Shared Memory in Design: A Unifying Theme for Research and Practice

S. Konda, I. Monarch, P. Sargent, E. Subrahmanian

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Suresh Konda
School of Urban and Public Affairs,
Carnegie Mellon University, Pittsburgh, Pa.

Ira Monarch
Laboratory for Computational Linguistics,
Carnegie Mellon University, Pittsburgh, Pa.

Philip Sargent
Engineering Design Centre,
Cambridge University, UK

Eswaran Subrahmanian *
Engineering Design Research Center
Carnegie Mellon University, Pittsburgh, Pa.

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* Comments are welcome and appreciated, please send them to sub@edrc.cmu.edu or to the above address.

Abstract

This paper presents a new unifying theme for design theory by emphasizing the importance of context . We arrive at our conclusions by examining and then refuting the legitimate bases for universal methods in design upon which he critical importance of context emerges. The collaborative aspects of design focuses attention on the conception of shared meaning. We introduce and elaborate the concept of shared memory as the embodiment both of context and of shared meaning. Using "shared memory" in vertical and horizontal forms, within and between disciplines respectively, we both account for past observations of design in practice and recommend actions to improve design in the future. We examine several practical implications of the growing importance of institutionalized shared memory and are able to recommend specific research programs which will help designers make better effective use of this critical resource.

1 Introduction

1.1 Design, Negotiation, Success and Failure

Design is usually thought of as a practice, mediated by scientific and engineering knowledge, aimed at the transforming of a set of needs into an artifact. However, needs are not always well-understood at the beginning of the design process, and a designer's understanding of these needs often undergoes considerable modification as the design process unfolds. Needs must be specified and negotiated based on several social environments: the environment within which the artifact will be marketed and used, as well as the small group environments within which the artifact is designed and produced. As shown by Bucciarelli (1984, 1988) and Engelmore and Tannenbaum (1990), engineers spend a significant portion of their time (more than 50%) in documenting and communicating -- much of it in the form of formal or informal negotiations. If we accept that the design process transforms needs, we must also recognize that the *requirements* based on needs are linked with economic, social, political, legal, ecological, and firm-specific factors reconciled with scientific and technological factors, resulting in requirements being continually modifiable and negotiable throughout the design process.

When an artifact is constructed which violates known physical laws or engineering principles the failure is not a design failure but a technical failure. For it to be a *design* failure, the failure must be a consequence of integration, communication or coordination failures, or socioeconomic failures. An example of the first three was the failure of the Kansas City Hyatt Regency Hotel skywalks where it was the failure of the walk-way architect to provide a complete specification of how to construct the beam and support. This required a re-interpretation of the "detail" by a fabrication engineer which led to the catastrophe (Petroski 1985).

An **example** of socioeconomic design failure is the case of Sony's Betamax video technology. In large part, the failure has been traced to the failure of engineers to appreciate the customers' reluctance for **a** technology which provided one hour of viewing while most movies were around two hours long, despite the higher quality of display possible with the one-hour tape (Bermingham, **1991).**

1.2 Universal Methods Put in Their Place

Many design theorists still insist that design theory requires universal methods analogous to universal methods supposedly used in the natural sciences. We believe this is misguided on two counts. First, as has been argued over the last twenty years, the existence of a universal scientific method that legitimates and is practiced by all scientists at all times is a chimera. This has been most strongly advocated by Paul Feyerabend in *Against Method* (Feyerabend, 1975). Second, there is growing evidence that contex-free universal methods are most often inapplicable and inappropriate in design practice (Hykin and Lansing 1975, Gregory 1979, Tebay et al. 1984, Juster 1985,UUman 1988, Finger and Dixon 1989,).

2 Past Approaches to Design Studies

2.1 Emulating the Natural Sciences

In a 1980 article, Nigel Cross et al. suggest that for the previous 20 years design research had been predicated on the implicit desire to emulate natural scientists whose analytic and empirical techniques were supposed to exemplify a universal method legitimating scientific practice (Cross et al. 1980). On the other hand Cross also suggests that there was an equally implicit belief that design is not like science in that the latter is analytic and design is constructive, noting the paradoxical nature of having these two attitudes at the same time. In fact, Cross sees H. A. Simon's *The Sciences of the Artificial* (Simon, 1981) as the definitive statement intelligibly weaving these seemingly paradoxical attitudes together and laying the foundation for the practice of would-be "design scientists".

Simon outlined a series of elements that would embody a science of design - "a body of intellectually tough, analytic, partly formalizable, partly empirical, teachable doctrine about the design process." Examples of these elements are the methods of optimization (adapted from management science and significantly modified using the notion of satisficing) and methods of problem structuring based on hierarchical decomposition techniques.

2.1.1 From Rational Reconstruction to Social Construction

While the study of design was greatly influenced by Simon's book - many researchers believing that Simon had resolved the paradox - Cross remained unconvinced and looked to critiques of what he took to be the image or understanding of science accepted at the time by the "design scientists". He found it in the writings of Popper (1963 & 1968) and Kuhn (1970),

who both in their own ways recognized that pre-conceptions, or "pre-structures" are an unavoidable element in scientific method It should be noted here that although Popper's and Kuhn's work were seen as alternatives to the most well worked out and elegant theory of science of the time - logical empiricism - Kuhn's was seen as much more radical. As Cross points out, Popper's work may be viewed as an attempt to sidestep some of the internal deficiencies of the going view without sacrificing the basic principle of the logical reconstructability of science or, in Simon's case, the computational reconstructability of science. On the other hand, the upshot of Kuhn's work, according to Cross, casts doubt on the whole principle of logical and computational reconstructability of science, at least to the extent that it is possible to capture scientific development in universal weak methods that are essentially independent of specific context and a huge amount of background knowledge. Kuhn's approach was historical and case-based, pointing to social and psychological factors essential in scientific development that had not been considered by formal reconstructionists and that were difficult, perhaps even impossible, to formalize.

2.1.2 Conjectures and Falsifications

Popper disagreed with the proponents of logical empiricism that the growth of scientific knowledge could be reduced to the study of artificial languages built from or modeled on logical calculi. However, he did maintain that understanding how scientific theories are justified was best set forth in a rational reconstruction of science. In his early work, rational reconstruction was more or less independent of case studies in scientific development. Later he and especially his colleague Lakatos turned to the rational reconstruction of detailed case studies in the history of science. Popper has argued throughout that theories are well worked out conjectures that are never verifiable, but ought to prove their mettle through severe critical tests, that is the aim of scientists should be to *falsify* their theories rather than confirm them. Discoveries are therefore guided by theory, not observation.

However, Popper's falsification views have not gone without criticism. Both Kuhn and Feyerabend have pointed out that if they had been strictly adhered to, many examples of successful theories would never have been developed, since they would have been rejected in their infancy. As they see it, there are two essential problems with Popper's falsification approach:

1. **Falsification, as well as confirmation, with respect to two competing theories require a neutral observation language to formulate observation statements that can arbitrate between the theories. However, no such language exists, since all such observation is theory laden; and**

2. **Theories are always more than single hypotheses. They are usually an interweaving of a number of law-like or rule-like statements supplemented by an often larger**

number of auxiliary hypotheses concerning instruments used in testing them and specifications of initial conditions and experimental set-up also necessary for these tests.

When a theoretical prediction is not satisfied, any one of the elements needed for testing a theory can be blamed One could appeal to professional judgement, but in the case of competing theories, professionals may disagree.

The upshot is, as Feyerabend argues at length, that both experience and universal scientific methods underdetermine the establishment of scientific fact necessary for confirming or falsifying a theory. Social and sometimes cultural factors are always significantly involved in bringing scientific debate to a relative close and stabilizing concepts, facts (Fleck 1979) and artifacts (Pinch and Bijker, 1987). Unless debate is brought to a practical close, there is no sense in which:

1 *science progresses, at least in the practical sense of building up a body of knowledge that is socially useful and teachable.* This is why some theorists of science emphasize confirmation and problem solving.

2 *scientists can make mistakes and learn from them.* This is why other theorists of science emphasize falsifiability and some theorists of engineering emphasize the role of failure in successful design (Petroski, 1985). It is only in specific socially constructed practical contexts that failure can be established and fed back to future design practice.

Because rational constructivists tend to ignore the social processes involved in the practical closure of scientific problem solving, they do not provide an adequate account of scientific development and are especially lacking in providing an adequate model of the design process. The latter requires an account of the relative closure of design negotiations, whether the design process starts with analysis or conjecture, and also an account of how a design consensus is established for the stabilization of an artifact. It should be noted that the claim that universal methods underdetermine the stabilization of designs and artifacts is less controversial than the analogous claim that universal methods underdetermine the establishment of scientific facts.

2.1.3 The Views of Kuhn and Feyerabend

A key idea for Kuhn that enabled him to theorize some of the essential social aspects of science is his notion of a paradigm. A scientific paradigm embodies the concepts, methods and techniques that a community of scientists engaged in collaborative puzzle-solving shares. This constitutes the dominant phase of science Kuhn calls normal science. Such a community of scientists does not see problems as falsifying instances but as solvable with the tools of the paradigm, even if for the time being they are recalcitrant.

