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DTM AT 25: ESSAYS ON THEMES AND FUTURE DIRECTIONS

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ABSTRACT

This paper describes the development and evolution of research themes in the Design Theory and Methodology (DTM) conference. Essays containing reflections on the history of DTM,

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supported by an analysis of session titles and papers winning the "best paper award", describe the development of the research themes. A second set of essays describes the evolution of several key research themes. Two broad trends in research themes are evident, with a third one emerging. The topics of the papers in the first decade or so reflect an underlying aim to apply artificial intelligence toward developing systems that could 'design'. To do so required understanding how human designers behave, formalizing design processes so that they could be computed, and formalizing representations of design knowledge. The themes in the first DTM conference and the recollections of the DTM founders reflect this underlying aim. The second decade of DTM saw the emergence of product development as an underlying concern and included a growth in a systems view of design. More recently, there appears to be a trend toward design-led innovation, which entails both executing the design process more efficiently and understanding the characteristics of market-leading designs so as to produce engineered products and systems of exceptional levels of quality and customer satisfaction.

1 Introduction

It is no longer the case that design researchers need to justify the need for 'design research'. This situation was, of course, not true around the time of the establishment of the DTM conference series 25 years ago as recollections by David G. Ullman (Section 2 on page 2) affirm. At a time when 'design research' tended to be regarded as research about the behavioral and structural specification for a specific type or class of mechanical device, Finger and Dixon, in reviewing the state of mechanical engineering design research, identified the broad scope of 'design research' [1, 2]. They identified six areas of design research: *1*) descriptive models of design; *2*) prescriptive models of design, such as the Formal Design Theory [3, 4] further discussed in this paper in Section 5 on page 6; *3*) computer-based models of design processes; *4*) design representations, such as functional representations discussed in this paper in Section 7 on page 9; *5*) design analysis including the analysis of the affordance of designs as discussed in Section 6 on page 8; and *6*) design for the lifecycle. The significance and importance to industry and to other disciplines of design research as understood by the DTM community is now firmly entrenched, as evidenced by National Science Foundation (NSF) programs such as the former Science of Design (SoD) program and the current Failure-Resistant Systems (FRS) program and the promulgation of the concept of "design thinking" into the strategic management literature.

The aim of this article is to provide a meta-review of the research published in the DTM conference series. The review consists of two parts. In the first part, reflective papers by David G. Ullman (Section 2) and David Brown (Section 3) provide viewpoints on the original underlying aims of the DTM conference series and community. It is evident from their reflections, and confirmed by Clive Dym [5], that Artificial Intelligence (AI) was a strong organizing principle for research published in DTM during the first decade of DTM. We complement this reflective review with an analysis of DTM research topics. To obtain a historical view on DTM research themes, we compiled a list of session titles and Best Paper Award Winners (see Appendix A on page 16). We grouped the session titles into higher-level topics and visualised the number of sessions per topic with a TreeMap using the IBM Many Eyes software. Finally, Warren Seering (Section 4) discusses the influence of the research on set–based design by Allen Ward on concurrent engineering, an influence unfortunately cut short due to Allen Ward's untimely death in 2004.

The second part of the paper contains essays on the evolution of key research themes through the history of DTM. Dan Braha (Section 5) traces the problem of design representation, from individual parts, components, and tasks to complex networks of sub-systems, systems, and product development networks. Jonathan Maier and Georges Fadel (Section 6) bring together the set of ideas around the concept of affordance and its often tense relationship with the concept of function. Finally, Amaresh Chakrabarti and Kris Wood (Section 7) discuss the continuing intellectual discourse around the fundamental concept of function.

2 Why DTM Exists

Contributor: David G. Ullman

In the mid 1980's, an eclectic group of academics began looking at design as a formal area of research. Some approached it as an effort to understand and codify the process of design, others focused on the theory of design, while yet others were interested in grammars, graphics, and philosophy. At the time, "design" was on the back burner at many universities with mechanical engineering classes focused on the design analysis of machine components such as nuts, bolts, gears, bearings, and engines. There was very little research on the process of "design" itself. Rather, those interested in the topic focused their research on components, materials, or formal methods such as optimization or kinematics.

These academics, however, were interested in bringing new tools from the artificial intelligence community, new methods from psychology, process focus from industry, and other leading-edge concepts to design understanding and practice. They found common interest at various conferences like those sponsored by the Association for the Advancement of Artificial Intelligence (AAAI) (founded in 1979), Computer Supported Cooperative Work (CSCW) (begun in 1986 by Association for Computing Machinery (ACM)), and the American Society of Mechanical Engineers (ASME) Computers in Engineering (CIE) (begun in 1980). While providing a common meeting place and a view of other disciplines that could be applied to design, none of these conferences focused on design. At these conferences, design was just one of many areas of application.

In 1984 Dr Nam Suh was the Assistant Director for Engineering at NSF (essentially the dean for the college of engineering at NSF). Suh saw the need for research in design as a specific discipline. His interest was based on at least three factors. In 1984, Ken Wallace's English translation of *Engineering Design* [6] opened American eyes to a growing body of design research in Europe. Secondly, US industries had begun to see product design as a process, and less as 'magic'. Finally, Dr Suh himself was strongly interested in design as a faculty member at the Massachusetts Institute of Technology (MIT). Through his leadership the first NSF request for proposals (RFP) was published in 1985. The objectives of the program were to:

1. *Support fundamental engineering research focusing on the design process, contributing to our fundamental knowledge, theories, and concepts of design, and leading to improved quantitative and systematic methods for design.*
2. *Encourage the development of a recognized discipline of design theory, with its own knowledge base, conceptual frameworks, bodies of theory and practice, and an active community of researchers.*

In response to this call, many of the proposals came from the mechanical engineering community. This RFP, more than any other single action, fuelled interest in study of the design process in the US.

