INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

HIDDEN IN PLAIN SIGHT: AFFORDANCES OF SHARED MODELS IN TEAM-BASED DESIGN

Edelman, Jonathan Antonio[1], Larry Leifer[1], Banerjee, Banny[1], Jung, Malte[1], Sonalkar, Neeraj[1], and Lande, Micah[1]
(1) Stanford University

ABSTRACT

Current scholarship in cognitive science [3, 8, 18, 19] and Science Technology Studies [21], has reconsidered the role media plays in knowledge gathering and acquisition. While the use of low-resolution physical prototypes has been very successful in innovative practices in engineering design [2, 6, 14], to the authors best knowledge, there is no documented systematic study of this practice within the domain of engineering design itself.

Design thinking and communication occur in the presence of representation. It is through representation that group members can literally see what they say, and reflect on what they see. The quality of team engagement is predicated on the quality of the model. A representation or model can be in the form of a narrative, a sketch, a rough physical prototype, an enactment, a conceptual framework, a photograph, a CAD drawing, or an equation, to name a few.

We propose that the media which design engineers enlist are cognitive tools which extend and modify their ability to perceive, think and communicate [3, 8, 18, 19]. Furthermore, we propose that the characteristics of the series of media used during the course of a design project are a significant factor in successful project outcome.

Keywords: Engineering design, re-representation, media cascade, media model

1 CASE STUDY: REPRESENTATION IN ACTION

A major University's vehicle driving dynamics laboratory teamed up with a major automotive manufacturer to develop a new vehicle dynamics test platform, called the "X-1 Car" at the University's mechanical engineering research and fabrication facility. The development team consisted of two faculty advisors and six graduate students. The project leader, a Master's student in Mechanical Engineering, was charged with leading the team through the concept development and prototyping phases of the project. At the time of our observation and interaction with the development team (May through October 2007), the two year project had been underway for several months.

The first phase of the project was to envision and develop concepts for a modular suspension system for the X-1. Vehicle dynamics researchers wanted a vehicle which afforded reconfiguring and swapping out any number of four individual, independent suspension modules for each wheel. This meant that automotive engineers had to reconsider how cars had been typically designed.

During the concept development phase, the project leader and his team would develop potential directions for building prototypes. Following their conversations, the project leader made CAD models of the concepts and brought them to the team's meetings for review. The project leader felt it was too early in the project to lock in a single idea and wanted to keep generating more ideas. To his frustration, team members would resist discussing new ideas, they seemed to accept the idea embodied by the CAD model, and focused on refining that idea.

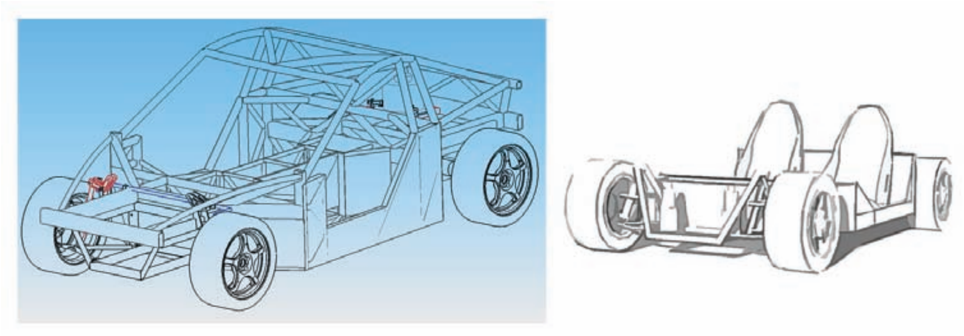

Figure 1: Two views of the X-1 pre-manufacture rendering (left) and pre specification rendering (right)

During the course of a series of interviews, the project leader indicated that he had hoped to use the CAD models to generate more and diverse concepts. The project leader reported that his solution to the problem was to make rough sketches of the CAD models. When he presented the rough sketches, the conversation of the team turned from refining the ideas to changing the *ideas* embodied in the sketches, and often diverged from the idea. We observed that this movement from high resolution model to low resolution model was not contrary to our normal expectation of increasing precision in models during the course of development. Later, when the project leader wanted the team to look more critically at a concept, he would present CAD drawings to the team.