A less prevalent phase of scientific activity for Kuhn are called revolutions. These are periods when a number of problems have either remained unsolved for a relatively long period of time (anomalies) or some one or other of them is covered by a new theoretical paradigm, even when, in other respects, it may have as many or more problems than the old paradigm. A relatively short but usually intense period of competition follows in which the competing paradigms vie for practioners and resources in a much wider social context than is the case for normal science practice. Revolutionary activities, for the most part, do not adhere to any of the proposed universal scientific methods or techniques. In fact there may be strong disagreement over which methods and techniques are scientifically acceptable, for example, in 17th century mechanics, a great deal of rhetoric and controversy was generated as to what role experiment played in physics and how important it was and whether instruments like the telescope can be relied on to challenge the venerable Aristotelian-Ptolemaic theory and support the new Galilean-Copernican theory.

Kuhn's view of revolutionary science was particularly distressing to many rational reconstructionists because he viewed rival paradigms as incommensurable; that is, as having no shareable meta-language that would enable adherents from both sides to evaluate respective merits and demerits. Moreover, the revolutionary process, situated as it is in wider social contexts, were described by Kuhn as requiring a more political mode of behavior than is necessary in normal science. This made the process of paradigm switch a matter of rhetoric and politics rather than rational judgement and evaluation.

Feyerabend developed a position that challenged rational reconstruction and had much in common with Kuhn's. His major difference with Kuhn was his scepticism concerning the demarcation between normal and revolutionary science. For Feyerabend the wider social context, rhetoric and politics is always an essential part of scientific practice. There are always competing groups of scientists vying for practioners and resources. Science is always a matter of interpretation and negotiation. It is only through social interaction that scientific knowledge is relatively stabilized. For examples which argue for social stabilization of scientific problem solving in various sciences, see Latour and Woolgar, (1979) for biochemistry, Pickering, (1984) for elementary particle theory and DeMillo et.al., (1978) for program verification in computer science.

We conclude, following Feyerabend, that there can be no rational reconstruction of science exemplifying universal methodological principles that all scientists in a given discipline follow, even for short periods of time. Given that images and theories of science have been instrumental in suggesting models for design studies, the history of design studies from Simon's seminal work to the present seems to stop somewhere between Popper and Kuhn, though a good deal closer to Popper than Kuhn, at least according to an update of Cross et al.'s 1980 article (Roozenburg and Cross, 1991).

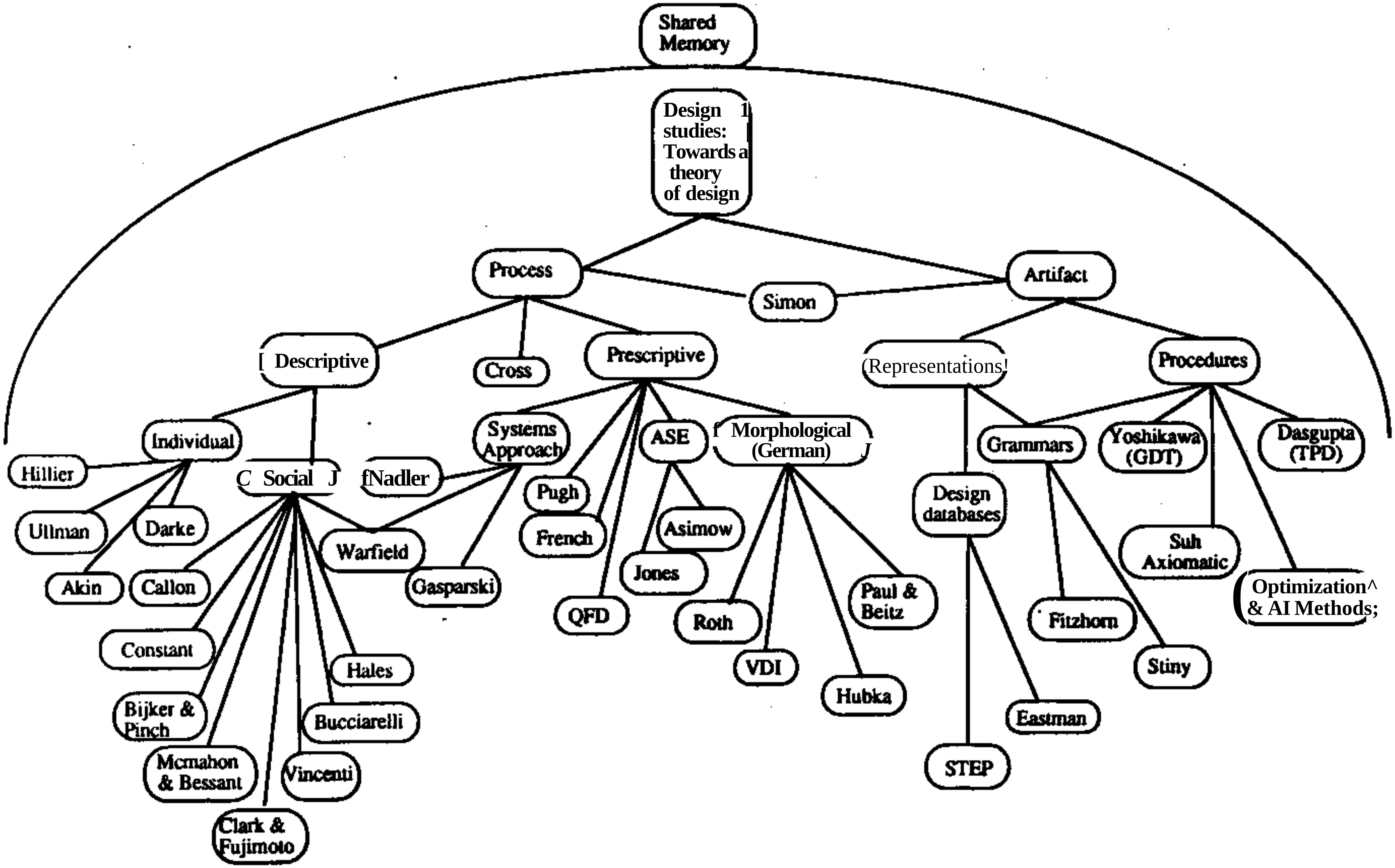

Figure 1: A Taxonomy of Design Research

As Hales (1989) says, "..it is... necessary to gain a better understanding of the engineering design process in practice, which calls for more accurate analysis of what actually happens as distinct from what is presumed to happen.". Hence, insofar as design studies emulate the natural sciences, rational reconstruction of past design behavior is not useful for the positive task of understanding design either in theory or in practice. Nor is it useful in the normative task of assisting in doing design since prescriptions based on the wrong understanding of how one goes about doing design will result in the prescriptions either being ignored, or worse, followed, with poor consequences. In what follows, the recent development of design studies are summarized and then criticized for not being more in accord with the social construction perspective.

2.2 Design Process Models

In a recent paper, Roozenburg and Cross (1991) specify a simple taxonomy of design models that had been proposed over the last decade. Although it was not an explicit aim of theirs to provide an exhaustive taxonomy, it is a good starting point for raising some issues which will lead to a more comprehensive taxonomy (see Figure 1). Their taxonomy is divided into engineering models, which are all versions of what they call the "consensus model", and architectural models, which serve as critics of the engineering models. A feature of the consensus model is its emphasis on prescription, whereas a feature of the architectural models is an emphasis on description. There are a number of other prominent features that are important in their taxonomy which will carry over into ours. These will be discussed below.

Our taxonomy will differ form Roozenburg's and Cross's in a number of ways. For one, we call the primary division of engineering models versus architectural models into question, since we believe it rests on the incorrect assumptions that architectural models are different from engineering models in being 1) *descriptive* and acknowledging prestructure, starting from a conjectured solution rather than being 2) *prescriptive* and inductively based, starting from an analysis of the problem. However, there are a number of engineering models which recommend starting from conjecture and are prescriptive as well (Dasgupta, 1989). Moreover, their taxonomy leaves out an important group of models focusing on the artifact rather than the design process. We therefore propose a taxonomy with the primary division being that of design models focusing on *process* as against design models focusing on the *artifact* itself. Conjectural models appear both in process models (which are descriptive) and artifact models (which are procedural). Our taxonomy will also be a number of levels deeper than theirs and will include a group of models focusing on social factors in the design process. We are proposing this taxonomy for its use in its own right, but also as a simple example of the structuring of shared memory.

2.2.1 Consensus Model of the Design Process

In reviewing **the** history of design models of the design process, Roozenburg and Cross see a **convergence to what** they call the consensus model based on the German school of prescriptive design process **and** morphological generation of designs. These models are described in VDI publications (1977 & 1985) and in slightly different versions in several textbooks (Pahl and Beitz, 1986 & Hubka, 1989). The model describes the engineering design process as a sequence of activities leading to intermediate results: "performance specification, function structure, principle solution, modular structure, preliminary layout, definitive layout and documentation." There are four phases of activities: "clarification of the task, conceptual design, embodiment layout and detail design." The consensus model perceives and models engineering design problems much as if they were problems in the natural sciences. Objects to be designed are technical systems that transform energy, material and information. Functional behavior of a technical system is fully determined by physical principles and can be described by physical laws. While the *goal* of engineering design problem solving is somewhat *different* from those of the physical sciences in that the former seeks to define the geometry and find the materials of the system so that the required and prespecified physical behavior is realized in the most effective and efficient way, problems are set up and the methods implied for solving them are much like those in the physical sciences. Moreover it is assumed that design should proceed from the abstract to the particular and concrete in order to keep the solution space as large as possible and that complex problems should be split into subproblems for which sub-solutions are to be found and "synthesized" into overall solutions for the design problem.