In 1987, there were two US conferences focused on design. First, the NSF sponsored the meeting titled, *The Study of the Design Process: A Workshop* in February. This, Oakland, CA meeting was organized by Manjula Waldron, then of The Ohio State University. The core of this conference was sixteen papers covering the research in design funded by the NSF.

Later in 1987, the Europeans, seeing a growing American design interest, sponsored their biennial conference, International Conference on Engineering Design (ICED), in Boston. This was the fourth ICED; the first was in Italy in 1981 and the other two also in Europe. This outreach by the international community further fuelled interest in engineering design methods.

In searching for a common theme and an outlet for their work, some members of the community also attended the CSCW conferences (1986 in Austin and 1988 in Portland). At CSCW, the focus was very much on human-computer interaction in a design team environment.

Finally, in June 1988, the NSF sponsored the second NSF Grantee Workshop on Design Theory and Methodology and a proceedings titled *Design Theory '88* [7] were published. In the proceedings, John (Jack) Dixon wrote an article outlining the goals of the Design Theory and Methodology Program sponsored by NSF "to establish a scientific foundation of theory, principles and knowledge for engineering design" [8]. The NSF Program name would eventually become the name of the conference series.

Because of these events (or "In spite of them"), a core group of researchers coalesced and identified a clear need for a recurring conference that focused on: *i*) design and the impact of computers; *ii*) studies in artificial intelligence; and, *iii*) developments in psychology. The group embraced the growing research literature coming from Europe. NSF funding for design theory and methodology increased with growing industrial awareness of the importance of design to product cost and quality. With the corpus of the interest coming from mechanical engineering academics, it seemed natural to explore a conference within the ASME International Design Engineering Technical Conferences (IDETC) umbrella.

A self-appointed group approached the Design Engineering Technical Conferences (DETC) officers with a proposal, and with extensive help from John Wesner (then of AT&T Bell Labs) and Jack Dixon, formed a committee and the first formal DTM conference convened in 1989. It proved rather easy to put on the conference series as there was strong unanimity on the goals and focus. There was also a clear desire to make it a quality conference with stringent standards balanced with the desire to bring others, not in the core group, into the conference.

It is heartening that DTM still maintains the goals of the founders, and, with these, continues to be successful and relevant.

3 AI: the fierce king of knowledge

Contributor: David C. Brown

When the first DTM conference was held in 1989, the first issue of the journal *Research in Engineering Design* was being published, the *Artificial Intelligence for Engineering Design, Analysis and Manufacturing (AIEDAM)* journal had been going for two years, and the *AI in Engineering* journal (now renamed) had already been in print for three. With regard to conferences, the Applications of AI in Engineering conferences had just started in 1986, and the AI in Design conference started soon after in 1991 (later to become the Design Computing and Cognition conference series). In addition the International Federation for Information Processing (IFIP) WG5.2 series of workshops on Knowledge Engineering in CAD (and other similar titles) had started in 1985, with the next in 1987. So, in 1988, AI was in the air!

At that time the DTM field was already concerned with studying explicit representations and types of reasoning: including representations of designs, resources and influences on the design process, as well as how to reason with constraints, how to search, and how to model designing. The papers in the 1988 conference included terms such as satisficing, constraints, taxonomy, expert, goals, description language, knowledge, rules, inference, and representation. The "best paper" award winners in the next few years, shown in Table 1 on page 17, suggest an existing and continuing influence of AI in the early years of DTM.

Fig. 1 on page 5 shows a TreeMap visualization of the DTM sessions since 1989. A distinguishing research theme of DTM is Behavioural Research, that is, the study of designers. It represents the single largest block of session titles since 1989 and is a topic area that is not covered by any of the other IDETC/CIE conferences. The issues of representation and reasoning are still vital for DTM today [9]. The conference topics have been moving gradually to include inter-disciplinary perspectives such as: Affordances, Creativity and Ideation, Biologically Inspired Design, Functional Modelling, Human Behavior in Design, and Analogical Thinking in Design. These topics appear in the categories of Representation (Affordances), Behavioural Research (Creativity and Ideation, Human Behavior in Design, Analogical Thinking in Design), Function (Functional Modelling), and Bio Design (Biologically Inspired Design) in Fig. 1.

In 1985 I gave a tutorial at the ASME Eastern Design Engineering Show & Conference about Expert Systems for Design problem-Solving. At the ASME CIE conference in the same year there was a workshop given by Jack Dixon (and Mel Simmons) on Expert Systems for Mechanical Engineering (ME). I attended and was surprised to find his work being presented in addition to Jack's. Afterwards I introduced myself. That conference, and the one following in 1986 coordinated by Alice Agogino, included panels on AI in Mechanical Design.

In 1988, the influence of Expert Systems had spread quite widely, but AI researchers had already questioned the utility of rule-based technology for all such systems, and had started to move toward figuring out types of reasoning such as diagnosis by classification, configuration, and routine design. Some of this filtered through to DTM, but the CIE conference was slower to shake off the basic approaches to Expert Systems. DTM has been more focused and more selective in the AI influences it allowed.

