Massachusetts Institute of Technology
Engineering Systems Division

Working Paper Series

ESD-WP-2003-01.18-*ESD Internal Symposium*

THE LINK BETWEEN COGNITION AND THE COMPLEXITY OF ENGINEERING SYSTEMS DESIGN

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MAY 29-30, 2002

The Link between Cognition and the Complexity of Engineering Systems Design

By John R. Williams[1]

Abstract

This paper focuses on the role of human cognition in the design of large complex systems. It contrasts the physical system that is the product of the design with the cognitive model that is used by the designer to "understand" the system. The complexity of the system relevant to the designer is a function not only of the physical system, but also of the cognitive model that the designer holds in his mind. Furthermore, the level of cognitive model available to an experienced designer depends on the state of domain knowledge. To be useful in answering the question, "How complex is this system to design?" the state of the domain knowledge available to the designer must be assessed with respect to the level at which the design problem is posed. The concept of *conceptual distance* is introduced that depends on the disparity between the present level of integrated knowledge and the conceptual level of the design problem. This "distance" is a measure of the complexity of the design task and is called the *cognitive complexity* of the design. To investigate the concept of *cognitive complexity* a model of human knowledge is proposed along with a set of graphical abstractions. It is concluded that the *cognitive complexity* of the design task is neither wholly intrinsic (a property of the system) nor wholly subjective (a property of the mind) but requires an objective evaluation of the engineering problem with respect to present knowledge. It is noted that the structure of knowledge in a specific domain can be mapped and therefore a research program can be launched to systematically determine the difficulty of various engineering endeavors.

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Introduction

Why are concepts, which were difficult to grasp during your childhood, now simple? How are tasks that once were complex to perform, now be routine? This paper addresses the nature of what makes things complex or simple, specifically in the context of the system's design. Gell-Mann [1, 2, 3] has explored what makes systems complex or simple and has coined the term "Plectics"[2]. He identifies the fact that complexity may be in the "eye of the beholder" but focuses on the metrics that arise as a system scales e.g. as the number of components or connections increases. He and others have identified over 30 definitions of complexity, the majority of which are intrinsic i.e. are attributes of the physical system. Gell-Mann treats the cognitive part of the problem and the knowledge base as a constant for a given system type and argues that intrinsic complexity measures are most relevant. In contrast this paper proposes that non-intrinsic measures of complexity are needed to explain the difficulty of engineering large systems. While the knowledge base is fixed for a given system type at a given time, the problem being posed cognitively is not fixed. It is argued that the "distance" between the cognitive level of the problem and the level of the knowledge base determines the difficulty of the design problem. Intrinsic measure of complexity fail to explain how complex systems can become simple over time while this new measure takes into account the effect of new knowledge on the design difficulty.

While the physical view focuses on the system as a collection of components the cognitive view focuses on the mental model that the designer must hold in his mind in order to reason about the functioning of the system (Figure 1). The physical view is concerned with the physics of the components so that they function in a coherent manner to produce some desired behavior e.g. the gears and cams that make up an automobile engine. The cognitive view focuses on the mental model that determines whether or not we can grasp the system's essential behavior, and whether or not we "understand" the system such that we can design it to do our bidding.

It is the cognitive model that embodies the new concepts that are generated during creative design. It is this structure of concepts that can be taught to the next generation of engineers so that design for them is simpler than that of their predecessors. In order to understand what occurs when knowledge is generated we consider in more detail what knowledge is and how it is structured.

The knowledge of a domain consists of the structure of concepts and the methods for manipulating those concepts. It is knowledge that makes systems "understandable" and brings them within our cognitive grasp. When we say that a system is complex, we are generally

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[2] The name that I propose for our subject is "plectics," derived, like mathematics, ethics, politics, economics, and so on, from the Greek. Since plektos with no prefix comes from *plek- , but without any commitment to the notion of "once" as in "simple" or to the notion of "together" as in "complex," the derived word "plectics" can cover both simplicity and complexity.

making a statement not only about the system itself but also about our state of knowledge of that system within a given context.