We note here that there is no mention of the social factors involved in the design process. For example, negotiation can enter into all phases of the process changing the very character of the solution space and determining different decompositions of the design problem at any stage of the design process. Modifications to the linear sequential process by adding feedback loops is basically a concession to the real world of design; the strived-for ideal remains the linear approach with the elimination of iterative learning within a given design task.

There is also no mention of the problems of sharing knowledge amongst members of a design team responsible for different parts of the design, since each member of the design team is usually also a member of different research and engineering traditions which conceptualize problems differently and see the design as a whole, if they attempt to see it at all, on the basis of different analogical models. While Roozenburg and Cross perceive the need for an alternative to the consensus model in studies of architectural design, their studies point the way more to a Popperian type alternative and less to a Kuhnian or Feyerabendian one.

2.2.2 Architectural Models of the Design Process

In their summary of models of the design process in architecture, Roozenburg and Cross state that early architectural models were similar to engineering design models. However, in the early nineteen-seventies, they identify architectural design theorists who began to question the orthodox view, especially as to its insistence that designers should resist bringing their own preconceptions to bear on a design problem. For example Hillier et al. (1972) and Darke (1984) suggested that the prevailing analysis-synthesis model in which exhaustive problem analysis must precede solution synthesis was based on a mistaken view of the role of induction in science. Like Popper, they argued that design, just as science, must rely on a form of preconception -- the prior knowledge of solution types. This notion is also similar to Kuhn's notion of shared exemplars, but Hillier et al. are not concerned so much (or at all) with the social factors involved, but rather with changing the analysis-synthesis part of the received model to conjecture-analysis in which the designer must develop a solution conjecture which is then subjected to analysis and evaluation. Just as in the case for Popper with respect to scientific problem solving, they lack an account of the social processes involved in the closure of design problem solving, they provide no model of the process of the closure of negotiations and hence the stabilization of design. Similar views to Hillier et al., according to Roozenburg and Cross, are also set out by (Darke, 1984, March, 1984).

A view pointing somewhat in the direction being explored in this paper is expressed by Rittel (1984). There it is argued that design problems in architecture and planning are inherently ill-defined or in the words of Rittel "wicked problems" that the systems analysis approach was too limited to handle. Rittel characterizes design as a multi-disciplinary argumentative process maintaining that this is as applicable in engineering as it is in architecture. However, he does not specify any of the problems involved in sharing knowledge in multi-disciplinary projects nor does he provide an account of the nature of the argumentative contexts, especially as to how wider social contexts interact with more restricted technical contexts and what implications this has for the argumentation.

2.2.3 Architectural Models as Critics of the Consensus Model

Roozenburg and Cross argue that what these criticisms of the consensus model of design process show is that the linear, sequential, analysis-synthesis-evaluation scheme of this model must be rejected, at least in architecture, and replaced by one with an essentially spiral structure that emphasizes prestructures and a conjecture-analysis cycle in which an understanding of both the design solution and problem, the latter of which is thought of as ill-defined and not strictly hierarchically, are evolved in parallel. This is especially important in the phases of embodiment layout and detail design in which decisions are strongly interrelated and the process consists in continuously refining a concept, jumping from one subproblem to another, anticipating decisions still to be taken and correcting earlier decisions in light of the current state of the design proposal.

It is acknowledged that the differences between the consensus model and the architectural model may also be due to differences in knowledge domains and the nature of the respective problems; being well-defined and science-based in engineering, and ill-defined and arts-based in architecture. In any case, what Roozenburg and Cross recommend is steps towards integration of the models. However, their reasons are sparse and vague. They point out that it is obvious that designers need to progress their projects in a sequence of stages. But the criticisms stemming from the architectural model emphasized a non-sequential processing. Unless there is a better understanding of negotiation and trade-off in the design process as well as a better understanding of how knowledge is shared as decisions are made with respect to various parts of the design, the right mix of sequential and non-sequential processing will not be determinable. Moreover, there is no reason to believe that the right mix in engineering will be the right mix in architecture, or that the right mix in one engineering field will be the right one in another. This lack of uniformity in tradeoff between the two models is also applicable to the other points Roozenburg and Cross make, for example with respect to: problem-analysis and specification versus innovative solution-generation, as well as early solution-conjectures versus adequate problem clarification.

2.2.4 A Hybrid Model and What It Leaves Out

At the end of the article, the authors describe Cross's hybrid model (Cross, 1989). We consider this hybrid model an advance over the consensus model, but it has many of the problems just raised. Though it specifies a dependency at all levels of hierarchical decomposition: between problem definition and solution concepts and between identifying sub-problems and generating sub-solutions, though it recognizes the necessity of building an overall solution from sub-solutions, by generating, combining, evaluating and choosing appropriate sub-solutions, and though it seeks to be prescriptive as well as descriptive, it has nothing to say about the necessity of sharing knowledge across sub-problems and sub-solutions that would enable viable decomposition, coordination of decision-making in establishing sub-problems and pursuing sub-solutions and finally an overall solution. Moreover it proposes a set of design activities related to a set of design methods without indicating the specifics of the technical and social contexts in which they have been applied either successfully or unsuccessfully. It is our contention that while methods may be successful in some contexts, they may not be in others. For us, this means that design prescriptions should not be made in the abstract but with respect to the specific technical and social context of a posed design problem and the relative success or failure such methods have had in similar situations.

2.2.5 Warfield's Generic Design Science

Warfield, in his recent two-volume book on the Science of Generic Design, appears to have the most ambitious and comprehensive approach to design theory. As shown in the taxonomy of design **(see** Figure 1), his approach to design theory is from a systems perspective. However, he uses **a** rich collection of data from both studies of problem solving in individual and social settings.

Basic to his development are three claims. First, there exists "universal priors": the human being, language, reasoning through relationships, and archival representations. Second, is his proposed Domain of Science Model, wherein, at the aggregate level, there are four components: Foundations, Theory, Methodology, and Application. Finally, he requires the tracing of implications backwards to the Foundations and forwards to Applications with a direct link from Applications to Foundations to complete the cycle.

On the basis that there seems to be no end to large-scale system development, he argues for the necessity of a science of design. Using his claims given above, he characterizes design science and draws implications for its methods and applications. He distinguishes between specific design sciences (which are found in various disciplinary areas of study), generic design science (which deals with those matters common to all design activity but distinct from the specific design sciences), and general design science which integrates both. Based on his detailed laws, corollaries, and principles for generic design, perhaps a more accessible definition of generic science is that it pertains to the domain of general problem solving in the context of group activities.

While we question the status of many of his detailed laws, corollaries, and principles for generic design, a more fundamental problem lies in that his conceptualization of generic design requires that its theoretical component *specifies* the appropriate methodology for its domain (which is all of design) and therefore is committed to the existence of a general universal method for doing design. As such, it is of a piece with classical and, as we have argued above, essentially refuted, conceptions of the scientific method. The very same brush tars his design science.

2.3 Design Artifact Models

Artifact theories of design are based on the premise that design starts with a reasonably complete functional specification and that universal methods purportedly exist which can be used to produce artifact specification. General Design Theory (GDT), by Yoshikawa (1987), Tomiyama et al.(1989), is one such theory in which this transformation in the ideal case reduces to die problem of selection of an artifact fitting the required specification from a catalogue of artifacts. However, in the real world, GDT identifies this transformation process as step-wise refinement using a *conjecture-anatysis-evaluation* of design[1]. Dasgupta's Theory of Plausible Designs (1989), and other approaches in Artificial Intelligence (Smithers 1989) are very similar to GDT. Suh's axiomatic method (1990) is another artifact-centered approach. The methods of the conjectural solutions, at different levels of detail, use analysis tools from optimization, physical and virtual prototyping (simulation).

2.3.1 An "Artificial Intelligence" Approach

While we do not believe that it is useful to partition an area of design methods and to label them "AI approaches", many researchers outside the artificial intelligence community and unfamiliar with the range and variety of modern computer science techniques do appear to think that there is a distinct approach. Thus we attempt here to describe a common "outsider's view" but also describe why it is unnecessarily restricting.

Early AI approaches attempted to reduce all the variety of design methods into different kinds of "search" within problem-spaces. The most simplistic assumption is that the formulation of the design problem is complete and precise, and therefore that the problem-space can be defined exactly. The classic problem is where there is only one space and where it is too large for simple enumeration, but where there is a single evaluation function which is relatively cheap (in calculation time). If the space is monotonic, a variety of classic search algorithms (branch and bound, minimax, AO* etc.) can locate the optimum design with reasonable effort (Rich, 1984). This search is the process of synthesis of an optimum design. Note that a position in the problem space corresponds to a completely defined artifact so that the evaluation is performed quickly on *complete* designs.

