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Archstand Theory of Design for Innovation: 
The Integration of Design and Innovation Using 
Conceptual Architectures

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Abstract

There has been a steady and systematic growth in the research efforts focused on the fields of Design 
and Innovation since World War-II. Early days of design inquiry were restricted to the echelons of 
Architecture and Industrial Design. But today, the debate on design has been joined by almost every 
other applied field. Similarly, the study of innovation used to be primarily historical and biographical 
in nature. But today, the problem of innovation is no longer a matter of history; it is increasingly 
viewed by various management schools as something to be deliberately and strategically engineered. 
In all of this effort, seldom has the question been asked: in what manner is design related to 
innovation? How might one identify designs and design problems that may lead to the fundamental 
shift we call innovation? Is it possible to back-integrate and design for innovation?

Proposed is the Archstand Theory of Design for Innovation. It is a comprehensive theory on how 
innovations occur; and how one might pro-actively design and plan for it. Radical innovations are 
accompanied by major shifts in domain knowledge architectures. In order to bring about this shift, 
one needs an integrated external perspective (or the archstand) from where to architect this shift. For 
otherwise, one neither grasps the totality of change that is sought, nor systematically plans for it. 
The title archstand is in honor of Archimedes, the Greek mathematician who had proposed a similar 
approach for the discovery of mathematical theorems.

Design for innovation involves mapping the underlying cognitive processes onto a common frame-
work: the cognitive framework of knowledge architectures. This framework is validated in the context 
of the non-Euclidean revolution in geometry. Various other scientific/architectural revolutions and 
business/financial innovations are studied in order to glean the operative principles. From our stud-
ies we induce out the three fundamental approaches for establishing the archstand: the inductive, 
the abductive, and the integrative.

As an exercise in design for innovation, we apply the framework in the context of Construc-
tion Automation. The proposed archstand here is to re-engineer construction from a manufacturing 
perspective.

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Professor of Civil and Environmental Engineering

Date of Defense: July 7th, 1994
δόσ μοι ποῦ στῶ καὶ κινῶ τὴν γῆν.

Ἀρχίμηδης
Acknowledgments

The research reported in these pages is the distillation of ideas generated from numerous meetings, debates and discussions I was privileged to take part in, during the past five years of my doctoral work. These discussions have ranged from the esoterics of ancient philosophy, to the implementation details of multi-robot construction automation systems. It is thus with sincere pleasure that I acknowledge the various contributions.

Looking back, I know this research would not have been feasible without the constant support and guidance from my doctoral committee. For given the nature and scope of the problem at hand, it requires a unique renaissance frame of mind to range over the wide-band spectrum of issues that were unearthed during the course of the work. And all along, there has been a vision that has been driving us, a vision that attempts to do justice to the critical and central function that design plays in the realm of human action. Design is all encompassing. Even philosophy reduces to a problem of design. To thus provide a conceptual framework that renders the process of design legible is fairly substantial in scope. Given the scope of the research at hand, full credit goes to my doctoral committee for having provided me the needed focus and constant feedback through various one-on-one discussions and soul-searching committee meetings:

- Prof. John Williams (my supervisor and committee chair) has been both my mentor as well as philosophic companion throughout my research. During this period we have had more than a hundreded one-on-one hour-long sessions, with theoretical discussions ranging from design theories (such as Louis Sullivan’s Organic Design Theory) to philosophic theories (such as on Aristotle’s aesthetics. Immanuel Kant’s analytic-synthetic dichotomy, and Prof. Paul Thagard’s critique of the Kuhnian paradigm shift); with applications ranging from design analysis of common household utilities to large-scale software design. Throughout the vicissitudes of a long drawn out doctoral research, the sheer equanimity, leadership and good-will that Prof. Williams has projected has been a constant source of strength. But it is his passion for understanding things first-hand that has been most inspiring.

- Prof. Jerome Connor provided me with the grand vision of how one might transform and modernize the construction industry by re-engineering it from a manufacturing perspective. For in many ways, manufacturing has already pushed ahead and staked out technological leadership in areas where construction is today moving towards, namely mass-customization. It thus behoves us in the construction industry to study this emerging trend. My research on the Self-Articulating Formwork (SAFO) Cell approach to construction automation is a projection on this theme. Many of these ideas were conceived during Fall 1993 when I was given the privilege to co-teach with Prof. Connor, the graduate-level course on Large Scale Systems Engineering (1.964).

- Through his inspiring and commanding lectures. Prof. Nam Suh initiated my
interest (as well as a legion of many others) in researching the problem of design. It has been a unique privilege to work under such a visionary leadership. He has provided us many of the fundamental and enduring insights into the design problem. For example, throughout the thesis, one may notice the ample use I have made of Prof. Suh's design matrix approach in analysing various designs.

- Through his research seminars and lectures at Sloan School, Prof. Stephan Schrader provided me my first insights into the problem of management in the realm of technological innovation. Without this management context, I would have been hard-pressed in inducing out the unique focus of the research reported herein (namely, the integration of the design and innovation processes). Also having helped me articulate the inter-disciplinary research problem, Prof. Schrader has been fundamentally instrumental in shepherding me through the uncertainties of inter-departmental research. Without his constant support and timely feedback, the inter-disciplinary thrust of this research could very well have been abandoned.

Considering the above, it is no exaggeration to state that the research reported herein has truly been a team effort. I have been extremely fortunate to enjoy the exceptional stewardship and fellowship of my doctoral committee.

At the institute level, this research was conducted as an inter-departmental doctorate between the Intelligent Engineering Systems Laboratory (affiliated with the Department of Civil and Environmental Engineering) and the Sloan School of Management. Much of the credit in helping me structure the logistics of the research goes to Prof. Frank Perkins (Dean of Graduate School). Dean Perkins provided me the morale for the initial go-ahead of the inter-departmental research as well as the final logistics for my defense. Also at a more personal level, through our various meetings, Dean Perkins provided me the needed perspective to help me successfully weather the inevitable "ups-and-downs" of such an undertaking.

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Michael Dickens, Director of GE spinoff IBACOS (Integrated Buildings and Construction Systems) has been exceptionally supportive in helping me appreciate first-hand the mammoth problems of setting up a strategic alliance (between major manufacturers, architects, developers, and code bodies) dedicated towards bringing technological innovation in the housing industry (i.e., mass-customized housing) by tapping into the modern manufacturing/information system technologies. Through our various meetings (some of them lasting a whole day) Michael has instilled in me an appreciation for visionary leadership. In many ways, the archstand approach to innovation is also an approach for explicating a vision, both at the personal as well as
at the corporate level. Furthermore, my interaction with the whole IPACOS team (Brad O’Berg, Andrea Sciolla, Richard Rittleman, Naomi Yoran, Jennifer Fry and others) during the summer of 1991 has been exceptionally productive. It is during this phase that I had the opportunity to intimately observe first-hand the actual process of design both, at the the product as well as the organizational level. This included more than 24 hours of taped interviews elaborating on the various aspects of design.

It was Ms. Naomi Yoran (of the IBACOS team) who introduced me to Prof. John Habraken’s (former Head, Department of Architecture at MIT) pioneering work on the SAAR methodology. I have benefitted enormously from my personal interaction with Prof. Habraken. Having studied his approach (under the guidance of Prof. Eric Dhulosh) it is my conviction that the SAAR approach has much to offer in the context of mass-customization.

In the context of philosophy, I have drawn enormously on the works of late philosopher/author Ayn Rand and her intellectual heir Prof. Leonard Peikoff. Throughout my intellectual career, I have benefitted tremendously from the aristotelian rigour that Rand has brought into epistemology. The very idea that human knowledge has a definite human purpose and thus a definite architecture (i.e., the knowledge hierarchy) is of enormous economic value. For it provides fundamental insights into the problem of integration of human labor (the default branch in economics) which is the needed corollary to Adam Smith’s division of labor principle. Also Rand’s work on the “function” of aesthetics has been of great value in addressing the missing links in Louis Sullivan’s Organic Theory of Design. Furthermore, I have put to good use Prof. Peikoff’s essay on “The Analytic-Synthetic Dichotomy” in analysing Prof. Thomas Kuhn’s work on the epistemological process of scientific revolutions. Without these philosophic insights, I would have been hard pressed in making the proper conceptual integrations. I should nevertheless like to add that the research reported in this thesis in no way has the endorsement of the Ayn Rand estate.

I have made good use of Prof. Paul Thagard’s (cognitive scientist/philosopher from University of Waterloo) work on “Conceptual Revolutions”. The inferences that Prof. Thagard makes closely parallels my own work; however there are differences given our contrasting philosophic outlooks. But the greatest benefit I have received from Prof. Thagard’s work is his intellectual leadership in debunking the Kuhnian paradigm about paradigm shifts. I should also like to add that Prof. Thagard has been kind enough to loan me the software (ECHO/PI) that he has used in validating some of the research in “Conceptual Revolutions”.

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In the context of my budding research in Financial Engineering/Innovation, I am exceptionally indebted to professors John Heaton, John Cox and Jian Wang. Course work under them as well as one-on-one discussions have helped me cast the problem of Financial Engineering/Innovation from a design perspective.

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Chapter 1

Summary View

1.1 Introduction

This chapter provides the overview of the theory to come. We start off with generic definitions of design and innovation. We then show that human knowledge has a fundamental hierarchy. This could be part-hierarchy, kind-hierarchy or propositional-hierarchy. Using our grasp of the knowledge hierarchy, we then define (in a loose sense) what we mean by the terms innovation axis and innovation midwife. Then we set forth a full description of the cognitive processes of design. By mapping the design process against the knowledge hierarchy we are able to look at the microstructure of the design process. We also show how we might integrate Prof. Nam Suh's axiomatic approach [Ref. 1.2] into our design process map. Here we focus on the usefulness of the design matrix as well as those design principles especially useful in the context of innovation. These preliminary exercises will prove extremely useful; for they provide us the needed tools to later on integrate design and innovation from a cognitive perspective. We also sketch how to integrate the functional with the aesthetic aspects of design. With this in place, we now have for the first time, a complete theory of design.

We then sketch the archstand theory of innovation. This is the central thrust of the thesis. We briefly sketch the three fundamental approaches towards establishing the archstand (namely, the inductive, the abductive and the integrative). Having done this, we then integrate the design and the innovation theories.

The objective of this thesis is threefold:

1. To provide a conceptual framework to study the problem of design for innovation.

2. To validate the framework using historical examples.

3. To show how one might apply the design for innovation framework in the context of construction automation.

The prime motive of this research is to attempt and overcome the research lacunae that exists between the fields of design and innovation. It is the authors firm conviction that these two critical and burgeoning fields are fundamentally related and
could thus benefit from significant amounts of cross-fertilization. The framework we adopt is a cognitive, conceptual approach to study both design and innovation. We shall thus be using the nature and the structure of knowledge in framing both the problem of design as well as innovation.

During the course of our research we shall be drawing substantially upon historical examples to chart our course. Design and innovation are fundamentally human endeavors. These activities depict the way we, during the course of our long and tenuous history, have tried to overcome the fundamental limits that nature imposes upon us. By its very nature, our problem then demands that we cast it in the historical context.

1.2 Definitions

First of all let us try and define what we mean by design and innovation. While the definitions we set out with are bound to be approximate and tentative, it would nevertheless help us approach the problem systematically. Later on, having introduced the full scope and process of design and innovation, we may then modify our preliminary definitions to reflect the richer context.

As it is used today, the word design could mean either a noun or a verb. In the former case it is the end result or the final product that captures the plan or intend to make something: for example the set of blue prints that an engineer submits for construction. In the later case it is the very process of creation that is the focal issue, the process which finally results in perhaps the set of blue prints. Every process occupies a certain space and time. Design is a creative cognitive process. Its root locus is the human mind. Greater the planning and foresight involved in actualising a given artifact, greater is the element of design. It is thus the thought process that precedes the realization of the artifact that is the target of inquiry. The ability to conceive and rearrange natural elements is the basic creative power that man possesses. On one hand the design space is as broad as all of existence. On the other hand, the design space is limited and bounded by the laws of nature. As Francis Bacon rightly grasped: Nature to be commanded must be obeyed. Design thus involves understanding the operative natural laws that are involved within the given design context. Greater the understanding of the natural laws operative within the design context, more deliberate is the design.

But what defines the scope of the design context? To understand this one has to look into the causes for design. The act of design is undertaken for a definite human purpose. It is this final cause that sets the overall design context. But the final purpose is also not a given. This too has to be teased and induced out from the underlying raw experience that provokes it. Thus the need for food is first perceived as a pain. It is only then conceived as an abstraction namely, food when integrated with other similar experiences. The difference being that at this stage, it is not any specific food item, but food in general. It is this level of abstraction that provides the richness of a given design context. Thus the process of design also involves the act of abstraction that defines the problem of design. Higher the level of abstraction
reached in a given problem context, richer is the design context that gets established.

Transformation of an abstract human need into an artifact that overcomes that need is not a straightforward process. For at the crux of this is the element of human creativity that fundamentally distinguishes one design from another. Making the conceptual link between the abstract human need and the thematic design solution is an inductive step which lies at the root of the total design process. It is inductive in the sense that the proper thematic relationship between appropriate elements from the design space has to be mentally brought together into a comprehensive, integrated whole. Such an inductive, creative leap is intellectually the most demanding step during the entire process of design. It is intellectually demanding in the sense that it requires the designer to mentally stretch and encompass the overall context of the design problem as well as the design space and integrate between the two. Many of the sub-elements that jointly constitute the designer's ability to synthesize may be reduced to a collection of habits of thought the designer judiciously cultivates over a period of time. Certain of these habits are generic, others are domain specific (for example, the ability to spatially visualize amongst architects and other such designers). Study of these mental habits come under the purview of psycho-epistemology [Ref. 1.15]. It is the authors conviction that the greatest advances in the field of design will come from developments in this area. To the extend that the psycho-epistemology of habit formation (in the context of design) can be explicated and understood, the mysterious and enigmatic element of human creativity (which is at the core of the design process) may also be rendered legible. The end result would be to show that these habits of thought can be learned: or that "creativity" can be taught. Habits such as memory, focus, ability to integrate, ability to analyse, ability to visualize, ability to draw wide ranging analogies (which itself is built on a well organized memory), these and other such "designerly" habits probably constitute majority of what we mean by creativity. On account of resource limitations, we unfortunately will have to leave these intriguing speculations outside the scope of the current thesis. Our main focus is on linking design to innovation. However, in our final chapter on Research Directions, we shall be sketching the role of Cognitive Tools [Ref. 1.1] in developing such mental habits.

To summarize our preliminary findings on design:

1. Design is a creative, cognitive, goal-directed mental process.

2. It involves abstracting the problem statement from a given problem context.

3. Higher the levels of abstraction reached in a given problem context, richer is the design context that gets established.

4. Greater the understanding of the natural laws operative within the design context, more deliberate is the process of design.

5. At the root of the design process is the inductive, creative leap which spans across that which is (the how)\(^1\) to that which ought to be (the what).

\(^1\)The what and the how is in reference to Prof. Nam Suh's work on Principles of Design [Ref.
By focussing on its essential nature, design may thus be defined:

Design is the cognitive thought process that transforms abstract human needs into an organization of artifacts that satisfy those needs.

Here the genus is the cognitive thought process. The root locus of design as a process is the human mind. Design is a kind of mental thought process. To differentiate design from other kinds of thought processes (such as reminiscence), we provide the differentia namely, that it is a kind of goal-directed thought process: it transforms abstract human needs into an organization of artifacts that satisfy those needs.

Note that we have not included all the various facets of the design process that we earlier mentioned (such as problem abstraction, understanding of the laws operative in the design space, etc) in choosing the differentia. We have instead focussed on the fundamental character of the design process namely, that it involves a certain transformation, an inductive creative leap across that which is (the how) to that which ought to be (the what). Whenever we see that a normative link is being made, we may conclude that design is taking place. Note the placement of the words abstract human needs. Why abstract? And why human needs? We emphasize the word abstract because we wish to differentiate the conceptual approach to problem solving that is involved in design as against sensory or perceptual approaches one might find in lower order living entities. Why the emphasis on human needs? Why not non-human needs? After all when we design a dog-kennel, are we not trying to meet the needs of a dog? True, but ultimately even this refers to the wishes of a human dog owner to shelter his or her dog. By acknowledging that the design is organized around some human need, we are able to teleologically link the design process to an agent. What this gains us is the identification of a prioritizing valuer from whom we may elicit answers to the our questions while undertaking the problem of problem abstraction. Note also the words organization of artifacts that satisfy those needs. The end result of design is an artifact in the sense that it is not an organization occurring naturally in nature; it is a product of artificial character brought together by some human agency. We do not however specify whether it is a mental, a physical, or a social artifact. It could be either of these. Thus the conceptual organization that a teacher provides in order to help the students assimilate a given material may be considered as the design of a mental artifact. So also the putting together the constitution of a country would be an exercise in the design of a social artifact. We make these clarifications in order to show how vast the actual scope of design is. In the technical world, design has been too narrowly associated with only physical artifacts. It is important to make clear that design may involve physical, social, as well as mental artifacts. Finally, the word organization captures the fact that the design artifacts have been selected and placed into a causal relationship with one another in order to provide the function that has been asked for. This organization is the key inductive element in design. This completes our preliminary sketch on design. Later on we shall make even more precise the overall process of design.

1.2]. Using Prof. Suh's terminology, the inductive leap is from the physical domain to the functional domain. Prof. Suh's work is reviewed in Sec. 1.2.3 and Sec. 2.4
Before we turn to the problem of innovation, let us compare our definition with that in the Oxford English Dictionary [Ref. 1.16]. The OED is extremely useful in this regard on account of the etymological trace it provides. In the OED, design is defined both as a verb as well as a noun substantive:

1. **Design as a Verb:**
   (a) To form a plan or scheme of; to conceive and arrange in the mind; to originate mentally, plan out, contrive.
   (b) To have purposes or intentions (of a specified kind).
   (c) To intend to start upon a certain course; to mean to enter upon a pursuit.
   (d) To sketch, delineate, draw; to fashion artistically.
   (e) To make the preliminary sketch of (a work of art, a picture, statue, ornamental fabric etc); to make the plans and drawings necessary for the construction of (a building, ship, machine, etc), which the workmen have to follow out.

2. **Design(n) as a Noun Substantive:**
   (a) A plan or scheme conceived in the mind and intended for subsequent execution: the preliminary conception of an idea that is to be carried into effect by action; a project.
   (b) In weaker sense: Purpose, aim, intention.
   (c) The thing aimed at; the end in view; the final purpose.
   (d) A preliminary sketch for a picture or other work of art; the plan of a building or any part of it, or the outline of a piece of decorative work, after which the actual structure or texture is to be completed; a delineation, pattern.

Clearly our definition of design as a verb comes close to the first OED definition which emphasizes the cognitive locus of design. The element that is missing in the OED though is the normative transformation between the what and the how. The definition of design(n)\(^2\) as a noun substantive parallels our basic thought on this; in fact we shall use the first OED definition to define design(n).

We now turn to the problem of innovation. The business of innovation is to bring about change (both social as well as technological). And hopefully it is for the better. More fundamental and lasting the change that is wrought, greater is the innovative content. Every innovative process involves a certain element of design at its root, and also throughout its process. To the extend that the problem abstraction for the innovative design is geared towards the innovative shift, one may say that we have evidence for design for innovation. To the extend that it is fortuitous, we may adduce

\(^2\)In the rest of the thesis, whenever we use design as a product (a noun), we shall indicate it such:design(n): otherwise design means design as a process.
that the process of design stands independent of any future innovative developments. The focus here is on designs that eventually lead to a fundamental innovative shift regardless of whether or not it was attempted with an eye towards innovation. Thus we leave out designs that are of routine nature, except when we use them to serve as illustrative examples of design qua design. Depending on whether the innovation is deliberate or fortuitous with respect to design, we might expect different innovative tracks (at least in the initial stages). In the former case we would expect to see a certain element of surprise and lack of preparedness in the protagonists. In the later case, the innovators have made provision for the scale up that the innovation brings about. It is difficult to make the above distinction using history; for the design rationale that precedes the design is often not documented. But our purpose is not primarily to judge between deliberate and fortuitous innovators in the past; our purpose is to assist the process of deliberate innovation in the future. To put it differently, we wish to back-integrate innovation with design.

What distinguishes a radical innovation (such as James Watt’s Steam Engine) from a routine innovation (such as the Clap-On: the light switch that is triggered by a hand clap3)? This question has troubled researchers and technology forecasters for some time. It is easy to distinguish between them after the fact, i.e., one leads to a fundamental shift in the market, the other is (when marketed) integrated and assimilated into the current market framework. One causes major disruptions in the economic fabric of a given society; the other builds upon and enhances the current order. By designing a cheap source of mechanical power, James Watt provided the means by which England could take the lead in mechanizing various production systems, thus transforming the economy from largely a home-manufacturing base to that of large-scale factory production. From a historical perspective, this is the singlemost invention that epitomises the birth of the Industrial Revolution. In contrast, the Clap-On is a device that presumes and builds upon the electrical systems it provides an added control over. It does makes obsolete a certain amount of wiring by allowing the physical switch to be integral with the electric unit. But it might have a limited market demand in the sense that any extraneous noise could shut down the electric unit. It would thus probably be limited to a market segment that finds enough novelty and value in the design to tolerate or avoid noise triggered events.

Design and innovation correspond in many ways, except that innovation has an added shift factor associated with it. Just as design has its function-driven normative aspect, so also every innovation has a function driven normative shift associated with it. The shift corresponds to the before/after difference in how well the normative function is being met. In an economic context, usually the normative shift is measured in some order-of-magnitude scale difference in an economic metric (such as profits or revenue). Again, just as design has its artifact organization or architecture, so also innovation has its artifact architectural-shift associated with it. We shall make these terms clear with our two examples.

From the perspective of a business historian, both the Steam Engine as well as the Clap-On designs produce change. The difference though is in the scale and architec-

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3Distributed by Joseph Enterprises, San Francisco, CA-94104.
tural nature. One brings about massive changes; the other at best is merely a ripple. One is fundamental in nature; the other is peripheral. In order to detect the scale and fundamentality of change that is wrought by the design, first one has to map the scale and architecture of the economy (or some other underlying context) under consideration; then one has to plot and see the scale (or level) and architecture of the economy after the change. The economic context provides a viable foil to judge the scale and architecture of industrial innovations. For example, in the case of the Watt’s Steam Engine, the shift might be characterized as:

1. Background Context: British Economy.

2. Level of Analysis: Motive Power within the Production Systems of the British Economy.


4. Normative Shift (scale): payoffs from home-manufacturing versus large-scale factory production.

Actually there are five levels of analysis within this context (Fig. 1.1). At the base is the British Economy or Political Order that supports the economic activity such as the one under consideration. At the next level we have the various firms that are engaged in production of various goods. At the next level we have the production processes (which is the level of analysis at which Watts Steam Engine is situated). At the next level we have the product level (such as textiles and other goods). The markets are at the outermost level and are formed when citizens operating within the given economic/political context agree to exchange goods. It is rare to find an innovation that can penetrate more than one level. Watt’s steam engine was so tremendously rich in its innovative content that it could actually shift the whole of the British economy. Thus from the perspective of say a business historian, Watt’s Steam Engine brought about a change that was significant both in scale and fundamentality.

As we have seen, implicit in this approach is an assumption about the structure of the various inter-relating systems (be they physical, conceptual or social) wherein we wish to detect and study the innovative shift. Here the word context designates the embedding system; level designates that part of the system which is under focus for study. Thus implicit within the definition is the hierarchy between the embedding systems and the systems under study. Before we establish such inter- and intra-system relations, we need to specify the basis for such a classification. For example, in the James Watt case, suppose the basis to be foundational dependency, i.e., what needs to exist before something else can be built on it? Thus we might say we need to have a certain amount of economic freedom in the political architecture of a country before industrial firms can be founded. Within the firm, you need to have certain processes (in Watt’s case, Steam Engine driven processes) prior to manufacturing of the products (such as textiles). And markets for these products are formed when these firms offer their products to the public at large. Here, markets are not pre-existing
relationships; they are formed whenever agents agree to exchange goods. We thus have an hierarchy such as (Fig. 1.1):

\[
\text{(economic/political system (public, (firms (processes (products)))) (markets))}
\]

Here the public and the firms jointly agree to constitute the markets. Watt’s Steam Engine is at the process level of the firm. And as we mentioned, the Steam Engine was so tremendously innovative that it could penetrate more than one level and considerably shift the whole of the British Economy.

But surely the same may be said about the Clap-On device, if we add that the perspective is that of the end-user. For example, a handicapped person might regard the Clap-On device as a major innovation that helps him control his environment in a manner that is more natural to his condition; also it saves him significant amount of time and anguish during the execution of his day to day activities. Thus given the context of the user, the Clap-On device may be characterized as (Fig. 1.2):

2. Level of Analysis: Electrical Control Systems within the environment.
In contrast, suppose we were to take the perspective of the distributor of the electrical appliances, and say that the Clap-On is one of his minor products. The distributor therefore does not see a major shift in his practice with the introduction of the Clap-On. His distribution channels remain as is; his throughput remains more or less the same. But on the other hand, the introduction of direct marketing (using television and toll-free ordering) is a major threat to the elaborate distribution network of an appliance distributor. To him this would be an innovative shift he would have to take into account at the strategic level of his business. If he were to adopt it himself, he could potentially increase his customer base. Thus from the perspective of the distributor, introduction of direct marketing could be characterized as (Fig. 1.2):

1. Background Context: Traditional Business Enterprise of an Appliance Distributor.

2. Level of Analysis: Marketing networks within the business enterprise.


The term innovation is thus a relative term. It is therefore important to specify the perspective that is implicit in the analysis. Given different contexts and levels of analysis, the same design may be judged as innovative versus non-innovative.