Through the years DTM papers have moved through AI-influenced topics gradually in the rough order of Expert Systems, Functional Representation and Reasoning, Qualitative Reasoning, Analogical Reasoning, Design Rationale, and, most recently, Creativity (inspiration and measures). These session topics appear in the categories of Computation (Expert Systems, Qualitative Reasoning), Function (Functional Representation and Reasoning), Support (Design Rationale), and Behavioural Research (Analogical Reasoning, Creativity) in Fig. 1. As Table 1 shows, two papers on analogical reasoning have won an award for "best paper": DETC2008-49276 and DETC2012-70420.

Engineering, and Engineering Design in particular, is notoriously conservative. Tools and techniques take a while to be adopted by industry. It took a long time for Design study to be anything more than Analysis and prescriptive procedures. In 1994 Clive Dym took it upon himself to help move the field away from this deep-seated view by publishing the "Synthesis of Views" version of the book already cited above. The book described how approaches from AI could help clarify our view of designing, and potentially affect design pedagogy. It is to the credit of the DTM authors and organizers that the conference has embraced a similar synthesis of "inter-disciplinary perspectives" for such a long time.

It is exciting that DTM is seen as a high quality conference, perhaps "in spite of" that surrounding conservatism. It is well known that university Mechanical Engineering departments are suspicious of any publishing venues (especially journals) other than ASME ones when it comes to evaluating faculty for promotion and tenure. This has been a problem for journals such as AIEDAM: I've had authors tell me that they needed to publish something in an ASME journal before they could consider submitting to AIEDAM. This pressure may well have reduced the amount of AI-influenced research in design.

As Editor in Chief of AIEDAM from 2001-2011 I maintained and improved the connections between DTM and the journal that Clive Dym started. Special issues were announced and reports on publication statistics were presented at the DTM committee meetings and via the DTM mailing list. The journal has distributed hundreds of flyers at the IDETC conferences over the years. Currently, the latest Editor in Chief, Yan Jin, and some of the Associate Editors have DTM connections. In addition I helped arrange the Editorial Board appointments of DTM stalwarts such as Alice Agogino, Jon Cagan, Matt Campbell, Andy Dong, Warren Seering and Rob Stone. In addition, the journal has tapped DTM attendees such as Dan Frey, Li Shu, Amaresh Chakrabarti, Levent Burak Kara, Maria Yang, Maaike Kleinsmann, Pieter Vermaas, Kristina Shea, Irem Tumer, and Kemper Lewis to guest edit cutting-edge special issues.

For example, AIEDAM has had special issues on Function Representation and Reasoning. This is one area where a lot of work has been presented at the DTM conferences, with the gradual progress, applications, and evaluation of the Functional Basis being most visible. After some difficulty getting papers about function that were from a DTM perspective published in AIEDAM, I put together a special issue on "Engineering applications of representations of function" with Rob Stone and Amaresh Chakrabarti as guest editors. A paper by Professor B. Chandrasekaran was solicited to tie the DTM view of function representation with the more general AI view.

DTM authors need to keep tying fields together carefully; else we run the risk of dabbling in areas where other fields are strong, such as Creativity and Analogy, without making important and general contributions. In Creativity, for example, there is possibly relevant research in Psychology, AI, Marketing, Social Science and Pedagogy that can be related to design research. As always, people in one area tend to know nothing about work in another, which is tragic.

DTM should keep the links to AI active in order to keep up with the pressure to address more realistic design problems and activities, continuing the trend from simple problems with