The two reasons why this initial approach to formulating design problems is unrealistic is that two of the hardest parts of design are not addressed:

1 the process which leads to a complete, unambiguous specification of the design problem is not addressed, and

2 the evaluation function for complete designs is assumed to be "given" by the domain-specific knowledge.

Later work in this tradition allows the problem space to be infinite by defining it via a grammar, rather than a fixed representation. A further expansion of capability arises if the grammar is made context sensitive. What this achieves is the formal representation of a variety of possible

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[1] The Analysis-Synthesis-Evaluation (ASE) methodology embeds *iteration* as fundamental. The distinction between this and the *conjecture-analysis-evaluation* (CAE) model is where the alternatives being evaluated come from: ASE alternatives are constructed from a detailed analysis procedure, CAE conjectures are asserted as a means of making sense of the (under-determined) specifications.

problem specifications which can be explored by the designer using the search algorithm, rather than searching for a simple optimum (Coyne, 1991). Thus the designer can examine whether the original problem specification was sensible and whether a change in specification can yield a better design. Sometimes this is achievable all within the same problem space but, often it is more comprehensible if a problem space of "super-structures" is explored where each point in that space corresponds to a single specification and hence a whole space of possible designs.

Current research is taking this type of technique out of the "AI" domain altogether since modern mixed-integer non-linear programming (MINLP) algorithms can solve for optimal designs in the super-structure space (Grossman, 1991), indeed the label "AI" can now be seen to be inappropriate since "search" as a method entered the mainstream of computer science more than a decade ago. The entire multiple problem space method is now often envisaged as being implemented at several levels of detail so that only approximate evaluation functions are available at the higher levels of abstraction. Thus while evaluations must still be preformed on "complete" designs, these designs are complete in outline only. This relaxes the second limitation described above.

The recent construction of multiple-expert design systems is a characteristic of the late-80s. This significant and important development enables several different competing and collaborating software packages to generate a range of alternative designs which satisfy hard constraints in the specification and which have different behavior trade-offs. The designer operates as one of this team: as a *conductor* of the process rather than a *player*, where each player is concerned largely with a discipline-specific view of the artifact (Quadrel, 1991). Thus "AI" and other software-based artifact-centered approaches are no longer distinguishable.

Incomplete specifications always cause difficulties. Unlike human beings, current computable representations have strictly defined limits to their mutability and so will only be able to vary constraints in specific directions from those given in the initial specification of a design problem. More abstract representations reduce the limitations, but in the limit "common sense" knowledge is required and this is not yet available in software (Guha and Lenat, 1990) .

2.3.2 Artifact Models Summary

The main criticism of artifact theories is their restrictive scope and their goals of axiomatized theories of design. This approach, while amenable to parts of artifact design, are incomplete in their ability to trade off alternatives, which are mediated by inherently social processes. In their paper, "Social processes and proof of theorems and programs", DeMillo, Lipton and Perlis (DeMillo et al., 1978) illustrate how in mathematics and in engineering what is acceptable or reliable is a socially determined process. Using their argument, we propose that formal axiomatic parts of these design theories depend on the informally determined set of specifications. Hence, **the** reliability *and acceptability* of the formal specification is necessarily an informal social process. This formal part of design only becomes stable in the domain, i.e. becomes part of **the** shared memory, it comes to be established by **the** *social* process. For example, the use of optimization methods in chemical engineering is much more accepted and stable than in mechanical engineering.

The process of acceptance of formal methods is based on their reliability in a *situated context* of the domain of application. Thus if we accept that these formal theories of artifact design are actually informally based, to argue that these theories are *complete* theories of design misses the point However, we are not against formal methods and argue elsewhere that situated domain theories (for layout design, see Coyne & Subrahmanian, 1989) can be constructed empirically by using computational support environments that are cognizant of the formal and the informal.

3 Arguments for Shared Memory

In the previous section we argued that rationally reconstructed design theories which purport to result in generalized universal design methods have a number of problems that are perhaps better addressed by an alternative approach. Our alternative recommends that design methods need to be *contextualfy evaluated* using a rich historical record of design processes and outcomes. Capturing this record requires the creation of shared memory - with its connotations of accessibility and persistence across space, time, and disciplines. In this section we argue that understanding the role of shared-memory in design is central to any theory of design whether the theory is to be used to understand the results of design (theory for explanation) or to be used to improve the design process (theory for prescription).

3.1 **What is shared** memory?

The most immediate form of shared memory is all around us — it is the codified corpus of knowledge, techniques, and models (in the sense of useful and workable abstractions of reality) that exist in every professional group be they scientists, engineers, technologists, or artists. Indeed, one could argue that without this form of shared memory, there cannot be a professional group. For expositional convenience, we shall term this form of shared memory *vertical* memory since it is concerned with encapsulating increasingly detailed aspects of a given profession's knowledge. It is critical to understand that engineering science as commonly understood, or technology (for example, CMOS technology, fiber-optic technology etc.), is the elaboration and refinement of vertical memory, but that this, by itself, is usually insufficient for doing even the most focused of designs because negotiation and trade-offs are required between the designer and potential consumers, producers, and marketers in almost every case of design.

In addition to vertical memory, any artifact that requires the knowledge of more than a single **discipline (whether** manifest in **a** single individual or a design **team)** requires **that** meaning be **shared among multiple** disciplines, groups, and group members. **The** multi- and inter-disciplinary **nature of design** is critical. **We** shall call the record of this inter-disciplinary communication *horizontal* memory. Horizontal shared memory always requires careful mutual translation of **terms and** concepts across groups because members of design groups working on **the** same artifact do not share the same experiences, concepts, perspectives, exemplars, methods, or techniques. Perhaps the most concrete manifestation of this requirement lies in the observed differences between individuals in partitioning a given problem.

Horizontal shared memory not only concerns sharing among variegated professions but also among members of the same professions. The sharing across professions follows from the general observation that design is, *inter alia,* the collaboration between unlike disciplines or individuals. The need for horizontal sharing within a profession arises from the differences in functioning contexts (as in, for example, among chemical engineers in academe, in manufacturing plants, in design shops, in Pharmaceuticals, in petrochemicals, etc.) and meanings readily demonstrated in a host of case studies (for example, the ALCOA study by Sargent et al., 1991). Consequently, care should be taken to avoid the interpretation of shared memory as simply a cross-disciplinary "matrix" with its connotation of impermeable rows and columns. Thus, what distinguishes design from engineering is that the former emphasizes the creation and use of shared horizontal memory while the latter is more concerned with the elaboration and use of vertical shared memory.

3.1.1 Shared memory and shared meaning

In one sense, shared meaning and shared memory are nearly interchangeable. One cannot have a meaningful shared memory without shared meaning since memory that is neither accessible nor understandable can hardly be called shareable. In another sense, shared memory can have a more physical existence in, for example, databases, cross-indexes, models, papers, and so on. In this paper, therefore, the term shared meaning is always included in shared memory while the term shared memory is used when we include this *concrete* aspect of its existence. In other words, shared memory is materialized persistent (long lasting) shared meaning.

It is not necessary, in general, to assume the existence of a technology for integration of different views. As Evans (1988) and Clark and Fujimoto (1989) note, Japanese industries have directed their attention towards organizational integration of human specialists and have produced remarkable results without computer technologies. Hence, enhancing communication between human designers from different perspectives is feasible using organizational methods such as assignment of team responsibility and proximity of the designers, or through techniques such as Quality Function Deployment (QFD) for matching quality control and customer preferences (Hauser and Clausing 1988, Staley and Vora 1990).

If integration is to be directed towards the availability of the earliest or maximum sharing of information among those with different perspectives on the design but separated by significant space and time, computational systems become quite relevant - an issue we pursue in the next section of this paper.

3.2 **The Importance of Shared** Memory

"Simultaneous" or "Concurrent" engineering are terms that have gained a lot of currency recently. These terms have been used synonymously with a variety of other terms such as design for manufacture, design for assembly, life-cycle engineering, process driven design, etc. In each of these uses of the term, the underlying premise is that traditional design processes lack information on the later stages of the product realization process (such as production and operation) in the early stages of the development of the product

In a study analyzing the traditional design and development process (which is not concurrent) Danko and Prinz (1989) conclude that successful design depends on the exchange of information between appropriate groups in the process. Further, inadequate communication at critical times between different groups involved in the product realization process will result in the failure of the product or will require extensive redesign. Summarizing their analysis of traditional design processes they identify the following weaknesses in the traditional approach to design:

1 Design of product requires knowledge of the later stages of the product realization process and is held exclusively by those in the later stages.

2 If the knowledge of later phases are not available in the early stages then costly redesign occurs at the intersection of these phases.

3 Inadequate communication between phases lead to failure or extensive redesign. Design and research engineers are not knowledgeable enough to overcome the brittleness of the design without production and operational knowledge. The different levels of technological capabilities of the phases may lead to outstripping of the capabilities of one stage with respect another stage leading to mismatch and the need to redesign.