To summarize, one needs to first of all specify the context and level of analysis under consideration in order to judge if a given design is innovative or assimilative (i.e., non-innovative). Context is the background against which change happens. Level is the station within the context where the change is sought (it is the bottom line). Architecture is the fundamental nature of the business or activity. Given the context and level of analysis, one may then deduce the relevant architecture from it. It is thus important to specify both the context as well as the level of analysis when considering a given innovation. Specifying only the level without the context will not do: for we need the relevant context in order to grasp the change that occurs at the given level. Also, only specifying the context will not do; for we do not know at what level within the given context the change that is sought is taking place. Context is the foil against which things change at different levels. Given the context and level of analysis, an innovative design brings about a major shift at the level of analysis, and in a manner that is fundamental to the context. In contrast, the assimilative design makes changes at either a level peripheral to the level of analysis or in a manner that is not fundamentally different. The key questions to ask then are:

1. in what manner is the change wrought by a given design fundamental?

2. what is the level or scale at which changes wrought by a given design is targeted?

In a political/economical context, factors that might influence the outcome are:

1. the capacity for change a given design has.
2. the organizational apparatus the candidate design is supported by.

3. the economic viability of the market to accept the change.

4. the element of free-market choice.

Our primary focus is on the first of these factors namely, the capacity for change a given design has. But we shall be using the other elements in order to build the full context of innovation. Despite the fact that a given design might have all the qualities of being innovative, it still might fail on account of the other factors. For example, on account of organizational failures, Xerox was unable to establish itself in the world of personal computing despite the fact that it had pioneered most of the key concepts in this field. Former Soviet Union (and many other newly liberated East European countries) is (are) finding it difficult to accept free-market changes (partly) on account of the poor economic viability of the current context. Or for example, despite excellent improvements in pricing and engine performance, Fords Model-18 with the new V-8 engine did not succeed in the economically depressed markets of 1932 [Ref. 1.3]. So also it is difficult to introduce newer and more efficient typewriting keyboards to replace QWERTY on account of the force of habit that governs the free-market choice [Ref. 1.4]. These are some of the other crucial factors that determine the course of a given innovation.

With the above context having being established, we are now ready to formally
define what it is we mean by innovation; also when do we consider a design as innovative? From our preliminary analysis, we may define innovation as follows:

Given the context (economics, politics, aesthetic, scientific, technological, etc) and the level of analysis (for example, revenue in oil industry worldwide), innovation is the process by which fundamental change is wrought in the given context, at the given level of analysis.

Let us analyse this. In this definition we seem to be suggesting that the genus might be any process. On the face of it this would be too broad a genus for our definition. But this is not what is implied in the definition. For the genus would be modified and limited by the context that is established up-front. Thus if the context is economics, the process is an economic process: if the context is technological, the process then is a technological process, etc. The differentia also has to be modified similarly given the information that we are provided with up front. A word about the qualifiers: context and level. Whenever we speak of innovation, it is important to explicate the context and the level of analysis. Otherwise the usage is loose and ambiguous. It is like stating the speed of a car as 35 and leaving out the units. Furthermore, by making clear the terminology we propose to use, we now have the advantage of applying it across the whole spectrum of change, regardless of whether it is at the macro-industry level or at the micro-firm level. For if there exists generic innovative patterns, it should apply across the board.

If we drop the fundamentality constraint, we may also define innovation (in a weaker sense) as:

Given the context and the level of analysis, innovation is the process by which change is wrought (regardless of whether it is fundamental or peripheral) in the given context, at the given level of analysis.

Here, only the scale is relevant: fundamentality is not. The concept of incremental innovation [Ref. 15] (which as per the stricter definition would be considered as assimilative on account of fundamentality violation) falls now within the category of innovation in the weaker sense. However there is a clarification that ought to be made. The idea is not that things that are assimilative in nature, cannot, over a period of time, and through diverse similar assimilative occurrences, bring about change at the level of analysis we are targeting. Given sufficient mass, such assimilative changes could definitely add up over time, and penetrate down to the base level. However the nature of the enterprise does not fundamentally change. If we were to throw out the fundamentality constraint (as we did in our weak definition), we then have to say that taken as a whole, the whole ensemble of assimilative changes may be characterized as innovative. It is wrong to characterize each and every small assimilative change as something innovative. Taken independently, they do not initiate the necessary shift: neither in scale nor in the underlying fundamental structure. It is perhaps better to call it ensemble innovation rather than incremental innovation. For that way one is clear that we are talking about the whole set of incremental improvements rather than each improvement stand-alone. We need to remember that we define in order to
differentiate one set of existents from another. In our present context, we are trying to differentiate between that which is innovative from that which is not (i.e., that which is assimilative). By substituting the term “incremental innovation” for that which is assimilative, we unfortunately make less clear the major distinction.

Given the above distinctions, we may now define the innovative design as follows:

**A design is judged as innovative if it has the potential to seed the innovation sought.**

Let us analyse this. It could be rephrased to put it in the following standard genus-differentia form: a innovative design is a design that has the potential to seed the innovation sought. Thus the genus is the earlier established concept of design; while the differentia makes clear the primeval link with the process of innovation. In contrast, an assimilative design may be defined as follows: an assimilative design is a design that does not have the potential to seed the innovation sought, but is capable of seeding change at peripheral levels. Note that these definitions cascade and make use of the earlier definitions.

Innovation may broadly be classified as of two kinds:

1. **Innovation at Genesis**: Here the scope of the problem is total and holistic. We try to innovate the system from scratch. We design the “acorn” that one day will become a new “oak tree”.

2. **Innovation at Maturity**: Given an existing system, we consider the types and kinds of changes feasible to the system. Each system has a certain capacity for change. Some of this could lead to lasting and fundamental change. Others are more peripheral and evanescent.

Innovation at genesis has greater latitude and risks. Innovation at maturity has to face significant inertia against change. As Thomas Hughes puts it [Ref. 1.6]:

Massive systems have a characteristic analogous to the inertia of motion in the physical world. Their mass of technical, organizational, and attitudinal components tends to maintain their steady growth and direction.

To conclude this preliminary essay, let us once again quote the OED [Ref. 1.16] on the evolution of the term innovation (the etymological trace and usage is in small font):

1. **To Innovate**:

   (a) To change a thing into something new; to alter; to renew. 1561 T. NORTON Calvins Inst. IV. XX. (1634) 737 A desire to innovate all things...moveth troublesome men. 1572 H. MIDDLEMORE in Ellis Orig Lett. Ser. II. III. 6. It shulde shewe very dangerous to every State to suffer the same any waye to be innovatyd or alteryd. 1621 G SANDYS Ovid's Met. IV (1626) 72 Scython who his nature innouates. Now male, now female, by alternate Fates. 1674 BOYLE Excell. Theol. I. i. 22 Theology teaches...that this world...shall either be abolished by annihilation, or..be innovated, and as it were, transfigured. 1751
2. **Innovation:**

(a) The action of innovating: the introduction of novelties; the alteration of what is established by the introduction of new elements or forms. 1561 T. NORTON. Calvin’s Inst. Table Contents. It is the duty of private men to obey and not to make innovation of states after their own will. 1796 BURKE Corr. (1844) III. 211 It is a revol of innovation; and therby, the very elements of society have been confounded and dissipated. 1824 L. MURRAY Eng Gram. (ed. 5) I. 65 This spirit of innovation has extended itself to other parts of grammar, and especially to the names of Tenses.

(b) A Political Revolution 1596 SHAKS. I Hen. IV, v.i.78 Poore Discontents. Which gape, and rub the Elbow at the newes Of hurly burly Innovation. 1601 R. JOHNSON Kingd. & Commw. (1603) 227 Neither doth he willingly arm them for feare of sedition and innovations. 1633 T. STAFFORD Pac Hib. I.XX. (1821) 206 For the same reason of innovation, he besought them to send unto him the old Secrets of powder with match and lead.

(c) Commercial: The action of introducing a new product into the market; a product newly brought on to the market. 1939 J. A. SCHUMPETER Business Cycles I. iii. 84 Innovation is possible without anything we should identify as invention, and invention does not necessarily induce innovation. 1958 J. JEWKES et al. Sources Invention ix. 249. It seems impossible to establish scientifically any final conclusion concerning the relation between monopoly and innovation. 1962 E. M. ROGERS Diffusion of Innovations v. 124. It matters little whether or nor an innovation has a great degree of advantage over the idea.
it is replacing. What does matter is whether the individual perceives the relative advantage of the innovation. 1967 J. A. ALLEN Sci. Innovation & Industr. Prosperity ii. 8 Innovation is the bringing of an invention into widespread practical use...Invention may thus be construed as the first stage of the much more extensive and complex total process of innovation.

3. **Innovative**: Having the character or quality of innovating 1806 F. HALL. Mod English 27 Some writers are, as to manner and diction, conservative, while others are innovative. 1970 N. ARMSTRONG et al. First on Moon i.20 The Air Force...sounded more exciting and more innovative. 1971 Times 6 Sept. 12 (Advt.). Well-known American company is introducing an innovative line of electro-optical measurement systems into the European Machine Tool and Metal Working industries.

4. **Innovator**: One who innovates; an introducer of novelties or new methods; a revolutionist. 1625 BACON Ess., Innovations (Arb.) 526 He that will not apply New Remedies. must expect New Euis: For Time is the greatest Innovatour. 1681 E. SCLATER Serm. Putney (ed. 2) 18 Moses was a Tyrant, and Aaron an Innovator.

5. **Innovatory**: Of innovating character or tendency. 1856 Chamn. Jrnl. VI. 401 Inveterate conservatives they are, despising all innovatory ideas. 1967 J. A. ALLEN. Sci. Innovation & Industr. Prosperity ii. 25 There has been little deliberate innovatory effort over a long period. 1971 Nature 2 Apr. 301/3 Historians have been so impressed by the innovatory nature of modern science.

The word is clearly emotionally charged in its historic origins. The context as well as the level of analysis that we attach to our definition is at best implicit in the above usages. As we mentioned earlier, the purpose of a new word is to distinguish a certain existant from another. In our case we are trying to differentiate between innovative versus assimilative designs. It is interesting to note that BURKE in 1796 was struggling to make clear exactly the same distinction as in note 1 (c) above:

It can not at this time be too often repeated, line upon line, percept upon percept...to innovate is not to reform.

Note also the distinction being made between conservative versus innovative:

1. 1806 F. HALL. Mod English 27 Some writers are, as to manner and diction, conservative, while others are innovative.

2. 1856 Chamn. Jrnl. VI. 401 Inveterate conservatives they are, despising all innovatory ideas.

This again makes clear the distinction between things that preserve the order versus things that challenge it. This completes our preliminary survey on the terminology as well as the overall scope of our problem. Later on, we shall make even more precise the overall process of design and innovation. But for the moment, the above framework should suffice.
1.3 Summary View of the Theory

In this section we briefly summarize the overall theory. Fundamentally, the theory is based on assumptions about knowledge architectures and knowledge dynamics. Later on we shall validate this using historical examples in science and mathematics. The processes of design and innovation take place against the context of knowledge hierarchies. When we study it in this manner we observe fundamental patterns emerge regardless of the minuteness or the macroscopy of the problem under study. Understanding the strategic significance of these patterns, one is able to plan for it in some sense. Planning or designing for innovation does not mean a fail-safe, riskless, deterministic strategy. Far from it, all that it implies is that one is aware of the nature of the innovation one is seeking; one is therefore better focused and goal-oriented. Also knowing the fundamental nature of the innovation process, one is better prepared in making early corrections on ones wrong decisions. The theory thus provides a fundamental and strategic grasp of both design and innovation, and the manner in which they are linked.

1.3.1 Knowledge Architectures and Knowledge Dynamics

Human knowledge is not a flat arrangement of atomic concepts and propositions. Given the human psycho-epistemology, there is a definite manner in which human knowledge is architected. As Prof. Peikoff puts it [Ref. 1.7]:

Human knowledge is not like a village of squat bungalows, with every room huddling down against the earth’s surface. Rather it is like a city of towering skyscrapers, with the uppermost story of each building resting on the lower ones, and they on the still lower, until one reaches the foundation, where the builder started—the foundation that supports the whole structure by virtue of being in direct contact with the solid ground... Knowledge, therefore, has a hierarchical structure...A hierarchy of knowledge means a body of concepts and conclusions ranked in order of logical dependence. one upon another, according to each item’s distance from the base of the structure, i.e., the perceptual data with which cognition begins.

Examples of such conceptual and propositional hierarchies are given in Fig. 1.3. Conceptual hierarchies consist of nodes and links arranged as shown (Example (a)). The nodes designate concepts and propositions. The links designate logical dependencies. Conceptual hierarchies are of two kinds: abstraction (or kind) hierarchies and part hierarchies. In the diagram they are designated as K and P respectively. The abstraction hierarchy indicates the genus the subject under study belongs to. Thus the “bird is an animal” is an example of the abstraction hierarchy. Part hierarchy is used to show the composition of an entity; example, “beak is part of the bird”. Design and design(n) use both abstraction and part hierarchies. But part hierarchies dominate design(n). It helps represent the composition or organization within the design(n).
Figure 1-3: Conceptual and Propositional Hierarchies [Source: Ref. 1.13]
While abstraction and part hierarchies are definitional in nature, propositional hierarchies assert the relationships that exist across the whole spectrum of diverse conceptual hierarchies. We shall illustrate these with categorical syllogisms from classical logic (Ref. 1.8). Thus when we assert the standard syllogism (Example (f), Fig 1.3):

1. Minor Premise: Socrates is a man.

2. Major Premise: Man is mortal.

3. Conclusion: Therefore Socrates is mortal.

we have asserted three (universal and affirmative: type A) propositions which may be represented as in lower left of Fig. 1.3. The filled and partially filled circles denote the distribution of the terms used. Thus when we assert that “man is mortal,” we mean all men are mortal. Thus as it is used in the syllogism, the term “man” is distributed over all the members of the family mankind. The term is thus fully distributed and thus represented by the filled circle. In contrast, the predicate of the proposition “mortal” is only partially distributed: there are other entities (such as giraffes) that would belong to the mortal category. The fact that the term “mortal” as used in the proposition is only partially distributed is indicated by the half-filled circle. Each proposition is indicated by the arrow that connects the subject to the predicate. The subject of the conclusion is the minor term (Socrates). The predicate of the conclusion is the major term (mortal). The premise that contains the major term is the major premise: that which contains the minor term is the minor premise. The term that connects the two premises is the middle term (man). The conclusion is the proposition that directly connects the major term to the minor term. This is indicated by the arrow that leaps upward across the conceptual hierarchy. Notice that we have mapped the terms in a manner that preserves the conceptual hierarchy. Coming up with the basic premises (in the first place) is inductive. Using them as we have done, is an exercise in deductive logic. In deductive logic, the conclusion cannot be more general than the premises.

The three other kinds of categorical propositions (apart from the type A discussed above) are (Fig. 1.3 middle):

1. Type E (Universal and Negative; Example-c): No Cat is a bird.

2. Type I (Particular and Affirmative; Example-d): Some people are blind.

3. Type O (Particular and Negative; Example-e): Some people are not blind.

The validity of a categorical syllogism may be visually checked using the following four rules:

1. In a valid syllogism. the middle term circle must be filled at least once (Example-f).

2. If either of the circles in the conclusion is filled, it must be filled in the premise in which it occurs (Example-f).
3. No valid syllogism can have two negative premises (Example-g)

4. If either premise of a valid syllogism is negative, the conclusion must be negative; and if the conclusion is negative, one premise must be negative (Example-h)

Notice that by merely looking at the form or structure of the argument (regardless of its content), we are able to judge its validity. The structural description gives us enough information to judge the validity of the argument. They tell us in what manner might one put together unit propositions in order to construct elaborate arguments such that the total structure does not collapse.

A different level of argument involves arguing about other arguments. These are the disjunctive and hypothetical syllogisms (Examples i & j respectively). Thus in Example-(i), p represents the proposition “All whales are Mammals.” And q represents the proposition “All whales are large fish.” Then “either p or q,” implies that it is one or the other. Thus if we know that whales are not “large fish,” we may conclude (by ruling out the alternatives) that they are whales. Similarly, in Example-(j) we have p which represents the proposition that “All whales are mammals.” And q which represents the proposition that “No whale breathes under water.” Now the hypothetical says that “if p is true, then q is true.” Thus if we know that whales belong to the mammalian family, we may conclude that none of them breathe under water.

Knowledge dynamics occurs whenever nodes and links are added or deleted. Higher the level at which these changes happen, more fundamental is the change. For example, deductively adding a new node such as “black hole” has posed major experimental and theoretical challenges in the domain of astronomy. Or for example inducing out the Newtonian principles based on Keplerian laws (and other similar empirical evidences) dramatically brought together terrestrial and celestial mechanics under one common order.

In Fig. 1.3 Example-a, we have indicated three other links which are basically different forms of the Type-A categorical proposition:

1. Instance I⁴: Tweety (the instance) is a canary.

2. Rule R: All bluejays are blue.

3. Has Property H: Tweety has property yellow.

This gives us enough foundations to study the various conceptual hierarchies we shall encounter. Let us now use the fact that knowledge is hierarchical in making certain crucial inferences.

First some evidence from large-scale engineering projects. The essence of a large-scale project is often buried in tomes of documents. Yet there is a critical pattern that one might observe. As Prof. Rechtin states it [Ref. 1.14]:

⁴These are the concretes that form the base of a knowledge hierarchy
Amid a wash of paper, a small number of documents become critical pivots around which every project's management revolves. This heuristic might be considered a kind of Pareto's law for documentation, that is, 20% of the documentation determines 80% of the system results, more or less. The trick is to choose the right 20%.

It is this 20% of critical knowledge that determines the breadth and scope of an enterprise and provides it with an integral spine. Also it is this spine of knowledge that undergoes fundamental change during innovation. In order to understand the processes of innovation, one has to study the various patterns by which the spine of knowledge is established and gets transformed. These patterns may also be derived by considering the hierarchical structure of human knowledge.

If one were to plot the hierarchy of the knowledge corpus within a given discipline, one would arrive at an architecture similar to the knowledge hump in Fig. 1.4. Given the relation of concretes to abstractions, there are fewer abstractions compared to the concretes. This results in a central bias within a given knowledge architecture. Within the knowledge-hump is a core set of concepts which we term the Innovation-Axis. It is the shortest path between the highest abstractions to the knowledge-base. This is what forms the 20% knowledge spine. I call this the innovation axis because any slight perturbation along this axis causes fundamental changes throughout the knowledge system. Whatever lies outside the innovation axis, I call that the Innovation Midwife (Fig. 1.4). It provides context and support to the innovation axis. The central problem of innovation then becomes the study of the knowledge dynamics centered around the innovation axis. Fundamental system-wide innovation takes place when the innovation-axis undergoes shift. Such an axis-shift corresponds to the aforementioned innovation-at-maturity. Examples of these include the birth of the Non-Euclidean geometries against the Euclidean foil in the 1820s. In contrast, innovation-at-genesis involves a new axis-erection. It corresponds to the establishment of a new discipline (for example the birth of calculus in the 1660s).

A caveat about the knowledge-hump diagram [Fig. 1.4]: the vertical axis captures the fact the concepts at a higher level are more abstract than those below (the vertical scale is thus the abstraction axis). The horizontal “axis” in contrast is not really an axis that measures any given metric; it is instead an identity “axis” used to indicate that things along this axis have different identities. Thus in Fig 1.3 (a), there is a definite conceptual hierarchy between bird and animal; however there is no common metric (along the horizontal “axis” between bird, mammal and reptile). Thus the reptile is not “so-many-units” of such-and-such as compared to the bird. The horizontal “axis” merely represents the fact that items separated along this “dimension” enjoy their separate identities. For there is only epistemological confusion to be gained by trying to represent the bird, the mammal and the reptile crowded within the same spot.
1.3.2 A Cognitive Theory of the Design Process

We need a framework of design that does justice to the cognitive psychology of design. In this section we lay bare such a framework. It is built on the above insight that knowledge is hierarchical. As we defined earlier:

Design is a cognitive thought process that transforms abstract human needs into an organization of artifacts that satisfy those needs.

When we map the process of design against the knowledge hierarchy foil, we may then discern the sub-parts that constitute the overall design process. Taken together as a whole, they constitute the St.Louis type arch of the design circuit or trace [Fig. 1.5]. The circuit involves the following characteristic activities, and in no particular order:

1. **Problem Perception:** Someone first has to perceive that a problem exists. It may be the customer complaints, it may be the chest pain the patient reports to the doctor, it may be the failure of an existing product, machinery, etc. Somewhere, someone, perceives that s/he has a problem at hand. In the knowledge hump diagram this is depicted as an oval at the perceptual base.

2. **Problem Abstraction:** Here the designer tries to diagnose and abstract out the nature of the problem. Depending on the nature of the study, the problem abstraction phase might be called market research, focus-group studies, user interviews, programming, etc. To get a better handle on the problem at large, one engages in problem abstraction. It consists of two steps:
Figure 1-5: Design Framework
(a) Problem Abstraction Synthesis: This involves moving from the concretes to the abstract. It is fundamentally inductive in style. This is represented as an upward pointing arrow leading off from the problem perception stage.

(b) Problem Abstraction Analysis: This involves (deductive) analytics in order to check the validity of the problem synthesis. Since analytic tools could refer to other parts of the knowledge domain (including other parts of the design trace itself), the analysis is represented merely as a floating arrow orthogonal to the design trace.

The end-result of the problem abstraction phase is the problem statement which organizes the abstract need(s) into its traceable logical constituents. This completes the left-arch of the design trace.

3. Design Proper: Up until this point the cognitive tasks have been preparatory in nature. We have now framed the problem and abstracted out the problem statement. From this point on we enter the phase which traditionally has been called design. It consists of the following steps:

(a) The Creative Leap: This is the essence of the design process. It is the singular insight towards the solution of the problem. It provides the arch ordering principle or the theme for all subsequent design. Making the conceptual link between the abstract human need and the thematic design solution is an inductive step and lies at the core of the total design process. It is inductive in the sense that the proper thematic relationship between appropriate elements from the design space has to be mentally brought together into a comprehensive, integrated whole. When does it happen, what forms it take, how unique and original is it, how frequent is it—now all this depends on the maturity of the designer (i.e., the psych-epistemological habits of creative thought). At this stage the design is not an exhaustively worked out idea. It is merely a seed that is often discarded, and rarely makes it beyond the first draft. But if the seed seems promising, the designer pushes ahead. The design(n) is represented as a circle with its constitutive elements as the grains (x’s and ?’s within it. The Creative Leap is represented by the leftward leaning arch at the top of the design trace.

(b) Design Synthesis: The Creative Leap actually does belong to the synthetic stage. However it is special in that it is the first normative link between that which is and that which ought to be. The Creative Leap thus frames the rest of the design process. If one wishes to work outside the scope established by the Creative Leap composition, one has to go back and reject this and put together a new theme. The subsequent stages of synthesis that happens within the scope of the established theme is what is meant by design synthesis. It is similar in its inductive nature to the creative leap.
(c) **Design Analysis:** The design theme is a compact system of ideas closely architected to capture the essence of the design intent. Given the abstract conceptual design, the designer attempts to organize or synthesize various contributing elements around this theme. This involves two kinds of analysis along with the above mentioned design synthesis. The first kind of analysis checks for the validity of the thematic design; that is how well does the given design meet the requirements. It thus checks the rationale for the design(n). I call this the validity analysis. This is indicated by the floating arrow orthogonal to the synthetic trace. Traditionally, analysis has come to mean the kinds of numerical checks and estimations done on a given design(n). The more conceptual the design(n), the more qualitative the critique (for example, the design(n) review in an architectural studio). Methods of analysis such as the axiomatic method [Ref.1.2] belongs to the validity analysis part of the overall design trace.

The second kind of analysis involves hierarchically decomposing the thematic design (and the subsequent designs) into their constituent sub-requirements (around which the next synthetic stage can then start organizing and designing). I call this the decompositional analysis. As in the case of the highest level design, the ensuing sub-requirements are indicated by ?’s enclosed in an oval (representing the whats of the design) slightly displaced to left and below the higher level design(n). The design(n) itself is indicated by x’s enclosed in an oval (representing the hows of the design).

Part of the task in coming up with the sub-requirements is captured in the above decompositional analysis; but part of it also involves a nested series of problem abstraction steps. For each of these sub-requirements need independent ground support (i.e., meaning). It is one thing to say what does the design decompose into; it is something else to say, what does it entail; what does it mean. The problem abstraction that is involved in these nested stages is indicated by the floating right-ward arching arrow from the left pointing to the sub-requirements. While the result from the decompositional step guides the nested problem abstraction stage, it is the result of the nested problem abstraction (the nested problem statement) that motivates subsequent design steps.