Here I propose that the kind of complexity that designers need to address is not an intrinsic property of the system but depends also on our domain knowledge of the system within the given design context. The knowledge required to design a given system depends on the context of the design i.e. the design goal or the functional purpose. Good designers are able to identify the crux of the problem and can selectively focus on the critical issues. This selective focus results in knowledge being required at a certain level of granularity. For example, to design an arch of bricks and mortar it is not necessary to know the structure of every grain of sand in the mortar. The information about the sand grains can be integrated into a concept of "Material Strength". Integrating concepts allow us to consider the system at some level of granularity and with some selective focus.

The mental model of the designer at this granularity determines whether the system is complex or simple to design. The difficulty depends on the level of knowledge and the design task. I call the difference between the cognitive level of the design task and the knowledge available within a domain, the *cognitive complexity* of the design. The *cognitive complexity* is neither totally subjective nor totally intrinsic, but an objective synthesis of the physical system problem and the cognitive context in which it is held.

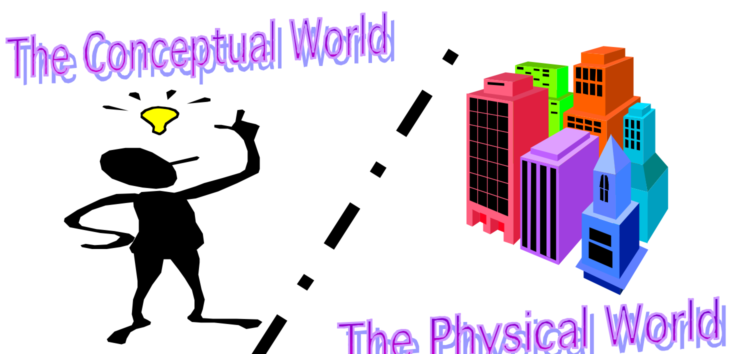

Figure 1 The Conceptual View of the Physical System

This paper addresses first the relationship between the physical system and the cognitive model of that system. The role of concepts in human knowledge is defined and a model of the structure of human knowledge is proposed. The role that concepts plays in integrating lower level concepts into a single new cognitive unit, thereby achieving unit reduction, is noted. The role of words in tagging concepts and the problem of floating concepts (concepts whose definition and meaning is unclear) are both stressed. It is then shown how lack of concepts within a domain gives rise to *cognitive complexity* because the cognitive distance between the available knowledge and the design task is large. In contrast, a mature field has an integrated set of concepts that span all the necessary problems posed by the design so that the highest level concepts achieve the unit reduction necessary for the system to be grasped easily by the human mind such that it appears to be a "simple" system. It is noted that the *cognitive complexity* of a design problem can be changed over time by creating new concepts.

The Physical System and the Cognitive Model

As engineers, our goal is to develop a vision of the world as it ought to be and to create the systems that fulfill that vision. Some systems are complex and stretch the limits of our understanding. The goal of systems engineering is to bring the functioning of complex systems with man's cognitive grasp, i.e. to make complex systems understandable, to make them simple.

The Need for Design

We, as humans, have physiological, psychological and social needs. In order to satisfy these needs we must pursue a specific goal across time in the face of obstacles and uncertainty. As conceptual beings we identify our needs and based on our knowledge of the world we generate strategies (designs) to satisfy those needs. Part of the process of satisfying our needs is called design. The product of design is a plan of action to satisfy an identified need. Design is often viewed as separate from the actual actions of satisfying the need - as a necessary precursor to satisfying the need. Design is a goal directed cognitive process which results in a plan to transform separate entities (artifacts) into a coherent whole. The core of design is the creative cognitive leap of conceptualizing how the need can be satisfied. As defined by John Thomas [4] - Design is a creative cognitive process that satisfies an identified human need by organizing artifacts into an integrated system capable of satisfying those needs.

We note that design occurs within the human mind and that it has a normative component. Although the results of design may be committed to paper or digital media (sometimes called the design or plan) these are but a concrete representation of the metal concept. Representations are important both to capture the design in a permanent form and to communicate the design to others. However, there is a distinction between the design in the mind and the design as represented by some medium, such as a drawing.