During the prototyping phase, one of the project's faculty advisors suggested to the team that they should not work in metal. Instead they should work in cardboard and wood. His rationale was that metal is too much like an actual car, and the choice of metal would cue the team to think about how cars *currently are* rather than how they *could be*. Occasionally the faculty advisor would allow the team to work in metal in order to see how the cardboard and wooden prototypes would translate into metal.

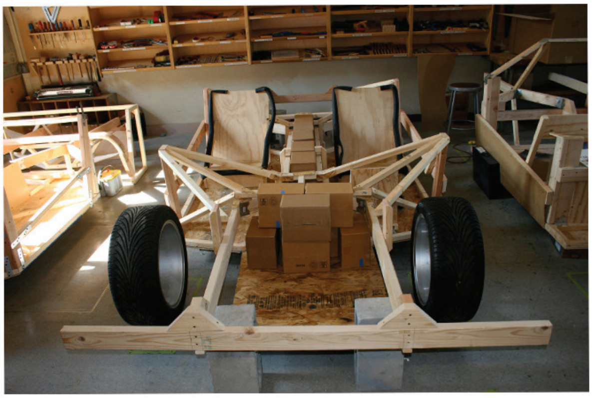

Figure 2: A wooden prototype of the X-1 Car, pre specification model

2 BACKGROUND

The problem facing cross-functional design teams is one of distributed cognition. Not all cognitive activity occurs inside the heads of individual team members [3]. Much of their knowledge can be said to reside in representations that team members create for and share with one another [8]. Shared representations serve as a fertile ground out of which healthy and effective collaboration can grow.

Representation in the field of engineering design encompasses a broad range of media, including rough sketches, physical prototypes, physical enactments, photographs, engineering drawings, stories, lists, charts, descriptions, and numeric digital files. Given representation's central role in design, it would seem that successful development of an engineered product may be largely dependent on the careful management of the many representations which characterize the design process.

The models designers use are active agents in the design process. Design thinking occurs in the presence of media, and the type of media conditions the kind of thoughts a design engineer has. In other words, we are "mixtures" with our media [20].

While it has been noted that it is common practice for design engineers to use different media for solving different types of problems [2, 14], we have found no documented systematic study of this practice within the domain of design engineering. In addition, Design Research has been relatively silent about the nature of the *sequences* of representations which are generated and employed during the various phases of a project, and how that sequence of representation effects the conversations and thinking of a design team.

3 TOWARD A GRAMMAR OF OBJECTS

Design engineering projects can enlist up to thousands of representations during the course of product development. Translation into various media of differing resolutions and levels of abstraction provides the flexible perspectives necessary to explore problem and solution spaces. Re-representation allows team members to assess how ideas have changed and consequently reframe their ideas with greater ease.

3.1 MEDIA MODELS

We define each representation in the context of the arc of collaborative design as a *media model*. Media-models are characterized by the dimensions of *resolution* and *abstraction*. By *resolution*, we mean the level of refinement which can be observed in the fit and finish of a media-model. By *abstraction*, we mean amplification through simplification and pulling specific characteristics out of context.

When the X-1 Car project leader represented his CAD models as rough sketches, he was lowering the resolution of the media. This had the effect of allowing the team to consider different potential directions the project could take. When the faculty advisor suggested that the team use wood instead of metal for prototyping, he was pulling an aspect of the car out of context, and thus adding a level of abstraction to the model.

In this paper we are concerned with three classes of media-models 1) mathematized media which include maps and highly realistic images, 2) ambiguous media which include rough sketches and rough physical models, and 3) hybrid media a class of representation possessing qualities of the other two classes.

Table 1. Types of media models

Type of media-model	Examples
Mathematized	Maps, charts, equations, highly realistic
Ambiguous	Rough sketches, rough physical prototypes
Hybrid	Informal 2x2's, rich maps

As we have seen, different types of models engender different kinds of conversations. Objects can be said to have a grammar that gives cues to design engineers. In a sense, they *ask* different types of questions, and the conversations design engineers have about them are responses to these questions.