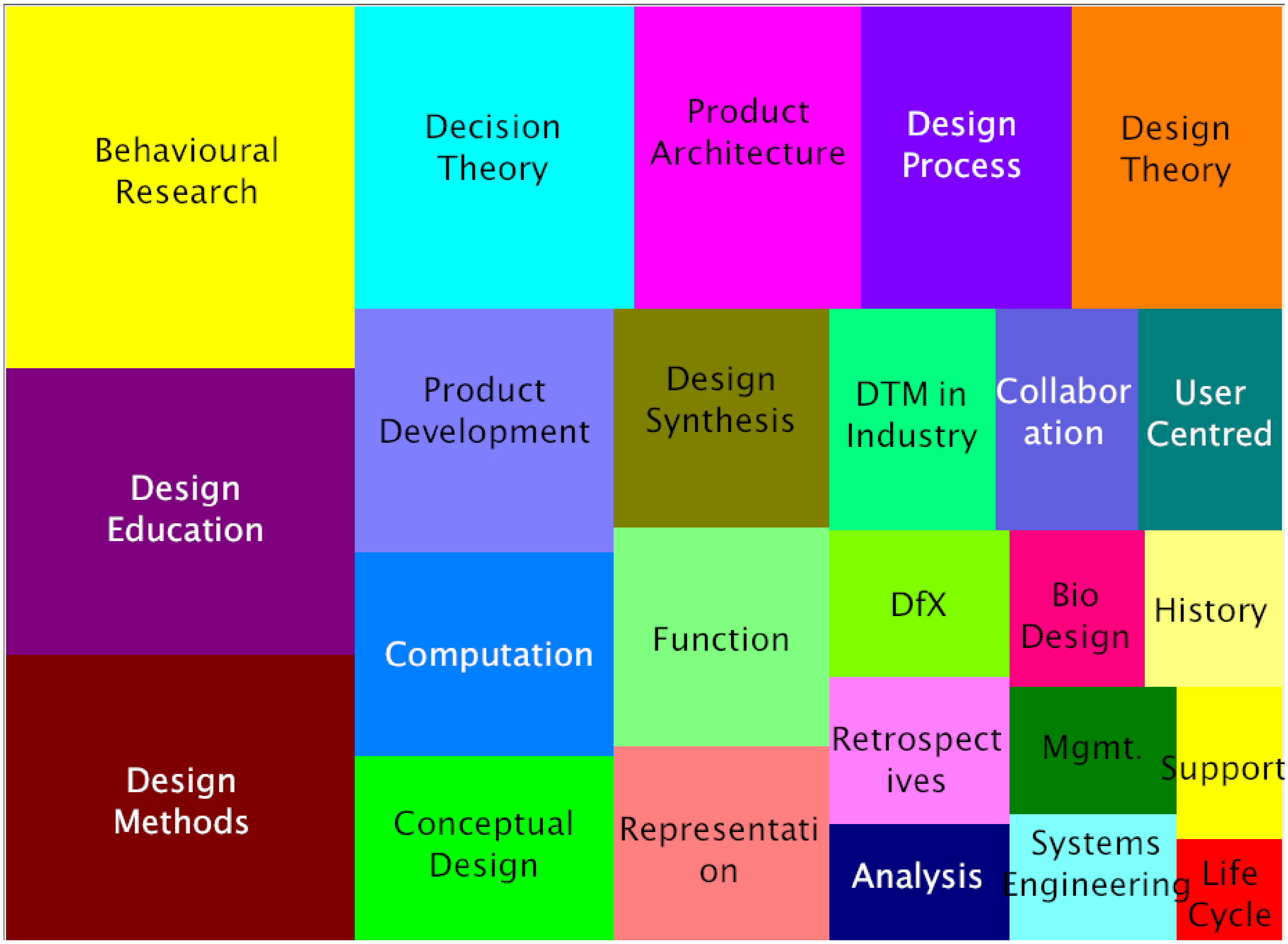

FIGURE 1. TREEMAP OF SESSION TITLES OVER 25 YEARS OF DTM

a single designer who is reasoning routinely, towards distributed teams using mixed media and multiple communication modes to solve large problems requiring creativity. This will need more inter-disciplinary study of real designers in social settings, for example. There's plenty of new knowledge to discover: plenty to keep us busy!

At one of the first ASME CIE conferences I attended, in Chicago, there was an exhibition of Todai-ji treasures at the Art Institute. A translation of some text on an artefact reads:

> The fierce king of knowledge transforms human passions into energies leading to enlightenment.

Here's hoping for another 25 years of passionate, energetic knowledge discovery DTM-style. Perhaps enlightenment will follow?

4 Set–Based Design and Allen Ward's 1989 DTM Best Paper

Contributor: Warren Seering

Allen ('Al') Ward saw things differently. He had an extraordinary mind, a passion for designing, and unique ways of thinking about design processes. In his 1989 Ph.D. thesis, *A Theory of Quantitative Inference for Artifact Sets*, he taught us how to reason about the range of a product's performance that can result when components selected from sets of options are integrated into the product. The logic rules of the theory enable us to eliminate from consideration components that are insufficient for the product's specified task given any combination of other components that might be chosen subsequently, and to propagate the consequences of this elimination iteratively through all the sets of elements as each design decision is made, leaving only the plausible candidates in play. The reasoning that motivated Al's work was that to discover the best design alternative we should design with all plausible options in mind and not eliminate design options unless and until there is a logical reason to do so. The paper that won the first Design Theory and Methodology Conference Best Paper Award (Table 1 on page 17) in 1989, *Quantitative Inference in a Mechanical Design "Compiler"*, was Al's explanation of this thesis work. His Theory of Quantitative Inference is the foundation for what has come to be known as set–based design.

What distinguishes set-based design from the more widely practiced point-based design is the emphasis on reasoning about sets of design options. Point-based design begins with the generation of alternatives and then the selection of a single alternative. This selection is followed by instantiate–analyze–improve cycles that continue until the designer is satisfied with the outcome. Set–based design also begins with the generation of design options. But instead of selecting one, the designer proceeds with an iterative cycle of examining the option set, eliminating infeasible combinations of options, analyzing the remaining set in more detail, eliminating the options newly found to be infeasible, and so on. Eventually, only feasible options remain and the best of those remaining can be chosen with confidence that it will satisfy the participating stakeholders. Infeasibility may be established by any of the stakeholders, the manufacturing or marketing teams for example. The cycles can be conducted concurrently by the various stakeholders; the intersection of the consequent sets is the feasible set. For this reason, set–based design is often referred to as set-based concurrent engineering.

The value of set–based concurrent engineering is illustrated by the following example. The manufacture of hardened stamping dies for automobile skin panels requires many months and so drives product development schedules. Consequently, detailed design of these panels must typically be completed long before the car goes into production. To shorten the production cycle, the designers can share with the die makers early in the design process the set of panel shapes being considered. The die makers then can begin to design and even manufacture dies which, when finished, can be used to make any one of the set of panels that the designers might ultimately choose. As more panel options are rejected, the dies can be brought nearer to completion. Also, as the design work proceeds, the die maker can feed into the process information about panels in the working set that would be difficult to manufacture.

In the early 1990's, with colleagues Jeffrey Liker, John Cristiano, and Durward Sobek, Al conducted a series of studies of the Toyota Production Process and found that various of Toyota's practices, including the practice of working with the die makers as explained above, could be described as examples of set–based concurrent engineering [10]. Their findings were published in the *Sloan Management Review* in spring of 1995 [11] and updated in the winter of 1999 [12], garnering a great deal of attention and triggering rapid growth of interest in set–based design.