Design as Concept Formation

Creative design is the identification (conceptualization) of a new entity which has never before existed. The conceived entity has its own new identity which is separate from that of its parts.

The designer has conceptualized a new entity which behaves a certain way, which has never before existed. The design has its own new identity and often has a new word associated with it e.g. Telephone. Examination of the behavior of the individual parts does not reveal the behavior of the entity. Only when one has grasped the entity as a single integrated cognitive unit (a new concept) can one grasp its behavior. It is only then that one has created a new design. The cognitive focus of the new design is not a single entity but a whole new class of entities, as in the case of Telephones. The design document is the plan of how to bring those referents into existence. The novelty of the design can be judged by the distance of the concept from existing concepts.

Design as Component Combination

Design ultimately involves the bringing together of components in the manufacturing phase of product development. However, the bringing together of components is not the essence of design. One can develop an infinite number of new ensembles by the random combination of components. However until the creative leap of identifying the new concept occurs, the ensemble remains a conglomeration of parts. Even if one has the correct parts in the right place one must still grasp the central concept of the system i.e. one must perform the creative leap of identifying the system as a single integrated entity. Just as a pile of sand cannot be said to constitute a system, the same sand when bound together with concrete and shaped into a mould may constitute a bearing wall. The design as a system is more than the sum of the parts. It is a new integrated entity and furthermore it is the product of a new concept. Before the design the concept did not exist. Before the product was made the entity did not exist. The power of a concept cannot be overestimated. It was the concept of the *steam engine* that led to the Industrial Revolution. It was the concept of *futures* that led to the Chicago Exchange. If the concept is valid then once grasped it is difficult to see the system again as components. The components automatically form themselves in our mind into a single entity e.g. telephone.[3]

Integrating Principles

Man-made physical systems involve the reorganization of physical entities to produce some new behavior, which the individual components alone cannot produce. A man-made system is an integration of components with a characteristic behavior that serves an identified human need. The genus of the definition of a system is that a system is an integration of components. By “an integration” I mean a mental integration as well as a physical integration. For example, a natural system, such as the solar-system, simply exists. It is the human mind that identifies an integrating principle that both separates the component entities from all others in the universe, and also

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[3] Can the computer form new concepts? No it cannot. No matter how many combinations the computer spews forth they remain as conglomerates. It requires the human mind to identify the symbol shuffling of the computer as a valid system with identity. Here I reject the view of some who would identify all the combinations of components as new entities, or worse still, as new concepts.

integrates them into a single unit, namely the *solar-system*. Thus, the identification of a system consists of drawing a boundary around certain existents to include some and exclude others. This is why I identify a system as "an integration". The method by which this integration is achieved is by the cognitive process of concept formation.

Definition of System

A man-made system is an integration of components into a whole that has an identified function and behavior, satisfying a human need. Essentially a system is an integration, perhaps physical but always conceptual. - *J. R. Williams*

A man-made system is an integration of components, which has a specific behavior and satisfies an identified need. The components can be either physical or conceptual. I will argue that even in the case of a physical system, it is the associated conceptual system that is the prime subject matter of the discipline of engineering systems design. There are many examples of large scale systems for which the accompanying conceptual system is not yet in place. Indeed, the definition of large scale complex system implies a lack of the appropriate conceptual hierarchy i.e. we lack knowledge.

Knowledge

We as humans have a mind that has a definite nature and works a certain way. In particular, the mind has definite cognitive abilities and limitations. For example, it is easily demonstrated that we cannot hold more than seven to nine concretes in our short term memory. Similarly our ability to recall, and to synthesize or analyze information is limited. It is these limitations that force us to hold our knowledge in a certain form and to use it in a certain manner. We hold knowledge in the form of concepts, propositions and principles. The beginning of knowledge is our senses and from the information we receive from the senses we form percepts and then by integrating instances of these percepts together we form concepts. Relationships between concepts we call propositions and generalizations of propositions we call principles.