Media-models encourage two types of *completion* which frames discussion. All media-models present a profile of incompleteness; a manufactured product is no longer a model, it is the thing itself. A media-model's profile of incompleteness affords a design engineer the opportunity to fill in the presented gaps.

Mathematized media, maps, and highly realistic images are completed through refinement of what is presented, or through convergent conversations. These media-models present themselves as sacrosanct, and in observed practice seem to resist substantial changes. In both field studies and controlled laboratory studies we have observed that generative discussion, which makes significant change to an idea, is almost always accompanied by the production of rough ambiguous media.

Ambiguous media, such as rough sketches and rough physical prototypes, on the other hand, can be completed in many different ways; they serve as a scaffold for engineers to fill in the gaps by positing many possible formulations of an idea. They are pluri-potential objects, so to speak, and may express as variants depending on the experience and knowledge of each design engineer who works with them.

High resolution media-models afford for *parametric* adjustment, while low resolution media-models afford *paradigmatic* shifts. Thus high resolution media-models designed to reduce uncertainty constitute cognitive high pass filters, and low resolution media-models designed to promote ambiguity constitute cognitive low pass filters. Hybrid media allows design engineers to make agile shifts between parametric and paradigmatic thinking.

MATHEMATICIZED MEDIA

In “Thinking with Eyes and Hands”, Bruno Latour examines the modern way of knowing with respect to embodiments of knowledge in common use. “We can hardly think of what it is like to know something without indexes, bibliographies, dictionaries, papers with references, tables, columns, photographs, peaks, spots, and bands” [12]. These are all part of what Latour calls “immutable mobiles”, distilled pieces of information which can be easily transported, shuffled and combined without damaging the contents.

The “grammar” of immutable mobiles, which enlists lines as boundaries, is seen in the grammar utilized in maps. Maps are a prime example of how the specifics of a place can be generalized and packaged, transported and potentially acted upon from afar. This is the same grammar which can be seen at work in engineering drawings. Within the context of the framework offered in this paper, we would consider Latour’s immutable mobile as a media model with the characteristics of high resolution and high abstraction: not only are they highly refined, but they are simplifications stripped from their original context for the purpose of amplifying specific features of unparsed phenomena.

Archeologist Timothy Webmoor’s insights into the agency of maps are particularly useful in unpacking the use of engineering drawings in the engineering design process. For Webmoor, maps in particular and media in general are not neutral.

In his paper "Mediational Techniques and Conceptual Frameworks in Archaeology”, Webmoor examines how the production and use of maps conditions and restricts the thought process of the map reader. Maps, Webmoor argues, are media, and as such they carry a “message”. The map, according to Webmoor, is “a fundamental conceptual framework that archaeologists utilize in directing their methods and formulating interpretations” [20] and these frameworks “predispose certain interpretations.” In Webmoor’s view, the word “map” is considered to include, "any spatial representation conveying visual information in a strictly coordinate, graphical manner.” [20].

The purpose of mapping, Webmoor explains, “revolves around the identification of boundaries” [20]. Again, these lined boundaries, like the lines of maps and engineering drawings, characterize "knowledge". This is more than the language of disengaged, removed perspective; it facilitates the portrayal of all surfaces as abstracted and mathematized, and is associated with a knowing that is concerned with the contemplation of unchanging, immutable truths.

Maps are a necessary ingredient for navigation. The trouble is that the map is a construct, with a claim to authority because of its mathematical referencing. A map, like an engineering drawing or an equation, may exhibit compelling internal consistencies, but may not accurately refer to a real place or object. The practice of reading maps can be considered a “media-system” which encourages the reduction of local features to being secondary to the knowledge on the map. In respect to this practice, maps claim a truth of their own. They have an authority by virtue of the coordinate grid upon which illustrated boundaries are marked. Made popular by Descartes in the seventeenth century, the coordinate grid has found its place in science as the *sine qua non* of analytic tools.

Webmoor speaks of how the grammar of the map changes the nature of the phenomena it represents: "The detail of the cartographic map can often, however, elide the very feature – or for that matter, an urban or built architectural space – that it presumes to envisage in its visual conventions… Furthermore, maps, by virtue of their 'univocal scientific strategy' flatten sensory data into the restricted medium of articulated lines and create 'gaps' and 'blank spaces'" [20].