4 The design process is not robust enough to to react to unanticipated changes that may occur due to changes in legislation, availability of materials, etc.

In recent literature on simultaneous engineering, experiences with integration of two or three phases of the design process (Mohan 1977, Reid 1984, Givens 1988, Boothroyd, 1988) are described. For example, the design of the Ford Fiesta was integrated from the point view of serviceability, and design of the Ford Taurus from the point of view of marketing, design aesthetics, service, production, advertising, and legal regulations (Eigner and France 1978, Vogt 1988). The beneficial results of even limited integration leads to the conjecture that a completely integrated design process, by synthesizing a holistic view of the product, would address tradeoffs in a systematic way. In describing a completely integrated approach, Takeuchi and Nonaka (1988) and Clark and Fujimoto (1991), use the game of rugby as a metaphor. The game of rugby, by virtue of its rules forces a co-operative behavior since it relies on the movement of the entire team from start till they reach the goal. It also emphasizes the importance of coordinating the special skills of the members of the team on a dynamic basis.

Takeuchi and Nonaka (1986) identify six basic characteristics that are shared by the organizations that appear to have addressed integrated engineering: built-in instability (see the section on Organizational Learning below); self-organizing project teams; overlapping development phases; multi-learning (across disciplines and functional responsibilities); subtle control (not relevant to shared memory); and organizational transfer of learning.

The conclusions of Clark and Fujimoto (1991) based on their study of American, Japanese, and European automobile companies is that Japanese firms are organized to maximize knowledge sharing between departments (product and process), between suppliers and the parent (through long term contracts and reliance on supplier's engineering capability), and through very quick problem solving cycles that involve the departments. They call this approach integrated problem solving and show that the lead time to manufacture a product has a direct relationship to the extent of integrated problem solving. "...fundamentally, the emphasis in the Japanese system on direct working relationships between engineers and long-term involvement helps reduce mistakes and rework and enables tool and die shops to handle changes with fewer transactions and less overhead" (pg. 187).

They document the approach taken by Japanese firms to facilitate maximum knowledge transfer between the different product development stages and the firm and its suppliers. They argue that the integration of problem solving has a direct bearing on a number of measures including product lead time, stage simultaneity, development productivity, and total product quality (cf. figure 8.9). The essence of their study is that Japanese companies have directed their entire organizational structure towards the creation and maintenance of what we have called shared memory on a continual basis. Nevertheless, as we argue in the succeeding section, organizational means to shared memory are limited in that the memory is constrained due to the narrow perspectives of individuals and susceptible to the departure of these individuals.

In interpreting these findings, note that the underlying phenomenon being described is that of collaboration (or, in the traditional approach, lack thereof) among individuals separated by discipline or functional responsibility. However, following Schrage (1991), collaboration does not ineluctably follow from the transfer of information -- it requires a rich set of both technical and behavioral antecedents and support, and is consonant with the creation of what we have termed shared meaning, the persistent form of it being shared memory. In short,* effective simultaneous engineering is effective interdisciplinary design which, in turn, is the creation of effective shared memory.

Clark and Fujimoto (pg. 332) also argue that "Computer technology may dramatically raise the level of product development performance for the industry as a whole, but by itself it is unlikely to create long term advantage for one group of companies. Competitive advantage will lie not in hardware and commercial software, but in the organizational capability to develop proprietary software and *coherently integrate software, hardware, and "hwmnware" into an effective system"* (italics added).

In the language of this paper, this is the process of creation, and perhaps jealous "guarding", of firm-specific shared-memory. There are thus two aspects of commercial advantage: having a system which can integrate effectively and having specific shared memories in an accessible form.

3.2.1 Expertise

Several studies comparing the performance of novices and experts have shown that the crucial difference between the two lay in the formers* lack of experience (see, for example, Chi et al. 1982 and Glasser 1984 in several problem domains; Jeffries 1981 in software). More particularly, experts and novices differ in their access to and use of knowledge; i.e., in their access to shared memory. Thus, these findings lend support for the "knowledge use" theory as against the "design schema" theory (Jeffries 1981).

3.2.2 Creativity and Shared Memory

Another line of argument for the centrality of shared-memory can be derived from the observations of a variety of students of creativity: that creativity in the sciences, arts, or technology is significantly influenced by the act of collaboration. That is, in order to understand most significant acts of creativity in most realms, observations of the lone creative actor are both inadequate and misleading (Weisberg 1986, Lederberg and Uncapher 1989, Schrage 1991). Note that we categorically deny that design can be classified into normal and creative design - rather we follow Vincenti's (1990) distinction between normal design and radical design with creativity being an element in either forms of design. As Schrage observes, collaboration is not the consequence of communication as information transfer (while the latter is a necessity for collaboration, it is not sufficient); rather collaboration is the creation of a shared meaning not just among unlikes (marketing scientists with mechanical engineers) but also among likes (i.e., biologist with a biologist).

The argument is not that the lone creative genius in the arts or the sciences is wrong - rather it's just not complete. The concept of the lone worker needs to be expanded when we are to consider variegated, generalized, creative acts which are the acknowledged domain of the design theorist Shared memory is the taking-hold of shared meaning created in specific design situations and applied to other design situations. Shared memory creation is very difficult and may require resources beyond any given design project. It needs a substrate, or an infrastructure, in which the initial construction of a shared language are stored and perhaps reactivated at a later time on the same or a different project

3.2.3 Organizational Learning

Argyris (1982) in his analysis of organizational learning, shows that organizations have defined methods for problem-solving. Failure to solve the problem appropriately (defined as a mismatch between observed consequences and the desired consequence) leads to changes in these defined methods which are incremental and within the context of the larger, more rigid, organizational culture. A mismatch that is not solvable by these incremental changes requires changing the governing variables in the organizational structure; i.e., the organizational culture. As he points out, even if the problem is recognized, the actors in these organizations are trapped in a situation where they either cannot recognize the problem or do not know how to rectify the problem. Further, the current organizational structure and their skills could prevent changes from occurring at all.

Warfield, in following Argyris' observations, points out that this situation exacerbates the difficulty of solving a design problem. Any attempts to alleviate this situation would require changes in the larger organizational context and hence will probably threaten the stability of the organization in terms of structure and power hierarchy. Hence, improving design would require mechanisms to live with such instability which will have to become an integral part of the organization.

The validity of this conclusion is reinforced by the findings of Takeuchi and Nonaka (1986). In their case studies of six Japanese design organizations, they point out that such an instability was built into these organizations. To achieve this "stable state of instability", Takeuchi and Nonaka show, these organizations have institutionalized continual learning - transfer of appropriate (successful and relevant) methods and actions takes place within and across projects in the organization thus preventing the rigidification of any particular methods or actions in a project Zuboff (1988), in describing other organizational contexts, also reaches similar conclusions about the coming of institutionalized instability by arguing that computer technology acts to loosen traditional authority structures. A comparison of hierarchical structures in the U.S. and Europe with those of the Japanese also reinforces these prescriptions for organizational learning (Moses 1990, Clark and Fujimoto 1991). The latter have wide shallow structures which, along with constant lateral movement, act to loosen traditional organizational authority roles and permit rapid and continual information flow and exchange. For our purposes, it is sufficient to observe that these conclusions are managerial and organizational responses to the need to create and maintain shared memory in order to achieve improved organizational problem solving.

3.2.4 Organizational Structure and Innovation

Organizations, **based on** their size and social history, have evolved into different structures. However, many studies on organizations indicate that innovation has been inversely correlated with the size of organizations (Burns and Stocker 1962, Takeuchi and Nonaka 1986). A partial explanation of this correlation lies in the fact that integration takes place more easily in a small organization leading to innovative solutions, while the hierarchical structure and other barriers deemed necessary in large organizations, stifle the percolation of innovative ideas from different parts of the organization.

Further barriers to integration could take place when a manufacturing organization relies on a variety of sub-contractors to manufacture subassemblies of their product. In these situations, the structure of bidding and contracting procedures make the integration task difficult Examples of how these difficulties were overcome by including the vendors early in the design process, changing the bidding and contracting procedures, and devising new principal and sub-contractor links show the role of shared memory in efficient product design and manufacture (Clark and Fujimoto 1991, Evans, 1988, Givens 1988).

In assessing the need and impact of integrated manufacturing, most authors point to the existing organizational cultures and the need to change them (Takeuchi and Nonaka 1986, Vasilish 1987, Bucciarelli 1988). Takeuchi and Nonaka point out that a team-based integrated engineering approach simulates the advantages normally found in small organizations. The observation that small-scale industries account for large proportions of innovations in the U.S. also substantiates the potential advantages of the team-based approach to integrated engineering. The idea of simulating small organizations within a large organization, according to Takeuchi and Nonaka (1986), results in the large organization behaving as a venture capitalist financing small and creative groups. In any event, all these approaches are structural methods to create, sustain, and transfer, shared memory within an organization. Firm-specific design data, and short communication paths, are likely to be the reason why small firms innovate more readily than larger firms in which the shared memory is much more fragmented

Finally, deep and rigid hierarchical organizations with formal channels of communications and distinct areas of responsibilities, actively contribute to a "Taylorism" of the mind. This reduction, apart from being rooted in a discredited model of work, actively destroys shared memory since it militates against the exchange of information and the necessary voluntary coming together of people and getting hold of shared meaning.