Naming Using Words

We perceive reality by observing it with our senses. Over a period of time we identify and set apart from the blur of sense data. individual existents. We identify particular existents as separate entities with specific identity. We have ostensive knowledge of these existents and they are called concretes. They are the base of knowledge and all higher level concepts depend upon them.

Once we have identified an entity we name it. For example, we identify a "chair" and name it CHAIR. We identify other existents with similar attributes as this chair and name them chair. The process of grouping together certain existents is called abstraction and requires identifying their common attributes. Our use of the word CHAIR at this stage refers to the group of chairs we have explicitly seen i.e. the set of chairs (Figure 2). This is an abstraction but not yet a concept.

Figure 2 Instances of Chair Leading to the Abstraction Chair

Concepts

Concepts are ultimately rooted in our identification of physical entities and the grouping of them into abstractions. As we have just described entities are identified by the human mind and are named. When we see a number of say chairs, we notice that there are some differences between them, but also some common features. We selectively focus on the common features and attribute the word CHAIR now to the whole set of chairs that we have seen. This is the abstraction *chair*. The common features may have some distribution along some metric e.g. color. Finally we recognize that there may be chairs with colors that we have not yet seen that will still be chairs. At this stage we have a "concept" of a chair. It is like an infinite series of chairs (Figure 3). Once we have spotted the pattern we can tell if a new chair belongs to the series or not. For example, consider the concept of an even number. While each of us has seen many even numbers it is unlikely that we will have seen the number 877698219876 before. Yet we can instantly recognize it as an even number because we have the concept of evenness. Thus the concept *even* condenses into a single cognitive unit every even number we have seen and every even number we have not yet encountered.

Figure 3 Concept Chair that Applies to Chairs as Yet Unseen

Higher Level Concepts

In the case of *chair* the referent is a concrete existent. Similarly *table* and *couch* are other concrete existents. Now we play the same integration game and identify commonality between these items and generate a new concept and name it FURNITURE (Figure 4). The concept *furniture* depends on the lower level concepts of *table, couch, footstool* etc. We must be careful not to confuse the definition of the word FURNITURE with the concept *furniture*.

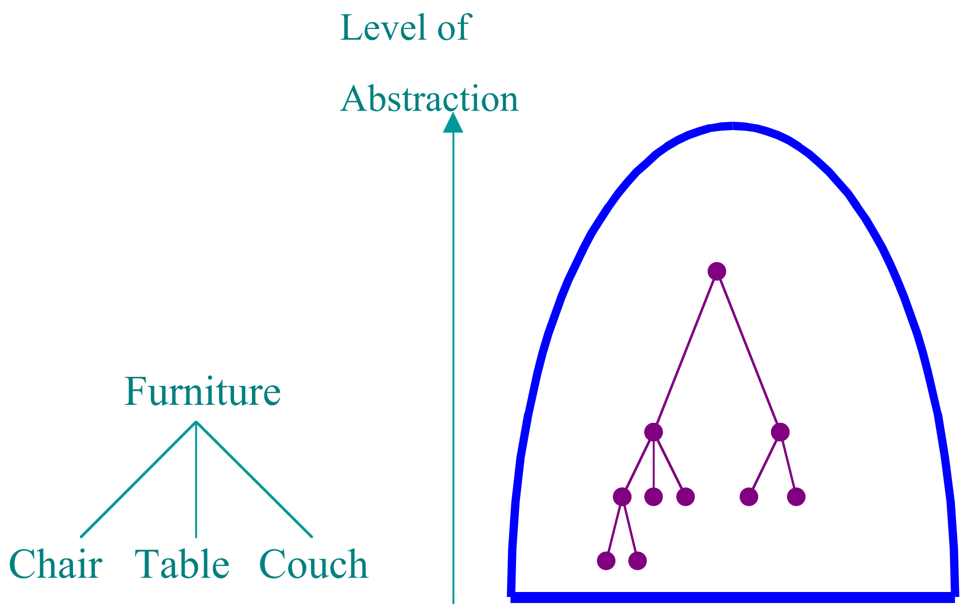

Figure 4 Graphical Abstraction Illustrating the Hierarchical Structure of Concepts

The act of identification is fundamental to all knowledge. Knowledge creation IS identification. It involves the identification of a new concept that subsumes other concepts or concretes.

