Vision

“The world we live in today is much more a man-made, or artificial world than it is a natural world.”
(Simon, 1969, pg 3.)

This statement remains as true today as when Simon first published it in The Sciences of the Artificial. Further, the complexity of the artifacts with which we interact is increasing rapidly. In the past, an artifact may have served one purpose; currently the trend is for multi-purpose devices. In the past, a single craftsman or a group of similarly skilled craftsmen may have created an artifact; currently, the trend is toward artifacts that involve many disciplines in their making. Correspondingly, educating designers is becoming both more difficult and more important. Simon’s claim that “the proper study of mankind is the science of design, not only as the professional component of a technical education, but as a core discipline for every liberally educated person” (Simon, 1969, pg. 83) not only remains true but, we argue, is increasing in importance. To address this multi-disciplinary complexity in the design of artifacts, we propose a Center for the Science of Design Learning.

Our vision is to develop a common and learnable understanding of design that can be applied across domains. Researchers and practitioners in the artificial sciences will share this understanding, in much the same way that researchers and practitioners in the natural sciences share a common definition of scientific method. This shared understanding will enable researchers and practitioners to more effectively collaborate to build complex artifacts and enable educators to better teach students to be more effective in solving design problems. A shared view of design will replace the diverse domain-specific and often philosophical views we hold now. As many problems—arguably, all problems in the artificial sciences—are design problems, developing systematic ways of teaching and learning design in the large will have wide applicability and practical impact.

We begin with the following observations.

First, the complexity of the artifacts that our society needs is increasing. Second, this increased complexity means that making successful artifacts requires the skills of diverse designers. Third, this complexity is compounded by the fact that this diverse group of designers cannot communicate effectively. Fourth, this failure to communicate can be traced to a failure to educate designers to deal with this complexity. Collectively, these observations lead us to conclude that we must restructure the way that those in the artificial sciences think about design and that we must change the way we educate designers. We expand on these observations below.

Increasing complexity often results from users’ expectations. The co-PIs of this proposal are writing these words using word processors on personal computers. These computers also are used to videoconference, maintain our separate calendars, and perform many other functions. This trend toward increased complexity is not so much being pushed by technology as pulled by system users. Collectively, we, as a society, see the consolidation of functions that we view as related as a positive move.

The design of a complex artifact, for example a passenger plane, a cruise ship, or a software application requires the skills of diverse designers—mechanical and electrical engineers (for the plane or ship) as well as programmers and software engineers, information designers, cognitive scientists. It is notoriously difficult for a diverse group of designers to communicate effectively. Each knows what is most important and each knows the best way to achieve that goal. Each often does not recognize the importance of the others’ goals nor understand the others’ methods. Rittel (1984) refers to this situation as a symmetry of ignorance: The knowledge of each participant is needed; yet what they have in common is that each is ignorant of some important aspect that someone else knows. This situation is further complicated in the design of complex artifacts in that even within a given discipline designers seldom share a common view of design.

This failure to communicate can be traced to a failure to educate designers to deal with this complexity. In The Sciences of the Artificial, Simon (1969, chapter 3) outlines a curriculum for the science of design, which is the core of the artificial sciences. This curriculum, however, has never been the mainstream approach used by our universities. This is not because professors refuse to teach this curriculum. Rather, we do not understand this science well enough to teach it. While design is central to a large fraction of human problem solving activities, especially in science and engineering, it is conspicuously absent from
formal education. Although we teach students how to design in particular domains and with particular and narrow definitions of design, we lack a science of design. The proposed effort addresses this core problem.

We must restructure the way that those in the artificial sciences think about design and we must change the way we educate designers. The distinction between artificial and natural sciences was noted by Simon in the Karl Taylor Compton Lectures in 1968. Our prehistoric ancestors engaged in artificial sciences long before they engaged in physical sciences. Figuring out how to arrange tree branches to make a shelter, or how to select the best seeds to sow for the next harvest, or how to preserve an ember so that fire could be restored at a later time, were all design tasks. The artificial science underlying these problems was understood long before the natural science was even contemplated. In application, the artificial sciences are ancient, not new. In terms of formal definition, however, the natural sciences are much better established.

For the past few centuries, the natural sciences have shared a common search to define a scientific method. Across domains, natural scientists agree on the proper way to investigate the properties of natural objects or phenomena. Such agreement is absent in the artificial sciences. Indeed, as Buchanan (2001) notes, there is even doubt that there is a significant body of design knowledge: “Despite a growing body of research and published results, there is uncertainty about the value of design research, the nature of design research, the institutional framework within which such research should be supported and evaluated, and who should conduct it. In short, there is uncertainty about whether there is such a thing as design knowledge that merits serious attention.”

The goal of education within the artificial sciences, such as computer science, information science, architecture, and engineering, is to create problem solvers. When we are successful as educators, we produce professionals who can synthesize solutions to open-ended or ambiguous problems. We produce designers.

Individually, we know what design is. Within a discipline, these definitions merge into a fuzzy pattern. Across disciplines, one definition seems to have little connection with another. However, there is no single, accepted, actionable view of what design is or how to educate people to do it.

We believe that there is a science of design that has yet to emerge from these various views. We further believe that understanding that science will enable the artificial sciences to better educate problem solvers. In this Catalyst project, we propose to organize the intellectual capital needed to define a Center for the Science of Design Learning.

Design and the Learning Sciences

In this section, we summarize two important relationships between design and the learning sciences that motivate our proposal. First, we argue that while design serves as a vehicle in constructionist and problem-based learning strategies, there the meta-strategies of design problem solving remain implicit. In its own right, design is an important kind of problem solving that is different from problem solving in the natural sciences. Second, we note the emerging area of design-based research in education, and observe the synergies and complementarities of this research direction with our goals to develop a shared understanding of the science of design.