In the almost 20 years since the *Sloan Management Review* publication [11], many researchers in both departments of engineering and of management have conducted research on and prescribed methods for deploying processes related to set–based design. Among these researchers are several members of today's DTM community. But the methods of set–based design have established themselves in communities far beyond ours. Set–based design is now considered a core element of the lean product development process and is espoused by organizations such as the Lean Enterprise Academy. The principles of set–based design have been adapted for use in the construction industry and are being taught by such professional groups as the Lean Construction Institute. Another profession in which set-based design has taken hold is the ship building industry. The most recent U.S. Navy Acquisition Process Guidelines call for the use of set–based design in establishing the system level specifications for Navy ships. It is fair to say that publication of Al's *DTM* paper in 1989 initiated a process that has subsequently influenced the professional work of many designers and improved the methods by which products in an array of fields are designed [13, 14, 15, e.g.]. Interestingly, it is also fair to say that few of those influenced by its content are aware of the original paper.

A book based on a manuscript that Al wrote was edited by John Shook and Durward Sobek and published in 2007. The book, *Lean Product and Process Development* [16], defines methods for deploying the principles of set–based design. Another book, *The Toyota Product Development System* [17] by James Morgan and Jeffrey Liker, was dedicated to Al and his work.

While Al's work on set–based design has influenced design practice extensively, there is still a great deal of research to be done in the area. As our community moves in the direction of digital prototyping, set–based design is a natural complement. Despite its value having been well established, set–based design is rarely taught to students in design classes. Its deployment is still limited by the shortage of user–friendly processes for implementing the method, particularly for large and complex system designs. There is every reason to believe that the influence of Al's ideas will continue to grow as our community proceeds with addressing these limitations. Al Ward passed away in 2004 before he could appreciate the full impact of his ideas.

5 The Evolution of Design Theory: From Individual Design Forms to Complex Networks

Contributor: Dan Braha

There are two critical questions in design theory: the characterization of design forms and the design processes used to create them. I have studied these issues for over 20 years, and developed a theoretical and algorithmic framework for design called Formal Design Theory (FDT) [3, 4]. The first question was addressed by introducing an algebra for design representation, which is based on three constructs: modules, relationships, and rules for combining them to create complex design representations (akin to a network representation). The second question was addressed by establishing an analogy between the design process and biological evolution. According to this approach, evolving design solutions "adapt" to design specifications, which in turn evolve based on new information generated by emerging design solutions. Mathematically, this process was cast in the framework of general topology, logic and finite automata, information theory, adaptive learning, constraint-based design, and geometric reasoning. This theory was put to practical use by developing effective knowledge-based design systems with applications to a wide variety of engineering domains [3]. The question of quantifying the complexity of engineering design fascinated me from the start. Using the 'module-relationship' representation of design, I have introduced information-theoretic methods and computational complexity analysis to measure the amount of information and inherent difficulty embedded in design products and design processes [3, 18, 19].

While the efforts leading to the formation of a formal design theory were off to a good start, the theory dealt mostly with design processes from the perspective of a single designer. Large-scale product design and development is often a distributed process, which involves an intricate set of interconnected tasks carried out by hundreds of designers, and is fundamental to the creation of complex man-made systems [20, 21, 22, 23, 24, 25, 26]. This complex network of interactions and coupling is at the heart of large-scale project failures (see, e.g., the London Stock Exchange Taurus project or the Federal Aviation Administration Advanced Automation System). Connectivity and coupling is also at the heart of large-scale engineering and software system failures (see, e.g., the 2003 Space Shuttle Columbia disaster or the New York City blackout of 1977). A new approach was needed to understand and prevent these failures. Beginning in 2002, I have started [27, 28, 29, 30] to apply social networks analysis and complex networks theory to analyze the statistical properties of very large scale design products and engineering projects, which were represented as networks of "nodes that are connected by "links". Others in the DTM community who have taken this approach include Sosa [31, 32] and Sarkar [33]. The "nodes" could represent "people", "tasks", "subroutines" or "logic gates", which communicate via "links" representing "engineering change orders," "parameters," "specifications," or "signals" (e.g., forward logic chips with 23,843 logic gates and 33,661 signal links; open source software systems with 5,420 subroutines and 11,460 calling relationships among subroutines; or, a product development process with 889 tasks and 8,178 information flows). The study of such engineering networks has led to many surprising results. It has shown that these networks have structural (architectural) properties that are like those of other biological, social, and technological networks [28, 29, 30]. The dynamics of engineering networks can be understood to be due to processes propagating through the network of connections, including the propagation of changes, errors, and defects in complex product design and development projects. I have presented a generic model of error dynamics embodying interactions through the network [30]. Remarkably, it is shown that the reported network structural properties provide key information about the characteristics of error and defect propagation, both whether and how rapidly it occurs. Moreover, these architectural properties have implications for the functional utility of engineering systems including their sensitivity and robustness (error tolerance) properties and quality [32]. Below is a brief summary of the main findings [28, 29, 30]:

Sparseness and 'Small-World'. Complex engineered networks are sparse, that is, they have only a small fraction of the possible number of links. Moreover, despite being primarily locally connected and modular, such networks exhibit the "small-world" property of short average path lengths between any two nodes.