As defined by Rand [1] - A concept is a mental integration of two or more units, which are isolated by a process of abstraction and united by a specific definition. By organizing his perceptual material into concepts, and his concepts into wider and still wider concepts, man is able to grasp and retain, to identify and to integrate an unlimited amount of knowledge, a knowledge extending beyond the immediate concretes of the given, immediate moment. …Man retains his concepts by means of language.

Words as Tools of Thought

We as humans use names (words) to stand in place of concepts. However, when we do this we must be careful about the difference between 1) the word itself as a tag, 2) the definition of what the word means and 3) the concept for which it stands. The relationship between the word, its meaning and the referent was discussed by Ogden and Richards in The Meaning of Meaning [2].

"Between a thought and a symbol causal relations hold… When we hear what is said, the symbols both cause us to perform an act of reference and to assume an attitude which will, according to circumstances, be more or less similar to the act and the attitude of the speaker. .Between the Thought and the Referent there is also a relationship; more or less direct (as when we think about or attend to a colored surface we see), or indirect (as when we 'think of Napoleon'), in which case there may be a very long chain of sign-situations intervening between the act and its referent: word - historian - contemporary record - eye-witness - referent (Napoleon). "

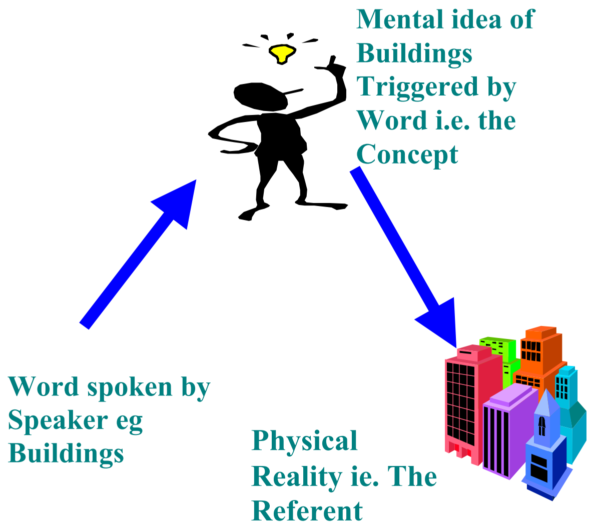

Figure 5 Relationship between Words (Symbols), Mental Concepts and the Referent of the Concept in Reality

The symbol stands in place of the concept and triggers the concept in the mind of the listener (Figure 5). The definition of the symbol allows us to focus on certain characteristics of the concept that distinguish it from other concepts. However, the definition is not equivalent to the concept and cannot stand in place of the concept in reasoning. Similarly there is no direct relationship between the symbol and the referent other than through the mind of the human. This is why all knowledge is knowledge processed by the human mind. The physical representation of that knowledge in books or as sound waves in speech is only the tag for the concept. Thus we arrive at the critical difference between information and knowledge. Information is the physical symbols that we write in books or store in the memory of the computer. While we often talk about books as holding knowledge this is not correct. Books contain symbols (physical pages with typed words for example) that when read by the human can be interpreted as concepts and made into knowledge. It is these active concepts in the mind of the human that are knowledge.

The Role of Definitions

When we use the word (symbol) for man ie MAN, as typed on this page we recognize that it stands in place of something else. The question is, “Does it stand in place of the definition of MAN?” or “Does it stand in place of the concept man?” The two are NOT equivalent and the confusion between the definition and the concept has led to seeming contradictions in the field of philosophy.