Learning to design (vs. learning by design)

Many Learning Sciences researchers make design as an essential component of the successful learning environments they propose, develop and study (Kafai & Resnick, 1996; Kafai & Ching, in press; Harel, 1991; Edelson, Pea, and Gomez, 1995; Puntambekar, et al., 1998). Their approach has roots in Papert’s constructionist approach and in problem-based learning, building on pedagogical directions outlined earlier by Dewey, Montessori, and others. In Georgia Tech’s Learning by Design project, for example (see http://www.cc.gatech.edu/projects/lbd/whatis.html), K-12 students design projects that require them to acquire and apply knowledge and skills in science and mathematics. Design offers a practical vehicle for exercising knowledge and it also motivates acquiring this knowledge. One is much more likely to be interested in learning the principles of aerodynamics and structural engineering when one is trying to design a kite, and the kite design problem provides a meaningful and memorable context in which to store science and mathematics knowledge for later re-use. Design also provides a context in which to learn and practice collaboration skills.
We agree with the central role that these researchers have identified for design in learning processes, and therefore we propose a closer look at the structure of learning, knowing, and teaching, specifically in the context of design. However, in contrast to using design problems as a vehicle for learning principles of natural science and mathematics, we propose instead a central focus on learning to design. In our complementary approach, specific domain knowledge that comes into play is less important than strengthening learners’ abilities to solve design problems. Learning how to teach the skills and abilities associated with design—to reason with uncertainty, to handle open-ended problems, to balance multiple objectives, to satisfy— is crucially important if we are to educate successful design problem solvers, yet it is hardly addressed in most learning sciences research programs. In short, we believe that learning to design, an (the) essential skill in the artificial sciences, is as important as the currently predominant educational emphasis on acquiring knowledge and experience with specific natural science concepts.

Attaining our goal of understanding design and design problem solving will offer additional side benefits to other aspects of the learning sciences. For example, the program solicitation to which this proposal responds (Science of Learning Centers, NSF 03-573) identifies “visualization and representation of complex phenomena and multidimensional data” as an area of potential interest. Here we can learn from practicing designers. In order to cope with open-ended, ambiguous problems as well as high degrees of problem complexity and to deal with these problems on an intuitive as well as analytical level, designers develop and work with representations—such as sketches and diagrams—that encapsulate problems in ways that render them more easily workable. However, this expertise is for the most part tacit, and our modes of teaching and learning it are ad-hoc. How sketches and diagrams (and more generally, external and visual representations) support design reasoning is an active area of design research today, and an important topic in the science of design. Focusing on the artificial science perspective of learning to design will also shed light on the complementary focus of using design problems to teach natural science concepts.

**Design based research**

In a quite different way, design has also become a focus of research in the learning sciences, in what has come to be known as design based research. Collins’ influential article “Towards a Design Science of Education,” calls for a systematic approach (design theory) to designing experimental interventions in learning environments: “Technology provides us with powerful tools to try out different designs so that, instead of theories of education, we can begin to develop a science of education. However, it cannot be an analytic science, such as physics or psychology, but rather a design science, such as aeronautics or artificial intelligence. For example, in aeronautics the goal is to elucidate how different designs contribute to lift, drag, and maneuverability. Similarly, a design science of education must determine how different designs of learning environments contribute to learning, cooperation, and motivation... Our goals, then, will be (a) to construct a more systematic methodology for conducting design experiments, and (b) to develop a design theory that can guide implementation of future innovations.” (Collins, 1990)

A recent article by the Design-Based Research Collective echoes this need for a science of design that could apply to the learning sciences, “We hope for a scholarship of design in education that adopts common communicative approaches and links theory to local applied understandings, similar to research in architecture or engineering.” (Design-based Research Collective, 2003) We share the sentiment towards a science of design applied to learning. However (as we argue elsewhere in the proposal) we believe that progress in this direction will depend in part on elucidating an overarching science of design. We find that the science of design in architecture or engineering, however much more developed than in education, remains at a preliminary and precarious state. That is why we propose to address the science of learning design head-on.

**Current State of Knowledge**

*Design* is a term that brings many people together. Conferences, publications, and professional societies are formed to support the design research community. These, and other venues, are formed to support the design practitioner community. Collectively, we distinguish ourselves from others by the fact that we are designers. *Design* is a term that pushes people apart. Not everyone sees as design the new fashions in Milan’s boutiques. While some are impressed with the design of a new telephone, not everyone sees this as design. While we might collectively agree that interface design is different from interaction design is
different from user experience design, we will not agree on which is the real design task. Design unites us, but design divides us. As a community, we believe it is important. But, as a community, we lack a common definition of what it is. Many views and several classifications of design have been proposed.

In this section, we begin by providing a brief history of design. Then, we summarize some influential views of design and look at previous design taxonomies. However, unlike earlier efforts to classify design approaches, which are based primarily on the analysis of one or a few people, we want to find the classification that the global community of designers uses. To this end we use cocitation analysis to present a classification of design, based on the collective wisdom of the global design community. Our goal is to discover how the various views of design are related and to use this as a basis for building an overarching theory of design. This will provide us with a map of the schools of design and guide us in selecting the people and the ideas that must be included to form an effective Center for the Science of Design Learning.

A Brief History of Design Research

People have practiced design for millennia. As Mayall (1979) notes in Principles of Design, design, viewed as the creation of artifacts used to achieve some goal, traces back to the development of stone tools. However, formal descriptions of design methods, systematic approaches, theories of design, and categorizations of design have existed for only a few decades. Clearly, current design is much more complex than the design of stone tools. But, what has changed about the nature of design over this time?

Mayall (1979) notes that early design was driven by the belief that new is better and that technology is good. The designer was largely unaware of the end-users of products and did not consider unintended effects those products might have on individuals or society.

Until the 1950’s a traditional approach adequately served designers. Given a description of the desired characteristics of a design, by applying technical knowledge such as properties of materials and principles of mechanics, a designer could produce a design that met specifications. Moreover, designers worked as individuals or in small teams and therefore there was little demand for communicating design information or for making explicit the rules, assumptions, and knowledge that lay behind a specific design proposal. There was no apparent need for explicit design methods, and certainly no need for developing a science of design.