Right-Skewed and 'Fat-Tailed' Degree Distributions. Complex engineered networks are characterized by very uneven distributions of incoming and outgoing connections of nodes (often power-laws with cutoffs). Some nodes are very highly connected ("hubs"), while most have small degrees (the number of nodes a particular node is connected to). More specifically, the dynamics of engineering networks is dominated by a few highly central information-consuming and information-generating nodes ("information bottlenecks").

Asymmetric Information Flows. While both the incoming and outgoing connections of nodes have been shown to follow a power-law (with cutoffs) with exponents that are consistent with recent discoveries of biological and social complex networks, it was shown that the incoming link distributions have sharp cutoffs that are substantially lower than those of the outgoing link distributions. It was conjectured that this asymmetry may be related to differences between each node's capacity to process information provided by others and the node's capacity to transmit information over the network.

Disassortative mixing by degree. Disassortative mixing by degree refers to negative correlations between degrees, that is: *1*) the tendency of nodes with high (in- or out-) degree to connect to others with low (in- or out-) degree, and similarly for low degree; or *2*) the tendency of a node with high in-degree to have low out-degree, and similarly for low in-degree. Assortative networks, on the other hand, imply positive correlations between degrees. Since degree is a structural property of networks, assortative mixing leads to more complex structural properties including the appearance of cycles and loops, which tend to amplify the propagation of design changes and errors through the network. It has been empirically observed that engineering networks exhibit disassortative mixing by degree – a property which has also been shown to be closely related to the dynamics of defects in large-scale engineering systems [30].

Hierarchical network organization. It has been shown that the system-level structure of complex engineering networks is best approximated by a hierarchical network organization with seamlessly nested modularity [27, 28]. In contrast to current intuitive views of modularity, which assume the coexistence of relatively independent groups of nodes, real-world networks have an inherent self-similar property: There are many highly integrated small modules, which group into a few larger modules, which in turn can be integrated into even larger modules.

Sensitivity and Leverage. The "wild" variability and right-skewness of the connectivity distributions provide a strategy for harnessing complex engineering networks. More specifically, a remarkable improvement in the performance of engineering systems (measured, for example, in terms of defects or development time) can be achieved by focusing engineering and management efforts on central information-consuming and information generating nodes.

Robustness and Fragility. The dynamics of engineering systems is ultra-robust and error tolerant when negative design changes occur at randomly selected nodes; yet highly vulnerable when perturbations are targeted at "information-bottleneck" nodes.

Many others within the DTM community have sought to understand and quantify the 'complexity' of engineered systems using both information-theoretic [34, 35, e.g.] and complex networks theory [36, e.g.]. Elements figuring into the calculation of design complexity include size, coupling, and solvability of the design problem, process, and product [37]. Some remain skeptical whether complexity measures based upon information theoretic principles provide mathematically valid descriptions of complexity [38] or whether a single metric of complexity is even warranted [33] given that the complex networks field uses an array of characteristics to describe the complexity of a system but not a single number [39]. However, complex networks theory is gaining more acceptance within the community. The problem of identifying sub-system modules in engineered products [40,41,42,31,43,44] and the relation of architectural modularity to the complexity of the product [45] is now being studied from the complex networks perspective, and the problem of community detection in complex networks, using techniques such as spectral analysis [33]. Similarly, new techniques for understanding the failures of complex engineered systems are also applying graph-based [46] and complex networks approaches [47].

Large-scale design is a self-organized process that involves hundreds or thousands of designers developing, tweaking and tinkering architectural designs each optimizing their piece in the larger puzzle. The amazing thing is that this tinkering process leads to large-scale universal patterns and system properties that were not written in the initial specification sheet or anticipated from the outset. Is it possible that engineering design and biology have a deeper connection than we ever thought possible?

6 Retrospective on Affordance Based Design

Contributors: Jonathan R.A. Maier and Georges Fadel

When Herbert Simon published *The Sciences of the Artificial* in 1969, he probably had little inkling that his insights into the connections between his favorite research areas – economics, organizational behavior, AI, decision making, complexity, and so on — would spark a revolution in engineering design [48]. Until then, scientists and engineers largely regarded design as art, not something amenable to scientific study. The calls from some forward looking researchers, recognizing the breadth of design practice just begging for rigorous inquiry, went largely unanswered because they provided no scientific framework upon which to base such investigations.

Simon stepped forward at just the right point in history to suggest that information processing be the foundation upon which design theory and methodology should be built. As noted in the Introduction, Simon's intellectual leadership in this area can be seen by the emphasis on AI in the first decade of DTM research. Other fields in which Simon did pioneering work, cognitive psychology and AI in particular, shared the same basis, that memories stored models, and then minds made decisions based upon those models.

But by the 1970s, neuroscientists and AI programmers were having great difficulty attempting to map the massively parallel connections in a brain to anything single processor computers were capable of processing. Early attempts at AI algorithms to compete against humans in games such as chess fell woefully short of their ambitious goals.

Meanwhile, some psychologists were never entirely comfortable with the proposition that the human mind was simply a cold, hard information processor. One psychologist in particular, James Gibson, was inspired by how quickly Air Force pilots responded to incredibly fast changing stimuli. Gibson then turned his attention to how other animals perceive their respective environments. In 1979 he proposed a radical new theory: that minds are capable of perceiving some things without any information processing at all. He called his idea direct perception, and the sorts of things that brains are capable of perceiving directly he termed affordances [49].