When we define an entity we do so in terms of the attributes that set it apart from other entities under consideration. The general class of entities is the *genus* and the defining characteristics are the *differentia*. Thus, when we say that man is a rational animal, it is the attribute of *rationality* that we focus on in order to separate man from the general class of all other *animals*. However, all the other attributes of man, such as the fact that he has two eyes and two legs, still exist and should be held cognitively as part of the concept of man. Kant and others have confused the definition of a concept with the concept itself by making them equivalent. The definition is NOT equivalent to the concept and the definition cannot be used in place of the concept. [4] The word MAN typed on this paper or held in computer memory is NOT the same as the concept of "man" that you hold in your mind. This distinction resolves many problems in philosophy including the famous Analytic, Synthetic Dichotomy of Kant and also the problem caused by the Rationalists.

The purpose of the name MAN is that it stands for the concept man in your mind. The symbol MAN is used by your brain as a shorthand tag for the total concept. You do not need to hold all the attributes of man in your mind and the word acts to reduce the number of units on which you focus. In this way words are used as a tool of thought. Indeed, WORDS are man's main TOOL of THOUGHT. To the extent that you know what the words you are manipulating in your mind mean, your thoughts will be precise and clear. To the extent that they refer to fuzzy concepts your thought will be blurred and non-functional.

Methods of Building Knowledge

The building of valid knowledge is not an automatic process for humans. We often make false integrations that lead to invalid concepts. Therefore, we need a strict methodology to determine if concepts are valid or false. Invalid or false concepts can pollute our ability to think. For example, the concept of Value proposed by Karl Marx is that value is an intrinsic property of the commodity and depends on the amount of social labor that has been "put into" it[5]. This concept led to his whole theory of economics and possibly to a disastrous political system. Once accepted into one's knowledge, false concepts can cause havoc with one's thinking. Therefore, man must take care about the process of building knowledge. In particular, we must be fastidious about our concepts and about our definitions of those concepts. In order to build one's own knowledge so that it is coherent with reality and internally consistent one must apply a rigorous method – the method of reason. Reason here means non-contradictory identification as captured by the Law of Identity.[6] Only knowledge gained by a rational process of observation, integration, concept formation and deduction can be relied upon to be valid. However, even this framework there is considerable room for inventing new methods of knowledge synthesis and knowledge analysis.

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4 This last point is critical in understanding why computers cannot hold concepts and cannot think. The concept exists within the human mind. The word or tag that identifies the concept can exist in the computer but the word is not the concept.

5 What is the common *social substance* of all commodities? It is *labour*. To produce a commodity a certain amount of labour must be bestowed upon it, or worked up in it. And I say not only *labour*, but *social labour*. Karl Marx, Value, Price and Profit – Address to the Working Men, *The First International Working Men's Association, 1865*

6 The axiomatic law of identity, A is A, implies existence of A, implies that it is an entity, implies the law of causality that A will behave in accordance with its identity, and implies the invariance of A in that its essential characteristics will remain constant throughout time.

In the context of design the normative problem has received little attention.

Immature and Mature Knowledge Structures

The problem of concepts (Universals in Plato's language) is the subject of much of philosophy and obviously I do not have room to cover it in depth in this paper. However, even from the brief outline given here we can make certain statements about knowledge structures that have implications on the design of engineering systems.

1. The human mind has certain cognitive attributes and limitations that require knowledge to be held in a definite form and acquired by a definite method.
2. The base of knowledge is the identification of physical entities (concretes) via our senses.
3. Abstractions and concepts are formed by selective focus on the essential attributes of a class of entities and giving it a name.
4. The naming of concepts (words and language) is man's means of holding in memory his conceptual knowledge. It provides a method of unit reduction necessary to overcome our cognitive limitations.
5. Language is a tool of thought as well as a tool for communication. To think clearly we must know what words mean. i.e. we must clearly define our concepts.
6. Knowledge is hierarchical, with higher level concepts built upon lower level concepts which ultimately are built upon ostensive concretes.

Knowledge in a mature field is well structured and the hierarchy is clearly defined. A mature field will have higher level concepts and principles that integrate the domain such that the human can grasp the whole field at once. For example, the concepts of stress and strain tensors in mechanics integrate together a long string of lower level concepts that are based upon the displacement of a point relative to another point.