In the 1950’s, things begin to change. As technological growth accelerated, the focus shifted to the objective of “serving the convenience of man in industry as well as elsewhere” (Mayall, 1979, pg. 11). The demands of the salesman encouraged a new definition of design for products, which bought the focus back to the effects of the artifact on people and society, as well on the artifact itself. Society became aware of the limitations of simple mass-production methods, which focused on efficiencies in manufacture at the cost of variety, flexibility, maintenance, and other life-cycle concerns.

By the 1960’s, new technologies and new uses for systems had reached the point where a step-by-step approach to design was no longer feasible. Christopher Alexander (1964) acknowledges in Notes on the Synthesis of Form, that many design problems were reaching “insoluble levels of complexity.” Problems that were once somewhat simple in nature had somewhat simple solutions, but as technology, and materials, and social structures changed, and changed more and more rapidly, so did the nature and complexity of design problems. Soon it became evident that traditional design methods were inadequate. This brought about a discussion in the literature and a call for change in traditional approaches to design problems, an understanding of the nature of the rising complexity in problems facing designers, as well as a need to develop new methods to handle the enormous number of interacting variables in design problems. Among those calling for change in traditional approaches were Cross (1984), Jones (1970), Mayall (1979), Rittel (1984), and Simon (1969). At the same time the inadequacies of professional education and the need for a change in the academic curriculum became apparent (Schön, 1990; Simon, 1969).

Much of the literature that emerged from the recognition of this gap in traditional design methods derives from individual disciplines while striving for integrative insights. Alexander (1964) writes about the built environment, Nigel Cross (1984) about industrial design engineering, Horst Rittel (1984) about urban planning. Pelle Ehn (1989) approaches design with a focus on the user in cooperative design methods, while Rasmussen et al (1994) and Vicente (1999) focus on sociotechnical man-machine systems (e.g., nuclear power plants). Herbert Simon, in The Sciences of the Artificial, approaches design from the
perspective of economics but, as with all these design researchers, Simon’s discussion of design is not field specific; it applies across different domains.

By the 1980s design research was seen as a legitimate cross-disciplinary area of study with conferences and symposia (American Society of Mechanical Engineers (ASME) Design Theory and Methodology conferences, later the Mudd Design Workshops) and journals such as Design Studies, Research in Engineering Design, Computer Aided Design, as well as funding streams (Newsome, Spillers, & Finger, 1988). Several disciplines developed specific design methods, for example, Mead & Conway’s method for VLSI design (Conway, 1981), or Pahl & Beitz’s method for mechanical engineering design (Pahl & Beitz, 1996). NSF’s Engineering directorate established a program in Design and Manufacturing (now DMII) and with NSF support, Carnegie Mellon University established an Engineering Design Research Center. Recognizing the need to produce graduates with experience applying theoretical knowledge to real-world design problems, university engineering programs began to add design courses to curricula that had previously emphasized analysis. Accordingly, interest surged in methods of teaching and learning design. Example courses include Flowers’s 2.70 at MIT, ME 310 at Stanford and an interdisciplinary design course at George Tech (Kolodner et al 95). Perhaps due to the constraint of university departmental structures, and despite the growing realization that many design problems demand multi-disciplinary collaboration, much of this work remained within the boundaries of specific disciplines (Workshop on Teaching Design Skills, 1992; Design education Workshop, 1997). The growth of powerful personal and networked computing also led to new tools that render tractable more complex and computationally intense methods of design (e.g., Gero, 2002), as well computer support for collaborative work (CSCW), which in turn has provoked a demand for a better understanding of design processes.

These trends have continued into the current decade. With tremendous growth of the software industry design has become a priority of both the software engineering and human-computer interaction communities, which continue to search for systematic, learnable methods of design. The interest that these communities have shown in design methods from other domains (such as patterns language, ergonomics and human factors, participatory design) lend weight to our conviction that there is indeed a researchable science that underlies all design practice and would therefore inform design learning.

**Views of Design**

*A Sampling of Definitions*

No single concise definition of design is universally accepted. Table 1 presents a sampling of definitions of design proposed by various authors; we discuss these below. Although our list is not exhaustive, we have attempted to include a diverse set of frequently cited authors.

| Herbert A. Simon | …devising courses of action aimed at changing existing situations into preferred ones |
| J. Christopher Jones | …initiating change in man-made things |
| Christopher Alexander | …the process of inventing physical things which display new physical order, organization, form, in response to function |
| Horst Rittel | …structuring argumentation to solve “wicked” problems |
| Donald Schön | …a reflective conversation with the materials of a design situation |
| Pelle Ehn | …a democratic and participatory process |
| Jens Rasmussen/Kim Vicente | …creating complex sociotechnical systems that help workers adapt to the changing and uncertain demands of their job |

Table 1. A sampling of definitions of design

*The Sciences of the Artificial*, one of the most highly cited resources in the modern design literature (Simon, 1996) offers, in many respects, an encompassing view of design. Simon concludes that in large
part, “the proper study of mankind is the science of design, not only as the professional component of a technical education, but as a core discipline for every liberally educated person” (Simon, 1996, pg. 138).

Simon’s discussion of design concerns the construction of artifacts, that is, things people make to help them meet their goals. This discussion of artificial things lays the foundation for Simon’s argument that design, transforming a current situation into a preferred one, is at the “core of all professional training and the principal mark that distinguishes the professions from the sciences” (Simon, 1996, pg. 111).

Simon, an economist, argues against the once widely accepted view of a designer as rational decision maker looking for optimal solutions, proposing instead that humans are actually bounded by their cognitive capabilities and other constraints. Referring to these constraints as bounded rationality, he argues that given all the alternative possibilities, decision-makers set feasible goals and use decision methods that seek good, or satisfactory solutions, rather than optimal ones as rationality suggests. Simon refers to this as satisficing.