In the succeeding decade, as the consumer electronics boom hit in the 1980s, and consumer products became so complicated that users were having trouble operating them, usability appeared as a research topic. Donald Norman, a psychologist interested in this area, applied Gibson's ideas, in particular that designers must pay attention to the affordances of their designs in order to make their products more usable [50].

At about the same time Gibson published his theory, the physicist Douglass Hofstadter attempted to explain why AI algorithms were having such a tough time competing with real humans in games such as chess. Hofstadter argued that computers as information processors executing fixed, predictable algorithms, stripped out the kind of complexity inherent in the real world that physicists and mathematicians had known formally (through Gödel's celebrated incompleteness theorem) since the 1930s. Some researchers, particularly in robotics, attempted to integrate these unorthodox ideas, and began building robots that have been capable of perceiving their environments *sans* explicit internal models for almost 20 years [51, 52, 53, e.g.].

In engineering design, these developments went largely unnoticed, but their effects proved inescapable. By the year 2001, the design researchers Tate and Nordlund looked for a unifying paradigm indicative of a mature field described by Kuhn [54], but they found none [55]. Instead, most researchers had focused on developing methodologies to solve specific problems, and relatively little progress had been made in elaborating design theories.

At the same ASME DTM conference in 2001 at which Tate and Nordlund presented their paper, another pair of researchers, Maier and Fadel, presented their work looking at the parallel legacy of Simon's work in other fields, and proposed that some of the problems facing engineering design were due to the same reasons, and shared the same solution, as what had been unfolding in cognitive psychology and AI — namely that information processing, while useful, is insufficient to handle real world complexity including issues such as usability, safety, and aesthetics. Maier and Fadel argued that engineering design researchers had been missing relationships not readily described by functions with simple inputs and outputs [56]. In fact, these relationships already had a name, affordances, the term coined by Gibson back in 1979.

In the years that followed, Fadel and coauthors have presented a series of papers more fully explaining these ideas and broadening their application. Gradually other researchers in the DTM community have leveraged the benefits of considering affordances. Among the first were Galvao and Sato, who investigated designing functions and affordances of consumer electronics such as cell phones [57, 58]. Notably, their first paper won the DTM best paper award in 2005 (see Table 1 on page 17). Subsequently Yong Se Kim and his colleagues applied affordances to interior design [59, 60, e.g.]. At about the same time, Brown and Blessing [61] debated the appropriate distinctions between the concepts of function and affordance. More recently, John Gero and his colleagues have incorporated the concept of affordance into Gero's long standing function-behavior-structure (FBS) framework [62, e.g]. Meanwhile, these ideas have been disseminated among wider audiences through several important design journal articles [63, 64, 65, 66, 67, 68, 69, e.g.]. Parallel discussions have also occurred in the related field of architectural design [70, 71, 72, e.g.].

The fractures that linger in the many fields Herbert Simon helped to illuminate speak to their richness of substance, and their closeness to the irreducibility of the human spirit. No one theory has emerged in psychology, AI, organizational theory, or engineering design, powerful enough to encompass all of the interesting phenomena to be studied. Hence it is no surprise, really, that Affordance Based Design has developed into a useful theory and increasing body of methods, but has not itself become an over-arching paradigm. Design researchers can, however, take solace, knowing that their endeavors share the same fruits and frustrations of our fellow laborers in our sister fields of the artificial sciences, and continue our noble efforts to understand just what design is, and how it should be done better.

7 Trends in the Evolution of Research into Functional Reasoning in Design

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Functional reasoning research focuses on understanding the concept of function, and the processing, representation, and formation of judgment about function, either cognitively or computationally, that can and should be carried out in design. Function is a central, core, and 'cardio vascular concept' in design, and, therefore, functional reasoning has been pursued since the genesis of design research as a scholarly and applied endeavor. Although misconceptions exist about the role of functional reasoning in design, the literature and evidence is clear that functional reasoning is fundamental across research communities and is essential in industrial practice [73]. Due to its interdisciplinary and intrinsic nature, there are a number of major, inter-twining trends in functional reasoning research, as discussed below.

What is meant by 'function'? Researchers have proposed various definitions of function [74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86]. The definitions provide a spectrum of viewpoints. In one part of the spectrum, function focuses on the level of the system or environment at which actions are initiated and performed (e.g., device-centric vs. environment-centric functions [80, 81]). In another part of the spectrum, function is considered as input-output transformation or states of a system [74, 87, 82, 88, e.g.], function as state-change [76, 85, 89, 90, e.g.]. Functions as input-output is the most common systems view, even though some researchers articulate alternative perspectives on this view [85].

How can complex functions be represented? A significant trend has been to develop a basic repository of functions through which more complex functions can be described, although Vermaas [91] speaks of the arbitrariness in what constitutes basic or complex, with a possible resolution using the definition of function by Kitamura and Mizoguchi [84]. The basic functions of Rodenacker, Generally Valid Functions in Pahl and Beitz [6], and the list of functions proposed by Keuneke [92] are some of the initial attempts at creating such a repository. Various function based ontologies have been developed [84, e.g.]. The effort to develop a basic functional language has culminated in the functional basis [93, 94]. This language and a number of significant companion research efforts consider cognitive processing, design representation, and ideation approaches with function [95, 96, 97, 98, 99]. Research on how to represent complex functions with additional features or properties, e.g. that of how a door lock functions in enabling locking, unlocking, and transition between these, continue to take place; approaches for representing some of these functional features and properties, and for supporting their synthesis, have been proposed [100, 90].