An immature field has many low level concepts that may appear contradictory or seemingly unrelated (Figure 6). There will be lists of facts and cases that are not yet integrated under any central principles or concepts. There may be high level concepts that appear to be "floating" in that they are loosely defined and unrelated to lower level concepts.

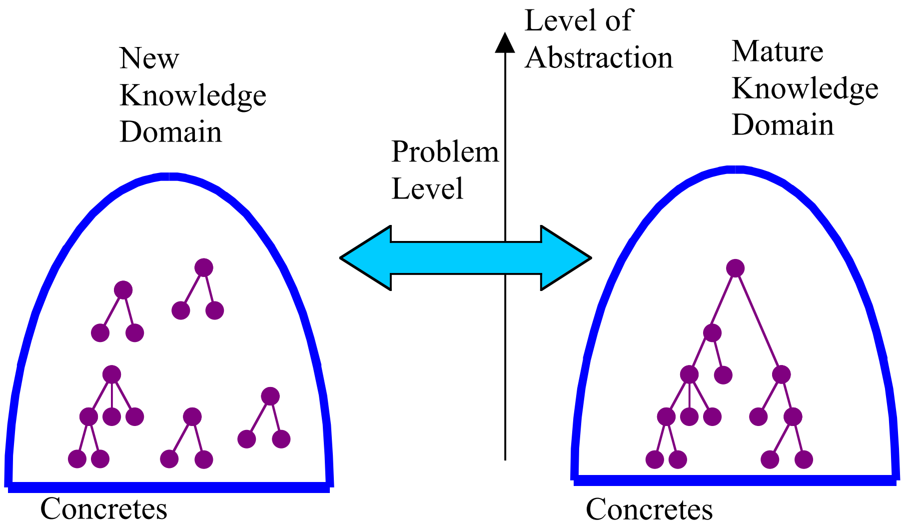

Figure 6 Graphic Abstraction of a New Field and a Mature Field of Knowledge

Immature systems will be difficult to grasp cognitively and there will necessarily be some divergence of opinion as to the organization of concepts in the field.

The mapping of knowledge domain can be accomplished as shown by Paul Thagard in his seminal work called Conceptual Revolutions [3]. In this he maps out the concepts and links involved in several knowledge domains, including chemistry (Lavoisier's theory) and the Copernican revolution of planetary motion. John Thomas in his MIT PhD thesis also maps out how innovation occurred in the shift from Euclidean to Non-Euclidean geometry and the main concepts behind the steam engine [4].

Defining the level at which a problem is posed is part of the design process. To some extent the designer is free to pose the problem at a higher or lower level of abstraction. Nam Suh illustrates the importance of posing the design problem in his book on Axiomatic Design [5]. In this he exploits Louis H. Sullivan's[7] famous edict "Form follows Function" to break the design process into two (or more) spaces, the first being the "What" and the second being the "How". The normative process (the "What") has received little attention in design, yet it is arguably the primary. It is the "What" that determines the level of conceptual difficulty of our task. An example of changing the level at which the problem is posed is illustrated by automobile design.

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[7] Louis Sullivan was born in Boston, Massachusetts in 1856. He studied architecture at the Massachusetts Institute of Technology for one year.

It is quite straightforward today to design a car to safely transport people. However it is not easy to design a car that is “socially responsible”. This latter problem involves the concept of “societal responsibility” which is a very high level concept[8] related to the ethical concept of “the good”. The problem of creating a coherent body of knowledge that encompasses these concepts so that they can be related to system design is formidable. However, we have an outline of the steps by which we must proceed if such designs are to be made “simple”.

The method to simplify a complex system is to build knowledge about it by inventing new integrating concepts. These concepts will be identified by new words. The mark of an active field in which knowledge is being built is the appearance of new words. As discussed above there is a kind of Occam’s Razor in that concepts should not be needlessly multiplied. However, I am sure that the next years we will see powerful integrating concepts emerging in the field of Engineering Systems.

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[8] These and other concepts are ill defined and philosophically depend on Bentham’s Hedonic Calculus