In Cognitive Work Analysis Kim Vicente (1999) approaches the design of work support system using 30 years of Jen Rasmussen's research. The social concerns associated with the Union movement of the 1970's, “safety, productivity, and worker health”, are an important component to this approach. Vicente discusses the design of work support systems that match workers' performance criteria and leave them space to learn and develop their expertise (pg. xi). Primarily concerned with task analysis, Cognitive Work Analysis advocates a holistic approach to design. The design of information systems should be based on an explicit analysis of work and used as a means to “derive implications for design” (pg. 13). Designers can use this analysis to create tools that help workers adapt to unexpected situations as well as the changing demands of their jobs and the job environment.

Cognitive Work Analysis is described as a formative model for design. This approach describes the requirements for a system to behave in a new desired way. It identifies requirements — both technological and organizational—that must be satisfied if a device will support work effectively (pg. 110). In contrast, a descriptive model focuses on simply portraying work; while a normative model expresses how a system should behave. An important goal of the formative approach is to “design a future work practice rather than to design the details of the device” (pg. 112).

Christopher Alexander in Notes on the Synthesis of Form (Alexander, 1964) shares with Simon, Rasmussen and Vicente a focus on the environment. He addresses the problem of design complexity by focusing upon the problem in its potential environment of use. Alexander first defines the ultimate object of design as form. Every design problem begins with an effort to achieve fitness between two entities, the form of the artifact to be designed and its context (pg. 15). The form is the solution to the problem; the context defines the problem. Yet design isn't simply about making form, but the ensemble of form and its context. A necessary property of this is good fit. Alexander argues that we don't recognize good fit, but rather, we recognize what doesn't fit. For example, it is almost impossible to name the characteristics of a house that fits into its context but simple to name the specific aspects of a house that does not.

Alexander also discusses the underlying structural correspondence between a pattern and the process of designing a physical form that answers a given problem. He proposes a process of identifying patterns in the problem and then decomposing those pieces and units of the problem. Alexander concludes that every form can be understood as a structure of its components. He sees each component with a dual nature, first as a unit and second as a pattern. “Its nature as a unit makes it distinct from its surroundings, while its nature as a pattern specifies the arrangement of its own component units. ...as the program clarifies the component sources of the forms structure, so its realization in parallel will begin to define the form’s physical components and their hierarchical organization.” (pg. 131). By looking at the problem in its context and then breaking the problem components into smaller components Alexander later goes on to identify a pattern language for building. (see Alexander, 1977).

Horst Rittel, like Simon, notes that design problems are different from problems in the natural sciences. He refers to problems in natural science as tame or benign because the end mission is clear. Problems in natural science have a finishing point; one can tell when a solution has been found. Rittel terms problems in the artificial sciences as wicked problems, because they lack those two clarifying traits.

Some criteria distinguish wicked problems from other kinds of problems. Rittel states that the information needed to “understand the problem depends upon one's idea for solving it”. In other words, “the process of formulating the problem and of conceiving a solution (or re-solution) are identical...” Traditional rational
problem-solving models do not work for design and Rittel believes that wicked problems should be approached using a model of planning as an argumentative process, in which the “image of the problem and the solution emerge gradually... as a product of unremitting judgment which has also been subjected to critical argument” (Rittel, 1984, pg. 138).

Like Simon’s Sciences of the Artificial, Donald Schön’s (1983) The Reflective Practitioner, highly cited by writers in the design community, is at a theoretical level. It presents a theory of how professionals learn. Unlike Simon, however, Schön discusses several distinct domains of application.

The Reflective Practitioner is based upon Schön’s conviction that universities are not devoted to “the production and distribution of fundamental knowledge in general, but in a particular epistemology that fosters selective inattention to practical competence and professional artistry” (preface). This claim forms the foundation for his discussion of how professionals think in action when situations arise that are a surprise or do not fit a known model or method for finding a solution. The everyday work of a professional is in the “tacit knowing-in-action” (pg. 49). It is how we do things somewhat automatically without consciously thinking about them. Schön distinguishes reflection-in-action as an aspect of professional practice that comes about when a practitioner encounters an unexpected, surprising or unknown situation for which their knowledge base has no frame. As the practitioner tries to make sense of this situation, a reflection takes place upon the “understandings, which have been implicit in his action”. This artful manner of inquiry by which practitioners sometimes deal with uncertainty Schön calls “a reflective conversation with the situation” (pg. 268).

Schön touches upon reflection-in-action as an elemental part of the design process. The reflective conversation takes place when the designer reflects-in-action on the “construction of the problem, their strategies of action or the model of the phenomena which were implicit in his moves” (Schön, 1983, pg. 79). Design and teaching reflection-in-action is discussed in more detail in Educating the Reflective Practitioner Schön, 1990).

In Work-oriented Design of Computer Artifacts, Pelle Ehn (1989) notes that the design of systems to function in complex situations, such as large technology-oriented companies or interdisciplinary design domains, requires a deep understanding not only of the application domain, but also of the practice of the people who will use the systems. Designers do not start with this understanding, but must work to attain it. A central theme of Ehn’s approach to design is that users and developers must work closely together. Ehn’s approach is sometimes called the Scandinavian approach to design, or participatory design, as well as work-oriented design. Communication among all those involved in a design effort is facilitated by a language of doing that helps to overcome the lack of a common vocabulary among users and designers.

Taxonomies of Design

The natural division of design problems along different disciplines, and the very apparent dissimilarities of the end products each field works with, would make it easy to divide the literature by discipline: engineering, architecture, urban planning, information systems, sociotechnical systems, etc. Certainly, designing a house is nothing like designing a nuclear power plant, nor is designing an information system anything like planning a city or designing a servo system for controlling a conveyor motor via a delaying mechanism (Glegg, 1969). But, in a larger sense, isn’t design still design regardless of the application domain? Therefore we look at how design researchers have categorized design, independent of domain.

In Design Methods, Jones (1970) reviews ancient and modern design methods from craft evolution and design-by-drawing to logical, scientific and creative techniques. By describing different methods and discussing their nature and subsequently classifying them, Jones attempts to help designers and planners find a method to suit a particular design activity.