3.2.5 National Collaboratory Proposal:

A significant assertion in the recent report by Lederberg and Uncapher (1989) -- on the support needs of scientists -- is that the process of scientific work (not the outcome) is a social process where collaboration, communication, the demarcation and definition of "new" knowledge all imply "a community of scientists and science as inherently a social enterprise". It takes little imagination or argument to extend this notion to design -- where not only the process but the outcomes (artifacts) are both socially determined and evaluated. As is argued therein, "..even the isolated investigator works within a social definition of discovery,..".

The report's conclusion about the need to provide infrastructures to facilitate collaboration in order to advance the scientific endeavor is completely consonant with our argument that the core of a general theory of design (whether positive or normative) must not only involve the social sciences but must understand and facilitate collaborative activity -- what we have termed the creation of shared meaning through the generation of shared memory. While adequate research has not been conducted into the nature of effective collaboration, the recent initiative of the National Science Foundation in creating the Division for Coordination Theory and Collaboration Technology, is a welcome beginning.

3.2.6 Design Reuse

One of the critical characteristics of a discipline which has reached the status of "engineering" is the existence of the handbook (Shaw, 1990) -- a perfect example of vertical shared memory freezing and legitimizing the collective knowledge of the discipline with a practical purpose. The building code (around in some form since Hammurabi) along with the ship-building guidelines of Lloyd's of London are more ambitious versions of the handbook in that they contain elements of horizontal shared memory. This shared memory is the fruit of the work of multiple disciplines as applied to building construction in the first case and ship building in the next. The underlying purpose of such repositories is the enabling of reuse at increasing levels of granularity -- from nuts and bolts to bathrooms and HVAC (heating, ventilation, and air-conditioning) to buildings and ships. Reusing the knowledge of successful (or least not yet unsuccessful as Petroski points out) designs and design methods is perhaps the fastest, most efficient, high quality route to improving design. Nevertheless, reuse is not as wide as one might expect for two reasons. First, existing repositories tend to be for vertical shared memories only and with limited information (as described above, considerable variations in language, meaning, storage, etc exist even within a given discipline when other social and cultural factors vary). Second, the "returns" to reuse increase dramatically as the granularity of reuse increases -- however, increasing granularity necessarily requires increasing understanding between individuals in different disciplines, professions, organizations, cultures, and societies. Not only does reuse require that multiple views be articulated and reconciled, but our arguments against universal methods require that all the relevant context of a design be recorded and used in evaluating the potential for design reuse - both process and product We discuss the production of "standard" handbooks later in this paper.

Of equal importance is avoiding the reuse of unsuccessful approaches, models, methods, and artifacts (Pttrosld 1985). One can rely on traditional institutions (academe, publications, conferences, etc.) to, at least partially, create shared memory of successful methods. It would require special efforts to retain the memory of failures in order that they be avoided though spectacular failures are usually retained More often they are swept under the rug. However, the myriad approaches, methods, tools, and designs, which failed are rarely recorded The impact of even simple systems (structured field-service records and using free-text search for unstructured information) which revolutionized some vertically-integrated companies (Cassidy, 1991), underscores the role of failures. A lack of appreciation for the importance of failure and the pervasive role of shared memory in design, could thus lead to the continued use or re-invention of failed methods best left unused but not forgotten.

More generally, shared memory cannot be universalized - the context of the item must also be retained. This implies, of course, that the entire enterprise is predicated on a case-study approach to the observation and recording of design activities. Hence, the concept of shared memory further reinforces our conclusions about the status of design theory where we concur with Hales (1987), Besant and McMahon (1979) and Leifer (1991) on the need to develop rich empirical evidence on design.

4 Theoretical Visions and Implications

4.1 Theoretical Aims

We have argued that it has been a mistake for design theories to heretofore have taken as their primary *raison ditre* the goal of recommending a set of universal prescriptions for designers to follow. In arguing thus, we have maintained it is unlikely there are any universal methods that are not either nearly vacuous or more or less inapplicable or inappropriate unless specifically adapted to particular situations or particular types of situations. Implicit in our argument has also been the rejection of the idea that design theories are merely tantamount to recommending universal design methods. Rather, and now we make this explicit, we take a classical view of the aim of theories and maintain that one of their essential aims is to explain. This means, in the case of design theories, that not only should they have a prescriptive dimension, but also they should be able to explain why, for example, methods woric as well as they do, how they might work better if adapted to specific situations, or why they fail. This emphasis on explanation, in turn, also has implications for the prescriptive dimension because the latter must be understood in terms of the explanatory framework being developed. In the research program or theoretical schema we have been sketching, we have situated the prescriptive dimension in specific design settings, emphasizing social as well as technical factors and demonstrating the need in these situations to share meaning and information, i.e., the need to create shared memory. The upshot has been a new way of approaching the prescriptive dimension - challenging the status of universal methods and recommending a case-based approach to formulating and evaluating design methods, techniques and tools.

4.2 The Need for Design Theory: Prescription, Description and Context

The need for design theories was recognized as a means to deal with the complexity of the design process *and thus to increase its speed and quality.* The response to this need was to prescribe theories of design whose main objective was to formalize the design process. Such prescriptive theories while formalizing the design process did not take into account the complete empirical phenomena. They were descriptively incomplete. This is evident from observational studies we have cited showing that this perspective overlooked important aspects of design practice. Ullman (1991) also discusses these limitations of the current state of design research in the United States.

Stauffer and Ullman (1988) using a summary of findings from empirical studies of the actual design process conclude "...[data]... point to a dynamic, heuristic approach to design as it is actually performed by human designers". Instead of forcing increasingly varied empirical data into a general prescriptive theory that becomes nearly vacuous, inappropriate or inapplicable, we are recommending that the design process should be captured without sacrificing its specific richness and the details of the social context in which it is carried out From our point of view, the emphasis should be on the specifics of this context, especially the features which enable classifying various approaches and practices arising in a given case, whether they actually fail or succeed, as to similarities and differences with respect to other known cases. In this way, a theory of the design process can be constructed which emphasizes the empirical and descriptive aspects of design, moving away from contextless prescription while at the same time preserving its prescriptive efficacy.

Our theory of design is that there is no discipline of design. We contend that "a body of intellectually tough, analytic, partly formalizable, partly empirical, teachable doctrine..." (Simon, 1981) is not a coherent discipline and any attempt to force it to be coherent loses the essence of design. A critical aspect of design is that it is multi- and inter-disciplinary. By this we mean that it is the interactions between individuals (human or otherwise) with *different ways of looking at the same problem* that creates the problems which theories of design attempt to manage. Rendering design into a single discipline removes this difficulty for the design theorist but not for design.

Since we reject context-free universal methods, it follows that it is impossible *a priori* even to identify which disciplines are required to be involved for any design problem except through past records of similar cases: shared memory.

4.3 Shared Memory: The implications for design

We have argued that an emphasis on shared memory should replace the emphasis on universal methods as the aim of design research. More pragmatically, we suggest that shared memory needs to be created by appropriate organizational structures, creating necessary technical substrates, and generating tools and methods to codify knowledge.

It is clear that some degree of horizontal memory is created by individual mobility of designers and judiciously creating appropriate reward systems to encourage the transfer of information. The Japanese organizational style of achieving this needs to be more thoroughly understood in order that organizational approaches more suitable to other cultures can be derived. In many ways, the organizational and managerial styles prevalent in the U.S. today act to prevent the creation of shared memory. Yet these styles might have a certain legitimacy from other perspectives. Institutionalized instability jeopardizes existing authority and status structures and is bound to be resisted. Hence, the process by which such institutionalization is to occur needs to be investigated by careful field studies of real organizations which have, successfully or unsuccessfully, attempted to become stably unstable organizations.

Depending on how much integration is emphasized, specialists in each product realization phase can be teamed together to varying degrees. The rules of the integration game will have to be such that it fosters co-operative behavior. The level of co-operative behavior achieved will be based on the necessity of, and reward structures accompanying, such a behavior. In general, since, as we have argued, design is a socially mediated process and shared meaning must be consensually established, the existing reward systems which are highly individually oriented (at least in the U.S.) would need to be suitably modified. What possible alternatives exist, how they are to be injected into a design organization and the reaction of the labor market to such reward systems are issues which need to be investigated. Clark and Fujimoto (1990) have begun some of this work in their comparisons of Japanese, European, and U.S. automobile firms and have identified successful variants in other U.S. industries; in short, it *can* be done.

Organizational approaches, however, are limited because the investiture of shared memory in individuals leaves the organization vulnerable to individuals quitting the organization though retaining individuals for longer within the firm will help. . They are also limited by the cognitive limitations of any individual. In addition, generating horizontal shared memory is, we anticipate, a difficult task. For all these reasons, a substrate which helps in generating and retaining shared memory is also required. Additionally, no single organization has the incentive to share its knowledge and experience with its competitors. Hence, third parties (academe, the National Science Foundation, consortia) need to be tasked to generate shared memory repositories.