4. **Design Communication:** Realization of a large-scale system typically involves inter-disciplinary approaches. Modern industrial society is based on the integration and division of labor that large scale enterprises demand. Proper integration and division of labor requires an objective communication of facts, theories and intents. Thus at various levels along the design trace, one would find squiggly lines departing and entering the design trace indicating the communication trace connecting various knowledge humps.

5. **Market Feedback:** Ultimately the value of the design has to be communicated back to the customer and the feedback that is received integrated into the next loop along the design trace. Such a feedback mechanism might be through focus
group studies, lead-user study, beta-testing at select sites, initial performance of
the product in the market, surveys on how people actually use the test product,
etc. Ideally it would be best if one could lead the final user all the way back
through the whole of the design trace in order to check with the user for the
validity of the design; and also for the user to understand and appreciate how
best to use the artifact. Depending on how significant is the problem to the
customer; as well as the overlap of the design trace and the customers knowledge
base, one would expect different degrees of design appreciation and thus market
feedback. Thus the lead-users might be able to more closely approximate the
design trace (or perhaps do even better) than say a “late adopter” [Ref.1.10].
But in general, the market-feedback communication arch does not replicate
the design trace. It is displaced from it and the details of the design(n) often
suppressed.

The communication of the design intent is only part of the market feedback
mechanism. As we mentioned, it is for the user to appreciate and understand the
design(n) for its proper application in the context of the original problem. The
main thrust of the market feedback is the perceptual and conceptual information
the user provides after having used the artifact. This is what re-initiates the
process of design once again and helps fine-tune the design(n). The user has
to perceive that the final implemented design(n) does indeed solve the basic
problem. The market feedback loop is represented by the arch below the design
trace, starting at the design(n) base, meeting at the problem perception node
(but slightly shifted to indicate the improvements if any), and then pointing
upwards to indicate the begin of the next loop. Over time, and with better
understanding, the feedback-loop and the design trace loop would closely align
at least along the left arch⁵.

The above framework may not approach the actual conceptual order nor style of a
particular designer. It may not reflect the implicit/explicit workings of a struggling
mind. Yet what it provides is a general framework around which one may build the
individual subtilities. For example, in order for the designer to make the creative leap,
he or she would have to have a well articulated, well organized, well structured design-
space. This is often not the case to begin with. For the structuring of the design-space
is bottom up. Over time, the novice designer gets to know the design space intimately
and is comfortable synthesizing at the higher levels. Thus experience gained from one
design impacts another. Just as the market-feedback loop adjusts upwards over time
with customer usage and interaction, so also the design trace adjusts upward with
experience gained from multiple designs.

Given the nature of the various cognitive tasks involved in design, the question
one might ask is the following: which tasks along the design trace are best executed

⁵A caveat about the St. Louis type design-trace arch [Fig. 1.5]: as we mentioned earlier, while the
vertical axis of the knowledge-hump captures the conceptual hierarchies, the horizontal “dimension”
merely represents identity. Thus descriptions like the “left-arch” and the “right-arch” of the design
trace does not have any positional significance except that we choose to represent the problem
abstraction phase towards the left; and the various stages of the design(n) results towards the right.
by the human, and which tasks by the machine (i.e., the computer). Or in other words, what is the proper division of labor between the human and the machine? If we are dealing with a well-structured domain, the computer could be a major aid, especially during the various analytical stages (on account of its deductive nature). But whenever the domain is ill-structured, it is very difficult to replace the human inductive faculties. Also, in a well-structured domain, it is difficult to replace the human element wherever "fresh induction" has to be done (for example the programming or problem abstraction phase in Architecture). In its broadest sense, design and induction are intimately related. Induction is the creative element that opens up the new. This then is the fundamental human edge. Thus induction versus deduction is the fundamental basis for a proper division of labor between the human and the machine. For it is in the synthesis of artifacts (whether physical, social or mental) that humans will find their fundamental economic niche as compared with manual tasks or analytic thinking (where the machine has the advantage). Now this does not mean that training and education should focus solely on the synthetic skills. For the ability to synthesize requires a broad range of skills and experiences, including things manual as well as analytical. What it though means is that analytic/manual skills stand-alone would not provide the needed economic advantage. Thus, of the three, the synthetic skills are primary. In view of this, educational institutions ought to be cognizant of the kinds of human skills we will be requiring in the not-too-distant future; and thus provide training to attain it.

So far we have described the functional design process. The question is where does the aesthetic element belong? First of all, could it be considered as an additional function? In a general sense yes. But the specific aesthetic requirement is often not explicit until after the functional design is complete. After the functional design is complete, the designer then analyses the design(n) (given the problem context) and is inspired by an emotional theme which he then uses to reintegrate the overall design. In this sense, the aesthetic design trace is a trace that is born out of the function/design(n) integration. It thus rides over and above the design trace. This is indicated in Figure 1.6 where the details of the design trace are hidden (we have supressed every other detail except the essential element, namely the creative leap); and the aesthetic design trace is seen as riding over and above the functional design trace. We shall elaborate on this part of the design in far greater detail when we review Sullivans Organic Theory of Design [Chapter 2].

1.3.3 The Axiomatic Approach for Validity Analysis

A study of many successful designs led Suh, Bell, and Gossard [Ref. 1.2] in 1977 to propose a set of hypothetical design(n) axioms which help in the analysis and structuring of the design(n). In this section we review the basic elements of the axiomatic approach.

The axiomatic approach may fruitfully be used at the validity analysis level of the design framework we laid out. For as Prof. Suh says [Ref.1.2]:

What the design axioms do is to complement and aid the creative process
by providing the analytical tool for evaluation of the synthesized ideas so as to enable the selection of only good ideas.

Fundamentally, the design(n) axioms embody two basic concepts:

- the fulfillment of a given functional requirement ought not compromise any of the other functional requirements.

- a good design is minimally complex.

These are formalized in the normative form as follows:

- **Axiom 1**: Maintain the independence of functional requirements.

- **Axiom 2**: Minimize information content.

Functionally, a design(n) usually has more than one purpose. This is especially true at the detailed level of the design process. A photocopier performs the fundamental photocopying function. It also has to provide for various forms of paper-handling. A building is designed as an enclosure that is safe and separate from the elements outside. Its interior is structured around specific human needs. A pen has a cap to protect and the writing body that writes. A kitchen knife provides a sharp edge for cutting various food items. Its handle is designed for ease of maneuver. Thus each of
the functional requirement is mapped into one or more design(n) parameters. (DP’s).
Stated mathematically:
\[
\begin{align*}
\{ \text{FR} \} &= \begin{bmatrix} \text{DM} \end{bmatrix} \{ \text{DP} \} \\
\end{align*}
\] (1.1)
where,

- DM is the design(n) matrix that maps the FR’s to the DP’s.

Consider the example of the pen. Its design(n) parameters are the writing body and the pen cap. Stated in formal terms:
\[
\begin{align*}
\{ \text{FR1}: \text{Write on Paper} \} &= \begin{bmatrix} X & O \\ O & X \end{bmatrix} \{ \text{DP1}: \text{Writing Body} \} \\
\{ \text{FR2}: \text{Protect from Damage} \} &= \begin{bmatrix} O & X \\ X & O \end{bmatrix} \{ \text{DP2}: \text{Pen Cap} \} \\
\end{align*}
\] (1.2)
The O’s and X’s in the design(n) matrix indicate zero and non-zero elements. They imply a causal link (Aristotle’s final cause) between the respective FR’s and the respective DP’s. Thus FR2 is causally linked with DP2, and FR1 with DP1. For when the pen is capped, it is not being used for writing; also when the pen is used for writing, the user is assumed to be attentive; thus the need to protect is not material. Thus as per the design(n), these two functions are uncoupled along time. And the design(n) matrix reflects this in that it is diagonal. Such a design(n) is called an uncoupled design. An uncoupled design(n) satisfies the independence axiom.

Consider the example of the kitchen knife. Its design(n) parameters are the cutting edge and the supporting handle. Stated in formal terms:
\[
\begin{align*}
\{ \text{FR1}: \text{Cut Food Items} \} &= \begin{bmatrix} X & O \\ O & X \end{bmatrix} \{ \text{DP1}: \text{Cutting Edge} \} \\
\{ \text{FR2}: \text{Ease of Maneuver} \} &= \begin{bmatrix} X & + \\ + & X \end{bmatrix} \{ \text{DP2}: \text{Supporting Handle} \} \\
\end{align*}
\] (1.3)
Here FR2 is causally linked with DP1 and DP2. For the ease of maneuver (FR1) is linked with the sense of balance the cutting edge (DP1) provides. Actually it is a bit misleading to qualify the causal link between an FR and a DP as a boolean yes (X) or no (O). In fact the causal link between an FR and a DP could be qualified as positive (+), negative (-), or neutral (O). Thus, in the above example. FR2 is not adversely coupled with DP1; for it is good that the knife edge provides enough balance as we slice with the knife, with the food item as the fulcrum. Furthermore, the actual cutting action is dependent only on the sharpness of the knife edge. Thus we are able to achieve our purpose without compromising either of the requirements. But we do need to design the handle by taking into account the balancing weight of the knife edge. Thus the process of design is coupled, but the design(n) as a product is not. Using the non-boolean qualifiers, we have:
\[
\begin{align*}
\{ \text{FR1}: \text{Cut Food Items} \} &= \begin{bmatrix} + & O \\ O & + \end{bmatrix} \{ \text{DP1}: \text{Cutting Edge} \} \\
\{ \text{FR2}: \text{Ease of Maneuver} \} &= \begin{bmatrix} + & + \\ + & + \end{bmatrix} \{ \text{DP2}: \text{Supporting Handle} \} \\
\end{align*}
\] (1.4)
We thus see that if the design(n) matrix is triangular, it may be possible to select the DP’s in a manner so as to satisfy the first axiom. Such a design(n) is then called a decoupled design(n). A design(n) that is neither uncoupled nor decoupled is
a coupled design. It has negative elements in its design(n) matrix. Such a design(n) is in violation on the first axiom and could therefore lead to compromises on one or more of the functional requirements of the design(n). It might be possible to put up with such compromises on a small scale design(n). For the requirements might be few in number, and there might be DP contributions that compensate each other with regard to the FR. But such a procedure inevitably fails as the scale of the design(n) becomes large.

In order to apply the information axiom we require some metric on information or the complexity of the design(n). This is usually not easy during conceptual stages of design. But Corollary 2 which is derived from axiom 2 gives us an opportune way to apply this axiom [Ref.1.2]:

- **Corollary 2**: Minimize the number of FR's and constraints.

Also theorems 1, 2, and 5 are particularly relevant in the context of design(n) for innovation [Ref.1.2]:

- **Theorem 1**: When the number of DPs is less than the number of FRs, either a coupled design results or the FRs cannot be satisfied.

- **Theorem 2**: When a design is coupled due to the greater number of FRs than DPs (i.e., \( m > n \)), it may be decoupled by the addition of new DPs so as to make the number of FRs and DPs equal to each other, if a subset of the [original] design matrix containing n x n elements constitutes a triangular matrix.

- **Theorem 5**: When a given set of FRs is changed by the addition of a new FR, or substitution of one of the FRs by a new one, or by selection of a completely different set of FRs, the design solution given by the original DPs cannot satisfy the new set of FRs. Consequently, a new design solution must be sought.

Many are the problems of design(n) for innovation that may be reduced to the idea behind Theorem 5. As Prof. Suh elaborates [Ref.1.2]:

Theorem 5 is... a very important design principle that is frequently overlooked by many designers, causing many problems in terms of cost overrun, less than optimum design, and marginal products. Instead of searching for a completely new design when the set of original FRs is changed by addition or deletion of the FRs, many designers simply change the existing design to satisfy the new set of FRs. This can be a serious mistake...it is more prudent to go back to the beginning and reconceptualize the solution.

Elsewhere Prof. Suh calls the "going back to the beginning and reconceptualizing the solution" as designing in a "solution-neutral environment." One of the questions we will be taking up includes the problem of "mental-lock" a designer faces (on account of the existing design solutions) when attempting a "solution-neutral" design. We then suggest ways and means to overcome this problem.

The above review of the axiomatic approach is by no means exhaustive. We have abstracted out of the axiomatic framework those principles we most often will be
using. The concept of the simple but elegant design(n) matrix will prove extremely useful in portraying various design(n)s. In the next section we provide an overview of the basic thrust of the thesis.

### 1.3.4 The Theory of the Archstand

Earlier we briefly touched upon the innovation-axis and the axis shift. Majority of innovations correspond to the axis-shift paradigm. What then brings about such an axis-shift? The following is the outline of the theory that provides the organizing principle for such an axis-shift. In order to embark on an axis-shift, one has to first of all establish an external point of reference outside the current knowledge corpus. Such an external point of reference I have termed the archstand\(^6\) [Fig. 4(a)]. It is usually a fundamental, philosophical point of departure from where one may critically appraise the totality of a given body of knowledge. The new knowledge-axis is synthesized around such an external point of reference. The term archstand alludes to standing outside a given corpus of knowledge. Placing oneself within a large-scale conceptual system, one is unable to perceive the system as a whole nor objectively evaluate it for its weaknesses (if any). Thus there is no motivation to challenge and transform the same. In order to bring about fundamental change within a large-scale system, one has to first of all establish a valid external point of reference at a level that is fundamental to the knowledge corpus. This brings a dynamic within the existing system; the whole system is perceived with a clarity that is holistic in nature. This is what happened (150 years ago) during the discovery of the Non-Euclidean geometries. The Non-Euclidean archstnads were formed after perturbing the fifth postulate (one each for hyperbolic and elliptic geometries). A 2000 year old system was suddenly challenged and forced to bring greater clarity to its various implicit definitions and common notions. The end result was the birth of the non-Euclidean geometries which later provided the mathematical foundations for Einstein’s theories of relativity.

Knowledge dynamics based on archstands exhibit the fact that having an external point of reference can provide a powerful perspective to evaluate and modify existing systems. Standing within a given knowledge corpus, it is extremely difficult to critically evaluate the same nor see the overall structure as a whole. To give a physical analogy, it is like standing within a building and apppreciating it as compared to standing outside. Standing outside, one is able to observe the whole structure. Standing within, one is aware of only the immediate environment, say the room that one stands in.

Our mental constitutions are such that we find it difficult to modify a system while standing within its conceptual architectures. We need an external point of reference

\(^6\)In honor of Archimedes, the Greek mathematician who said, “Give me a place to stand, and I will move the earth.” Ancient Greek mathematicians have been notoriously cryptic regarding the epistemological method by which they first arrived at their results. In 1906 Heiberg discovered a Greek MS on the works of Archimedes which included an exposition on his method of mathematical discovery. The idea is quite simple: how do you leverage one discipline from the perspective established by another discipline. Thus Archimedes was able to leverage out geometric insights by first casting it as mechanical problems [Ref. 1.17].
in order to grasp the overall architecture in its essence; and then strategically and systematically bring about the innovative shift. It is the external point of reference which provides us the “neutralizing” influence in the above mentioned “solution-neutral” design.

To put it as an aphorism: Outside Knowledge is Power. This is in contrast to Prof. Davis’s play [Ref. 1.11] on the Baconian dictum:

1. Francis Bacon: “Knowledge is Power.”

2. Randall Davis: “In Knowledge is Power.”


The archstand is the point of leverage for bringing about system-wide changes. It is like the trim-tab [Fig. 1.7] that facilitates the movement of a ship. As Dr. Senge puts it [Ref. 1.12]:

A trim tab is a small “rudder on the rudder” of a ship. It is only a fraction the size of the rudder. Its function is to make it easier to turn the rudder, which, then, makes it easier to turn the ship. The larger the ship, the more important is the trim-tab because a large volume of water flowing around the rudder can make it difficult to turn.

The analogy is as follows:
• Trimtab → Archstand
• Rudder → Innovation Axis
• Ship → Domain Knowledge

The problem of design(n) for innovation then essentially reduces down to the following issue:

How might one go about systematically finding innovative archstands in a given problem context?

Given the fact that it is outside the existing knowledge architectures, it cannot be simply deduced from what we already know. Thus there has to be an element of externality to the formation of the archstand. Fundamentally there are three ways one might go about finding archstands. These are:

1. The Inductive Approach: The archstand is formed primarily by inducing out the external perspective from a fresh set of facts which somehow disagree with the existing views [Fig. 1.7 (c)].

2. The Abductive Approach: Here a mixture of inductive and deductive methods are brought to bear in order to put together the external perspective. It is primarily deductive in nature; however the deductive logic has to be modified somewhat in order to incorporate the facts and propositions that have been newly induced out [Fig. 1.7 (d)].

3. The Integrative Approach: In this case two contradicting knowledge architectures (or conflicting parts of the same knowledge architecture) are brought together and integrated upon to generate the external perspective. We thus resolve contradictions within or without a given knowledge corpus [Fig. 1.7 (e)].

Having found an innovative archstand, the next question that arises is:

Given the archstand how do we perform the needed knowledge transformation?

The primary target of the archstand is the innovation-axis, the command and control of a given knowledge architecture. The task here is to establish a systematic procedure for archstand induced knowledge transformation.

During or after the process of axis-shift, we would like to see how we might systematically reap the innovation potential of the archstand? For just like arbitrage in the field of finance, archstands provide perspectives on fundamental knowledge inconsistencies waiting to be tapped. We take this up in the next section.

The Integrative archstand could very well be either of the inductive or the deductive kind [Fig. 1.7(e)]. For example, Prof. Suh’s Theorems 1 & 2 (combined) provide us an illustration of how one might deductively come up with an integrative archstand (in the context of an existing design trace as compared to the more general approach as above for a whole knowledge corpus). On its own Theorem 1 only makes us aware
of the problem (i.e., the design is coupled). But when combined with Theorem 2, we
now have an actual point of reference outside the current design trace, namely that
we need to add an extra DP. Such an archstand targetted explicitly on the design
trace would be even more immediate to design as compared to an archstand that is
targetted at the whole of knowledge (which contains the design trace). But the op-
opportunities to find such a generic archstand is more wider when considering the whole
of knowledge in a given domain, as compared to the more limited context provided
by the design trace. Yet in those domains where knowledge is not well explicated,
but where the state of art is such that it provides well understood design traces, a
design-trace based archstand (such as that provided by Theorems 1 & 2 combined) is
invaluable in extending the state of art. As we shall see, James Watt’s steam engine
invention may be understood on the basis of the archstand that Prof. Suh’s Theorems
1 & 2 combined provide. In the various cases that we shall study, we shall find enough
examples that illustrate the above framework.

1.3.5 Design for Innovation

Earlier we set up a design framework and defined the design circuit as consisting of
the following activities [Fig. 3]:

1. Problem Perception

2. Problem Abstraction
   (a) Problem Abstraction Synthesis
   (b) Problem Abstraction Analysis

3. Design Proper
   (a) Creative Leap
   (b) Design Synthesis
   (c) Design Analysis
      i. Validity Analysis
      ii. Decompositional Analysis

4. Design Communication

5. Market Feedback

In this section we address the problem of coupling design to innovation. How does
the design-trace get modified in the context of innovation? The difference between
innovation in the knowledge architecture as a whole as compared to the innovation
in the design-trace is that here one is dealing with a very limited context. One is
not attempting an overarching conceptual revolution [Ref. 1.13]. But the similarity
between the two is that each is orchestrated from an archstand outside the current
context. Innovation in the knowledge architecture is orchestrated from outside the
current knowledge corpus. Innovation in the design-trace is orchestrated from a point outside this “trace.” But nevertheless, the external perspectives in each case are arrived at by the means of similar patterns of discovery.

The concept of the innovation axis and the shift that it suffers is slightly different in the context of design. For here the innovation axis or the core set of concepts exists within both halves of the design-trace arch. The design-trace axis is shown as the shaded core in both halves of the design trace arch (Fig.1.8.). This bicameral splitting up of the overall design trace is significant in that it provides two different contexts (the left-arch market context versus the right-arch technology context) from which the archstand might be induced. Note that is the design-trace innovation-axis that suffers the shift in the context of innovation. And we observe this as the fundamental “architectural” shift we discussed earlier in the context of defining innovation. The fundamentality of the innovative-shift is in reference to the innovation axis.

Under the influence of an archstand, the design trace is modified and experiences a shift (in a sense one might say that the re-integration of design that happens after the aesthetic theme has been introduced is an example of such a shift). Each of the various units that constitute the design trace may suffer a shift [Fig. 1.8] (from problem perception stage to market feedback stage). One might add that from a socio-economic perspective, the fundamental task of design(n) for innovation is to bring about this shift in a smooth and systematic manner so as to not cause unnecessary disequilibrium. If we can design(n) and plan for innovation, we would not be so much at the mercy of the “winds of creative destruction” [Ref.1.3]. However this demands a far greater understanding of the integration of labor principle, the long missing twin of Adam Smith’s division of labor economic principle. It is hoped that the knowledge-architecture based research reported in this thesis (that explicates the process of defining a vision, i.e., the fundamental integration of labor) will help mitigate this problem.

Note that given the dual usage of the word design (design versus design(n)), the term “design for innovation” may be used to denote either the design of the innovation process or the design(n) of an innovative product. The emphasis in this thesis is on the former usage.

1.4 Conclusion

In this introductory chapter we first defined our terms. We then briefly sketched the overall theory. Our theory is based on certain assumptions regarding knowledge architectures and knowledge dynamics. Having sketched the knowledge architectures and the dynamics that is involved, we then showed how design and innovation could be studied against the foil of knowledge architectures. We briefly touched upon the potential of the archstand, a point of reference external to a given knowledge corpus.

In the following chapters we shall develop this theory in a systematic manner. We first review the literature and pull together the relevant context for grounding the theory [Chapter 2]. We then elaborate on our findings on knowledge architectures and knowledge dynamics and integrate the resulting insights into our theory
Figure 1-8: Design for Innovation
of the archstand [Chapter 3]. Having established the necessary context, we then validate the archstand induced knowledge dynamics using the developmental history of non-Euclidean geometries [Chapter 4]. We then use the archstand framework in analysing various historical business/financial innovations [Chapter 5]. In Chapter 6 we summarize our findings and lay down some directions for future research. Herein we elaborate on our approach to Cognitive Tools.

Finally as an exercise in design for innovation, we apply the framework in the context of Construction Automation [Appendix]. Here the archstand used is “Construction from a Manufacturing Perspective.” We show evidence in the construction industry where practices from the more advanced manufacturing discipline is slowly transforming this industry. A significant fraction of cost of construction of concrete facilities is the labor and material costs involved in concrete formwork. Proposed is the Self-Articulating Formwork (SAFO) Cell system which could help mitigate construction costs while at the same time offering greater design flexibilities.

1.5 References


Chapter 2

Literature Review

2.1 Introduction

The literature directly related to the topic at hand (namely, design for innovation) is rather sparse. However considerable literature exists on the two related fields namely, design and innovation. In this chapter we review the work that is most closely related to our purpose. The review is primarily made along a historical timeline. Although our primarily focus is on the literature review pertinent to our problem, throughout this chapter we are actively involved in theory building. The exhaustive quotes within this chapter are deliberate; for they provide the rich cognitive thought involved in design.

The chapter consists of the following sections:

1. The Organic Theory of Design: We begin with Louis Sullivan's Organic Theory of Design developed during 1880s. This is our work-horse on which we shall build. Here we review Sullivan's fundamental design principle, that form follows function, or more generally that design(n) follows function. Our case study on Sullivan will afford us the following integrations:

(a) It will help us partly validate our framework on the design process. For by analysing Sullivan's writings we glean corroborative evidence regarding our design theory, including the following design process principle: that the design(n) of design follows function.

(b) Through this example we are able to illustrate the primary mode of all archstand induced innovations, namely the inductive mode.

(c) Illustrate Prof. Suh's square-one principle of innovation in the context of the birth of the skyscraper.

(d) Build a comprehensive theory of design which includes the aesthetic element.

We follow up the case study on Sullivan with the writings and designs of Frank Lloyd Wright. Wright provides us more insights into the mental process of design; he also gives us our first insight into the archstand approach via his
"throw away" principle and his (implicit) "mental standardization" comments. Also his insights on "style" provide us a valuable perspective on the current trends towards "mass-customization."

2. Aesthetics Proper: On Why We Need Art?: This section is a philosophical discussion on the "functional" role of art. For throughout our analysis of the above Organic Theory, we find only metaphorical answers to the problem of aesthetics. Our main source is the writings by philosopher/author, Ayn Rand. In the current context of our knowledge on design, we might not appreciate the material in this section. But in our mass-customized future, the aesthetic element will prove itself of central value. It is important therefore to explicate this element.

3. Design Methodologies as a Discipline: In this section we review the burgeoning literature on design methods and capture the various phases (the "prescriptive" (1962-67), the "descriptive" (67-73), the "observational" (late 70s), the "reflective" (72-82)) the movement has evolved through. We then juxtapose Sullivan's comments (from 100 years ago) to show how to overcome some of the problems the discipline is currently facing.

In this regard, the on going revolution in "cognitive science/engineering" could offer fresh insights into the design problem. This then becomes our Cognitive Science archstand for future research directions (we take this up in our concluding chapter).