He divides design methods into three perspectives. The first is creativity, or the black box, which implies that the valuable part of the design process goes on inside the designer’s head and partially out of reach of the designer’s conscious control. The next perspective is the rational or glass box view, in which design methods are based on rational assumptions. The process is assumed to be completely explicable and designers have full knowledge of what they are doing and why they are doing it. The third perspective sees the designer as a self organizing system. The self-organizing system carries out the search for a suitable design while also controlling and evaluating the parameters of the search (Jones, 1970, pg. 55). This model
of self-plus-situation enables each member of a design team to understand the degree to which the search actions do or do not produce an acceptable balance between variables.

Dym (1994), Candy & Edmonds (1995, 1996), and others have proposed similar taxonomies. In summarizing work in engineering design, Dym (1994) classifies design problems as creative, variant, or routine. Creative design involves the creation of a new product or invention and is initially characterized by a lack of domain knowledge. Variant design typically involves revisions of an existing design. While the designer typically has the requisite domain knowledge, there is challenge in how to fit the modified components into the overall design. In routine design the designer has all the knowledge needed to solve the problem. Candy & Edmonds (1995, 1996) propose a model for understanding how designers work, based on observing designers in a variety of domains. This process model describes design activities as involving (1) Exploration and Evaluation, (2) Generation and Invention, and (3) consideration of Constraints and Requirements. These three phases parallel the taxonomies of Jones and Dym.

These taxonomies have a great deal of intuitive appeal and, we expect most members of the design community, including both practitioners and theorists, would agree that these taxonomies make sense. Although these taxonomies give us ways to think about design, they stop short of describing how one design method might relate to another or how one method might be better suited than another for a given problem. The most significant shortcoming of such taxonomies is that they represent the thoughts of a few people. They do not capture the collective wisdom of the larger design research community. How we might do this is the topic of the next section.

Collective Categorization of Design

Bibliometrics is the quantitative study of literatures as they are represented in bibliographies, such as the reference lists of journal articles (White and McCain, 1989)). In scholarly communication the references cited in the bibliography allow readers to locate the source of the materials and it is assumed that these cited works have a subject or other connection with the citing article.

We performed an author cocitation analysis on the literature of design research (Atwood, McCain & Williams, 2002). For our particular interest in design methodologies across different disciplines, author cocitation analysis allows us to visualize the interconnectedness of authors writing about design across many different fields such as engineering, architecture, urban planning and information systems, as recognized by hundreds if not thousands of commentators. ACA reveals unseen structures embedded in the literature. For reviewers unfamiliar with this method we summarize it below.

**Author Cocitation Analysis**

In the 1970s, Henry Small and Belver Griffith introduced the notion of document cocitation analysis—the study of changing patterns of co-occurrence of highly cited documents in reference lists—as a way to visualize structure and change in scientific fields (Small, 1973, Small & Griffith, 1974). Documents frequently cocited have a subject relationship; clusters of cocited documents represent research specialties. Author cocitation analysis (ACA) is a related approach that focuses on cited author’s oeuvres rather than individual cited documents (White, 1986; White, 1990; McCain, 1990). The frequent cocitation of two authors’ names may be evidence of the similarity of their work, or of citing authors’ recognition of their opposing views on a topic of joint interest.

**Establishing a set of authors**

The first step in ACA is to establish a set of authors to be searched as cited references. The authors can be chosen for a variety of different reasons, but the ultimate goal is to develop a list that is varied and representative of the breadth of the domain of interest. This list was compiled through discussion with domain experts and by looking at published literature on design methodologies in different disciplines. The initial list of authors expanded to include 54 authors from Software Engineering, Urban Planning, Architecture, Engineering, User Interface Design, and Cooperative Design as well as other subject areas. We validated this list by presenting it to other frequently cited writers on design who confirmed that the collection of names was representative of different views in the design literature. Twenty authors were eliminated in preliminary analyses—authors with low citation and cocitation counts and a set of authors representing Software Engineering design methodologies. (Software Engineering authors were found to be
essentially unconnected with the remainder of the author set. We return to this topic later, in the Research and Education Activities section.

**Cocitation Analysis**

The raw cocitation counts for the remaining 34 names were retrieved from the citation databases published by the Institute for Scientific Information and accessed via the Dialog service for the years 1990 – 2000; this portion of the database includes more than 10 million source articles and 230 million cited references (Web of Science documentation, 2001). We searched across all three ISI databases, SciSearch, Social SciSearch, and Arts & HumanitiesSearch, eliminated duplicate sources, and compiled cocitation counts for each unique pair of authors’ names as a matrix. The numbers in the cells count all papers that cocite that pair of authors.

**Data Analyses**

We inserted the cocitation values for each author pair into the cocitation matrix and then converted the raw cocitation counts to a matrix of Pearson correlation coefficients (Pearson’s r). In this proximity matrix of inter-author similarities, the higher the value of the cell representing the intersection of Author A and Author B, the more similar the authors. We performed a cluster analysis to identify groups of authors with similar cocitation patterns. We also performed a multidimensional scaling procedure to produce a two-dimensional visualization of the similarities data as a whole.

**Discussion**

Figure 1a shows the results of the hierarchical cluster analysis as a dendrogram. All hierarchical agglomerative cluster analyses begin with a set of individual objects and, step by step, join objects and clusters until a single cluster is achieved. The dendrogram shows the cluster structure, beginning with 34 individual authors on the left and ending with a single cluster on the right. Two authors are joined, an author is added to a cluster, or two clusters are merged, based on the distance criterion. The horizontal distance traveled between mergings indicates the integration or isolation of the authors or clusters. Authors clustered together generally have an identifiable link based on the subject matter of their writings, their geographic or institutional affiliation, school of thought, or other intellectual connection. Inspection suggests that a seven-cluster solution is a good representation of the cocited author structure of this data set.