The same can be said of engineering drawings and other reductive models like CAD drawings and Finite Element Analysis software. In respect to engineering design, it is precisely within the gaps and blank spaces to which Webmoor refers, that the work of innovation is made. While CAD and FEA representations provide necessary and essential embodiment of knowledge, at the same time they parse out information which may be critical to translating idea to manufactured object.

Ambiguous mediation is not limited to sketches in the practice of design engineering. Rough physical prototypes are created, not only because they are quick and inexpensive, but because they afford many of the same benefits of ambiguous sketches. One additional characteristic of a successful rough prototype is that it generates many stories from the group. Users discuss ways in which to augment the piece; members complete the model in different ways and in different scenarios, which is to say they speak qualitatively about it.

Engineering drawings, on the other hand elicit discussion concerning optimization, and measurable aspects of the object they represent. Discussions are quantitative in nature. Engineering drawings are an abstraction: they obscure and amplify features of the object they represent. These drawings depend on the conventions of linear perspective, which is a process of homogenization which allows all elements to be combined and reshuffled like a pack of cards [12]. CAD drawings take this homogenization further by stripping away a single, unique point of view, offering virtually unlimited mathematized views through the movement of a trackball or mouse.

AMBIGUOUS MEDIA

Barbara Tversky has shown how sketches may be considered as "cognitive tools". One of the many uses of sketches is "to promote inferences and new ideas; to organize and convey information. For the former, ambiguity is productive; for the later clarity is necessary." One of the significant features of an ambiguous sketch is that it promotes creativity, "as it allows reperceiving and reinterpreting figures and groupings of figures." Furthermore, the experience of the practitioners using rough sketches is a factor governing the ability to interpret them. Experts are "more adept at making functional inferences than novices, whose inferences are primarily perceptual" [18].

This ambiguity allows for the creation of what Tversky calls "new knowledge", or new ideas [19]. This is a different knowing from that of canonical scientific knowing, which is to say the kind of knowing we do with equations. This is a process of knowing that allows for making functional inferences about potential objects. The ability to interpret and to reason based ambiguous sketches, Tversky tells us, improves with practice.

Maps, on the other hand, exhibit clarity. They "omit some information, and highlight, even distort, other information." [18]. Maps stand in contrast to rough sketches and perform different work for the creators and the people who use them.

HYBRID MEDIA

Hybrid media embody characteristics of mathematized media and ambiguous media. In a sense, media-models in this category are in the sweet spot for design engineers. Hybrid media allow several kinds of operations, and discussions.

Hybrid media include informal 2x2's, common conceptual frameworks in the Academy. Informal 2x2's are a method to compare both qualitative and quantitative data on a coordinate system. Less rigorous than 2x2 frameworks used in the academy, informal 2x2's are used with greater flexibility than a rigorous scientific graph, and used as a quick method of comparison in order to discover differences and affinities in disparate collections of phenomena. Examples of informal 2x2's include comparing hot/cold on one axis with up/down on the other axis, or graphing time on one axis with events on the other axis.

Another type of hybrid media can be seen in the work of designer Carissa Carter. Carter combines physical prototypes and rich sensory data with coordinate systems. Carter, originally a geologist, consciously uses hybrid media as a way of mixing the two ways she has learned to know: collecting and analyzing. The physical media are kin to the rock samples she collected; the coordinate system is akin to the scientific analytic tools she used to catalogue the samples. Carter's use of media in this way is an example of what archeologist Michael Shanks has termed "deep maps" [17]. The purpose of a deep map, Shanks argues, is to preserve tactile and sensate qualities of the thing or place one wishes to study.

In a manner similar to Bruno Latour's description of botanists moving plant samples around on a table to make connections and distinctions [13], Carter moves images and text around to find affinities and a way of moving forward. Unlike Latour's account of the botanist's process, in which associating the samples on a grid happens later in the process, Carter uses a coordinate grid while parsing through her prototypes as a generative method.