We conclude this section with a summary of Prof. Suh's axiomatics in the historic context. We also show where Prof. Suh and Sullivan agree/disagree.

4. Innovation Literature Review: In this last section we review the literature on innovation. We have selected the literature to specifically highlight the current emphasis on incremental or regular innovation. What we have is a research lacunae on radical innovations.

Perhaps Prof. Kuhn's persuasive framework on the gestalt-switch approach to radical changes is partly to blame. For with the assumption of irrational abrupt discontinuities, very little can be said about radical innovations except that it does happen from time to time. Hence the research lacunae. [In our Chapter 3 we give reasons why we ought to reject the Kuhnian framework based on Prof. Thagard's cognitive perspective. This will give us the needed motivation to study the conceptual patterns preceding major innovations].

Despite the self-restarit in the research community regarding the study of radical innovations, there is a lot that could be attained from the current research, especially in Prof. Kim Clark's paper which closely approximates the cognitive perspective. Here Prof. Clark is studying the regular innovation, but from a conceptual framework. It will therefore not be too difficult to extend this later to meet our needs.

Before we begin, a word about the extensive quotes on design and design intent. The nature of the problem at hand requires that this be so. Our purpose is to
capture the ideation process as well as the theoretical framework of the designer. Our purpose is to focus on writings of those designers who have practiced extensively, who are visionary, who have made valuable contributions to their art, and who have been able to articulate their thought processes in a coherent fashion. It provides us the rich data and the context for us to build on. It also provides valuable concepts that help us link-up our two main concerns: design and innovation (for example, the concept of “concept standardization” we shall encounter).

2.2 The Organic Theory of Design

In this section we review Louis Sullivan’s Organic Theory of Design which he developed during 1880s. But before we begin, a few overarching insights from Aristotle on design.

Design as a subject has been of intellectual interest at least as far back when Aristotle wrote about the three different kinds of knowing [Ref. 2.1]:

1. Man the Maker: Productive Thinking (when engaged in making things such as wheels and ploughs and pottery),

2. Man the Doer: Practical, Moral or Social Thinking (when engaged in moral and political judgements as in jury duty),

3. Man the Knower: Speculative Thinking (when engaged in works of science such as physics and biology)

Aristotle lays out this framework throughout his various treatises, and especially his works on Ethics, Poetics, and On the Soul. The word poiesis in Greek in fact means “to make things.” Our focus here is on man the maker. It is extremely profitable to review what Aristotle thought about man the maker in order to grasp the importance of purpose in human action. Consider the following events:

1. Forest fire that a lightning starts.

2. Forest fire caused by a cigarette butt carelessly dropped by a person.

3. Camp fire made by a picknicker to cook his food.

The first event is clearly an act of nature. The second event is caused by man, but it is an accident. It was not intentional. “The absence of any human purpose, planning, or foresight puts it on the natural side of the line that divides the natural from the artificial. It was man caused but not man-made. It resulted from something that a human being did, but man is a part of nature just as much as lightning. Not everything that results from human behavior is a human production of a work of art [Ref. 2.1].” The third event is deliberate and purposeful; the purpose being to cook food. Human action of this kind is purposeful action. It is these kinds of events that are under the purview of design.
Unfortunately, the Aristotelian approach to design was not developed in any substantial manner until recent times. In the interim, the approach to design was Vitruvian or traditional [Ref. 2.30]. According to the Encyclopaedia Britannica, Vitruvius (the Roman architect) was:

the chief authority studied by architects, and in every point his precepts were accepted as final. Bramante, Michelangelo, Palladio, Vignola, and earlier architects were careful students of Vitruvius.

Vitruvian principles were primarily directed by aesthetic principles which were based on symmetry, harmony, and proportion. Function was left implicit in the design.

The rediscovery of the Aristotelian approach to design in modern times was by the American architect Louis Sullivan (1856-1924), considered the father of the modern skyscraper. Here is the autobiographical context in which he makes his arch principle, that "form follows function" [Ref. 2.2]:

..his conviction was this: That the architectural art to be of contemporary immediate value must be plastic; all senseless conventional rigidity must be taken out of it; it must intelligently serve—it must not suppress. In this wiser the forms under his hand would grow naturally out of the needs and express them frankly, and freshly. This meant in his courageous mind that he would put to the test a formula he had evolved, through long contemplation of living things, namely that form follows function, which would mean, in practice, that architecture might again become a living art, if this formula were but adhered to. [Emphasis Added]

Sullivan arrived upon the principle by observing forms in nature. Based on this, Sullivan came up with the Organic Theory of Architecture where the aesthetic is not imposed from outside, but instead is born out of the form/function integration. Following is an extended quote from Kindergarten Chats [Ref. 2.3] published in 1902, wherein Sullivan speaks about its meaning in a poetic but pregnant style:

S: The integration of function and form...it stands to reason that a thing looks like what it is, and vice versa, it is what it looks like...For instances: the form, oak-tree, resembles and expresses the purpose or function, oak; the form, pine-tree, resembles and indicates the function pine; the form, horse, resembles and is the logical output of the function, horse; the form, spider, resembles and is the tangible evidence of the function, spider....the form, bird, tells us of the function, bird; the form, eagle, is the function, eagle, made visible; the form, beak of that eagle, the function, beak of that eagle...And so, in man-made things, the form, literature, means nothing more or less than the function, literature; the form, music, the function, music; the form, knife, the function, knife; the form, axe, the function, axe;

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1Henceforth all original emphasis in italics or bold; all added emphasis in sans serif
2Sullivan's theory presented in the form of a dialogue between an architect (S) and his apprentice (A)
the form, engine, the function, engine. And again, in nature,...the form, reeds, the function, reeds; the forms, fly above the water and bass below the water—their related functions...and so on, and on, and on—unceasingly, endlessly, constantly, eternally—through the range of the physical world—visual, microscopic, and telescopic, the world of the senses, the world of the intellect, the world of the heart, the world of the soul: the physical world of man we believe we know, and the borderland of that world we know not—that world of the silent, immeasurable, creative spirit, of whose infinite function all these things are but the varied manifestations in form, in form more or less tangible, more or less imponderable—a borderland delicate as the dawn of life, grim as fate, human as the smile of a friend—a universe wherein all is function, all is form...Like sees and begets its like. That which exists in spirit ever seeks and finds its physical counterpart in form, its visible image; an uncouth thought, an uncouth form; a monstrous thought, a monstrous form; a thought in decadence, a form in decadence; a living thought, a living form....

Is there then form in everything? Form is everything and anything, everywhere and at every instant. According to their nature, their function, some forms are definite, some indefinite; some are nebulous, others concrete and sharp; some symmetrical, others purely rhythmical. Some are abstract, others material. Some appeal to the eye, some to the ear, some to the touch, some to the sense of smell, some to any one or all or any combination of these....[Mans] highest thoughts, his most delicate yearnings arise, through an imperceptible birth and growth, from the material sense of touch. From hunger arose the cravings of his soul. From urgent passions have the sweetest vows of his heart arisen. From savage instincts came the force and powers of his mind. All is growth, all is decadence. Functions are born of functions, and in turn, give birth or death to others. Forms emerge from forms, and others arise or descend from these. All are interrelated, interwoven, intermeshed, interconnected, interblended. They exosmose and endosmose. They sway and swirl and mix and drift interminably. They shape, they reform, they dissipate....

Sullivan clearly saw the broad scope of design (which included the mental realm). Also he saw how forms could lead to forms, and functions to functions. However he is not very precise exactly how this is supposed to happen, whether this development is directly function to function or function to form and then function. Note also the poetic meter in which these thoughts are expressed. In many ways it reflects the “fluid state” of our knowledge on human creativity. With greater understanding about this matter, our language ought to become more precise.

It is no accident that Sullivan named his approach the Organic Theory of Design. For he induced out the design principle form follows function by observing designs(n) as they exist in nature. In fact he was using his inductions from observations in nature as an archstand from which to approach his problem. This is the fundamental external perspective he brought to architecture as it was traditionally practiced until
late 1800's.

As to why Sullivan is considered "father of the modern skyscraper," Claude Bragnon writes [Ref. 2.2]:

Louis Sullivan has the distinction of having been, perhaps, the first squarely to face the expressional problem of steel-framed skyscraper and to deal with it honestly and logically. Later solutions, in so far as they are good, have been along the lines that he, by percept and example, first laid down. This, to the layman, needs a little explaining. The academically educated architect of the generation which produced the skyscraper found something that refused to submit itself to the canons and categories with which his mind had been filled: he could neither fit it into his mental frame, nor could he expand that frame to fit it. So he produced architectural monstrosities.

Now along comes Louis Sullivan, fresh from Europe, but unglamored by the light of its magnificent yesterdays. He held the conviction that no architectural dictum, or tradition, or superstition, or habit, should stand in the way of realizing an honest architecture, based on well-defined needs and useful purposes: the function determining the form. the form expressing the function. To him the tallness of the skyscraper was not an embarrassment, but an inspiration—the force of altitude must be in it; it must be a proud and soaring thing, without a dissenting line from bottom to top. Accordingly, flushed with a fine creative frenzy, he flung upward his piers and disposed his windows as necessity, not tradition, demanded, making the masonry appear what it had in fact become—a shell, a casing merely, the steel skeleton being sensed, so to speak, like bones beneath their layer of flesh. Then, over it all, he wove a web of beautiful ornament—flowers and frost, delicate as lace and strong as steel.

His inexorable logic, resulting as it did in so many surprising simplifications and admirable economies, imposed itself upon the minds even of architects averse to his philosophy and indifferent towards his work, with the result that the more obvious merits of our upstanding colossi of the market are traceable, however deviously, to Louis Sullivan's influence.

Regarding the context in which Sullivan's architectural expression of the skyscraper was born, biographer Hugh Morrison writes [Ref. 2.4]:

The high building was a comparatively new arrival in American architecture. It may be said to date from 1874, when Richard Morris Hunt erected the ten-story New York Tribune Building, one of the first of the "elevator buildings." Prior to that time six stories was the general height limit, due to a universal human disinclination to walk up more than five flights of stairs. The steam passenger elevator had been gradually developed from 1850 on, but was not used in an office building until 1871, and the hydraulic elevator was not patented until 1872. During the decades of the seventies and eighties the height of the tallest commercial structures
Figure 2-1: Masonary Aesthetic of Tall Buildings prior to Sullivan [Source Ref. 2.4]
did not exceed twelve stories. The skyscraper in the technical sense of skeleton construction was an even more recent development, dating from 1884. The principle of supporting the exterior wall on a metal frame was first used by William LeBaron Jenney in the Home Insurance Building in Chicago, built in 1884-85. The second skyscraper was the Tacoma Building in Chicago, designed by Holabird & Roche and built in 1887-88. The Tower Building, designed by Bradford Gilbert, built in 1889, was the first skyscraper in New York...In spite of these advances, the logic of skyscraper construction was not immediately recognized...in the year 1889 the number [of skyscrapers] was probably less than half a dozen, most of which were in Chicago. The Wainwright Building, Adler & Sullivan’s first skyscraper, was begun in 1890, and was thus one of the early examples...

From this brief review it may be seen that in 1890 the high building of “masonry” construction was about fifteen years old, and that the skyscraper was still in an experimental stage, although the fundamental structural principle had been applied. What was the nature of the architectural treatment of the high building at that time? The problem had not been solved successfully, even by the country’s greatest architects. To realize the tremendous advance achieved by Sullivan in the Wainwright Building some familiarity with the appearance of other high buildings of that time is necessary. The Wainwright Building is a fine building even in comparison with the best structures of today, but it becomes far more impressive when placed beside its contemporaries...[Fig.2.1]

The primary characteristics of these large office buildings, in contrast to the other architectural types of the day, were their commercial purpose, their height, their volume, and the uniformity of their plan, story by story. These characteristics might logically be expected to have determined their architectural treatment. Actually they did not. Utilitarianism was not yet accepted as a valid source of artistic inspiration; great height and great volume were considered artistic liabilities rather than assets; and uniformity was considered monotony. Critical writings in the architectural journals of the time are full of discussions as to what might be done to the new giants to make them architecturally respectable, and the general conclusion arrived at was a confession of failure: that the skyscraper was an artistically intractable problem which could best be solved by a series of compromises endeavoring to make it look like something else. The following devices were almost universally resorted to: the use of elaborate decoration to exalt the mere office building into a “mercantile palace”; the use of single stories or groups of stories as units of design, dividing the building horizontally so that through suggesting traditional modes of composition in lower buildings the effect of height might be diminished; the division of facades vertically by oriels, projecting or receding bays, pilaster strips, or other means, to disrupt the continuity of the bounding surfaces and thereby reduce the effect of the great volume. In common with all other
buildings of the time, skyscrapers were decorated by past styles, generally accenting the picturesque and romantic qualities conceived as attributes of the "mercantile palace." These ornamental details were greatly enlarged in scale to conform to the size of the building, and since they had been traditionally limited to a certain size, the effect was to diminish the apparent size of the whole building. Finally, no architectural distinction was made between tall buildings of skyscraper structure and of solid masonry structure; both types were treated with the time-honored masonry aesthetic. This summary of style applies to all high buildings from the time of their appearance down to 1890, and, of course, to many buildings erected after that date.

This is the architectural context in which Sullivan's Wainwright Building was designed. The primary innovation that gave rise to the design conflict was of course the cheap production of structural steel (which itself was born out of the needs to meet the prodigious demands of the railroad industry). Mass production of structural steel (along with the invention of the Otis elevator and also enhanced fire-safety) allowed architects to safely and economically build into the vertical dimension. But as Morrison mentions, this created major architectural challenges. The problem was of expressing the vertical-dimension (in a manner that was true to the nature of the building), of means by which one could take advantage of natural lighting, of organizing the office spaces for their respective functions. Aesthetically, the problem was of rising up to the challenge of expressing an enduring emotive element out of the "monotonous uniformity" of large office buildings. As we mentioned, the architectural practice that was prevalent at that time was Vitruvian in style. In the Vitruvian style, the function is implicit within the design; it is the aesthetics that governs (based on time-honoured traditions). If we were to represent the same using the design(n) matrix, we would depict it as follows. Denote the aesthetic requirements (such as visual appearance) as AR; the aesthetic parameters as AP. Denote the non-aesthetic requirements (such as the need for sufficient office-work space) as NAR; the non-aesthetic parameters as NAP. The prevalent design(n) could then be represented as:

\[
\begin{align*}
\{ \text{FR1: AR} \} &= \begin{bmatrix} + & - \end{bmatrix} \{ \text{DP1: AP} \} \\
\{ \text{FR2: NAR} \} &= \begin{bmatrix} - & + \end{bmatrix} \{ \text{DP2: NAP} \}
\end{align*}
\]

(2.1)

The design(n) was coupled. It started off with the prevalent masonry aesthetic. It then somehow tried to fit the tall-building functions within the prescribed aesthetic form. The result was a coupled design(n). It was too incongruous to satisfy the masonry aesthetic. And its utilitarian functions were compromised on account of the strait-jacket masonry aesthetic it was required to fit. As Morrison puts it:

Critical writings in the architectural journals of the time are full of discussions as to what might be done to the new giants to make them architecturally respectable, and the general conclusion arrived at was a confession of failure: that the skyscraper was an artistically intractable problem which could best be solved by a series of compromises endeavoring to make it
look like something else.

Between 1874 and 1890, the primary response to the aesthetic problem of tall buildings was to extend the prevailing "masonry aesthetic" in order to clothe it, thus creating the aesthetic incongruity as described. The design "principles" at this time were mainly Vitruvian in style; and time-honored traditions were unable to meet the need.

Sullivan had to induce out fundamental design principles based on his observations in nature. He then applied it first-hand to solve the aesthetic and design(n) problems that the innovation in steel (as a cheap building material in the context of tall buildings) posed. Such is the cascade effect of one innovation on another. In such a context, one has to go back to the fundamental principles (in this case induce out the fundamental principles of design as Sullivan did) and look at the problem fresh, without being constrained by established traditions. This in itself constitutes a principle, an attitude or approach towards innovation: that in the context of a cascade innovation, one has to go back to square one. Let us call this the square-one principle. Stated informally, it states:

In the context of a cascade innovation that challenges established traditions in a given practice, it is important to go back to the first principles and look at the problem first-hand.

Stated formally, it is Prof. Suh's Theorem 5 on "solution-neutral" design(n) that we saw in our introductory review.

The primary advantage of tradition is that one does not have to solve problems already solved; thus allowing the designer to "build by standing on the shoulders of giants." But in the face of a major innovation, these traditions offer no significant advantage; in fact they merely constrain free-ranging thought. Thus our first principle of innovation states that in the context of a major innovation, it is important to redo the problem by disregarding established traditions. With these remarks being made, let us now return to how Sullivan fundamentally solved the problems posed by tall-buildings.

Continuing the quote from Morrison [Ref. 2.4]:

The Wainwright building was designed in 1890, and construction completed in 1891.... The exterior is faced by materials which give a rich harmony of reds and browns. The base of the building to a height of two feet above the sidewalk is of red Missouri granite; the lower two stories are of finely-jointed brown sandstone ashlar; the continuous piers from the third to the tenth floor are of red brick; the spandrel panels set back between the piers and the top story and cornice are of red terra cotta....The two lower stories form a simple and substantial base, penetrated by severely rectangular and unadorned openings. The only touches of ornament in this base are the narrow carved bands framing the main doors entering the building. Above the second story is an emphatic string-course clearly separating the base of the building from the shaft. This string-course is
Figure 2-2: Sullivan's Wainwright Building [Source Ref. 2.4]
broken at the corners, however, to permit the uninterrupted sweep of the vertical masses of the corner piers from sidewalk to top story.

The treatment of the main group of stories is emphatically vertical. At the corners are broad piers, over seven feet wide; and on the sides narrow piers two and a half feet wide, each alternate pier enclosing a steel column. The narrow piers rest on a very small base and have a slight face ornament at the bottom and a terminal of terra cotta ornament some four feet high at the top. Thus the piers resemble pilasters, although the proportion and detail are entirely non-traditional.... Apart from the slender brick piers, the only solids of the wall surface are the spandrel panels between the windows. Since these are carried on the steel spandrel beams they serve no other structural purpose than that of thin screens to keep out the elements, and are thus subordinated to the piers by being recessed behind them, and serve as appropriate fields for decoration. They have rich decorative patterns in low relief, varying in design and scale with each story.

The top story and cornice division is marked off from the shaft by a string-course carried all the way around the building, even across the corner piers. The most striking enrichment of the exterior occurs in the opulent foliate designs facing the entire tenth story. This forms a luxuriant frieze penetrated by small round windows. Above it a simple block cornice with a wide face and considerable projection terminates the facade in a decisive fashion. Such a cornice is manifestly useless, but it expresses vigorously the upper termination of the composition.

The construction of the building embodied the most advanced practice of the day. The foundations were of the isolated footing type, made of reinforced concrete, and carried to a depth of sixteen feet. The framework was entirely of steel, with riveted columns and girders, and spandrel beams carrying the exterior wall on shelves at every floor. All steel work was encased in fireproof tile, and all interior partitions were constructed of fireproof material. Interior partitions on the office floor were so constructed that any or all of them might be moved or eliminated, according to the needs of the clients. The ten stories total 135 feet in height, and the cost of the building was $561,255—slightly over thirty cents a cubic foot.

The plan and arrangement of the interior are of particular interest in attempting to interpret the exterior design as an expression of the interior functions. The basement floor, containing boiler, pump, and dynamo rooms, lavatories, and storage space, utilizes the entire plot. From the ground story up the plan is U-shaped, with an open light-court to the north, assuring outside light to every office; this light-court occupies almost 20 percent of the total lot area [Fig.2.2]. The ground floor has nine stores of different sizes on the street fronts, and a large office in the north-
west corner. The second floor is divided up into twenty-five offices and the necessary corridors. This is exactly the same as the typical plan of the office floors from the third to the ninth. In the typical office floor the alternate wall piers (the ones containing no steel columns) serve no structural purpose other than the support of window frames, since in no case do they serve even as terminus of interior office partitions. All told, there are two hundred offices, and the net rental area of the typical office floor amounts to 53 percent of the total lot area, representing an efficiency in planning which is seldom exceeded today. The tenth story is used for large lavatories and a barber shop, lighted by skylights, but chiefly for great steam mains employed in an overhead heating system and for other mechanical utilities. Its function is thus quite distinct from that of the floors below.

We now turn to Sullivan for his own original thoughts on the Tall Building Design⁴:

The architects of this land and generation are now brought face to face with something new under the sun—namely, that evolution and integration of social conditions, that special grouping of them, that results in a demand for the erection of tall office buildings...

Let us state the conditions in the plainest manner. Briefly, they are these: offices are necessary for the transaction of business; the invention and perfection of the high-speed elevators make vertical travel, that was once tedious and painful, now easy and comfortable; development of steel manufacture has shown the way to safe, rigid, economic constructions rising to a great height; continued growth of population in the great cities, consequent congestion of centers and rise in value of ground, stimulate and increase in number of stories; these successfully piled one upon another, react on ground values—and so on, by action and reaction, interaction and inter-reaction. Thus has come about that form of lofty construction called the "modern office building." It has come in answer to a call, for in it a new grouping of social conditions has found a habituation and a name....

It is my belief that it is of the very essence of every problem that it contains and suggests its own solution. This I believe to be a natural law. Let us examine, then, carefully the elements, let us search out this contained suggestion, this essence of the problem.

The practical conditions are broadly speaking these: Wanted—1st, a story below-ground, containing boilers, engines of various sorts, etc.—in short, the plant for power, heating, lighting, etc. 2nd, a ground floor, so called, devoted to stores, banks, or other establishments requiring large area, ample spacing, ample light, and great freedom of access. 3rd, a second story readily accessible by stairways—this space usually in large subdivisions, with corresponding liberality in structural spacing and expanse of

⁴The Tall Office Building Artistically Considered (1896) Ref. 2.5
glass and breadth of external openings. 4th, above this an indefinite number of stories of offices piled tier upon tier, one tier just like another tier, one office just like all the other offices—an office being similar to a cell in a honeycomb, merely a compartment, nothing more. 5th, and last, at the top of this pile is placed a space or story that, as related to the life and usefulness of the structure, is purely physiological in nature—namely, the attic. In this the circulatory system completes itself and makes its grand turn, ascending and descending. The space is filled with tanks, pipes, valves, sheaves, and mechanical etcetera that supplement and complement the force-originating plant hidden below-ground in the cellar. Finally, or at the beginning rather, there must be on the ground floor a main aperture or entrance common to all the occupants or patrons of the building....

This tabulation is, in the main, characteristic of every tall office building in the country. As to the necessary arrangements for light courts, these are not germane to the problem...These things, and such others as the arrangement of elevators, for example, have to do strictly with the economics of the building, and I assume them to have been fully considered and disposed of to the satisfaction of purely utilitarian and pecuniary demands. Only in rare instances does the plan or floor arrangement of the tall office building take on an aesthetic value, and this usually when the lighting court is external or becomes an internal feature of great importance.....

The practical horizontal and vertical division or office unit is naturally based on a room of comfortable area and height, and the size of this standard office room as naturally predetermines the standard structural unit, and, approximately, the size of window openings. In turn, these purely arbitrary units of structure form in an equally natural way the true basis of the artistic development of the exterior. Of course, the structural spacings and openings in the first or mercantile story are required to be the largest of all; those in the second or quasi-mercantile story are of a somewhat similar nature. The spacings and openings in the attic are of no importance whatsoever (the windows have no actual value), for light may be taken from the top, and no recognition of a cellular division is necessary in the structural spacing.

Hence it follows inevitably, and in the simplest possible way that...we will in the following manner design the exterior of our tall office building, to wit:

Beginning with the first story, we give this a main entrance that attracts the eye to its location, and the reminder of the story we treat in a more or less liberal, expansive, sumptuous way—a way based exactly on the practical necessities, but expressed with a sentiment of largeness and freedom. The second story we treat in a similar way, but usually with milder pretension. Above this, throughout the indefinite number of typical office tiers, we take our cue from the individual cell, which requires a window with its
separating pier, its sill and lintel, and we, without more ado, make them all look alike because they are alike. This brings us to the attic, which, having no division into office cells, and no special requirement for lighting, gives us the power to show by means of its broad expanse of wall, and its dominating weight and character, that which is the fact, namely that the series of office tiers has come definitely to an end...

However, thus far the results are only partial and tentative at best;...our building may have all this in a considerable degree and yet be far from that adequate solution of the problem I am attempting to define. We must now heed the imperative voice of emotion.

It demands of us, what is the chief characteristic of the tall office building? And at once we answer, it is lofty. This loftiness is to the artist-nature its thrilling aspect. It is the very open organ-tone in its appeal. It must be in turn the dominant chord in his expression of it, the true excitant of his imagination. It must be tall, every inch of it tall. The force and power of altitude must be in it, the glory and pride of exaltation must be in it. It must be every inch a proud and soaring thing, rising in sheer exultation that from bottom to top it is a unit without a single dissenting line...