![Cluster analysis dendrogram](image)

![Author cocitation map](image)

Figure 1 (a) Cluster analysis dendrogram; (b) Author cocitation map.
Figure 1b shows these results as a two-dimensional MDS map, enhanced by the clusters identified in Figure 1a. Multidimensional scaling attempts to represent the entire data matrix as a two (or higher) dimensional display. Points, representing authors, are positioned so as to approximate their similarities in the original matrix. Authors with many links to others tend to be placed near the center of the map—the compass rose. Authors with fewer links appear closer to the periphery and authors with links to others are generally placed close together (within the limits of the dimensional solution chosen). Closely positioned authors in different clusters have important secondary links and may be considered boundary spanners. The overall arrangement of author clusters along axes can point to trends in scholarly activity, strong contrasts in theoretical position or other domain-specific themes.

What do the figures above tell us? Collectively, the design research community sees seven clusters of authors and, correspondingly, seven clusters of ideas within the global topic of design. Before describing these clusters, however, we want to point out some interesting aspects of the map shown in Figure 1b.

**There is no central focus that holds the design research community together.** The compass rose in Figure 1b is at the center of the design research community. An author here would share similarities with many other authors in this analysis. This author would be the center of the design community. But, no author appears here. Closest to this center are Carroll, Fischer, Gruber, and Lee. But their grouping with this center is not as tight as other groupings in Figure 1b. We conclude that design is not one community with diverse interests, but several sub-communities grouped under a common theme.

**Some views of design focus strongly on people, others do not.** The right half of Figure 1b seems different than the left half. On the left, we have clusters for participatory design, user-centered design, and cognitive engineering. On the right, we have clusters for design complexity, design taxonomists, design rationale, and design theorists. The relationships among authors on the left (people) side of the map are much closer, compared to their relations with authors on the right, which focus more on the philosophy of design.

**Some design researchers build theory, others build systems.** Moving from the bottom of Figure 1b to the top, there seems to be a shift from using existing theory toward building useful systems. The bottom-most point in this figure represents Simon. His writings on design are arguably the most theoretical and the farthest removed from application of all those in this analysis set. Also near the bottom is the cognitive engineering cluster, a cluster largely focused on applying cognitive theory to system development and as a result enriching cognitive theory. Toward the top of Figure 1b is the participatory design cluster. Motivated by a belief that design should be a participatory and democratic process, this cluster is driven more by the pragmatic concerns of building successful systems than by existing theories. This is not to say, of course, that their results will not influence theory, only that their actions are not motivated by theory. Similarly, the top portion of the design rationale cluster contains authors who work on building design rationale support systems.

**The seven clusters.** Next we briefly describe the clusters represented in Figures 2a and 2b and comment on the relations between clusters.

*Participatory design.* The cluster in the upper left of Figure 1b includes Kyng, Greenbaum, Ehn, and Bodker. This cluster is the strongest advocate for involving users in the design process. Cooperative design and participatory design emphasize the need for designers and users to work actively together. In addition to the focus on participation, this cluster sees design in use, system tailoring, and work-oriented design as essential. Work environments are not static and systems must be designed to accommodate change. As Figure 1b indicates, Grudin, although more tightly grouped in another cluster, also gravitates toward this focus on people.

*User-centered design.* The middle cluster on the left side of Figure 1b includes Grudin, Marchioni, Nielsen, Gould, Shneiderman, Carroll, and Card. All argued for a shift in perspective on the part of designers. For example, Grudin (1989) argues that the goal of user interface consistency directs attention away from users and their tasks; Gould and Lewis (1985) encourage designers to shift away from traditional methods and focus on empirical measurement, iterative design, and an early focus on users. The work by Card and his colleagues on GOMS (Card, Moran, and Newell, 1983) calls for a focus on the cognitive properties of users. What holds this cluster together is a balanced focus on users and their tasks.
While the cluster above focuses primarily on people and the one below focuses primarily on their work environment, this cluster balances between the two.

**Cognitive engineering.** The bottom cluster on the left side of Figure 1b includes Wickens, Norman, Reason, Hollnagel, Rasmussen, Vicente, and Woods. What brings this cluster together is a strong focus on the cognitive properties and on how these properties determine how people interact with systems in some environment. Norman’s *Design of Everyday Things* (1988) and Vicente’s *Cognitive Work Analysis* (1999) are good examples of this focus.

**Design rationale.** The top-most cluster on the right side of Figure 1b includes Conklin, McCall, Fischer, Klein, Gruber, and Lee. It is important to note that Rittel, who is included in a separate cluster, is also close to the center of this cluster. Rittel viewed design as a *process of argumentation* and the authors in this cluster all focus on the communication that supports design. Many of the representative works in this cluster focus on *design rationale*, a concept initiated by Rittel’s work on Issue Based Information Systems (IBIS) (Kunz and Rittel, 1970). Other works, such as Fischer’s *domain-oriented design environments* focus on overcoming the *symmetry of ignorance* problem that Rittel (1984) sees as preventing communication between designers and users. The groupings in this cluster are not as tight as in other clusters, reflecting the many views that exist within the *design rationale* sub-community.

**Design complexity.** This cluster that includes Rittel, Alexander, and Argyris locks together the remaining three clusters on the right side of Figure 1b. Argyris’ *action science* (Argyris, Putnam, and Smith, 1985) Alexander’s *patterns* (1977), and Rittel’s *argumentation* (1984) are all ways to help designers to manage the complexity of a design problem. The three remaining clusters on the right side see complexity as a significant problem and look to this cluster for ways to reduce it.

**Design taxonomists.** The cluster containing Jones, Ullman, and Cross has in common the collection of different views into a single source. These authors are cited not only for their own ideas but also for their collections of the ideas of others. Interestingly, this cluster links more closely with the clusters on the right of Figure 1b than with those on the left. Perhaps, it is more appropriate for taxonomists to deal with the *theoretical* right hand side of Figure 1b than with the *people* oriented left hand side.

**Design theorists.** The cluster containing Schön, Simon, March and Williamson seems to have in common that these authors approach design and designers from a theoretical level and do not deal extensively with concrete applications of those theories. This cluster is closely associated with the *theoretical* right hand side of Figure 1b, but, as a whole, is reasonably close to the center of the map.