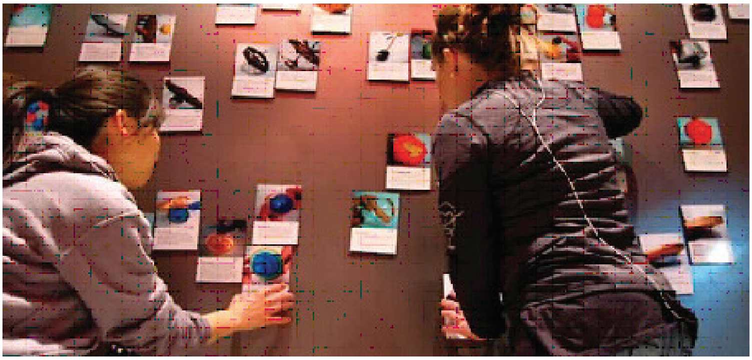

Figure 3: Hybrid media a "rich map" (courtesy of Carissa Carter)

In one representation of her exploration into spinning objects, Carter places magnet-backed photographs of prototypes along with descriptions of what she learned from experimenting with them on a wall sized ferrous sheet. Interested in developing a method for enlisting the perspectives of casual participation, Carter invites other designers to arrange and rearrange the image/text elements in order to discover latent connections between the pieces.

3.2 MEDIA-CASCADES

We define the sequence of media-models through which ideas develop and unfold in different media during the course of a development cycle as a *media-cascade*. The series of translations from media-model to media-model forms the basis of shared ground for design teams and thus drives the design process.

Figure 4: A media-cascade from student project "Simple Step Snowboard Binding"

In his book "Pandora's Hope" [12], Bruno Latour introduces his notion of "circulating reference", which illustrates the method scientists use to do the work of making knowledge from a field study done at the threshold between the Amazon Rain Forest and the Savannah. With the eye of an anthropologist, Latour shows that scientists make a chain of steps from the site to raw data to knowledge.

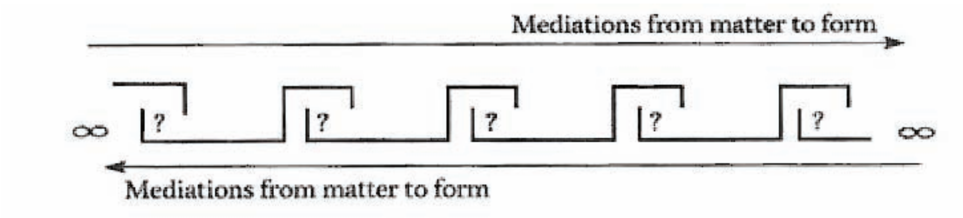

Figure 5: Latour's Circulating Reference [13]

There are gaps, Latour tells us, but they are very small gaps. Latour's chain of events moves from phenomena to knowledge in a fairly straight path. Latour eloquently unpacks the place between phenomena and a scientific paper. There is not a single chasm, but there are many small and rationally negotiable gaps [13].

Gregg Myers offers a series of images which serve as a concrete illustration of Latour's circulating reference. Myers [16] has made an excellent outline of how media is used in scientific writing in his essay "Every Picture Tells a Story: Illustrations in E.O. Wilson's *Sociobiology"*. Myers categorizes representations along a continuum ranging from "more gratuitous detail" to "less gratuitous detail".

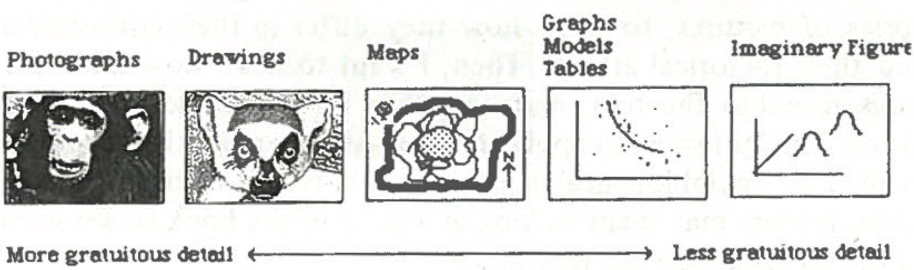

Figure 6: A media-cascade: categories of pictures in Wilson's Sociobiology [16]

In the context of the framework presented in this paper, Latour's notion of circulating reference and its small rationally negotiable gaps is but one kind of media-cascade. Design Theory and Methodology studies depart from Science Studies in that design *creates* the phenomena (a product or experience) which it then subjects to rigorous mathematical operations in order to optimize it, where as Science applies mathematical operations to existing phenomena.