The man who designs in this spirit and with the sense of responsibility to the generation he lives in must be no coward, no denier, no bookworm, no dilettante. He must live of his life and for his life in the fullest, most consummate sense. He must realize at once and with the grasp of inspiration that the problem of the tall office building is one of the stupendous, one of the most magnificent opportunities...ever offered to the proud spirit of man....

Sullivan’s writing is remarkably evocative; his words rise up in a crescendo to capture the heroic spirit in which he built. These last two paragraphs also captures the fundamental aesthetic difference between Sullivan’s Organic School versus the purely functional Bauhaus School. According to Sullivan, the purely functional approach is rather stale and “inadequate”. After the functional design is complete, the designer then analyses the design(n) (given the problem context) and is inspired by an emotional theme which he then uses to reintegrate the overall design. We shall build on this theme in greater detail shortly.

But continuing on Sullivan’s essay (a careful reading of the which will show where exactly Sullivan differs from the the earlier mentioned Aristotelian approach) [Ref. 2.5]:

Certain critics, and very thoughtful ones, have advanced the theory that the true prototype of the tall office building is the classical column, consisting of base, shaft and capital—the moulded base of the column typical of the lower stories of our building, the plain or fluted shaft suggesting the monotonous, uninterrupted series of office-tiers, and the capital the completing power and luxuriance of the attic.
Other theorizers, assuming a mystical symbolism as a guide, quote the many trinities in nature and art, and the beauty and conclusiveness of such trinity in unity. They aver the beauty of prime numbers, the mysticism of the number three, the beauty of all things that are in three parts...

Others, of purely intellectual temperament, hold that such a design should be in the nature of a logical statement; it should have a beginning, a middle, and an ending, each clearly defined—therefore again a building, as above, in three parts vertically.

Others seeking their examples and justification in the vegetable kingdom, urge that such a design shall above all things be organic. They quote the suitable flower with its bunch of leaves at the earth, its long graceful stem, carrying the gorgeous single flower. They point to the pine-tree, its massy roots, its lithe, uninterrupted trunk, its tuft of green high in the air. Thus, they say, should be the design of the tall office building: again in three parts vertically.

Others still, more susceptible to the power of a unit than to the grace of a trinity, say that such a design should be struck out at a blow, as though by a blacksmith or by mighty Jove, or should be thought-born, as was Minerva, full grown. They accept the notion of a triple division as permissible and welcome, but non-essential. With them it is a subdivision of their unit: the unit does not come from the alliance of the three; they accept it without murmer, provided the subdivision does not disturb the sense of singleness and repose.

..I regard [all these] as secondary only, non-essential, and as touching not at all upon the vital spot, upon the quick of the entire matter, upon the true, the immovable philosophy of the architectural art.

This view let me now state, first it brings to the solution of the problem a final, comprehensive formula.

All things in nature have a shape, that is to say, a form, an outward semblance, that tells us what they are, that distinguishes them from ourselves and from each other.

Unfailingly in nature these shapes express the inner life, the native quality, of the animal, tree, bird, fish, that they present to us; they are so characteristic, so recognizable, that we say, simply, it is "natural" it should be so....

Whether it be the sweeping eagle in his flight or the open apple-blossom, the toiling work-horse, the blithe swan, the branching oak, the winding stream at its base, the drifting clouds, over all the coursing sun, form ever follows function, and this is the law. Where function does not change form does not change. The granite rocks, the ever-brooding hills, remain for ages; the lightning lives, comes into shape, and dies in a twinkling...
Shall we, then, daily violate this law in our art? Are we so decadent, so imbecile, so utterly weak of eyesight, that we cannot perceive this truth so simple, so very simple? Is it indeed a truth so transparent that we see through it but do not see it? Is it really then, a very marvelous thing, or is it rather so commonplace, so everyday, so near a thing to us, that we cannot perceive that the shape, form, outward expression, design or whatever we may choose, of the tall office building should in the very nature of things follow the functions of the building, and that where the function does not change, the form is not to change?

Does this not readily, clearly, and conclusively show that the lower one or two stories will take on a special character suited to the special needs, that the tiers of typical offices, having the same unchanging function, shall continue in the same unchanging form, and that as to the attic, specific and conclusive as it is in its nature, its function shall equally be so in force, in significance, in continuity, in conclusiveness of outward expression? From this results, naturally, spontaneously, unwittingly, a three-part division, not from any theory, symbol, or fancied logic.

Before we analyse Sullivans thoughts, let's turn to Morrison for an epilogue on the Wainwright Building [Ref. 2.4]:

The influence of the Wainwright Building on contemporary architecture was immediate and extensive. Almost without exception, tall buildings for the next twenty-five years followed its scheme of accenting vertical lines, of recognizing volume through undifferentiated facades, of leaving the shaft of the building between a base and an enriched top sheer and uninterrupted. To be sure, architects crystallized the example of the Wainwright Building into a formula, considering the tall building as an analogue of the classic column, with base shaft, and capital, and employing almost any form of historical ornament; so that Sullivan's creative method of approach was completely lost while the superficials of his results were being most widely copied.

Sullivans thoughts on design contain rich material to help us approach the problem of design:

1. On Sullivans untenable Teleology: Unlike Aristotle, Sullivan extends his teleology over all of nature (both organic as well as inorganic). For example, one could easily imagine Sullivan asserting that the function of the stream is to carry water; its winding shape thus reflects the manner by which it discharges this function over an uneven terrain. On the face of it, it looks convincing. But if we were to ask, wherefrom this function, there is really no answer: to this unless one is willing to posit a divine purpose in all of nature. It is crucial to make this distinction; for there is no such thing as a function that stands apart from a living agent (be it a human, an animal or a plant). In the various organic examples that Sullivan cites, it is the basic life or death alternative that living
entities face which in turn entails subordinate survival form/function complexes such as the shape of the eagles beak to tear things apart. In human action, the form/function integration can be abstract, deliberate and intentional. In other living entities, it is either evolutionary, sensory or perceptual. To summarize, design as a verb indicating cognitive intent pertains to human agents. Also, the concept of functionality ultimately has to refer back to a living agent. And in the case of non-cognitive living agents, it is natural evolution that brings about the form/function integration.

Yet if we were to imagine that the function of the stream to be to carry water over an uneven terrain, then does not its shape reflect this function? Yes, but such anthropomorphic relations could then be attributed to any causal relationship. And this is not warranted. For there are various other "functions" we could then imagine the stream exhibiting, depending upon which causal relationship we focus on:

(a) Function: To erode the terrain; Form: The winding shape, for at each bend erosion is acute.

(b) Function: To evenly irrigate the terrain: Form: The winding shape, for it tries to distribute the water evenly, as compared to a straight line form.

(c) Function: To mix the sediments; Form: The winding shape, for at each bend the sediments are thoroughly mixed through impact.

Each of these are causal links, not form/function links. A designer, by understanding these causal links, is able to enrich his design space. Thus for example, when he wants to design a mixer, he could adopt the winding shape.

2. On Form follows Function: Much more can be said about design than merely that "form follows function." For form ("shape, form, outward expression, design or whatever") is merely one aspect of the overall design. It is the geometrical organization of the various parts in the system under design. For example, one may also say that the bio-chemical organization within a cell follows a certain function; that the social organization in an ant hill follows a certain function; that the conceptual organization of a given knowledge corpus follows a given function, etc. Or in general, that design(n) (used as a noun) follows function. Sullivan's principle is an application of this larger principle.

But what really does it mean to say that design(n) follows function? Various things:

(a) That there is no element in the design(n) which lacks a purpose. Thus no vestigial organs, no purposeless elements cluttering up the design(n) from achieving its function.

(b) That the elements of the design(n) are organized around the function; thus design(n) follows function in that the selection and organizing principle for the design(n) is in the function that needs to be met. This does not mean
that the process of design has to wait until all the functions have been established. It could be better if temporally it did; but it does not have to. For example, in domains that are not well established, one often has to work out the causal relationships that are involved between candidate design elements. Here the designer is studying the design space and establishing the basic organizing units that eventually go towards composing a more involved design(n). It is important to remember that Sullivans design principle is a selection/organizing principle; not a temporal relationship between form and function.

(c) But there is nevertheless a logical temporal order involved in the process of design once the domain has been structured. For example, as Sullivan establishes, first comes the placement of the entrance, then the internal design based on utilitarian principles (such as human factors, area needed, circulation, etc.) and pecuniary interests. Then follows the basic aesthetics of entrance, then the facade (i.e., the ground floor and the second floor, then the stack of similar office floors, then the final attic). This temporal logic falls out of the functional logic. The interior floor design(n)'s have to be established before the exterior skin. As Sullivan writes, “these purely arbitrary units of [internal] structure form in an equally natural way the true basis of the artistic development of the exterior.” Here the word arbitrary does not mean literally arbitrary. For Sullivan also says that these internal designs “have to do strictly with the economics of the building.” Also that the “practical horizontal and vertical division or office unit is naturally based on a room of comfortable area and height, and the size of this standard office room as naturally predetermines the standard structural unit, and, approximately, the size of window openings.” So the implication is not that the internal design is functionally arbitrary, but that it is aesthetically arbitrary. This too he modifies by stating that “only in rare instances does the plan or floor arrangement of the tall office building take on an aesthetic value.” In any case, one may see the temporal sequence between the internal and the external design dictated by the logic of the design(n). After the functional design is complete (along with the basic aesthetics), the design(n) is then re-integrated based on an emotional theme such as “loftiness” which the designer abstracts out of the problem context as well as the functional design. Call this aesthetic re-integration the emotive aesthetics. Basic aesthetic addresses the aesthetic problem of each of the functional components as stand-alone. The emotive aesthetic on the other hand provides an overall re-integration of the total design(n) centered around the emotive theme.

So the question remains, how does design(n) as a product influence design as a process? Does design follow function because design(n) follows function? Design as a process is a function of two things:

- What the designer knows, and
- What the design(n) which follows function entails.
If after everything is said and done, after the designer had somehow come up with a design(n) that obtains the required function, if we were to step back and ask, in what manner would the designer have attempted the problem given the perspective he now has, the answer would probably reflect the second factor more than the first. Thus after the Wainwright design(n), Sullivan would be more deliberate in his design process. Also those others who were (as Morrison indicates) cashing in on Sullivan’s “formula”. In other words the process of design is a design problem in itself. And looked at it this way one may argue that the design(n) of design follows function.

These clarifications are necessary, because many are the contemporary misinterpretations around Sullivan’s principle. For example, in the otherwise valuable narrative on the evolution of everyday things, Prof. Petroski writes [Ref.2.6]:

Imagining how the form of things as seemingly simple as eating utensils might have evolved demonstrates the inadequacy of a “form follows function” argument to serve as a guiding principle for understanding how artifacts have come to look the way they do.

Such an argument is (implicitly) equivocating between design and design(n) Sullivan’s principle cannot directly be applied to design as a process. As we have seen, it applies only indirectly; the remaining factor being the status of understanding the designer has with regard to the design space. And this knowledge has to be gathered inductively over a period of time. It is this aspect of design, that the various historical examples that Prof. Petroski provides is actually highlighting.

3. On the Value of a Clear Problem Statement: What does Sullivan mean when he states that it is of the very essence of every problem that it contains and suggests its own solution? And that he believes [this] to be a natural law? Viewed metaphysically, this is a statement about design(n) as a product. For by focussing on the word contains, one sees that this is merely a re-statement of Sullivan’s direct principle, that design(n) follows function. Viewed epistemologically, this is a statement about design as a process. For by focussing on the word suggests, it is an informal statement of the indirect principle, namely that the design(n) of design follows function. Further, why does he think this to be a natural law? For the first is a metaphysical statement, induced from causality as exhibited by the various design(n)’s in the living order; the other is an epistemological statement, derived from the nature of human consciousness. The epistemological complexity involved in trying to design for every requirement all at once is beyond the human faculties, especially if the number of requirements are large. Instead (with experience), we find a logical order between the various requirements and design parameters. We then use this to organize the process of design. This then is the “dead-reckoning” approach to the design process.
It thus leads to the indirect principle namely, design(n) of design follows function. The above statement shows that Sullivan is aware of both his principles, although he explicates only the first.

A clear problem statement “suggests” a solution in various ways:

(a) It helps focus the search through the designers existing design space.

(b) It helps focus the process of research required to establish the appropriate causal links in a new design space.

(c) And finally, it helps prioritize the design sequence between the select design elements.

Here is Sullivan’s own words on this from his Kindergarten Chats [Ref. 2.3]:

A: I am still puzzling over your statement that every problem contains and suggests its own solution; and that to seek the solution elsewhere is a waste of time. Now I can’t see that a problem contains its solution; still less can I see that it suggests it.

S: I admit the impeachment. It is likely to happen, when one has given years of thought to a particular subject, that his working idea concerning it is apt to concentrate into a statement so terse that, while axiomatic to himself, it is not self-evident to others....

...to give a very simple case: if you are given a peanut-pod and the problem is to find the peanut, you simply open the pod and there is your peanut. The conditions are extremely simple, but the truth is there: the germ of a universal truth...

If we gradually enlarge our problem, we find its husk of conditions becoming complicated, and its contained germ of solution less and less obvious. But when we have solved our problem by confining our attention to it, we find the “law” holds good. And when we have had further experience, we become aware that the very nature of the limiting conditions suggests to us what must be the nature and the limitations of the solution. If you are searching for a peanut you come to know by experience that you will not find it within the burr of a chestnut. Thus a given problem takes on the character of individuality, of identity. And you become aware that your solution must partake of that identity. If you come across a problem which does not possess an identity, you know by such token that the problem is not a problem but a figment. As the problem becomes more complex it becomes the more necessary to know all the conditions, to have all the data, and especially to make sure as to the limitations.

As we shall see, this approach again has fundamental implications in the realm of design for innovation. For it gives us a starting point if we find a problem which has good potential to result in an innovation.
4. On the Aesthetic Re-integration: The above material elaborated upon the functional aspects of design(n) and the design process. But the real triumph of Sullivan's approach is in integrating it then with the aesthetic element by giving it the final integrative status. As Sullivan writes:

However, thus far the results are only partial and tentative at best:...our building may have all this in a considerable degree and yet be far from that adequate solution of the problem I am attempting to define. We must now heed the imperative voice of emotion.

It demands of us, what is the chief characteristic of the tall office building? And at once we answer, it is lofty. This loftiness is to the artist-nature its thrilling aspect. It is the very open organ-tone in its appeal. It must be in turn the dominant chord in his expression of it, the true excitant of his imagination. It must be tall, every inch of it tall. The force and power of altitude must be in it, the glory and pride of exaltation must be in it. It must be every inch a proud and soaring thing, rising in sheer exultation that from bottom to top it is a unit without a single dissenting line...

After the functional design is done (along with the basic aesthetics), the designer then considers the design for an element of character that suggests a human emotion. He then uses it as the main theme around which the design is then re-integrated without compromising any of the design functionalities. In other words, the central aesthetic element in the design is provided for by re-integrating the form/function complex around an emotional theme abstracted out of the design complex, which theme expresses the human condition in some fundamental sense. This then is the emotive aesthetic re-integration that happens. And in a nested sense, the basic aesthetic is again an illustration of the emotive aesthetic, but at a lower component level. Thus when Sullivan writes “beginning with the first story, we give this a main entrance that attracts the eye to its location, and the reminder of the story we treat in a more or less liberal, expansive, sumptuous way,” the aesthetic integration is again emotive in nature and is now applied at the sub-system level. It is this framework of design which we explicated (in Chapter 1) in the context of knowledge hierarchies. We reproduce the functional/aesthetic design trace in Fig. 2.3.

One might say, why not introduce the aesthetic as an extra function that the design needs to satisfy. In a general sense one could say that; but in a specific sense, the emotive theme is not known a-priori. The full context for it to be abstracted out has yet to be established, namely the first form/function integration. The designer has to analyse this first-cycle design and find “the chief [emotive] characteristic of” the design. It is in this process that the designer is imprinting his character, his personal touch, his signature to the design. Thus we can learn about the character of the architect by studying his design. And Sullivan makes this explicit when he says:
The man who designs in this spirit and with the sense of responsibility to the generation he lives in must be no coward, no denier, no bookworm, no dilettante. He must live of his life and for his life in the fullest, most consummate sense. He must realize at once and with the grasp of inspiration that the problem of the tall office building is one of the stupendous, one of the most magnificent opportunities...ever offered to the proud spirit of man.

Some of the intriguing questions that this poses include:

(a) First of all, why do we need the aesthetic element? After all, aren't the functions sufficient? What are the consequences of ignoring it?

(b) If indeed it is a necessity, how general is the requirement? Is there any relation between the levels of abstraction involved in the design versus the acuteness of the need for aesthetic accompaniment? Does the aesthetic necessity apply to all man-made artifacts, including say human knowledge? Would there thus be an aesthetic element to the design of human knowledge?

(c) What is the nature of the process by which the emotive element is arrived at?

To answer some of these questions, we need to go back to Sullivan from his *Kindergarten Chats* [Ref. 2.3]
S: ...I wish to warn that a man might follow the [form follows function] program .[I]. have just laid down, to the very last details, and yet have, if that were his make-up, a very dry, a very pedantic, a very prosaic result. He might produce a completely logical result, so-called, and yet an utterly repellent one—a cold, vacuous negation of living architecture—a veritable pessimism.
A: How so?
S: Simply because logic, scholarship, or taste, or all of them combined, cannot make organic architecture. They may make logical, scholarly, or “tasty” buildings, and that is all. And such structures are either dry, chilling or futile.
A: Well then, tell me...what characterizes a real architect?
S: First of all a poetic imagination; second, a broad sympathy, humane character, common sense and a thoroughly disciplined mind; third, a perfected technique; and finally, an abundant and gracious gift of expression.
A: Then you don’t value logic.
S: It has its excellent uses.
A: But cannot everything be reduced to the syllogism?
S: So the text books would seem to claim; yet I should not wish to see a rose reduced to syllogism; I fear the result would be mostly syllogism and that poetry would “vanish with the rose.” Formal logic cannot successfully deal with the creative process, for the creating function is vital, as its name implies, whereas the syllogism is an abstraction, fascinating as a form of the function, so-called pure reason; yet when subordinate to inspiration, it has a just and high value. I say there is a logic over and above book-logic, namely, the subconscious energy we call imagination. Nevertheless, formal logic has its purpose and its place.
A: Then you do prize logic?
S: I surely do. It is a power of the intellect; but it has its limitations. It must not play tyrant.

This answers two of our questions, namely:

(a) That without the aesthetic element, the design is dry, chilling or futile, a cold, vacuous negation of living architecture.

(b) Regarding the process by which the emotive element is abstracted out, Sullivan is less definite. However he is clearly aware of the root locus of the process (namely the subconscious). He also thinks that there is a logic which is at work here; although it is not the same as “book logic.” In other words there are causal relations that he is aware of at least in himself in relation to the subconscious. Also that this emotive process is intimately connected with the faculty of imagination. Thus Sullivan says, “I say there
is a logic over and above book-logic, namely, the subconscious energy we call imagination." The laws by which the subconscious operates, not being known in any explicit sense currently, it is difficult to explicate the aesthetic process in an exhaustive sense. But in our following discussions, we shall come as close as we can, to provide some benchmarks as well as highlight some of the key issues involved.

For our remaining queries, we once again go to Kindergarten Chats for elaborations from the chapter on the Art of Expression. Again the inductive element from nature is the guiding theme [Ref. 2.3]:

In the springtime, greeting the sun when ice and snow are gone, sap mounts within the trees, seeds awaken, a new utterance of life begins. Out of the darkness, out of the silence of winter, comes a song. The filigree of Nature’s resurrection reappears. She chants of her deliverance.

And thus, the dormant soul of man awakening to the sun of sympathy, he puts forth the beginning of his springtime—the utterance of things long forming, long hidden, long obscured, long unfelt, but now stirring toward the light, seeking form, seeking growth, seeking expression.

Thus does Nature, thus does Man burgeon the promise of fertility....

For, if the moving spectacle of spring shall not invade you to the depths, you may never truly learn how sonorous are the great words in our art; how fluent, how satisfying the lesser ones; how sweet the many minor sayings.

An art of expression must flow from an inner reservoir. It must be the gathered and stored force seeking outlet. It is not as a garment—a something to be worn or not worn—it is inseparable from life, a symbol of life.

Hence, an Art of Expression should be the earliest upbuilding element to enter into the curriculum of a thorough education. It should grow as the body grows and mature as the will evolves. It should evidence human capacity and human possibility. It should open the mind, open the heart, to direct impressions at the very beginning. These are to the human what sunlight, soil and rain are to vegetation. Then, let utterance of these impressions begin so soon as it is evident that they are impressions. After which, new impressions, then new utterance—ever continous, ever reciprocal, ever broadening, surely organizing, unfolding, ever growing in power more coherent, more plastic, more fluent; ever growing in receptivity, ever growing in aspiration; ever growing in mobility, ever growing in serenity; ever growing more complex—paralleling the complexity of life; ever growing more simple—paralleling the the simplicity of life; ever gaining in strength, ever gaining in delicacy: ever in ferment, ever clarifying those elemen-
tal powers which are so subtle yet the most potent of all—the power of receiving, the power of uttering!

Then, in clarity, one may see not merely over the surface of things, but into the being of things, and of man.
Then may one express life, because he has lived.
Then will one’s work be poems, for they shall spring from life, its needs, and its desires.

Now it has been part of our work to expand and concentrate the meaning of words, of phrases. To extricate them from their provencial confinement and let them go free in the world of men. Such a parlor-phrase is now before us, namely: the art of expression. Its use has been limited almost exclusively to the so-called fine arts and perhaps particularly to the art of writing, poetry and prose. That is to say, it has retained a strictly feudal meaning, in the sense that it is a direct expression of the ego in a quite limited aristocratic and subservient sense....The phrase therefore needs liberation. It must take on a great expansiveness and power of symbolism. It must be exalted into a universal guiding principle and power: else shall it fail to satisfy and inspire the brain, the heart of a democratic work. In short, we must change its significance from feudal to democratic. We must so broaden the scope that it shall include every human activity. For it is the function of Democracy to liberate, broaden, intensify and focus every human faculty; to utilize every human power now unused, abused, or running to waste....

Thus it is necessary in a democracy that men in all walks of life (especially those who assume to be leaders in thought) qualify, each in his way, in the all-inclusive art of expression. For Democracy has real things to express, it insists on their expression....It is in the development of the technique of such art that modern man is to concentrate his thought, bend his faculties, and exercise his superb powers as creator.

It is needless that I should go further into detail. The implications should be obvious...

...my object all along has been, first, to isolate the architectural art as a specialized social activity and then to show how inextricably, in its genuine state, it is interwoven with the needs, the thoughts, the aspirations of the people, that it cannot have a real life without them, and then to raise it into the higher realms of interpretation. That, to become a real art of expression for us, it must be inspired by the democratic urge, it must take its vigorous origin in the direct practical, utilitarian needs, fully utilize the resources. Then and then only is it justified in entering the realms of sentiment and poetic imagination; and then only for the purpose of giving to the utilitarian its needed aspect of beauty, thus contributing its share to the happiness of mankind—to the poem of Democracy. Then and then only may architecture worthily be

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called an art of expression.

Much less do I need to go with you into the technical details of our art. Nature furnishes the materials and you have but to use them with intelligence, and feeling. All geometric forms are at your disposal, they are universal; it is for you to utilize them, to manipulate them, to transmute them, with feeling and intelligence. Engineering science has substantially solved all problems of construction. The industrial arts, the so-called fine arts, mechanical skill, craftsmanship are at your disposal. The organized building arts, transportation, communication are at your disposal; language is at your disposal. Nature’s manifold expressions of function and form are at your disposal. What more do you need as a medium of expression. The rest is “up to you” as it is said.

To make these things, these instrumentalities, plastic to your ends is your business; indeed it is to be your career. I have carefully avoided laying down rules—they tend to merely circumscribe and repress. What I have attentively laid stress on is underlying principles; I have shown how simple, how universal they are. I have shown you also something of the complexity of their unfolding.

This again explains the issue only partly. Nevertheless Sullivan is unequivocal about the following:

(a) That we should “so broaden the scope” of the phrase art of expression “that it shall include every human activity.” Thus Sullivan means to apply the art of expression principle to everything man-made, including such things as human knowledge. Thus there ought to be something called the aesthetic of human knowledge. And so also in the making of common things such as telephones, and dish washers, and door knobs. Also as Industrial Designers well know, the aesthetic of the design(n) is a critical factor in how the customer values the product.

But why should we so broaden the scope? For as he says, it helps liberate, broaden, intensify and focus every human faculty; to utilize every human power row unused, abused, or running to waste. Now here we have some fundamental answers. Sullivan is here connecting the act of design with the fundamental human need, namely, to live a full life, “to utilize every human power now unused, abused, or running to waste.” Yet it is somehow incomplete. Firstly, why should one live a full life, meaning life which includes artistic expression versus not including it? In what sense is the later supposed to be partial and incomplete? Secondly, why should a client pay for such artistic “extravaganza” beyond the bare form/function integration? What does he stand to gain? If the artist is the one benefiting from “living a full life” should he not then be paying the client for providing him this luxury of living a full life? Or is there some similar manner in which the client also benefits? In other words, why do we need art? Apparently,
every human culture has engaged in this. But the question is why? Here we finally recognize the need for philosophic guidance, for here we are at the doorsteps of aesthetics proper. We take up this issue in Section 2.3.