More specifically, creation of horizontal shared memory is not synonymous with the creation of accessible databases or usable tools. How individuals create shared meanings, what special languages, representations, models and so on, are required to enable different individuals to share knowledge and experience, are all issues that need careful investigation before a reasonable substrate can be created Some approaches to these problems are given later in this paper but a scan of the literature shows that considerable work remains to be done in this area.

This substrate must also facilitate capturing the context and history of a particular design in order that the experience, good or bad, can be reused (or not used) within another design context This also implies that as much of the negotiation among designers and with other relevant parties, such as users, needs to be facilitated and captured. The recent elaboration of the various dimensions of design artifacts and processes is a start towards contextualizing design (cf. Westerberg, 1989).

The importance of horizontal shared memory does not in any way detract from the importance of vertical shared memory. Indeed, most of the work currently being done by engineering and design researchers can be characterized as the codification of specialized knowledge which is, thus, adding to the corpus of vertical shared memory. Hence, our work does not suggest that such efforts and the methods that are derived from them are either invalid or inappropriate. It does suggest, however, that creating such vertical memory does not, ipso facto, create horizontal shared memory. That is, explicit efforts will be required in order that these tools and methods can be shared in the horizontal sense.

As we have repeatedly stated, creating shared memory, especially horizontal shared memory, is not an easy task. It is also important to recognize that this is both an expensive and long-term task. Even in the limited case of Toshiba's "software factory" (Brackett, 1991), their system to maximize software reuse took nearly a decade to create positive pay-offs and was very expensive. Observe that both time and money are required of both the organizational and substrate approaches to creating shared memory. Hence, a short-term perspective (a widely discussed, and criticized, orientation of American management) will render this task infeasible.

4.3.1 Implications for Design Education and Continuing Education

The existence of disagreement in the legitimacy of particular methods in design (or in science) is often signalled by the phrase, "..you can't *do* that!*'. Innovative design often leads the development of analytical method, a designer with a deep appreciation of a subject can easily create a design for which there is no appropriate analysis but which nevertheless "feel right". Over-emphasis on analysis in the education of designers has a stultifying effect on their creativity ~ but this is already well-known.

What our shared memory model proposes, however, is that true understanding of an area of engineering is much more than simply a good familiarity with the relevant mathematical methods and underlying engineering science. Practicing designers know this well, but course syllabuses are often squeezed to contain merely the core analytic techniques because emphasis

on empiricism is felt to be indefensibly unscientific. **We hope that we have shown a strong fundamental basis for the** importance of practical **knowledge which will help design educationalists express their deeply-held** beliefs in ways which might **be** more convincing to their **more "scientific" colleagues.**

4.3.2 **Implications** for Authority and Standards

One might well ask: if "horizontal'* shared memory is cross disciplinary and cross **group,** who **has the authority to decide what** belongs and what does not **belong in shared memory and whose responsibility** is it **to collect,** organize and maintain it? **We do not believe, as must be the case with Warfield's** integrated design science, that shared **memory is necessarily the** responsibility of **a** discipline which has authority over specific disciplines to determine what belongs in shared memory and what does not If past history is any indication, no specific discipline **will ever** willingly give up this authority to an integrated discipline in Warfield's sense. Warfield argues for a single integrated discipline, on the contrary we maintain that independent views, even incommensurate views, are vital.

All that shared memory requires, at least with respect to its content, is the joint and collaborative activity of relevant groups or disciplines to create it This means that these groups must agree on procedures for organizing shared information and agree on protocols for accessing and storing it. This agreement can only result from negotiation.

4.3.2.1 Scope and Interlinguae

The scope of inter-disciplinary agreements is problematic. Negotiations are most easily resolved at the level of individual designs, but the long-term use of shared memory requires more long-term and thus more broadly scoped partitioning. The usual mechanism for reaching such agreements is through consensus standardization.

The goal is for individual engineers' and scientists' specialized knowledge, and thence the relevant *implications* for each other's knowledge, to be shared. However their limited cognitive capacities and incommensurate terms, languages, and methods, mean that they must consensually arrive at some *inter linguae* to convey shared meanings, limited as they might be. It must be the responsibility of each discipline to record and update design history information according to the agreed mechanisms, using standardized *inter linguae* if necessary. There exist concepts for which direct translations do not exist between disciplines, but which nevertheless define critical information for designs, e.g. aesthetic and structural concepts. They are only directly accessible by persons prepared to put on the mind-set of the originating discipline. Two incommensurate disciplines do, however, communicate through the medium of a proposed artifact: the physical location of a beam and column are unambiguous to both architects and engineers. Incommensurate concepts have to be stored in shared memory and can be interrelated but do not require translation languages.

Therefore, these "languages" cannot coalesce into a single common language, but will remain a diverse, disordered collection of overlapping common languages rather than a proper super-set of all.

4.3 2 2 The Quality of Shared Memory: Standards and Certification

While process-oriented suggestions to improve design practice leave the responsibility clearly in the hands of active designers, persistent shared memory as an important contribution to design raises the problem of "standard" or "certified" data. Engineering practice places great reliance on standards, handbooks and guidelines, and the organizational infrastructure which supports their production is extensive, complex and intricate. The production of standards is also extremely time-consuming.

Many standards represent collections of horizontal, multi-disciplinary information required to designate the quality of specific types of product, for example, the metallurgical and practical definitions for copper pipe for plumbing. Other standards apply more abstractly to less-immediately useful information but with a wider scope in use, for example, the allowed range in chemical composition of a stainless steel alloy. Modern industrial practice (e.g. QFD) also results in company-specific information enforcing the preferred modes for operating individual machines (for producing copper pipe perhaps).

Clearly the elaborate standardization mechanisms are inappropriate for ephemeral guidelines and yet we are recommending that such guidelines be stored more persistently, and that working practice be remembered for longer than has hitherto been the case. This raises the problem of distinguishing valuable shared memory from the rest and is also related to the indexing problem mentioned later. We must be careful that we do not replace the problem of the lack of relevant information with the problem of too much irrelevant information. However, even if the shared memory is directly applicable, how does a user know that it is right ? The personal authority of the originator, or the originating company even, may be meaningless to the user.

The example of the evolving community of materials property information suppliers may give a clue to the future, even though such information is atypical of engineering in general (Sargent, 1991). While some information for critical use is re-evaluated by each company, other data is re-evaluated on an industry-wide basis and published as handbooks (the military aerospace materials handbooks, for example). Some information companies re-sell originally public-domain data with value added in the structuring and quality control with attention to context while yet others merely survive by improving access and providing compendia. The establishment of a market in shared memory data for engineering design will be a slow but necessary business.

4.3.3 Implications for Design Environments

Currently popular research and development efforts such as integration frameworks, though intriguing from our perspective, are partially misleading -- they, by and large, still refer to creating consistent interfaces to and between the specialized tools of a particular profession and not for creating channels of communications or tools for collaboration between professions.

Modern research projects developing multiple-expert "AI" design systems do, however, address these issues of making multiple views work together on a common problem *without* requiring their integration or direct communication because they can communicate through the medium of the software representation of the artifact itself, just as architects and structural engineers can always fall back on the engineering drawings to see the implications of each other's reasoning even if they do not understand the reasoning itself. (e.g. Quadrel, 1991).

From our perspective we view these integrated design "frameworks", "workbenches" or "environments" as curiously limited to aiding activity rather than awareness. By activity we mean access to software tools which perform some processing of information, whereas we believe that awareness results more from perceiving context and is therefore related to information retrieval. This bias arises, we feel, from the prejudice that databases are dull but that software which "does something" is intrinsically more interesting.

4.3.4 Meaning and Widely-Applicable Techniques

We should not confuse widely applicable software tools as performing the task of creating horizontal shared-memory. For example, it is, arguably, the case that optimization techniques are universally applicable in design contexts: they can be used in marketing, each of the engineering sub-disciplines, manufacturing, sales, etc. It does not follow from this that the study and use of optimization techniques creates or facilitates shared memory since the substance of specific models, not the structure, is what determines context. The latter manipulation of these procedures can reasonably be understood by all those trained in optimization methods, the former -- the specific interpretation -- remains opaque without explicit translation, communication, and discussion; in short, without the deliberate creation of shared meaning. While the study, elaboration, dissemination of such widely usable techniques is essential, it is equally essential that we distinguish between what they accomplish from what they do not -- they do not form the currency of meaningful discourse let alone that of the creation of shared meaning.

4.3.5 Why Prescriptive Process Models are Sometimes Useful

Although we have derided prescriptive process models as representing an infeasible and unrealistic view of design, the fact remains that they are often useful. If our approach is to have any *useful* validity then we should be able to explain why useful techniques work, whatever the theoretical foundations they claim to be based upon.

Our experience with complex design problems is that the negotiations between parties exploring trade-offs are greatly aided if the context of the trade-off is clear whether a general policy is being enunciated or whether a specific fix is being proposed, i.e. in discussion across abstraction or resolution levels (Humphreys, as quoted by Hales, 1989). The appropriate context marker here is the level of abstraction and this is conveniently related to the "phase" of the design activity: initial specification, conceptual, embodiment or detailed These phases can be used managerially to structure meetings and document categories and so avoid inter-level misunderstandings.