Using Myers' taxonomy, the following (*Figure 7*) illustration suggests an way of thinking about how producing the phenomena (e.g.: a product) and the subsequent optimization of the product for manufacture would look like as a media-cascade:

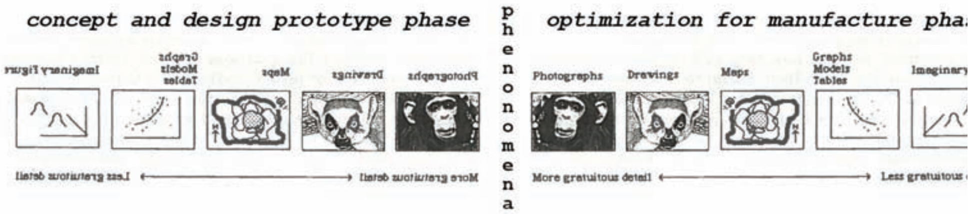

Figure 7: Extending Myer's media-cascade to encompass product design

It is important to note that successful product development in its *early or generative phases* does not seem to follow the orderly links that Latour outlines in his notion of circulating reference, which is a transit from material to what Latour calls "immutable mobiles", by which he means a two dimensional document or signifier of the original entity. Engineering design is in the business of making new things, which differentiates this practice from the practices about which Latour speaks. The path from idea to a pre-optimized object seems to resist the type of linear path that Latour uncovers. It is our belief that Latour's description does apply to the optimization phase of product development in which a pre-optimized object becomes an immutable mobile (in this case an engineering drawing, a series of equations, a data base). In any event, Latour's methodology of following the media enlisted in a process provides a model for looking at the process of engineering design.

The generative phase of product development is when the concept of a product is brought into being. In this phase, objects are not simply taken apart and out of context, to be shuffled around like playing cards, though that might be an analytic activity in which design engineers engage. Analytic thinking is only one kind of thinking in which design engineers engage, and the media which supports analytic thinking is different than the media of generative thinking.

4 UNDERLYING MECHANISMS

We would like to suggest three mechanisms, or three theoretical perspectives which form the foundation for the taxonomy of media-models and media-cascades. The first is Convergent and Divergent thinking, as outlined by research in Design Theory and Methodology. The second is drawn from Social Anthropology, and concerns two ways of making one's way in the world, Wayfinding and Navigation. The third is based on work in Cognitive Science, and looks at cognitive loading.

4.1 CONVERGENT AND DIVERGENT THINKING

The work of Ozgur Eris [5] has made a positive correlation between mixed occurrences of two types of questions design engineers ask while designing. These he terms Generative Design Questions (GDQs) and Deep Reasoning Questions (DRQs). These types of questions map to divergent and convergent thinking. GDQ's are questions which ask, "How many ways can such and such be accomplished?", and thereby inviting more possibilities for consideration. They are questions which have no concern with the logical status of a proposed solution. DRQ's are questions which reduce the number of options, and are concerned with the logical status of the proposed solution. DRQ's ask, "Is this the way to accomplish such and such?"

A recent re-examination of Eris's work has led us to hypothesize that GDQs are the result of low resolution, highly abstract media-models, and that DRQs are the result of high resolution, highly abstract media-models.

Brereton [1] has shown that team performance is improved when characterized by many movements between the theoretical space and the use of hardware. This supports the notion that innovative product development requires that the problem space develops concurrently with the solution space [4]. Brereton's framework shares a fundamental structural similarity to the work of Eris, though posits the notion that effective collaboration on a team requires multiple forays between the theoretical and concrete instantiations of a project.

Researcher Micah Lande has proposed a model which describes a movement between what he terms "engineering models" and "design models" [11]. Engineering models have clarity and are mathematical. Design models are ambiguous models, which are evocative of what can potentially be, rather than what actually is.

We propose that a healthy media-cascade is characterized by a wide range of media-models that describe a high frequency of translation between the poles of high and low resolution as well as high and low levels of abstraction.