(b) That the primary form/function integration ought to precede the aesthetic expression. Thus the design must take its vigorous origin in the direct practical, utilitarian needs, fully utilize the resources. Then and then only is it justified in entering the realms of sentiment and poetic imagination; and then only for the purpose of giving to the utilitarian its needed aspect of beauty. Why must this be so? For example, is it not possible to start with an aesthetic theme and build everything around this, including the form/function integration? Or is this arbitrary? Also what happens if the functions that need to be satisfied become numerous and complex? Is it still feasible to start with an aesthetic theme? In all of this, it is the authors conviction that these chronological orders depend upon the maturity of the designer, upon how well he understands the knowledge domain under focus. Thus there would be many different approach during the discovery phase, including the sequencing between the functional design versus the aesthetic design. But once the main elements of the domain have been captured, Sullivan is right in emphasizing the strict precedence of the functional design.

(c) That each designer has to find his own unique signature; that in the context of art as expression, there is no point “laying down rules”; for “they tend to merely circumscribe and repress.” The only principle Sullivan is willing to lay down is to say that right from early childhood, one must be engaged in taking impressions and making expressions; thus one must constantly be engaged in “the power of receiving, the power of uttering.” This reticence is so because one is here in the realm of the subconscious; and the logic of the subconscious has yet to be discovered.

5. Analysis of the Skyscraper Design(n): We are now ready to do the validity analysis on Sullivan’s design(n) using Prof. Suh’s design(n) matrix. If we use the notations we described earlier in the context of the coupled “Vitruvian” design, we would see that at the top level of the design(n), Sullivan made the design(n) for the basic aesthetic requirement (BAR) contingent on the design(n) for the non-aesthetic requirement (NAR). He made the non-aesthetic function primary. We thus have the following triangular design(n) matrix:

\[
\begin{align*}
\{ \text{FR1: NAR} \} = & \begin{bmatrix} + & O \end{bmatrix} \{ \text{DP1: NAP} \} \\
\{ \text{FR2: BAR} \} = & \begin{bmatrix} + & + \end{bmatrix} \{ \text{DP2: BAP} \}
\end{align*}
\]

(2.2)

Here DP1 is the non-aesthetic parameter (NAP); and DP2 is the basic-aesthetic parameter (BAP).

Sullivan further decomposed the non-aesthetic part (NAR) into the following seven requirements:

(a) Entrance Requirement \((ER)\): Need to access the building from public streets.
(b) Primary Utility Space Requirement (UR₁): Need space for the primary location of the utilities, the "boilers, engines of various sorts, etc.—in short, the plant for power, heating, lighting, etc."

(c) Primary Retail Space Requirement (RR₁): Need primary retail space devoted to "stores, banks, or other establishments requiring large area, ample spacing, ample light, and great freedom of access."

(d) Secondary Retail Space Requirement (RR₂): Need secondary retail space similar to RR₁, but of subordinate interest.

(e) Office Space Requirement (OR): Need an arbitrarily large amount of office space (for commercial purposes) whose interior design is for the client to modify and develop as per his/her changing commercial needs, unconstrained by the overall design(n).

(f) Secondary Utility Space Requirement (UR₂): Need space for the secondary location of the utilities, where the "space is filled with tanks, pipes, valves, sheaves, and mechanical etcetra that supplement and complement the force-originating plant hidden below-ground in the cellar."

(g) Circulation Space Requirement (CR): Need space for the circulatory system that connects the various other spaces and thus provides access between.

And the generic design(n) that Sullivan proposed for these requirements was:

(a) Entrance Space (ES): Space located conveniently at street level accessing the building from public streets.

(b) Basement Space (BS): Space located under the ground level as the primary location of the utilities.

(c) Ground Floor Space (GS): Space located at the ground floor as the primary retail space.

(d) Second Floor Space (SS): Space located at the second floor level as secondary retail space.

(e) Office Floor Space (OS): Depending on the amount of office space needed, provide as many floors stacked vertically, with loads carried by steel columns so that clients may individually do the interior design without structural obstructions.

(f) Attic Space (AS): Space at the top of the building to complement the primary utility system in the basement.

(g) Circulation Space (CS): Space that cuts through all the various levels of the building and interlinks them for providing transportation for goods, people and utilities.
The design(n) begins with the following coupled matrix:

\[
\begin{align*}
\{ \text{NAR}_1: ER \} &= \begin{bmatrix} \oplus & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad \text{NAP}_1: ES \\
\{ \text{NAR}_2: UR_1 \} &= \begin{bmatrix} c & \oplus & 0 & 0 & 0 & 0 \end{bmatrix} \quad \text{NAP}_2: BS \\
\{ \text{NAR}_3: RR_1 \} &= \begin{bmatrix} c & 0 & \oplus & 0 & 0 & 0 \end{bmatrix} \quad \text{NAP}_3: GS \\
\{ \text{NAR}_4: RR_2 \} &= \begin{bmatrix} c & 0 & 0 & \oplus & 0 & 0 \end{bmatrix} \quad \text{NAP}_4: SS \\
\{ \text{NAR}_5: OR \} &= \begin{bmatrix} c & 0 & 0 & 0 & \oplus & 0 \end{bmatrix} \quad \text{NAP}_5: OS \\
\{ \text{NAR}_6: UR_2 \} &= \begin{bmatrix} c & 0 & 0 & 0 & 0 & \oplus \end{bmatrix} \quad \text{NAP}_6: AS \\
\{ \text{NAR}_7: CR \} &= \begin{bmatrix} c & + & + & + & + & \oplus \end{bmatrix} \quad \text{NAP}_7: CS \\
\end{align*}
\]

(2.3)

Here major positive and negative influences are denoted as \(\oplus/\ominus\); minor ones as \(+/-\). The \(c\) denotes that an earlier design(n) decision constrains the design(n) space for the requirement the \(c\) is associated with. Using the \(c\)'s along with the \(+/\ominus\) qualifiers, one is able to capture also part of the design process using the design(n) matrix. For the natural order is to first design for those requirements that are least constrained. In this sense one may extend the design(n) matrix approach to capture the design process logic (i.e., design(n) of design follows function) through various snapshots.

We see that the design(n) of the circulatory system might compromise most of the other space requirements on account of the fact that it is cutting thru these spaces in order to link them. Thus in the second iteration, one might want to add extra floors at various levels in order to compensate for this negative effect. Thus in the analysis of the final iteration, the design(n) could be rendered completely diagonal:

\[
\begin{align*}
\{ \text{NAR}_1: ER \} &= \begin{bmatrix} \oplus & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad \text{NAP}_1: ES \\
\{ \text{NAR}_2: UR_1 \} &= \begin{bmatrix} 0 & \oplus & 0 & 0 & 0 & 0 \end{bmatrix} \quad \text{NAP}_2: BS \\
\{ \text{NAR}_3: RR_1 \} &= \begin{bmatrix} 0 & 0 & \oplus & 0 & 0 & 0 \end{bmatrix} \quad \text{NAP}_3: GS \\
\{ \text{NAR}_4: RR_2 \} &= \begin{bmatrix} 0 & 0 & 0 & \oplus & 0 & 0 \end{bmatrix} \quad \text{NAP}_4: SS \\
\{ \text{NAR}_5: OR \} &= \begin{bmatrix} 0 & 0 & 0 & 0 & \oplus & 0 \end{bmatrix} \quad \text{NAP}_5: OS \\
\{ \text{NAR}_6: UR_2 \} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \oplus \end{bmatrix} \quad \text{NAP}_6: AS \\
\{ \text{NAR}_7: CR \} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & \oplus \end{bmatrix} \quad \text{NAP}_7: CS \\
\end{align*}
\]

(2.4)

The constraints \((c)'s\) have been supressed, for we are merely representing the design(n) rather than the design. But as we mentioned before, by capturing the design(n) matrix at various stages, we may capture the actual process of the evolving design (compare Eq.2.3 with 2.4).

We now look at the aesthetic design(n). The overall aesthetic is a factor wherever the structure is visible from the outside. The visible areas include the entrance, the ground floor, the second floor, the office floors, and the attic. Thus the basic aesthetic requirements are five in number, one for each of the spaces as defined by the non-aesthetic design(n):

(a) **Entrance Aesthetic Requirement** \((ES_a)\): design the main entrance such that it "attracts the eye to its location."
(b) Ground Floor Aesthetic Requirement \( (GS_a) \): design the ground floor in a "more or less liberal, expansive, sumptuous way—a way based exactly on the practical necessities, but expressed with a sentiment of largeness and freedom."

(c) Second Floor Aesthetic Requirement \( (SS_a) \): design the second floor in a similar way as the ground floor except with a "milder pretension."

(d) Office Floor Aesthetic Requirement \( (OS_a) \): design all office floors to look alike, for their functions "are alike." Arrive at the aesthetic by looking at the internal organization. Take the cue from "the individual cell, which requires a window with its separating pier, its sill and lintel."

(e) Attic Floor Aesthetic Requirement \( (AS_a) \): The attic "having no division into office cells, and no special requirement for lighting, gives us the power to show by means of its broad expanse of wall, and its dominating weight and character, that which is the fact, namely that the series of office tiers has come definitely to an end..."

The basic aesthetic design\( (n) \) depends upon the specific design\( (n) \) problem. We will thus not be able to specify the actual aesthetic design\( (n) \) parameters. Nevertheless, we denote the aesthetic design\( (n) \) as follows:

(a) Entrance Aesthetic \( (EA) \).

(b) Ground Floor Aesthetic \( (GA) \).

(c) Second Floor Aesthetic \( (SA) \).

(d) Office Floor Aesthetic \( (OA) \).

(e) Attic Floor Aesthetic \( (AA) \).

And the design\( (n) \) matrix for this looks like:

\[
\begin{align*}
AR_1: ES_a & \equiv \begin{bmatrix}
\oplus & O & O & O & O
\end{bmatrix} \quad AP_1: EA \\
AR_2: GS_a & = \begin{bmatrix}
O & \oplus & O & O & O
\end{bmatrix} \quad AP_2: GA \\
AR_3: SS_a & = \begin{bmatrix}
O & O & \oplus & O & O
\end{bmatrix} \quad AP_3: SA \\
AR_4: OS_a & = \begin{bmatrix}
O & O & O & \oplus & O
\end{bmatrix} \quad AP_4: OA \\
AR_5: AS_a & = \begin{bmatrix}
O & O & O & O & \oplus
\end{bmatrix} \quad AP_5: AA
\end{align*}
\]

(2.5)

Again the design is diagonal.

The overall non-aesthetic and basic aesthetic design may thus be represented
as:

\[
\begin{align*}
\begin{bmatrix}
ER \\
UR_1 \\
RR_1 \\
RR_2 \\
OR \\
UR_2 \\
CR \\
ES_a \\
GS_a \\
SS_a \\
OS_a \\
AS_a
\end{bmatrix}
\begin{bmatrix}
\oplus \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
+ \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
\begin{bmatrix}
ES \\
BS \\
GS \\
SS \\
OS \\
AS \\
CS \\
EA \\
GA \\
SA \\
OA \\
AA
\end{bmatrix}
\end{align*}
\]

(2.6)

Note that as the design reaches into greater details, the earlier off-diagonal matrix that coupled BAR to NAP is filled in with the appropriate coupling elements as in the above bottom off-diagonal terms.

Having now completed the non-aesthetic design(n) (NAP) as well as the basic aesthetic design(n) (BAP), we are now ready to attempt the emotive aesthetic design. The emotive aesthetic design(n) is as follows:

- **The Emotive Aesthetic Requirement (EA):** Need to convey the emotion that the structure is “lofty” as a symbol to the “proud spirit of man...”

- **The Emotive Aesthetic Parameters (EP):** The structure “must be tall, every inch of it tall...without a single dissenting line...”

This is a second level design, in the sense that it is modifying the basic design that has already been established. In that sense it could modify and stylize every single parameter that has until now been established. However the chances are that it would predominantly modify the skin, i.e., the BAP parameters. And this stylizing which is required to convey “loftiness” has to be done without compromising any of the existing functions. In the initial iterations, it indeed might compromise the design(n). However, with refinement, the emotive aesthetic could also be incorporated. And the overall design would like as
follows:

\[
\begin{align*}
ER & = \begin{bmatrix}
\oplus & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
UR_1 & 0 & \oplus & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
RR_1 & 0 & 0 & \oplus & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
RR_2 & 0 & 0 & 0 & \oplus & 0 & 0 & 0 & 0 & 0 & 0 \\
OR & 0 & 0 & 0 & 0 & \oplus & 0 & 0 & 0 & 0 & 0 \\
UR_2 & 0 & 0 & 0 & 0 & 0 & \oplus & 0 & 0 & 0 & 0 \\
CR & 0 & 0 & 0 & 0 & 0 & 0 & \oplus & 0 & 0 & 0 \\
ES_a & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \oplus & 0 & 0 \\
GS_a & 0 & 0 & 0 & + & 0 & 0 & 0 & 0 & 0 & 0 \\
SA & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
OA & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
AA & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
EP & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \\
& = \begin{bmatrix}
ES \\
BS \\
GS \\
SS \\
OS \\
AS \\
CS \\
EA \\
GA \\
SA \\
OA \\
AA \\
EP
\end{bmatrix}
\end{align*}
\]

(2.7)

The notation in the last line of the design(n)-matrix is self-evident, and reflects the relative importance of the various elements. With this we are now able to see how exactly the aesthetic (both basic and emotive) modifies the utilitarian design.

6. **Sullivan’s Theory versus Prof. Suh’s Theory:** In the last section we analysed Sullivan’s design(n) using Prof. Suh’s framework. Having done this, a question arises: how might one contrast Prof. Suh’s functional approach to design with that of Sullivan’s?

While Sullivan preceded Prof. Suh by more than 80 years, Prof. Suh’s approach provides greater insights into the explicit mapping between the function and the final design(n).

Other main differences:

(a) Sullivan is more ecumenical in regard to the scope of design (physical, mental, social); Prof. Suh defines design in a restricted sense (as applying to only the physical domain).

(b) For Sullivan, design is a mental process; for Prof. Suh location of design as a process could also be in the machine.

(c) For Sullivan, the aesthetic requirement is abstracted out of the form/function integration; for Prof. Suh, the aesthetic requirement is merely another function that needs to be satisfied.

(d) For Sullivan, the concept of design complexity was not a major issue; Prof. Suh on the other hand proposed an whole axiom to address this.

(e) Sullivans theory was induced by studying forms in nature; Prof. Suh’s was induced from examples in manufacturing. One is thus more “organic” and “poetic” in style; the other is more “industrial” and “machine-like” in style.
(f) Sullivan recognized the positive influence of the subconscious in the act of design, believed that there is a logic to it, and showed tentative ways on how to improve it; Prof. Suh is silent on this.

Despite these differences, one may easily detect the various occasions where both these approaches complement and coincide. For example, it is remarkable that both of them saw the hierarchical nested nature of the design process; both of them wrote explicit treatise on design in order to help the pedagogy on design. But most importantly, both of them saw that the design(n) is derived from the function.

This concludes our analysis of Sullivans writings. Despite the partial answers in the realm of aesthetics, we have gained fundamental insights into the problem of design/design(n) and innovation. In the context of design, the main insights we gathered were:

1. The direct design(n) principle induced from diverse examples in nature: that design(n) follows function.
2. The indirect design principle, namely, that the design(n) of design follows function.
3. That the scope of design is not restricted to the physical realm. Sullivan thus includes the physical world—visual, microscopic, and telescopic, the world of the senses, the world of the intellect, the world of the heart, the world of the soul
4. That design has a hierarchical nature. That functions are born of functions, and in turn, give birth or death to others. That forms emerge from forms, and others arise or descend from these.
5. That without the aesthetic elements, the design is dry, chilling or futile, a cold, vacuous negation of living architecture.
6. That the Art of Expression has to be cultivated from early childhood, both in the power of receiving, [and in] the power of uttering.
7. That the nature of the human subconscious is still unknown, but that it has a logic over and above book-logic.
8. That the emotive aesthetic design involves a re-integration of the basic design(n).

(f). That a well stated problem contains and suggests its own solution.

Over and above these, Sullivan also provides us evidence regarding the problem of innovation.

1. His approach in coming up with an archstand (the external point of reference in order to shift the prevalent "Vitruvian" practices) was inductive in style. He founded his archstand, that "form follows function," from diverse examples in nature.
2. Also the reason why Sullivan is considered "the father of the skyscraper" is because he understood that in the context of the cascade innovation (of tall buildings prompted by allied innovations in steel and elevator technologies), one has to go back to first principles and redo the whole problem. Thus his case is also an illustration of the "square-one" principle, or Prof. Suh's Theorem 5.

These are substantial gains. We now look at the writings of one of Sullivan's students, Frank Lloyd Wright for additional insights into the Organic Architecture.

One of the best exponents of the organic theory was architect Frank Lloyd Wright who used to refer to Sullivan as "der Meister." While Sullivan pioneered in the practice of commercial buildings, Wright pioneered in the realm of residential buildings. And perhaps the best example of this is the thought that went behind the creation of Fallingwater (Fig.2.4) by Frank Lloyd Wright for client Kaufmann (founder of the Kaufmanns departmental stores). In the words of Kaufmanns son Edgar Kaufmann Jr. (who apprenticed with Wright) [Ref.2.7]:

Fallingwater brings people and nature together in an easy relationship; that is the source of its great appeal, of its worldwide fame as one of Frank Lloyd Wright's masterworks.

The following are various quotes on the actual conception of the Fallingwater. They are extremely useful in studying the actual process of design. Note the manner in which Wright uses the subconscious during the lengthy idea gestation process.

In the words of Kaufmann Jr. [Ref.2.7]:

Wright did not like to rush to the drawing board. John Lautner, another apprentice, puts it this way: "He had the design totally in his head, as always. and as he recommended to the apprentices, if no whole idea, no architecture.

Regarding the actual birth of the idea for Fallingwater, Byron Mosher (another apprentice) writes [Ref.2.7]:

Mr. Wright was not at all disturbed by the fact that not one line had been drawn. As was normal, he asked me to bring him the topological map of Bear Run, to his draughting table in the sloping roofed studio at Taliesin, a rustic but wondrous room in itself....I stood by, on his right side, keeping his colored-pencils sharpened. Ev'ry line he drew, vertically and especially horizontally, I watched with complete fascination....Mr. Kaufmann arrived and Mr. Wright greeted him in his wondrously warm manner. In the studio, Mr. Wright explained the sketches to his client. Mr. Kaufmann, a very intelligent but practical gentleman, merely said..."I thought you would place the house near the waterfall, not over it." Mr. Wright said quietly, "E.J., I want you to live with the waterfall, not just to look at it, but for it to become an integral part of your lives." And it did just that. That evening, my colleague Ed Tafel and I stayed up very late and drew pencil perspectives looking up and looking down. Early the
Figure 2-4: Frank Lloyd Wrights Fallingwater [Source: Ref. 2.7]
next morning, Mr. Wright came into the studio, took my perspective, and finished it with his inevitable colored pencils.

Continuing, in the words of Kaufmann Jr. [Ref.2.7]:

Wright had kept the idea in his mind for exactly nine months. His sketches may have looked a little rough to Kaufmann, but they turned out to be remarkably complete presentation of the house as it would be built: the house had been conceived with an awesome finality. Behind the pencils in his hand stood an imagination as disciplined as it was free. He was well into the fourth decade of his mature practice, and he was able to realize as much as his imagination could suggest. "You see," he once wrote, "by way of concentrated thought, the idea is likely to spring into life all at once and be completed eventually with the unity of a living organism."

...The house on Bear Run was to serve the Kaufmanns on their weekends away from an active business life in the city. It was to be a country house, in communion with the forest and the stream. Wright conceived the house in terms of living space extended into the forest and above the falls, on terraces echoing the ledges of rock beneath the stream and along the cliffs: to him the rock ledges suggested terraces projected into space...he could imagine an entire house constituted from a series of terraces, staggered but secure, like the ancient rock ledges. He described the house as essentially an "extension of the cliff beside a mountain stream, making living space over and above the stream upon several terraces upon which a man who loved the place sincerely, one who liked to listen to the waterfall, might well live."

How could such terraces of space—a house, as he phrased it, seemingly "leaping out from the rock ledges behind"—be built without direct vertical supports, which would intrude on the natural beauty of the stream? By means of the cantilever, a beam system extended beyond its supports. Wright saw the cantilever as a profoundly natural principle, as in the outstretched arm. or the tree branch growing from the trunk. He thought that engineers had failed to grasp its real potentialities; that, with imagination, it could become the most romantic and most free of all principles of construction. The cantilever, he said, could perform remarkable things in liberating space and creating planes parallel to the earth, those long and continuous horizontal planes and lines that he believed to be the essential expressions "of human tenure on this earth," "the true earth-line of human life, indicative of freedom. Always."

The house would have a "definite masonry form" to be sympathetic with its site. But of course the cantilevers, on such scale, could not be of stone. For the first time in his experience, Wright said, reinforced concrete was truly necessary in building a residence. In itself, concrete was not a material that Wright found of interest. It was passive and without intrinsic aesthetic character. But it could be cast into any form: it was completely
plastic; and it had the exceptional property of growing ever stronger with age. When it was reinforced with steel, concrete acquired extraordinary strength.

By the waterfall on Bear Run, where the land was so ragged and precipitous, and the horizon line scarcely visible, an overriding rhythm of horizontal planes and lines became all the more essential to give the living space of the house the expansive and adventurous freedom that Wright believed to be basic to American life. The house would welcome the changes of season, of weather, of the light of day; at the same time, in those darker and more secure spaces shaped by the great masses of stone masonry that counterbalanced the cantilevered terraces, there would be comforting warmth and a sense of shelter and refuge, where the steady sound from the falls would reinforce the forest quiet.

When asked about the house many years later, Wright said [Ref.2.7]:

There in a beautiful forest was a solid, high rock ledge rising beside a waterfall, and the natural thing seemed to be to cantilever the house from that rock bank over the falling water....Then came (of course) Mr. Kaufmann's love for the beautiful site. He loved the site where the house was built and liked to listen to the waterfall. So that was a prime motive in the design. I think you can hear the waterfall when you look at the design. At least it is there, and he lives intimately with the thing he loves.

These extended quotes were by way of establishing the context for the structuring of thought that went into the design of Fallingwater.

We may note Sullivans "form follows function" principle structuring the course of the design process:

1. The Prime Motive/Function: Need the house integral with the waterfall in order that the client could live "intimately with the thing he loves".

2. Primary Design: Use the cantilever principle in order to place the house directly over the fall.

3. Function: Need a structural system that can support the cantilevered masses.

4. Design: Reinforced Concrete Cantilever

Note also the hierarchial yet natural development of the thought process. First the arch principles are established; then the subordinate ones are filled in. As we saw earlier, design doesn't necessarily have to follow such a top down format. Such an approach is feasible when the fundamental principles (such as the cantilever principle) in the field have already been well establised. Whenever the domain knowledge is yet to be established, design would be empirical and bottom-up. Even so, the design process is still hierarchical (i.e., bottom-up). These design-hierarchies are a consequence of the fact that by the nature of our mental constitutions, human concepts
are organized hierarchically; and the process of design is merely reflecting this fact. We shall pick this up in later chapters.

The fact that we have structured the design in a rather straightforward fashion might make one think, "if such is indeed the process of design, why did it take Wright more than 9 months to fuse it together?" Such a conclusion would be rather hasty. First of all, the complexity that is involved in the design has purposely been hidden away in order to trace the main thrust of Wrights thought process. Throughout the design trace, we focussed on just a single function, fundamental though it might be. Yet involved within the design complex are the other spatial organizations such as defining the interior living spaces, "those darker and more secure spaces shaped by the great masses of stone masonry that counterbalanced the cantilevered terraces, [where] there would be comforting warmth and a sense of shelter and refuge, where the steady sound from the fials would reinforce the forest quiet." Secondly, grasping the hierarchical structure of the thought process is akin to grasping merely the skeletal form of design; the "flesh" of design is missing. By flesh we mean all the adjacent thought processes, such as considering and rejecting stone as an alternative material to reinforced-concrete for providing the cantilever support. Thirdly, and most importantly, missing from the design trace is the inductive manner by which the crux of the problem was posed and solved. Why, for example, did Wright focus on the integration of the waterfall with the house as the main problem? In his interaction with his client, why did he choose to focus primarily on the fact that the client "loved the site where the house was built and liked to listen to the waterfall"? To appreciate these aspects of the process of design, we have to go to Wrights writings. We shall be quoting from the following four essays that appeared in the Architectural Record between 1914 and 1928 (the concepts we will encounter are listed underneath each title):

1. The Logic of the Plan (1928) [Ref.2.8]
   - On Conceiving the Plan in the Mind.
   - On Structuring the Design(n) Space.
   - On the Articulation of the Plan.
   - On the Art of Expression.