**Categorization of Design Wrap-up**

As we stated in the introduction, one goal is to construct an integrative theory of design. We know that when members of the design community write about design, they, collectively, see seven major topics. There are distinct sub-communities rather than a single community with diverse interests. But, this analysis was limited to the published literature on design, limited to the 1990-2000 timeframe, excluded the software engineering community and communities of practice, such as fashion design or graphic design, that tend not to contribute to the published literature. In summary, we have made significant progress, but we have not yet reached this goal. Additional work is addressed in this proposal and is summarized in the section below.

**Research and Education Activities**

To establish the organizational and intellectual capital needed to define a Center for the Science of Design Learning, this Catalyst project consists of four primary activities – (1) mapping the design community, (2) bringing that community together, (3) conducting limited research and education pilot programs, and (4) designing the Center for the Science of Design Learning. Clearly, it is premature to speculate on what form this intellectual capital might take. As there is no agreed upon definition of what constitutes the design community, we must leave open the possibility that understanding that community will lead to discoveries that will significantly shape later project activities. As a starting point, we believe that the activities summarized below are most appropriate.
Mapping the Design Community

During the initial phase of this project, we will substantively extend the analysis described in the previous section. In addition to software engineering, we plan to include work on artificial intelligence and design (e.g., Gero, 2002), early design methods (e.g., Spillers, 1974), and design activity theorists (e.g., Christiaans, Cross and Dorst, 1997). We expect to identify additional sources as this work proceeds.

There are other things that we would like to know; some of our current questions are summarized below.

*How do the various theories of design relate to a given problem?* It is likely that one method would work better for some problems than for others. We do not yet have a taxonomy of design problems that points to design methods. We plan to begin this by applying the analysis described in this proposal to the literature that describes applications of methods to problems.

*How does the view that we present based on 1990-2000 writings match that of previous decades or with the past few years?* We expect that it does not and we plan to trace the evolution of design topics by applying this analysis to earlier decades.

*Who have we left out of this analysis?* As we noted earlier, software design was excluded from this analysis because it was weakly linked to the rest of the literature used here. In effect, software design has its own literature. As our analysis was based on published literature, we have also omitted any design community that does not publish.

This is a significant point. Design researchers and design practitioners all work in the artificial sciences and all are part of the design community. Our current analysis, however, is strongly biased toward the design research sub-community and, since they tend not to publish archival papers, design practitioners were largely overlooked. This is a flaw in method, not a flaw in intent. We recognize the importance of including the design practitioner community. Cocitation analysis was designed to work with archival publications. In this task, we will focus on finding ways to extend this analysis to include ideas and relationships in the broader design community.

Bringing Together the Design Community

At present, there are multiple forums, rather than a single forum, in which designers meet to exchange ideas. During the second year of this project, we propose to host a single forum that includes representatives of the entire design community. We must therefore identify appropriate members of that larger community. During the initial year of this project, we will propose and lead workshops at a range of conferences. Candidate conferences include AERA (American Educational Research Association), Asia Design conference, ASME Design Theory and Methods, CHI (ACM Conference on Human Factors in Computing), DIS (ACM Designing Interactive Systems), INTERACT, UIST (User Interface Software and Technology) CSCW (ACM Computer Supported Cooperative Work), APCHI (Asia Pacific Conference on Computers and Human Interaction), DCC (Design Computation and Cognition), DUX (Design of User Experience), CSCL (Computer Supported Collaborative Learning), ICLS (International Conference on the Learning Sciences); and the Harvey Mudd Design Workshops. As we proceed we expect to identify additional target conferences. A workshop to be held in the second project year will aim to shape the Center for the Science of Design Learning. An additional possible outcome is a publication, or series of publications, on the nature of design.

Pilot Education and Research Initiatives

To provide materials for the workshops we propose to lead and for the workshop to be held in the second year, as well as to help us and the broader design community, move toward an integrative view of design, we propose to undertake a limited number of pilot initiatives in research and education. All these initiatives are either extensions of our current projects or build on existing collaborations. As we believe it important to address the similarities in design across different design domains, we must include a broad sample of domains. Ideally, we would study design in many domains and contexts. For example, we would like to consider information systems, architecture, fashion design, community design, and undergraduate education. However, because the level of effort supported by the Science of Learning Centers Catalyst program is limited, we will restrict our initiatives to a few domains. As appropriate, some of these studies will be observational or ethnographic, others will involve comparing design methods, and others will involve developing and evaluating design methods. Our intent is to compare different
approaches to design, applied to a common domain, and to use the results as discussion materials for workshops.

Information systems are of interest because the artifacts produced, such as software, are primarily logical rather than physical and because there is a premium on reuse. We have ready access to student projects and other research projects in this domain, but will also seek to involve one or more of our corporate collaborators. This is a convenient and likely worthwhile initial target.

For our second domain, we want a domain where the artifacts produced are decidedly physical, but whose form results from deliberations among many alternatives and criteria. We will look at architectural design. As with information systems, there is an established research base on which to build this effort. We will build on Mark Gross’ Design Machine Group at the University of Washington.

For our third domain, we want a domain where design has not been extensively investigated and for which there is not an established community of practice, but for which there is increasing interest and a growing interdisciplinary research community. We will study neighborhood design. This builds on a current joint effort with the Drexel University College of Nursing in which we are facilitating members of an inner-city environment to define the physical and logical aspects of their community.

Shaping the Center for the Science of Design Learning

Initially, the institutions represented in this project will be working toward building a Virtual Center for the Science of Design Learning. The virtual center will share resources and leverage expertise to do more than any one institution could accomplish on its own. We will begin with the institutions represented in this proposal. As we progress, other institutions will join this virtual center. We anticipate that the workshop to be held in the second year will shape the plans to add a physical center or centers and will result in a corresponding Science of Learning Center proposal in the summer of 2005.