Hatchuel and Weil have developed a logic based model of the design process in their work on C-K Theory, or Concept-Knowledge Theory [7]. Their motivation has been to help management understand the creative innovation process. In doing so, they have defined two "spaces": the "C-space" and the "K-space". These spaces are analogous to Eris's model of Generative Design Questions and Deep Reasoning Questions.

Hatchuel and Weil posit a fundamental proposition "design reasoning must always make a distinction between two related spaces: the space of concepts and the space of knowledge." These spaces are made in relation to one another; K is the precondition of C, and the contents of C can expand the set of K.

In C-K Theory movement of an idea from one space to another is called a "C-K transit" or a "K-C transit". These occur, respectively, when a concept acquires logical status, or when a concept is born. The natures of the C-K and K-C transits have neither been fully defined nor understood.

It is our belief that the nature of C-K and K-C transits can be best understood through observing the media-cascades through which designers share and communicate their ideas. The design engineer shifts perspective between these poles in order to give birth to a new product. To do this, the design engineer mobilizes different media, and implements these media through use of a grammar that embodies the implications of C-space and K-space. Often transits seem to take place incrementally in the "places between" C and K. Many models exhibit a hybrid nature, containing shades of difference, rather than being completely polarized as representative of Concept or Knowledge.

4.2 WAYFINDING AND NAVIGATION

In this paper, two types of representation that have been ear-marked as essential to design engineers: the rough sketch and the map. Tim Ingold [9, 10] discusses two methods of making one's way in the world, which are intimately bound to the sketch and the map. These methods, Ingold posits, are *Wayfinding* and *Navigation*.

The methodologies and tools of "Wayfinding" and "Navigation" suggest two paths similar to the methods and paths of design engineers. Wayfinding occurs when one walks through a landscape without a map. One relies on direct phenomenon and discussions with local inhabitants to move through a territory. It is direct, specific, and immediate. Navigation, on the other hand, requires a map. One determines where one is through consulting the map and comparing it to what one sees.

Effective engineering design process parallels the movement between Wayfinding and Navigation. When design engineers negotiate new territories, they negotiate a combination of both Wayfinding and Navigation.

Wayfinding occurs when dealing with raw, unparsed data. The rough sketches Tversky examines permit the Wayfinding of Ingold. They approximate the raw, unmathematized experience of making sense of a landscape. Rough, ambiguous sketches allow a design team to generate new, unexpected ideas; they open the possibility for serendipitous events and learning.

Navigation occurs when rigorous frameworks and optimization transport a prototype to the gates of manufacture. Engineering drawings serve as an instrument through which design engineers make sense of phenomena. The physical incarnation of a final product is brought to the world through the agency of the highly abstract, highly resolved media-models.

While it may be argued that Wayfinding and Navigation are only analogies, it seems that Ingold means them as more than such. They are two ways of acting in the world [9]. Successful design engineers have been observed to be able to do both.

4.3 COGNITIVE LOADING

The third mechanism for understanding media-models and media-cascades can be found in the work of G.A. Miller. Miller examined the limits of human capacity for processing information [15]. Miller found that when humans make judgments about one dimensional stimuli, they reach an upward limit of "seven, plus or minus two" elements. For example, in one study, subjects asked to judge auditory pitches. Data were analyzed and it was found that subjects reached a limit of identifying six different tones (or 2.5 bits) without error. Channel capacities for multi-dimensional stimuli go up considerably. When subjects were asked to make judgments about six different acoustic variables, listeners could discern about 150 different categories (7.2 bits) without error.

We propose that media-models with narrow profiles are analogous with low-dimensional sensory input. Fewer judgments about a product can be made with mono-dimensional media-models. For example, CAD models, limited to abstract geometry and dimension, present a low bandwidth of sensory data. Thus, only a limited kind of judgment can be made through the agency of a CAD model. This means that if a media-cascade is constituted by CAD models alone, the dimensionality of the media-cascade is not augmented. A design engineer may be making more judgments with five CAD models than one, but he or she is making the same kind of judgment, and is engaged in the same kind of thinking. The same can be said of media-cascades constituted of the same material, such as foam-core models.