2. In the Cause of Architecture (1914) [Ref.2.8]
   - On Simplicity Versus Complexity—a Psycho-Epistem-logical Perspective.
   - On Mass Customization.
   - On the Use of Design(n) Constraints.
   - On the Role of the Machine.
   - On the Value the Client Receives in the Context of the Art of Expression.
3. Standardization, The Soul of The Machine (1927) [Ref.2.8]

- On the Benefits of Standardization.
- On the Challenge it poses to Designers.
- On Mental Standardization

4. What “styles” mean to the Architect (1928) [Ref. 2.8]

- On Mental Standardization.

We shall analyse these concepts as and when the context is set.

In the following excerpts from Wright's essay on The Logic of the Plan [Ref. 2.8], he formally states his approach on plan, scale, articulation and style. Each of the fine arts (such as sculpture, painting, architecture, fiction-writing, etc.) have defined a set of closely related concepts explicating the basic artistic elements such as plan, plot, theme, style, etc. As we shall see, these concepts map elegantly onto our design-trace concept and help validate it from multiple perspectives:

Plan! There is something elemental in that word itself. A pregnant plan has logic—is the logic of the building square? stated...

A good plan is the beginning and the end, because every good plan is organic. That means that its development in all directions is inherent—inevitable. Scientifically, artistically to foresee all is “to plan.” There is more beauty in a fine ground plan than in almost any of its ultimate consequences....

All is there seen—purpose, materials, method, character, style. The plan? The prophetic soul of the building—a building that can live only because of the prophecy that is the plan. But it is a map, a chart, a mere diagram, a mathematical projection before the fact....

To judge the architect one need only look at his ground plan. He is master then and there, or never. Were all elevations of genuine buildings of the world lost and the ground plans saved, each building would construct itself again. Because before the plan is a plan it is a concept in some creative mind....

The original plan may be thrown away as the work proceeds—probably most of those for the most wonderful buildings in the world were, because the concept grows and matures during realization... But that plan had, first, to be made...

But to throw the plans away is a luxury ill afforded by the organizations of our modern world..

...conceive the building in the imagination, not on paper but in the mind, thoroughly—before touching paper. Let it live there—gradually taking more definite form before committing it to the draughting board. When the thing
Figure 2-5: Plot, Plan and Perspective, Ennis House (California) [Source: Ref. 2.8.]
lives for you—start to plan it with tools. Not before. To draw during con-
ception or "sketch," as we say, experimenting with practical adjustments to
scale, is well enough if the concept is clear enough to be firmly held. It
is best to cultivate the imagination to construct and complete the building
before working upon it with T square and triangle. Working on it with
triangle and T square should modify or extend or intensify or test the
conception—complete the harmonious adjustments of its parts. But if the
original concept is lost as the drawing proceeds, throw all away and begin
afresh. To throw away a concept entirely to make way for a fresh one—that
is a faculty of the mind not easily cultivated. Few have that capacity. It is
perhaps a gift—but may be attained by practice...

The several factors most important in making the plans—after general
purpose or scheme or "project" are,

- 2nd—Materials.
- 3rd—Building methods.
- 4th—Scale.
- 5th—Articulation.
- 6th—Expression or Style.

In matters of scale, the human being is the logical norm because
buildings are to be humanly inhabited and should be related to human
proportions not only comfortably but agreeably...Scale is really propor-
tion...Without a sense of proportion, no one should build...

In the matter of materials. These also affect scale. The logical mate-
rial under the circumstances is the most natural material for the purpose.
It is usually the most beautiful—and it is obvious that sticks will not space
the same as stones nor allow the same proportions as steel. Nor will the
spacing adjustable to these be natural to made-blocks or to slabs or to a
plastic modeling of form....

In the matter of building methods. These too are meantime shaping
the plan. In the Coonley house—the 4'-0" unit works with 16" centers as
established in carpenter practice for the length of lath, the economical
spacing of studs and nailing-bearings, standard lumber lengths...

Concerning articulation. The Ennis house [Fig. 2.5] will serve to
illustrate the principle, which once grasped is simple.

In the building, each separate portion of the building devoted to a special
purpose asserts itself as an individual factor in the whole.

The dining-room associated with terraces is one mass. The living-room
with bedroom attached, another mass standing at the center on a terrace
of its own—the dominating feature of the group.
Mr. Ennis's bedroom, semi-detached and used as a study or office, is another and terminal mass.

At the rear is the kitchen unit, a subordinate mass. All are connected by a gallery passing along the group at the rear. Finally the terrace-wall ends in a detached mass to the rear of the lot—the garage and chauffeur's quarters.

A little study will show how each separate room makes its own characteristic contribution to the whole mass.

The completed whole crowns the end of a high ridge in Hollywood and is a pre-cast slab-block building woven together with steel...These articulations are as obvious in the plan as in the perspective...

In the matter of expression and style. As a matter of logic in the plan it is easy to see there can be none except as the result of scale, materials and building method. But with all that properly set, there is the important human equation at work in every move that is made. The architect weaves into it all his sense of the whole. He articulates—emphasizes what he loves.

No matter how technically faithful his logic may have been...living in the atmosphere created by the orchestration of those matters, hovers the indefinable quality of style. Style emanating from the form, as seen by the man himself. And while it speaks to you of all those important matters, it leaves you imbued by dignity, grace, repose, gaiety, strength, severity, delicacy and of rhythmical order...

So every true building is of the quality of some man's soul, his sense of harmony and "fitness," which is another kind of harmony—more or less manifest in the fallible human process...

Let us analyse what Wright says:

1. On Conceiving the Plan in the Mind: Consider Wright's quote on conceiving the plan in the mind:

   ...conceive the building in the imagination, not on paper but in the mind, thoroughly—before touching paper. Let it live there—gradually taking more definite form before committing it to the draughting board. When the thing lives for you—start to plan it with tools. Not before. To draw during conception or "sketch," as we say, experimenting with practical adjustments to scale, is well enough if the concept is clear enough to be firmly held. It is best to cultivate the imagination to construct and complete the building before working upon it with T square and triangle.

Also recollect John Lautner's earlier comment:

He had the design totally in his head, as always, and as he recommended to the apprentices, if no whole idea, no architecture.
Elsewhere Wright says:

You see, by way of concentrated thought, the idea is likely to spring into life all at once and be completed eventually with the unity of a living organism.

Now this is the same approach that Nikola Tesla used as his main inventive strategy [Ref. 2.9]:

My method is different. I do not rush into actual work. When I get an idea I start at once building it up in my imagination. I change the construction, make improvements and operate the device in my mind. It is absolutely immaterial to me whether I run my turbine in my thought or test it in my shop. I even note if it is out of balance.

It is often recounted that some of the great geniuses throughout the ages were capable of intense concentration and focus. Socrates, for example, is said to have sat for hours, thinking in the middle of the marketplace, completely oblivious of the surroundings, as if caught in a trance. Such focal capacity is a rare faculty. Modern life is a bee-hive of distractions. While we may wish to retreat to a secluded post, far removed from the knock on the door and ring on the telephone, such luxuries are seldom permitted in modern life. Given such a scenario, we would appreciate within ourselves, a Socratic capacity to hold focus.

But suppose that it were possible to learn such skills. If so, what might be the payoff in the context of design(\(n\))? According to Wright the singular payoff of such a method is the “unity” or integrity of the design(\(n\)) concept that it leads to. But why would this be so? To understand this one has to focus on Wright’s statement that with concentrated thought the design is eventually completed with the unity of a “living organism.” To be unified is to be working in cohesion, to not suffer the state of a “house divided.” The unity of the design is to be found in the unity of the problem or purpose it tries to address. If the problem is singular, the design(\(n\)) would reflect this singularity. And if the subordinate designs are done properly without suffering any design(\(n\)) compromise, then the overall design would also be singular in purpose. Of course not all problems are singular. This is especially true in the context of social systems. But even here, if thru concentrated thought, one is able to abstract out the core essence of the problem which consists of not more than a few requirements, one might be able to arrive at an integral design. This is corroborated by Corollary 2 that we saw in Chp 1 in the context of axiomatic validity analysis (namely to minimize the number of functional requirements and design constraints). So the whole problem reduces down to how best to abstract out the core essence of the problem. This, evidently is a problem of induction. As a speculative element we might ask, what are some of the tools and techniques towards cultivating such internal habits of attention and inductive thinking? We will have a word to say on this in the context of design(\(n\)) of cognitive tools in our final chapter.
Now what about the actual design itself, of synthesizing the components that will answer to the problem? How is "working it out in the mind" superior to "working it out on an external medium?" Here is a plausible theory. Once the core of the problem has been reasoned out, the actual process of design could be assisted by getting the subconscious to work in the background. This is especially true during the crucial stages of conceptual design. In this context working it out in the mind is better than working it out in an external medium. For by placing the emerging ideas on an external medium relieves internal mental spaces that were charged up; thus leaving the integrative subconscious lacking in material. To test this out one would have to show that indeed representing things externally relieves mental spaces. In an informal sense one may verify this. For example, external aids such as calculators, pocket diaries for telephone numbers, "to-do" lists, all these aids do relieve internal mental space. Yet there is really nothing deterministic about it. Thus it is not impossible to have both internal as well as external representations. However, one is less motivated to hold things internally if a convenient external representation is available. And it is here that both Wright's and Tesla's comment apply. During conceptual design, by denying oneself the luxury of external aids, the mind is forced to retain crucial bits of information and integrate it, both consciously and subconsciously.

2. On Structuring the Design(n) Space: In the above quote (On the Logic of the Plan), note the manner by which Wright systematically structures his design space into various categories. He then organizes the logical sequence (thus scale before materials). This is the living trace that is left behind after one has attempted an ensemble of similar designs. Thus the design space for a well seasoned designer is not a homogenous collection of facts. There is a natural structure to it, derived from the general nature of the problem. The same was exhibited in the writings of Sullivan.

3. On the "Throw Away" Principle (modification of the "Square One" Principle). Implications in the Context of Mass Customization: Consider the intriguing comment by Wright on "throwing the original plans away":

   But if the original concept is lost as the drawing proceeds, throw all away and begin afresh. To throw away a concept entirely to make way for a fresh one—that is a faculty of the mind not easily cultivated. Few have that capacity. It is perhaps a gift—but may be attained by practice...

Here Wright hints that he really does not mean literally throwing away the plans; but to throw away the plans mentally. Wright also says that this is not an attitude cultivated easily. Let us probe and ask why this might be so? Why is it difficult to "throw away" existing designs (that have been well developed) and start at the very beginnings. Why is it psycho-epistemologically difficult to shift gears from a detailed phase to a conceptual phase? Also what could be done to overcome this inertia? Perhaps the case is that the original plan
and design(n) places a psycho-epistemologically mental lock that it is difficult for a person to stand apart from it. For lack of a better word, let us call this the mental-lock problem. Now if there were some means by which one could map the current conceptual framework, it would then be possible to perturb it at strategic locations in order to overcome the mental-lock. Also other allied frameworks could provide a valuable external perspective. These are intriguing options. Before we close on this, let us consider the following note regarding what it means at the organizational level:

But to throw the plans away is a luxury ill afforded by the organizations of our modern world.

Yet if this throwing away of the “plans” is not literal, but only a “throwing away” in the mind, the beneficial consequences should be very much the same. The implications are quite significant. Firstly, this “throw away” principle is slightly different from our earlier “square one” principle in that here we are proactively involved in “clearing the slate.” In other words we are deliberately looking for characterizing differences between one problem context and another which is closely aligned. And having found these (i.e., proactively looking for a different set of FR’s), we then redo the whole design. Now this has immediate consequences in the context of problem abstraction and problem solving in the context of mass-customization [Ref: 2.10]. For the essence of customization is to give each product a singular identity. In principle, this could be achieved either from the uniqueness of the problem; or the uniqueness of the solution to the problem; or both. The proactive “throw-away” strategy that Wright proposes is targeted at the last of these options. These are intriguing possibilities we need to consider further. But for the moment call this the “throw away strategy.” As we shall see, this will be a critical clue to advance our proposition namely, design(n) for innovation.

4. On the Articulation of the Plan: As we may notice from the Enis house example, the design(n) matrix is diagonal:

\[
\begin{align*}
\text{DiningF} & \quad \begin{bmatrix} \oplus_1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \oplus_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & +1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & +1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \oplus & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \oplus & + \\
\end{bmatrix} & \to \begin{bmatrix} \text{DiningR} \\ \text{LivingR} \\ \text{Kitchen} \\ \text{Gallery} \\ \text{Study} \\ \text{Terrace} \\ \text{Garage} \\
\end{bmatrix} \\
\end{align*}
\]

(2.8)

Here the \( \oplus \) in the Living Room row of the design(n) matrix reflects the composition, that this room is “the dominating feature of the group.” We have also indicated with subscripts those units that are composed together in a unit. Otherwise it is difficult to get this compositional information, merely by looking at the final matrix. Of course, all of this information is carried over from earlier
stages. These are some of the techniques to capture the earlier decisions in some form, in the final design(n).

By its very nature, space allocation problems have to lead to diagonal designs. For two things cannot occupy the same space. However, problems arise when an existing space-allocation design(n) has to be adapted to meet new needs. For it is difficult to be flexible about allocated spaces that are cast in concrete. When one designs for future flexibility, one inevitably reaches Sullivans approach with regard to office spaces, i.e., to leave it unobstructed for the client to organize as per his or her changing demands.

5. On the Art of Expression: In accordance with Sullivan, Wright caps his overall design(n) with the re-integration of the design(n) for aesthetic expression. With regard to some of the emotive themes possible in the context of buildings, Wright suggests the following:

And while it speaks to you of all those important matters, it leaves you imbued by dignity, grace, repose, gaiety, strength, severity, delicacy and of rhythmical order...

These thematic elements add to our vocabulary (for example, Sullivan's ideal of "loftiness") of the emotive-aesthetic aspects of design.

As to the deeper and more fundamental aspects of the art of expression, Wright hints that:

So every true building is of the quality of some man's soul, his sense of harmony and "fitness," which is another kind of harmony—more or less manifest in the fallible human process....

The theme here closely parallels what Sullivan wrote regarding designing tall structures to symbolize the "proud spirit of man".

We may speculate as to whether it was to suggest a sense of "gaiety" that Wright re-integrated the Kaufmann residence with the waterfall? Thus, was the site selection and every other design already done, and Wright happened to pick "gaiety" as the central theme? Or alternatively, did Wright redo his complete design when his final re-integration suggested a new theme? Figuratively speaking, did he "throw away his original plans?" Since the design trace is missing, it is not easy to tell. But if we were to liberally interpret Kaufmann's comment ("I thought you would place the house near the waterfall, not over it") differently from what is suggested in the earlier quote (from apprentice Byron Mosher), we could explain it as a complete reworking of the total scheme within Wright's mind (from a "off the waterfall" design to a "on the waterfall" design). The assumption here is that Kaufmann was privy to the initial design(n) decision. If this is what actually happened, then it would suggest that there is nothing sacrosanct about the design process; that one is free to make radical changes as suggested at any time prior to freezing the primary design concepts.
If such is the case, it would also partly suggests the value of “late binding” that Wright prefers (“conceive the building in the imagination, not on paper but in the mind, thoroughly”). This way, one may keep ones options alive.

We now return to Wright for further clarifications on expression and style. The following is excerpted from his essay on In the Cause of Architecture [Ref. 2.8]:

For seven years it was my good fortune to be the understudy of a great teacher and a great architect, to my mind the greatest of his time—Mr. Louis H. Sullivan.

Adler and Sullivan had little time to design residences. The few that were unavoidable fell to my lot outside of office hours. So largely it remained for me to carry into the field of domestic architecture the battle they had begun in commercial buildings...

In 1894...I formulated the following “propositions”...

I.—Simplicity and Repose are qualities that measure the true value of any work of art. But simplicity is not in itself an end nor is it a matter of the side of a barn but rather an entity with a graceful beauty in its integrity from which discord, and all that is meaningless, has been eliminated...

..An excessive love of detail has ruined more fine things from the standpoint of fine art or fine living than any one human shortcoming—it is hopelessly vulgar. Too many houses, when they are not little stage settings or scene paintings, are mere notions stores, bazzars or junk-shops. Decoration is dangerous unless you understand it thoroughly and are satisfied that it means something good in the scheme as a whole, for the present you are usually better off without it. Merely that it “looks rich” is no justification for the use of ornament.

II.—There should be as many kinds (styles) of houses as there are kinds (styles) of people and as many differentiations as there are different individuals. A man who has individuality (and what man lacks it?) has a right to its expression in his own environment.

III.—A building should appear to grow easily from its site and be shaped to harmonize with its surroundings if Nature is manifest there..

We of the Middle West are living on the prairie. The prairie has a beauty of its own and we should recognize and accentuate this natural beauty, its quiet level. Hence, gently sloping roofs, low proportions, quiet sky lines, suppressed heavy-set chimneys and sheltering overhangs, low terraces and out-reaching walls sequestering private gardens.

IV.—A house that has character stands a good chance of growing more valuable as it grows older while a house in the prevailing mode, whatever that mode may be, is soon out of fashion, stale and unprofitable.

Buildings, like people must be sincere, must be true and then withal as gracious and lovable as may be.
Above all, integrity. The machine is the normal tool of our civilization, give it work that it can do well—nothing is of greater importance. To do this will be to formulate new industrial ideals, sadly needed....

I do not believe we will ever again have the uniformity of type which has characterized the so-called great "styles." Conditions have changed; our ideal is Democracy, the highest possible expression of the individual as a unit not inconsistent with a harmonious whole. The average of human intelligence rises steadily, and as the individual unit grows more and more to be trusted we will have an architecture with richer variety in unity than has ever arisen before; but the forms must be born out of our changed conditions...

...self denial is imposed upon the architect to a far greater extent than upon any other member of the fine art family. The temptation to sweeten work, to make each detail in itself lovable and expressive is always great; but that the whole may be truly eloquent of its ultimate function, restraint is imperative....

Contrary to the usual supposition this manner of working out a theme is more flexible than any working out in a fixed historic style can ever be, and the individuality of those concerned may receive more adequate treatment within legitimate limitations. This matter of individuality puzzles many; they suspect that the individuality of the owner and occupant of a building is sacrificed to that of the architect who imposes his own upon Jones, Brown and Smith alike. An architect worthy of the name has an individuality, it is true; his work will and should reflect it, and his buildings will all bear a familial resemblance one to another. The individuality of the owner is first manifest in his choice of his architect, the individual to whom he entrusts his characterization. He sympathizes with his work; its expression suits him and this furnishes the common ground upon which client and architect may come together. Then, if the architect is what he ought to be, with ready technique he conscientiously works for the client, idealizes his clients character and his client's tastes and makes him feel that the building is his as it really is to such an extent that he can truly say that he would rather have his own house than any other he has ever seen. Is a portrait, say by Sargent, any less a revelation of the character of the subject because it bears his stamp and is easily recognized by any one as a Sargent? Does one lose his individuality when it is interpreted sympathetically by one of his own race and time who can know him and his needs intimately and idealize them; or does he gain it only by having adopted or adapted to his condition a ready-made historic style which is the fruit of a seed-time other than his, whatever that style may be?

...Simplicity is not in itself an end; it is a means to an end. Our aesthetics are dyspeptic from incontinent indulgence in "Frenchite" pastry. We crave ornament for the sake of ornament: cover up our faults of design with ornamental sensualities that were long time ago sensuous ornament. We
will do well to distrust this unwholesome and unholy craving and look to the simple line; to the clean though living form and quiet color for a time, until the true significance of these things has dawned for us once more...

Here we finally receive answers to many of the problems we posed earlier:

1. On Simplicity Versus Complexity—a Psycho-Epistemological Perspective: Wright orients us on his concept of simple versus the complex in the following quote:

   [A simple entity is]... an entity with a graceful beauty in its integrity, from which discord, and all that is meaningless, has been eliminated...

The word simple means, plain, unadorned, constituting a basic element, fundamental, not compound, straightforward, free from elaboration or figuration etc. The word complex means something that is hard to separate, analyse, or solve; something composed of confusingly interrelated parts. The word “complicated” on the other hand, is more epistemological in nature, and applies to our difficulty in trying to understand something.

In his essay, Wright provides an evolutionary approach to frame the problem of simple versus complex. The distinction he makes between the simple and the complex is in the addition of fine details. Adding decorative elements merely for its face-value, in lieu-of, say, providing the final emotional aesthetic re-integration could then be considered complex and “vulgar.” His evolutionary approach may be adduced from his statement that “decoration is dangerous unless you understand it thoroughly and are satisfied that it means something good in the scheme as a whole, [that] for the present you are usually better off without it.” Thus it is important to get the main proportions right, before even considering the problem of the complex and less essential functionalities.

This ties in well with our earlier analysis on achieving designs that have the “unity of a living organism”:

   You see, by way of concentrated thought, the idea is likely to spring into life all at once and be completed eventually with the unity of a living organism.

In order to achieve simple designs, one has to concentrate and abstract out a singular purpose; then design around this as the arch purpose. In contrast, that which is complex is that which has lost its main thrust and tries to impress with elaborate details built out of irrelevant practices from the past. Thus Wright says:

   We... cover up our faults of design with ornamental sensualities that were long time ago sensuous ornament. We will do well to distrust this unwholesome and unholy craving and look to the simple line; to the clean though living form...

Thus to Wright, the penchant for complex designs betrays the psycho-epistemological laziness on the side of the designer; a laziness that stops him from addressing
the real problem at hand, and instead use an approach of putting together "cut\&paste" solutions of existing designs regardless of the nature of the problem. Thus complexity in design is obtained in two ways:

(a) When the problem has not been abstracted out sufficiently to reveal a "singularity" of purpose.

(b) When designers put together "cut\&paste" solutions of existing designs regardless of the nature of the problem

These bi-cameral roots of complexity parallels the bi-cameral "St. Louis" type arch of the design trace; the left-arch corresponding to the former issue; the right-arch corresponding to the latter. The problem of complexity arises when the actual problem and the proposed solution conflict when implemented. This will ultimately result in either a breakdown or an information lump (in the form of customer complaints) along the market-feedback loop.

This is in contrast to Prof. Suh's approach to the simple versus complex. For according to Prof. Suh's second axiom, the terms simple versus complex are relative in sense: they apply only between different designs that have already been judged as functionally appropriate. Thus one needs an ensemble of functionally appropriate designs in order to judge which of them is minimally complex based on the criteria of minimum information content. Information content of a design is defined as the log of inverse of probability of success. Thus given the functions to be satisfied, one selects between candidate solutions based on the probability of success on each of the requirements. That which has the highest probability of success (given of course the cost constraints/requirements) is also judged as minimally complex. Note that the information axiom is actually an axiom about the process of design rather than the product; for it attempts to provide a metric on the information that went into its making. As it is implemented, this information is information at the implementation level. The good thing about this approach is that it provides a quantitative metric for information content. But the constraint is that (the way the information is defined), it can be applied only when the design meets the ground (or some level where quantitative measures exist based on probability measures at lower levels), i.e., at the bottom right of the design trace. Experienced designers can also interpret the concept of information more liberally (as the qualitative conceptual complexity along the design trace) and make qualitative judgements of complexity even before the design gets developed in any great detail. However such an approach does not stand the test of pedagogy, as to whether it can be taught. In this context, the quantitative rigour that Prof. Suh's approach provides is unmatched.

Nevertheless, both these approaches, namely, conceptual complexity versus implementational complexity ought to meet at some level. In a sense this is the same as the various "A for B" kind of back-integrations we see in the context of say design(n) for manufacturability, design(n) for constructability, design(n) for automation, etc. If only there were means by which the implementational
complexity could be percolated upwards to provide us a metric on the concep-
tual complexity of various design options. Much work needs to be done in this
regard.

While Prof. Suh’s approach focusses on the implementaion complexity, Wright
on the other hand is more concerned about the appropriateness of the functions
the designer is (often implicitly) trying to address. For Wright, the issue of
complexity has more to do with the proper judgements along the left half of
the design trace; for Prof. Suh, the issue of complexity has more to do with
the information content along the right half of the design trace. A true picture
of complexity perhaps arises when we put both these two halves together and
try to minimize the information content of the total trace. For in some sense,
the information contained within the design trace is the information that went into
the creation of a given design(n). This does have a parallel in philosophy. For
in a general sense, the above is an application of famous Occum’s principle
in philosophy, namely, not to create concepts beyond necessity (note: here in
Occum’s case, the design(n) is that of the human knowledge itself).

We may thus informally state our four normative principles:

(a) **The Direct Principle**: Design(n) follows function.

(b) **The Indirect Principle**: Design(n) of design follows function.

(c) **No Compromise Principle**: Do not compromise one function when trying to
satisfy another.

(d) **Minimum Information Design Trace**: Choose that design(n) which contains
minimum information along its design trace.

The first establishes the law that a design(n) has to be derived from its function
and nothing else. The third establishes the internal constraint when more than
one function is present. The second “suggests” the order of the design mapping
process. This may also be derived from the design(n) matrix used to check for
violation of the third principle. The fourth helps select designs that are minim-
ally complex. The first and the third are focused on design(n) as a product;
while if properly implemented, the second and the last are focused on design as
a process. In that sense, these two sets have orthogonal functions.

2. **On Mass Customization**: Apparently, Wright is the first person to articulate the
concept of mass-customization in the context of housing. For as he says:

> There should be as many kinds (styles) of houses as there are kinds
> (styles) of people and as many differentiations as there are different indi-
> viduals. A man who has individuality (and what man lacks it?) has a
> right to its expression in his own environment.