Intellectual Merit of the Proposed Activity

The intellectual mission of the modern research university is founded on an emphasis on inquiry in the natural sciences that dates at least to Galileo and Newton. As engineering, computer and information science, industrial, architectural, and software design and other artificial sciences (all those fields of inquiry that deal with the human-made world) grew in importance during the twentieth century, these disciplines established their place alongside the natural sciences. Whereas the natural sciences developed scientific method as a common means of inquiry, for the artificial sciences and their related professions design is the paramount skill. Although each discipline has specific and local understandings of design, we have yet to formulate a more general and global understanding of what some, including Nobel prize-winning economist Herbert Simon, have called the Science of Design. Without this science, teaching and learning in the artificial sciences remains particular, subjective, and ultimately ad-hoc. The Center for the Science of Design Learning aims to formulate this science of design and the methods and systems for teaching and learning design that go with it.

Broader Impacts

No human activity is more central to our lives and more pervasive in its effects than design. Every artifact we use, from brooms to bicycles, from cell phones to software, results from a process of design. Yet our understanding of how to design and our methods of teaching and learning design remain piecemeal, and ad-hoc. This results often in poorly designed artifacts, from inscrutable video players to frustrating software to inefficient social service infrastructures. Poor design is at best annoying, often costly; occasionally it is catastrophic, for example the February 2003 loss of the space shuttle Columbia. By establishing a fundamental science of design, the broader impact of the Center for the Science of Design Learning is a more reliable means of teaching practitioners in all fields of design, as well as methods and computer-aided tools based on a more thorough and systematic understanding of design. In turn this will lead to better design of the things and systems that we encounter in our daily lives.
Management Plan

Why this Team?
The Principal Investigators for this proposed project span three institutions and several complementary research disciplines. We are experienced in cross-disciplinary activities and are fully committed to interdisciplinary research. Collectively, we belong to or have strong collaborations with, each of the seven clusters of design discussed above. We believe that we have built an effective collaboration capable of achieving uniquely valuable results that will have impact on education, industry, and research.

Overall Management Schedule and Project Coordination
The management structure will consist of a manager and an advisory group. Michael Atwood of Drexel University will be the manager. The advisory group will, for this Catalyst project only, consist of the co-PIs and the faculty associated with the project. As we progress with this project, we expect that others will also serve in an advisory role and that by the end of this Catalyst project we will form an appropriate advisory group for a Center for the Science of Design Learning. The advisory group will set overall direction and policy via regular meetings convened by the PI.

Communications among the advisory group (phone, email, and Internet) will be supplemented by regularly scheduled interactions including videoconferences, teleconferences, and project meetings. Teleconferences and videoconferences including representatives from each institution will be the most frequently used approach to reviewing overall progress and coordinating project activities. These will occur approximately monthly, scheduled as necessary for specific issues.

We plan face-to-face project coordination meetings to address both technical and management issues at approximately six-month intervals. These meetings will alternate locations and may be held in conjunction with conferences or other activities.

At the beginning of the grant period the advisory group will determine policies of use and of intellectual property rights. These policies will be formalized in writing and changing them will require revision by the advisory group. The PI will be responsible for implementing the policies and monitoring their success.

The advisory board will work to ensure that students supported by this effort will benefit from interaction with all participants in this study, not only those from their home institution.

Research results will be disseminated through technical reports, Web pages, and publications in peer-reviewed conferences and archival journals.

Evaluation and Assessment
Design is a process in which knowledge and artifacts co-evolve. As Rittel (1972) reminded us "understanding the problem is identical to solving it". Evaluation, therefore, is not an activity that occurs at the end of a development process, but one that is a continuous activity throughout development.

An important activity in a program in which knowledge and artifacts will co-evolve is the evaluation that guides this evolution. Consequently, we consider evaluation to be an essential activity of this program, rather than an activity that happens last. The workshops that this project will lead provide an excellent and frequent source for feedback and evaluation from the population we plan to serve. The outcomes of the workshop we will hold in the second year also provide an in-depth formative evaluation of this work. Summative evaluations will occur at workshops held after this second year workshop.

Facilities, Equipment, and other Resources
This Catalyst project does not require facilities, equipment, or resources beyond those the co-PIs and their institutions currently possess. In addition to the project co-PIs and advisory board, the project will draw on the wealth of experience in engineering design education at the Center for Engineering Learning and Teaching (CELT) at the University of Washington. Similarly, at Drexel we plan to consult with faculty who are involved with the National Design Repository project and the CoDesign Studio. Also at Drexel, Prof. Gerry Stahl will serve as a valued resource for expertise in the learning sciences.
Sustainability

Defining the Science of Design Learning Center is a design activity and sustainability is one of the criteria which we must meet. Our design for creating this Center will include a design for sustainability.

Results of Prior NSF Support (Atwood)


Information is useless unless it can be utilized. This project is creating, identifying and testing new methods for information retrieval in the National Science Digital Library. An initial prototype was used for two terms in an undergraduate computer science course. A revised prototype, called Ask Alice, underwent usability testing prior to classroom use in early 2002. The current focus is on capturing and using the context in which a question is asked to better formulate an answer.

Publications:


Results of Prior NSF Support (Gross)

“Back of an Envelope an Architecture for Knowledge Based Design Environments” IIS-96-19856 and IIS-00-96138 sought to explore and demonstrate a recognition-based system architecture for freehand drawing as an interface to design application programs. Based on empirical studies of designers, the project developed a software framework and working prototype (“back of an envelope”) that recognizes freehand-drawn diagrams in 2-D (e.g., architectural diagrams) and links them with relevant domain knowledge (for example, simulated behavior).

Selected publications (see http://dmg.caup.washington.edu for more)


DMII-93-13186 “Avoiding Conflicts in Subsystem Layout in Architectural Design: a constraint based approach” to demonstrate the application of constraint based CAD in systematizing the layout of building components (1993-1995). This work resulted in the “Construction Kit Builder” software, described in the paper “Why can’t CAD be more like Lego?” (J. Automation in Construction 5:285-300. 1996). In the software, a designer creates and then works with two-dimensional CAD models in which the components have built-in assembly and placement rules.