assessing shared understanding in design teams, there is evidence to demonstrating the role that reflection plays in enabling teams to make decisions rationally to proceed. Thus, from the perspective of cybernetics, what distinguishes design as a first-order or second-order cybernetic system is whether the "controlling factors" are carried out reflexively by the observer who is constitutively part of the system or are carried out by "controlling factors" by the observer who is external to the system. Regardless, without appropriate controlling factors, the system becomes unstable. The likelihood of the system reaching the desired state is diminished.

If design is regarded as a socio-cultural cognitive system under observation as a cybernetic system, optimal "control" (or perhaps "intervention" in the case of second-order cybernetic system) of the system requires:

1. *Quantifiable and analytical metrics of the individual and distributed cognitive states of designers.* Traditionally, the effectiveness of design execution is measured in terms of competency with design tools and methods, e.g., how many unique, satisfactory design concepts can be generated, the reduction in ambiguity of design specifications, etc. However, measuring design execution solely as efficiency of technical problem solving is lossy. If one is also interested in understanding the social dimensions, this measurement is insufficient since it fails to capture social dynamics, for example, the confidence of the team to progress from one design stage to another, organizational learning of the design process, and shared understanding.
2. *Real-time analysis and assessment of the cognitive states of designers.* Computational analyses against the cognitive residua of designers in real-time offer the potential for constructive in-process improvement. Organisational behaviour methods for team performance management rely heavily on discourse analysis, psychometric evaluations, and human coaches – methods that are often unrealistic for practical implementations and cannot deal with the real-time nuances of team collaboration. Computational methods may lead to a new type of *autonomous agents* which cooperate with humans to monitor the socio-cultural cognitive effectiveness of teams.
3. *Proper selection and application of technical tools and methods to attenuate or amplify their mediation.* One such tuning strategy has been reported by Hauser [2001] in adapting product development teams to "strategic" product development metrics. By sampling product development goals such as time-to-market and customer satisfaction and organisational goals and then modifying the emphasis on the goals through rewards, the product development teams themselves modified their actions and allocations of efforts to suit the modified goals.

2. Conclusions

The purpose of this paper was to build a framework for describing design as a socio-cultural cognitive system. Design tools and methods constitute a "cultural medium" to facilitate the bridging of cognitive states within an individual designer and among designers in a social setting, the zone of proximity of social processes as illustrated in Figure 2. Aside from their literal purpose of solving specific engineering problems (e.g., optimizing the dimensions of an airfoil to generate the maximum lift to drag ratio), design tools and methods have the additional role of increasing shared perceptions and beliefs on the issues under consideration.

Consider, for example, an individual designer creating a handle for opening the door of an aircraft. To satisfy the requirement that the handle amplifies human effort by a given factor, the designer could solve a mathematical model, build a physical prototype, or construct a computer simulation. Cognitive processes associated with these tasks would include exploration and selection of design directions. Working alone, the designer could select any means to convince himself of the suitability of the artefact. Given a social situation, the designer might be 'constrained' to select tools and methods that accord with the norms of the design team. The team may prefer a mathematical model over a computer simulation. The designer has propagated agency to the tool to achieve the goal of convincing other designers of the suitability of the artefact. The output of the tool has associated social capital, what Boujut [2002] called the "double nature of design tools"; the tool is a medium for transferring the cognitive state of the entire design team. By affirming the social aspects of design, one must therefore recognise the socio-cognitive processes to form a sufficiently rich basis for exposing the foundations of design activities.

The basic argument of the socio-cultural cognitive theory of design is that design performance is driven by the social organisation of individual and distributed cognitive processes, which are afforded by technical design tools and methods (the "cultural medium" of the design team). The impact of this framework lies in pointing to a new direction for studying and teaching design in a way that is similar in philosophy to the study of human cultures. Established frameworks exist to compare human cultures by examining differences in symbols, heroes, rituals and values [Hofstede 1980]. While a direct mapping between these dimensions of human cultures to the culture of design teams is not obvious, we may do well to study and describe design team cultures by their socio-cultural cognitive orientation equivalently to the way social scientists research human cultures. The conventional "best-practices" view of canonical design teams operating under "best practice" processes, tools and methodologies may guard against failure but does not ensure success. Perhaps, the strategy is to tune tools and methodologies to optimise the output of this socio-cultural cognitive system called design.

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