Prescriptive-phase models of the design process create extra work because, in practice, designers are observed to move rapidly from very detailed to highly strategic issues and back again in the course of a minute or so. The representation of abstraction as phases of work with infrequent iteration is completely unrealistic, movement between levels is instead highly dynamic. If our supposition is correct, that prescriptive methodologies are useful because they enable effective sharing of meaning by making abstraction visible, then we would suggest that *explicit* representation of abstraction or intention by some notation that did not interfere with designers work would be even more effective. Currently this would not be easy.

4.4 Approaches to Creating Shared Memory

Here we outline a few current research projects which we feel serve as examples of the kind of work that explores the roles of shared memory in design. From our fundamental analysis of the matter of design we believe that universal methods do not exist and therefore that context must become an essential aid. These projects study how context is derived from shared memory and how these concepts can lead to clear improvements in the practice of design.

4.4.1 Design History Capture

A number of efforts in the recent past have focussed on capturing design history. Of special interest is the gIBIS system (Conklin and Bergman, 1990) which is designed to assist and capture design discussions and hence the rationale for the design. In actual experiments with using this system, it was found that the system was found useful despite initial doubts of its utility on the part of the designers. Several other systems which address aspects of design history rationale for constraint-based systems. Below, we describe two recent, and different, approaches to design history.

4.4.1.1 n-Dim: Shared Information Environment for Engineering Design

The n-Dim project, currently underway at EDRC, integrates a variety of efforts (including gIBIS) to capture design as it progresses, especially for large projects, (Subrahmanian, 1991). Its underlying hypotheses is that design engineers use a variety of models to represent and organize information and methods, and that design is inherently a social process where group cognitive views need support. Other important aspects are a task-level view for configuring and managing the design process and an information-management system that allows for defining and displaying a user's current design context. The approach is based on providing a uniform paradigm for structuring and hence modeling varied data objects: text, drawings, artifact models, and human and computational agents. The proposed n-Dim system is expected to evolve into a learning environment in which team members have increased abilities to notice, reflect and communicate in addition to the usual support for hypothesis formation, experiment, exploration and evaluation.

4.4.1.2 Engineering Design Notebook

The engineering design notebook (EDN) project at the Center for Design Research at Stanford is intended to provide a working environment in which an engineer can design productively for hours at a time. As well as supporting conceptual agility and processing of annotated drawings, it supplies organization and navigation facilities to construct a map of design activities indexed by project requirements (Leifer, 1991). The purpose is to test the hypothesis that design knowledge conservation (shared memory in our terms) is less expensive than re-invention.

No special user behavior is required for EDN to provide navigation assistance, but if the user chooses to use certain conventions when creating text-graphic items, then the utility of the system increases. An important component of EDN is the automatic summarizer which uses spatial parsing to organize sets of text-graphic pages into a hierarchy, though fully automatic generation of summaries is probably not desirable.

Clearly indexing and navigation of design knowledge is crucial to the effective use of all types of repository. While most historical data now is either pure text documents or graphical engineering drawings, we can expect that text-graphic information will grow in volume (especially as initial conceptual design is performed more frequently on the computer) and it presents unusual indexing problems which must be addressed if shared memory is to be truly useful.

4.4.2 Structuring On-Line Text to Support Sharing Information

Any attempt to record and organize information to create shared memory for design need to apply the best available techniques for information management. For an exemplary use of *human-selected* indexes of articles in technical domains to construct maps of changing shared memory see Callon et al. (1986). However, to tackle the problem of implementing shared memory and changing shared memory, *automated* indexing techniques are needed. Current automated technologies — string-based information retrieval (IR) — often fail to represent relevant information even in relatively small databases, and therefore new approaches need to be applied Moreover, the demands of structuring on-line text to support capturing and organizing shared information go beyond traditional IR because documents need to be characterized based on their conceptual content if it is to be useful in creating shared memory. If we expect our systems to perform such tasks, we must have the ability to capture and use the natural language of a text

Our hypothesis, in conformity with the CLARTT Project (Evans et aL, 1991), is that units of text greater than "strings between white space" or keywords are required to capture concepts and extend information management beyond current limitations. The role of selective natural language processing (NLP) is critical: it not only defines the units of information that are used in other processes but circumscribes the NLP task to insure that it is manageable and robust However, it is important to merge selective NLP with statistical, numerical, and heuristic techniques for text management

Just as important is the automatic construction of thesauri from very large text corpora using the results of selective NLP. Ideally these thesauri would capture the relevant and characteristic terminology of a domain, its interconnections and equivalence classes and aid in organizing the result into structures which are amenable to translation from one discipline or group to another. This would be a primary way of recording and organizing shared memory. However, to become really useful, these procedures must be able to handle corpora which are at a minimum in the gigabytes range. Not only will these corpora come from scanning texts on-line, but also, especially in the case of design projects, as it is produced in the design process. This means that these automated procedures must not only be able to handle very large corpora quickly, without glitches, and effectively, but they must also be able to update already produced thesauri when new textual data appears. The CLARTT Project is approaching the capability of being able to identify the relevant and characteristic terminology of a domain within the required parameters. There are three basic parts to the CLARTT approach to capturing and structuring shared information: 1) The utility of phrase-based indexing (Evans et al., 1991); 2) Automating the process of thesaurus discovery (Monarch et al., 1991); and 3) Using "latent semantics" to identify concept equivalence classes (Evans et al., 1991). All these are useful in shared memory implementation, though problems of identifying conceptual links will require new techniques (Monarch et al., 1991).

4.4.3 Representations in Al

The extensive research program in Artificial Intelligence in creating enabling technologies for knowledge sharing (Neches et al., 1991) is obviously of considerable importance. Investigating the creation and provision of access to extremely large knowledge bases, knowledge-based reasoning, case-based reasoning, and learning and knowledge acquisition, all contribute to the creation of shared memory. In a recent report by Reich et al. (1991), they suggest how learning could be integrated into a design system which specifies some of the issues and suggests some of the components involved in acquiring, maintaining and using what we call in this paper shared memory.

4.4.4 Engineering Concept Ontologies

An example of a project aimed more fundamentally at enabling communication between distinct disciplines is the recent development of a concept ontology at ALCOA Technical Center. There a novel method for systematizing the concepts behind the information stored in many disparate databases containing materials test data is being developed. The conceptual structure produced will be used as a basis for the development of software systems which integrate different types of engineers' easy access to the ALCOA "shared memory" of materials test data. The reason why the meanings of the concepts require explicit structuring are ambiguous vocabulary, multiple valid names and because similar information is obtained by different laboratories using different methods and different scientific conceptual structures. The complexity of the relationships between concepts required a new software technique ("CODE" produced by the Artificial Intelligence laboratory of the University of Ottawa) of unusual sophistication in its handling of defaults and inheritance (Skuce and Monarch, 1990).

Much of the structuring of concepts is a consequence of the physical fundamentals underlying materials properties and universally true facts relating properties to manufacturing processes. As a result, this ontology of the shared memory will be *generally* useful.

4.4.5 "Conventional" Concurrent Engineering Research

Current efforts focusing on new technologies, such as rapid prototyping, which allow multiple views from different disciplines to be quickly iterated, juxtaposed and integrated, and with wide applicability, need to continue. These clearly aid horizontal shared meaning formation but without attention paid to the persistence of this shared memory their major benefits may be less is hoped for.

Clearly, we have only provided a small sampling from the available literature that either directly, or with some modifications and re-interpretations, can be used in generating, maintaining, and propagating shared memory. In no way does this reflect upon the relevance or literature not explicitly covered which would require a separate paper.

5 Conclusions

We have argued that design research whose aim is to specify universally applicable methods is of dubious value. Rather the richness of the varied environments within which design occurs and its results used and evaluated should be matched with the capture of equally rich contextual information. We have also argued that design is almost always a collaborative act using perspectives and knowledge from several disciplines which, to be fruitful, requires that the parties involved create shared meanings of the design artifact. Shared memory, as an overarching theme, implements such contextual richness and makes shared meaning persistent. As the empirical evidence shows, an account of shared memory in design explains the successes and failures of design methods and artifacts. Equally significant, institutionalized shared memory would be important in improving the design process and therefore design outcomes.

In characterizing our concepts, we make the distinction between *vertical* and *horizontal* shared memory. Vertical shared memory embodies the collective knowledge of a specific discipline. Horizontal shared memory addresses sharing of meaning between individuals who are separated by disciplines, experience, space, time, organization, and culture. This distinction is not purely an academic one. It helps us understand the nature and potential role of specific design research. Perhaps of greater importance, it identifies the lacunae in current design research programs and identifies some of the challenges found by those attempting to fill such lacunae. In short, it helps in understanding design situations and identifying design research.

Finally, shared memory as a unifying theme for design practice and research is not a call to stop current approaches to design research. Rather it is a call to expand design research to include individual, organizational and social elements which help designers collaborate by creating shared meaning, and maintaining it as shared memory. In the spirit of Clark and Fujimoto, "comparative advantage will be in sensitive integration of hardware, software and humanware into an effective system for designing'*.

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