5 CONCLUDING REMARKS

While design drawings and numeric analysis make possible both high-tech invention and mass manufactured products, they often do not express many of the qualitative elements that make a product meaningful to a user. Successful product development is dependent on the ability of a design team to employ different cognitive strategies. Insight is gained through the translation of concepts through media which embody different levels of resolution and abstraction. It is through the agency of media-models, which serve as cognitive prostheses, that the various kinds of thinking occur.

Adaptive design thinking requires both local and global context dependent choice of media-models. The aggregate series of media-models form media-cascades. The shape of a media-cascade drives the depth and the breadth of the design process. It is our belief that designers can be trained to make informed, rational, and effective choices in real time. This in turn will lead to more effective development and implementation of products, services, and software.

BIBLIOGRAPHY

[1] Brereton, Margot "The Role of Hardware in Learning Engineering Fundamentals", 1999 Ph.D. Dissertation, Department of Mechanical Engineering, Stanford University

[2] Buxton, Bill *Sketching user Experiences*, 2007 Morgan Kaufmann Publishers, San Francisco

[3] Clark, Andy *Supersizing the Mind*, 2008 Oxford University Press, Oxford, UK

[4] Cross, Nigel *Designerly Ways of Knowing*, 2007, Birkhäuser, Basel, Switzerland

[5] Eris, Ozgur "Perceiving, Comprehending and Measuring Design Activity through Questions Asked While Designing", 2002 Ph.D. Dissertation, Department of Mechanical Engineering, Stanford University

[6] Frederick, Matthew, *101 Things I Learned in Architecture School*, 2007 MIT Press Cambridge, MA

[7] Hatchuel, Armand and Weil, Benoît "C-K Theory: Notions and Applications of a Unified Design Theory", 2002 Proceedings of the Herbert Simon International Conference on Design Sciences

[8] Hutchins, Edwin Cognition in the Wild 1995, MIT Press, Cambridge, MA

[9] Ingold, Tim *The Perception of the Environment: Essays on Livelihood, Dwelling and Skill,* 2000 Routledge, London, New York
[10] Ingold, Tim *Lines: A Brief History,* 2007 Routledge, London, New York
[11] Lande, Micah Personal Communication, 2008
[12] Latour, Bruno "Visualization and Cognition: Thinking with Eyes and Hands", in *Knowledge and Society: Studies in the Sociology of Culture Past and Present* 1986 Edited by H. and E. Long Kuklick, pp. 1-40
[13] Latour, Bruno *Pandora's Hope: Essays on the Reality of Science Studies*, 1999 Harvard University Press Cambridge, MA
[14] Lawson, Bryan *How Designers Think,* 1997 Architectural Press, Oxford, UK
[15] Miller, G.A. "The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information", *The Psychological Review*, 1956 vol. 63 pp. 81 - 97
[16] Myers, Gregg "Every Picture Tells a Story: Illustrations in E.O. Wilson's Sociobiology" in S. Woolgar and M. Lynch (Ed.) *Representation in Scientific Practice*, MIT Press 1990 Cambridge, MA
[17] Pearson, Mike and Shanks, Michael *Theatre/Archeology,* 2001 Routledge London
[18] Tversky, Barbara; Suwa, Masaki; Agrawala, Maneesh; Heiser, Julie; Stolte, Chris; Hanrahan, Pat; Phan, Doantam; Klingner, Jeff; Daniel, Marie-Paule; Lee, Paul; and Haymaker, John "Sketches for Design and Design of Sketches", 2003 Stanford University
[19] Tversky, Barbara "What Does Drawing Reveal About Thinking?", 2006 Lecture for *Visualizing Knowledge Seminar*, Stanford University
[20] Webmoor, Timothy "Mediational techniques and conceptual frameworks in archaeology: a model in mapwork at Teotihuacan, Mexico", *Journal of Social Archaeology,* 2005 5(1):52-84
[21] Woolgar, Steve and Lynch, Michael (Ed.) *Representation in Scientific Practice*, 1990 MIT Press Cambridge, MA

Jonathan Edelman
Stanford University
Center for Design Research/Department of Mechanical Engineering
424 Panama Mall
Stanford, CA 94305
650 380 7056
edelman2@stanford.edu

Jonathan Edelman is a PhD Candidate at Stanford University's Center for Design Research.