Can the various views of function be integrated into a logically consistent framework? The variety of types of function proposed in literature provide for multiple perspectives, capabilities, and genres of intellectual and practical pursuits. Some efforts point out the need for refined clarity [91, e.g.], and effort is on [101, 102] to integrate the concepts of function. One such effort [103, 104] uses a model of causality centred around physical phenomena and effects [105] to integrate the various views of function within a unified framework.

How do designers carry out functional reasoning, and how well do prescriptive functional reasoning approaches fare in reality? While much work in functional reasoning in the past has been prescriptive rather than descriptive [106], with few exceptions [107, 108], there has been a recent surge in work in this area [109, 110]. Descriptive perspectives provide how functional reasoning is carried out ‘as is’; thereby, from which an empirical basis for prescriptive approaches can be developed. Advances in research from this perspective and integration of its results into prescriptive approaches are exciting frontiers in design research.

How can functional reasoning be supported? This, understandably, has been the most prolific area within functional reasoning. The work can be divided within three broad tasks: functional representation (how should functions be represented?), functional synthesis (how can new solutions be created to carry out a function?), and functional analysis (does, or how well does, a given solution carry out a given function?). Much of this work is based upon the understanding developed within the earlier four trends. The variety of functional reasoning approaches [see [111, 112, e.g.] for a summary], the areas within which they are explored (e.g., in product or system architecture by Stone [44], in biologically inspired design [105, 113, 114, 115], in computational synthesis [116, 117, 118, 119, 120, 121], in design by analogy and analogical reasoning [122, 123, 96, 124, 125], and in efficient sharing and search [126, 127, 128]) are testimony to the prolific research in the area of function. A summary of functional representation approaches can be found in two special issues of AIEDAM [129, 130, 131], and a summary of major approaches within the other two tasks can be found in [111, 132, 112].

Overall, functional reasoning is a highly active area of research in the design theory and methodology community, with a particularly strong drive towards consolidation, integration, cognition, ideation-synthesis, and application. Clearly functional reasoning is foundational to design research and to design practice [73]. Exemplar major challenges that continue to remain as drivers are:

What are the various views of function and how do they fit together?
How to represent more and more complex engineering functions and associated systems?
How to improve industrial applications for functional reasoning research?
What are the advancements needed in functional languages and functional reasoning at the interface of cognitive science, social psychology, sociology, anthropology, engineering, industrial design, architecture, and the other sciences?

8 Discussion and Conclusion

As the essays describe, the research themes in the DTM conference have been heavily influenced by two underlying themes: artificial intelligence and product development. While DTM started with AI as an underlying theme, product development emerged as a significant issue around 2001 and the “best paper” Product Development Process Modeling Using Advanced Simulation (DETC2001/DTM-21691). While no one theme has dominated DTM, the theme of Behavioural Research has emerged as a clear distinguishing research area within DTM. At least 5 “best papers” have been awarded in this area. As DTM moves into its third decade, another underlying theme may emerge. If Dan Braha is right, perhaps complex systems will become the organizing principle integrating engineered systems and physical systems, as Herbert Simon’s research intimated in the beginning.

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APPENDIX A Best Papers

Table 1 lists the titles of all of the best paper award winners from 1989-2012.

Year	Paper No	Title
1989		Quantitative Inference in a Mechanical Design Compiler
1990		Representing and Recognizing Features in Mechanical Designs
1991		An Intelligent Real Time Design Methodology for Component Selection
1992		Fractal-Based Geometric Tolerancing for Mechanical Design
1993		Wavelet Transforms in Fractal-Based Form Tolerancing
1994		Optimal Tolerancing: The Link Between Design and Manufacturing Productivity
1995		Generalized Models of Design Iteration Using Signal Flow Graphs
1996	96-DETC/DTM-1505	HVAC CAD Layout Tools: A Case Study of University/Industry Collaboration
1997		Creative Design Methodology and the SIT Method
1998	98-DETC/DTM-5673	Agent-Based Synthesis of Electro-Mechanical Design Configurations
1999	99-DETC/DTM-8764	Product Architecture Development with Quantitative Functional Models
2000	DETC2000/DTM-14550	A Model for the Flow of Design Information in Design
2001	DETC2001/DTM-21691	Product Development Process Modeling Using Advanced Simulation
2002	DETC2002/DTM-34023	Creative Stimulation in Conceptual Design
2003	DETC2003/DTM-48654	Combinatorial Laws for Physically Meaningful Design
2004	DETC2004-57474	Insights on Designers' Sketching Activities in New Product Design Teams
2005	DETC2005-84525	Affordances in Product Architecture: Linking Technical Functions and Users' Tasks
2006	DETC2006-99043	Identifying Customer Needs - Disabled Persons as Lead Users
2007	DETC2007-34758	An Evaluation of the Pugh Controlled Convergence Method
2008	DETC2008-49276	Overcoming Blocks in Conceptual Design: The Effects of Open Goals and Analogical Similarity on Idea Generation
2009	DETC2009-87382	The Characteristics of Innovative, Mechanical Products
2010	DETC2010-28675	Potential Limitations of Verbal Protocols In Design Experiments
2011	DETC2011-48173	Understanding of Emotions and Reasoning During Consumer Tradeoff Between Function and Aesthetics in Product Design
2012	DETC2012-70420	The Meaning of "Near" and "Far": The Impact of Structuring Design Databases and the Effect of Distance of Analogy on Design Output

TABLE 1. BEST PAPERS SINCE 1989