He also anticipated the current trends towards mass-customization in a more
general sense:
I do not believe we will ever again have the uniformity of type which has characterized the so-called great "styles." Conditions have changed; our ideal is Democracy, the highest possible expression of the individual as a unit not inconsistent with a harmonious whole. The average of human intelligence rises steadily, and as the individual unit grows more and more to be trusted we will have an architecture with richer variety in unity than has ever arisen before; but the forms must be born out of our changed conditions...

Here he identifies the driving cause (from the market side) for such a trend, namely, that it is advances made at each individual level that leads to the call for "the highest possible expression of the individual as a unit not inconsistent with a harmonious whole."

3. On the Use of Design(n) Constraints: In the context of design, constraints are limitations imposed either by earlier design decisions or by the (metaphysical) nature of the problem. Depending upon the imperative of the design(n), one might challenge these constraints, or on the other hand work within its prescribed limits. From an aesthetic point of view, there is significant value in adapting the design to fit the natural setting. Thus Wright writes:

A building should appear to grow easily from its site and be shaped to harmonize with its surroundings if Nature is manifest there.

We of the Middle West are living on the prairie. The prairie has a beauty of its own and we should recognize and accentuate this natural beauty, its quiet level. Hence, gently sloping roofs, low proportions, quiet sky lines, suppressed heavy-set chimneys and sheltering overhangs, low terraces and out-reaching walls sequestering private gardens....

The above is an example of aesthetic constraints imposed by nature. One could violate this and build a vertically oriented structure; but the composition with the site would be marred. If on the other hand, one were building in a rugged mountaineous terrain, it would be more natural to emphasize the vertical dimension (for example, the pagaodas in Tibet). And so also in the man-made setting of a modern city such as New York.

Thus when used appropriately, the composition that works in accordance with the setting (whether natural or man-made) has a value of its own. However, it depends upon the imperative of the design(n). A design(n) that is meant to be innovative often challenges the settings dictated from higher levels.

4. On the Role of the Machine: Here we see Wright identify the crucial problem of our modern age:

The machine is the normal tool of our civilization, give it work that it can do well—nothing is of greater importance. To do this will be to formulate new industrial ideals, sadly needed....
There are two motives for studying this issue:

- In a local context, our motive for inquiring into this is in trying to frame the problem of mass-customization that we shall take up (in the appendix) in the context of self-articulating formwork, and construction from the perspective of manufacturing.

- But in a larger context, the implications are far wider. For example, a proper answer to this has enormous implications regarding the kinds of educational services we shall be needing in the future. Where should human resources be properly engaged so as not to get caught in economic deadends when face-to-face with the economies provided by the machine? What is the proper hand-shake between the human and the machine? The fundamental issue here is the proper division of labor between the human and the machine. We did introduce this issue in Chapter 1. But we will be elaborating on this in far greater detail in the next two essays by Wright.

5. On the Value the Client Receives in the Context of the Art of Expression: We had earlier asked why a client might pay for any artistic “extravaganza” beyond the mere form/function integration. Wright answers this by proposing that in some sense, a building is to a client as a portrait is to the subject. Thus an architect could possibly capture and highlight a person’s character in the form of a building; thus a building is a portrait in three-dimensions. Not a symbolic replica, as for example the figureheads on Mount Rushmore; but an abstraction captured in steel and concrete, such as the “loftiness” of a tall-building symbolising “the proud spirit of man,”; or the mixture of “gaiety and repose” of Fallingwater symbolizing the yearnings of Mr. Kaufmann.

We now see that the client could possibly value this artistic expression just in the same way that he would value a portrait made of him. For they both share in some sense, the same valuable quality that is somehow related to him. But what precisely is this quality? Earlier we heard Wright say that “every true building is of the quality of some man’s soul.” By this of course, he means the “soul of the architect.” He then alludes to the fact that the client and the architect share in the same quality, for the client comes to a particular architect because “he sympathizes with his work; its expression suits him and this furnishes the common ground upon which client and architect may come together.” But what does it mean to say “the quality of some man’s soul?” This is not very clear. Thus we still do not have explicit answers to the our earlier problem: “why art is necessary?” For unless this is explicitted, these “extravaganzas” could easily be dismissed as mere narcissistic and immature self-indulgences.

In his essay Standardization, The Soul of The Machine [Ref. 2.8] Wright elaborates on the Role of the Machine:

John Ruskin and William Morris turned away from the machine and all it represented in modern art and craft. They saw the deadly threat it
was to all they loved as such—and eventually turned against to fight it, to the death—their death... They did not succeed in delaying destruction nor in constructing anything. They did however, remind us of what we are losing by using the machine or, as they might have said, letting the machine use us.

Repetition carried beyond a certain point has always taken the life of anything addressed to the living spirit.

Monotony kills.

Human feeling loves the vigor of spontaneity, freshness, and the charm of the unexpected. In other words, it loves life and dreads death.

The Machine Ruskin and Morris believed to be the enemy of all life. It was and is so still, but only because the artist has shirked it as a tool while he damned it; until now he has been damned by it.

Standardization as a principle is at work in all things with greater activity than ever before. It is the most basic element in civilization. To a degree it is civilization itself.

An oriental rug, lustrous, rich with color and light, gleaming with all the brilliant pattern opulent oriental imagination conceived, has a very definite basis of standardization in warp and woof. In the methodical stitches regularly taken with strands of woolen yarn, upon that regular basis of cotton strings, stretched tight, lies the primitive principle of standardization. Serving the imagination full well.

Standardization here serves the spirit well—its mechanics disappear in the glowing fabric of the mind—the poetic feeling of the artist weaver with love of beauty in the soul.

*Standardization* should have the same place in the fabric we are weaving which we call civilization—as it has in that more simple fabrication of the carpet. And the creative artist-mind must put it into the larger more comprehensive fabric.

How?

Not so simple.

This principle of standardization has now as its tool or body—the Machine. An ideal tool compared to which all that has gone before is as nothing....

This is where the creative artist...[has to step] in: to bring new life of the mind to this potent agency: new understanding that will make living more joyous and genuine by abolishing the makeshift, showing up imitation for the base thing it is—saving us from this inglorious rampage and rapine upon antiquity. There is no artist conscience, it seems, in all this. The artist is like an hungry orphan turned loose in a bake shop. The creative artist is not in it...

...[the creative artist] may not however, have the technique to make his “knowing” effective and so remain inarticulate. But it is his duty to know, for his
technique is what makes him serviceable to his fellows as artist. Acquiring the
technique of the Machine as the tool of standardization, making the nature
of both, is the only thing now that will make him the living force necessary
to salvage the flotsam and jetsam of the "deluge," or, let it all go and begin
over again.

Begin another era: the modern era of the machine with all it implies,
economically making life more joyous and abundant as a matter of quality—as
well as quantity...

Standardization can be a murderer or beneficent factor as the
life in the thing standardized is kept by imagination or destroyed
by the lack of it.

Here Wright is elaborating on the Role of the Machine:

1. On the Benefits of Standardization: The benefit of standardization are of course
   manifold:

   (a) It has a major impact on bringing down the cost of production.

   (b) If properly used (as in the example of the oriental rug), standardization can
       provide the basis on which the artist-mind can build “the larger more com-
       prehensive fabric,” the “glowing fabric of the mind.” This attitude closely
       parallels Sullivans approach of transforming the standardized monotony of
       office floors in the tall building into the “soaring, lofty” structure meant
       to symbolize “the proud spirit of man.”

   (c) Standardization, coupled with the machine (in the modern context, flexible
       manufacturing), has the potential to provide enough flexibility to serve the
       artist-mind, provided the artist-mind understands “the techniques.”

2. On the Challenge it poses to Designers: The fundamental challenge that stan-
   dardization (coupled with the flexibility of the machine) poses to designers is
   the demand to master it and bend it to their will so that “the life in the thing
   standardized is kept by imagination.” The designer has to “bring new life of
   the mind to this potent agency.” The alternative that Wright forsees is rather
   bleak:

   Repetition carried beyond a certain point has always taken the life of
   anything addressed to the living spirit.
   Monotony kills.
   Human feeling loves the vigor of spontaneity, freshness, and the charm
   of the unexpected. In other words, it loves life and dreads death.

3. On Mental Standardization: When Wright writes about what “rampage and rap-
   ine” that blind standardization is bringing about, he also hints at the crucial
   connection between the standardization of the process/product, and the stan-
   dardization happening within the human mind:
This is where the creative artist...[has to step] in: to bring new life of the mind to this potent agency: new understanding that will make living more joyous and genuine by abolishing the makeshift, showing up imitation for the base thing it is—saving us from this inglorious rampage and rapine upon antiquity. There is no artist conscience, it seems, in all this. The artist is like an hungry orphan turned loose in a bake shop. The creative artist is not in it...

With flexible manufacturing today, we are able to overcome the gross standardization problem that Wright was concerned about. With the machine, the standardization was pushed one level down, into the process design rather than the product design. With the advent of the Computer Integrated Everything, the standardization is at the software level; at the thought that goes into the software. And at the designer level, the standardization is in the thought (or the lack of it) that goes into the design. The problem is not any more the gross standardization that Wright talked about; the problem is indeed that of the artist as the “hungry orphan turned loose in a bake shop.” For such is the vast scope of the design space now open before the designer. To master it, to rule it, to select and compose both functional and artistic artifacts from it is not an easy task. One needs a much more deliberate understanding of the process of design, and where exactly that intransigent element of human creativity is elemental. One needs to maintain this creative perspective. Without this, the mind freezes and allows itself to be regimented and standardized as before. Thus instead of the problem of standardization, the phrase perhaps ought to be the problem of mental standardization or mental locking that happens in design. So the main problem still remains: how to put life into the product, how to put the “creative artist-mind” into it.

Wright provides more insights along these lines in his essay on What “styles” mean to the architect [Ref. 2.8]:

In the logic of the plan what we call “standardization” is seen to be a fundamental principle at work in architecture. All things in Nature exhibit this tendency to crystallize—to form and then conform, as we may easily see. There is a fluid, elastic period of becoming, as in the plan, when possibilities are infinite. New effects may, then, originate from the idea or principle that conceives. Once form is achieved, that possibility is dead so far as it is a creative flux.

Styles in architecture are part and parcel of this standardization. During the process of formation, exciting, fruitful. So soon as accomplished—a prison house for the creative soul and mind.

"Styles" once accomplished soon become yard-sticks for the blind, crutches for the lame, the recourse of the impotent.

As humanity develops there will be less recourse to the “styles” and more style—for the development of humanity is a matter of greater creative power for the individual...
So this very useful tendency in the nature of the human mind, to standardize, is something to guard against as thought and feeling are about to take “form,”—something of which to beware,—something to be watched. For, over-night, it may “set” the form past redemption and the creative matter be found dead. Standardization is, then, a mere tool, though indispensable, to be used only to a certain extent in all other than purely commercial matters.

Used to the extent that it leaves the spirit free to destroy it at will,—on suspicion, maybe,—to the extent only that it does not become a style—or an inflexible rule—is it desirable to the architect.

It is desirable to him only to the extent that it is capable of new forms and remains the servant of those forms. Standardization should be allowed to work but never to master the process that yields the form.

In the logic of the plan we see the mechanics that is standardization, this dangerous tendency to crystallize into styles, at work and attempting to dispose of the whole matter. But if we are artists, no one can see it in the results of our use of it, which will be living and “personal,” nevertheless.

Here we find more evidence on the problem of mental standardization. For as Wright puts it, “so soon as [standardization is] accomplished—[it becomes] a prison house for the creative soul and mind.” Also note where Wright says that this tendency to standardize is in the nature of the human mind. This is a key insight. It is this mental or conceptual ossification that happens which ultimately is the link that connects design and innovation. And it is here that both share a common battle ground. And the answer to this is perhaps in Wrights “throw away strategy” we informally discussed earlier. Given our current context, instead of the word standardization, perhaps the words mental or conceptual standardization ought to be substituted. We thus transfer the phenomenon from the physical or the metaphysical realm to the real root of the problem, the mental realm or the epistemological (or better still, the psychospatial) realm.

Also note the differentiation that Wright makes between the fluid, elastic period of becoming..when possibilities are infinite versus the period when the style has set [and is] past redemption and the creative matter [is essentially] found dead. We shall see a similar theme when we review the literature on innovation later in this chapter. We now go back to the question we left with earlier, regarding why we need art?

2.3 Aesthetics Proper: On Why we Need Art?

In this section we review the literature on the fundamental question regarding why we need art? Let us look at what Aristotle had to say about the expression of art [Ref. 2.11]:

Epic poetry and Tragedy, Comedy also and Dithyrambic poetry, and the music of the flute....are all in their general conception modes of imitation.
[..they imitate] character, emotion, and action, by rhythmical movement. Since the objects of imitation are men in action, and these men must be either of a higher or a lower life. It follows that we must represent men either as better than in real life, or as worse, or as they are...Polygnotus depicted men as nobler than they are, Pheidias as less noble, Dionysius drew them true to life.

Imitation, then, is one instinct of our nature. Next there is the instinct for 'harmony' and rhythm...

Again, Tragedy is the imitation of an action; and an action implies personal agents, who necessarily possess certain distinctive qualities both of character and thought...the Plot is the imitation of action; for by plot I here mean the arrangement of the incidents...Every Tragedy, therefore must have six parts—Plot, Character, Diction, Thought, Spectacle, Song...

The Plot is the first principle, and as it were, the soul of the tragedy; Character holds the second place...Character is that which reveals moral purpose, showing what kind of things a man chooses or avoids...

...it is not the function of the poet to relate what has happened, but what may happen,—what is possible according to the law of probability or necessity...Poetry, therefore, is a more philosophical and a higher thing than history: for poetry tends to express the universal, history the particular....

The poet being an imitator, like a painter or any other artist, must of necessity imitate one of three objects,—things as they were or are, things as they are said or thought to be. or things as they ought to be....Sophocles said that he drew men as they ought to be; Euripides, as they are.

Aristotle saw as the function of art, the means by which to express universal truths; truths about human affairs as it ought to be. But he left unsaid wherefrom this function: why do we need these universals expressed as art?

Certain of the 18th and 19th century Romanticists upheld the Aristotelian premise that art has a fundamental "cognitive status": it is the "bearer of general truths. of Aristotelian universals, of teachable abstractions [Ref. 2.12]." Thus Wordsworth writes [Ref. 2.12]:

..[the object of poetry] is truth, not individual and local, but general and operative; not standing upon external testimony, but carried alive into the heart by passion; truth which is its own testimony, which gives competence and confidence to the tribunal to which it appeals, and receives them from the same tribunal.

Thus the truths being expressed somehow pertains to the self-conscious faculty, "the tribunal" to which it gives "competence and confidence." Further these truths are derived from the self-same faculty, for it "receives them from the same tribunal." Thus the root cause for art is to be found in our mental constitutions. The expression and experience of art is a self-affirmatory act; a judgement about the "competence and
confidence" of the conscious faculty. Yet what are these truths? And why do we need them to be expressed and experienced in such a manner?

Answers to these are to be found in the writings of late philosopher/author Ayn Rand who addresses the issue from a psycho-epistemological perspective⁴. Thus Rand in her seminal work, *The Romantic Manifesto* [Ref. 2.1.], writes:

Art is a selective re-creation of reality according to an artist’s metaphysical value-judgements. Man’s profound need of art lies in the fact that his cognitive faculty is conceptual, i.e., that he acquires knowledge by means of abstractions, and needs the power to bring his widest metaphysical abstractions into his immediate, perceptual awareness. Art fulfills this: by means of a selective re-creation, it concretizes man’s fundamental view of himself and of existence. It tells man, in effect, which aspects of his experience are to be regarded as essential, significant, important. In this sense, art teaches man how to use his consciousness. It conditions or stylizes man’s consciousness by conveying to him a certain way of looking at existence.

Rand agrees with Aristotle, in that art is “imitative” in nature, that it is a “selective re-creation of reality according to an artist’s metaphysical value-judgements.” But what are these metaphysical value-judgement? Also why does man need to bring these to “his immediate, perceptual awareness?” Again Rand writes [Ref. 2.13]:

Is the universe intelligible to man, or unintelligible and unknowable? Can man find happiness on earth, or is he doomed to frustration and despair? Does man have the power of choice, the power to choose his goals and to achieve them, the power to direct the course of his life—or is he the helpless plaything of forces beyond his control, which determine his fate? Is man, by nature, to be valued as good, or to be despised as evil? These are metaphysical questions, but the answers to them determine the kind of ethics men will accept and practice; the answers are the link between metaphysics and ethics. And although metaphysics as such is not a normative science, the answers to this category of questions assume, in man’s mind, the function of metaphysical value-judgements, since they form the foundation of all his moral values.

Consciously or subconsciously, explicitly or implicitly, man knows that he needs a comprehensive view of existence to integrate his values, to choose his goals, to plan his future, to maintain the unity and coherence of his life—and that his metaphysical value-judgements are involved in every moment of his life, in his every choice, decision and action.

Metaphysics—the science that deals with the fundamental nature of reality—involves man’s widest abstractions. It includes every concrete he has ever perceived, it involves such a vast sum of knowledge and such a long chain

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⁴“Psycho-epistemology is the study of man’s cognitive processes from the aspect of the interaction between the conscious mind and the automatic functions of the subconscious” [Ref. 2.13]
of concepts that no man could hold it all in focus of his immediate conscious awareness. Yet he needs that sum and that awareness to guide him—he needs the power to summon them into full, conscious focus.

That power is given to him by art.

Metaphysical values are the fundamental archstands in a persons life; they pertain to the highest level life-design(n) decisions. Art reduces these abstract decisions into a graspable form that may be assimilated into the subconscious. Like the other systems we encountered, philosophy too has a hierarchical structure to it:

(Metaphysics (Epistemology (Ethics (Politics, Aesthetics))))

While the questions addressed by aesthetics are metaphysical in nature, their answers are to be found throughout the hierarchy (and especially in ethics). When these answers are recalled back to its origins, these then constitute the metaphysical value-judgements. Art then expresses and reduces these remote abstractions into a concrete perceivable form in order to make them immediate and graspable.

Explicating for the first time, the fundamental function of art, Rand writes [Ref. 2.13]:

Art is the concretization of metaphysics. Art brings man's concepts to the perceptual level of his consciousness and allows him to grasp them directly, as if they were percepts.

This is the psycho-epistemological function of art...

Just as we illustrated Wrights writings by juxtaposing it with his design(n) examples (in our attempts to understand fine-arts terms such as plan and character and style), so also let us now study Rand's applications juxtaposed with her theoretical writings in order to fully grasp terms such as theme, theme-plot and style. Rand gives the following examples:

1. From Sculpture [Ref. 2.13]:

For instance, consider two statues of man: one as a Greek god, the other as a deformed medieval monstrosity. Both are metaphysical estimates of man; both are projections of the artists view of man's nature; both are concretized representations of the philosophy of their respective cultures.

2. From Literature, Sculpture, Painting [Ref. 2.13]:

Two distinct, but interrelated, elements of a work of art are the crucial means of projecting its sense of life: the subject and the style—what an artist chooses to present and how he presents it.

Thus the subject of an art work expresses a view of man's existence, while the style expresses a view of man's consciousness. The
subject reveals an artists \textit{metaphysics}, he style reveals his \textit{psycho-epistemology}.

The choice of subject declares what aspects of existence the artist regards as important— as worthy of being re-created and contemplated. He may choose to present heroic figures, as exponents of man’s nature— or he may choose statistical composites of the average, the undistinguished, the mediocrew— or he may choose crawling specimens of depravity. He may present the triumph of heroes, in fact or in spirit (Victor Hugo), or their struggle (Michelangelo), or their defeat (Shakespeare). He may present the folks next door: next door to palaces (Tolstoy), or to drugstores (Sinclair Lewis), or to kitchens (Vermeer), or to sewers (Zola). He may present monsters as objects of terror (Goya)— or he may demand sympathy for his monsters, and thus crawl outside the limits of the realm of values, including esthetic ones...

The theme of an art work is the link uniting its subject and its style. “Style” is a particular, distinctive or characteristic mode of execution. An artist’s style is the product of his own psycho-epistemology—and by implication, a projection of his view of man’s consciousness, of its efficacy or impotence, of its proper method and level of functioning. 

..a man whose normal mental state is a state of full focus, will create and respond to a style of radiant clarity and ruthless precision—a style that projects sharp outlines, cleanliness, purpose, an intransigent awareness and clear-cut identity...

A man who is moved by the fog of his feelings and spends most of his time out of focus will create and respond to a style of blurred. “mysterious” murk, where outlines dissolve and entities flow into one another, where words connote anything and denote nothing, where colors float without objects, and objects float without weight—a level of awareness appropriate to a universe where...nothing can be known with certainty and nothing much is demanded of one’s consciousness.

Style is the most complex element of art, the most revealing and, often, the most baffling psychologically. The terrible inner conflicts from which artists suffer as much (or, perhaps, more than) other men are magnified in their work. As an example: Salvador Dali, whose style projects the luminous clarity of a rational psycho-epistemology, while most (though not all) of his subjects project an irrational and revoltingly evil metaphysics. A similar, but less offensive, conflict may be seen in the paintings of Vermeer, who combines a brilliant clarity of style with the bleak metaphysics of Naturalism. At the other extreme of the stylistic continuum, observe the deliberate blurring and visual distortions of the so called “painterly” school, from Rembrandt on down-down to the rebellion against consciousness, expressed by a phenomenon such as Cubism which seeks specifically to disintegrate
man’s consciousness by painting objects as man does not perceive them (from several perspectives at once).

A writer’s style may project a blend of reason and passionate emotion (Victor Hugo)—or a chaos of floating abstractions, of emotions cut off from reality (Thomas Wolfe)—or the dry, bare, concrete-bound humor-tinged raucousness of an intelligent reporter (Sinclair Lewis)—or the disciplined, perceptive, lucid, yet muted understatement of a represser (John O’Hara)—or the carefully superficial, over-detailed precision of an amoralist (Flaubert)...

3. Building upon the Aristotelian principles on aesthetics in the context of the novel Rand writes [Ref. 2.13]:

The most important principle of esthetics of literature was formulated by Aristotle, who said that fiction is of greater philosophical importance than history, because “history represents things as they are, while fiction represents them as they might be and ought to be.”

...A novel is a long, fictional story about human beings and the events of their lives. The four essential attributes of a novel are:

Theme—Plot—Characterization—Style.

These are attributes, not separable parts. They can be isolated conceptually for purposes of study, but one must always remember that they are interrelated and that a novel is their sum. (If it is a good novel, it is an indivisible sum.)

1. Theme. ...theme is the summation of a novel’s abstract meaning. The theme of Victor Hugo’s Les Miserables is: “The injustice of society toward its lower classes.” The theme of Gone with the Wind is: “The impact of the Civil War on Southern society.”

Louis H. Sullivan’s famous principle of architecture, “Form follows function,” can be translated into: “Form follows purpose.” The theme of the novel defines its purpose. The theme sets the writer’s standard of selecting, directing the innumerable choices he has to make and serving as the integrator of the novel.

2. Plot.... Since art is a selective re-creation and since events are the building blocks of a novel, a writer who fails to exercise selectivity in regard to events defaults on the most important aspect of his art.

The means of exercising that selectivity and of integrating the events of a story is the plot.

A plot is a purposeful progression of logically connected events leading to the resolution of a climax.

...The plot of a novel serves the same function as the steel skeleton of a skyscraper: it determines the placement and distribution of all the other elements. Matters such as number of characters, background, descriptions, conversations, introspective passages, etc. have to be
determined by what the plot can carry, i.e., have to be integrated with the events and contribute to the progression of the story. Just as one cannot pile extraneous weight or ornamentation on a building without regard for the strength of its skeleton, so one cannot burden a novel with irrelevancies without regard for its plot. The penalty, in both cases, is the same: the collapse of the structure.

...the theme and the plot of a novel must be integrated— as thoroughly as mind and body or thought and action in a rational view of man. The link between the theme and the events of a novel is an element which I call the plot-theme. It is the first step of the translation of an abstract theme into a story, without which the construction of a plot would be impossible. A "plot-theme" is the central conflict or situation of a story—a conflict in terms of action, corresponding to the theme and complex enough to create a purposeful progression of events.

...The theme of Les Miserables is: "The injustice of society toward its lower classes." The plot-theme is: "The life-long flight of an ex-convict from the pursuit of a ruthless representative of the law."

The theme of Gone with the Wind is: "The impact of the Civil War on Southern society." The plot-theme is: "The romantic conflict of a woman who loves a man representing the old order, and is loved by another man, representing the new."

The integration of an important theme with a complex plot structure is the most difficult achievement possible to a writer, and the rarest. Its great masters are Victor Hugo and Dostoevsky. If you wish to see literary art at its highest, study the manner in which the events of their novels proceed from, express, illustrate and dramatize their themes: the integration is so perfect that no other events could have conveyed the theme, and no other theme could have conveyed the events.

3. Characterization. Characterization is the portrayal of those essential traits which form the unique, distinctive personality of an individual human being.

Characterization requires an extreme degree of selectivity. A human being is the most complex entity on earth; a writer's task is to select the essentials out of that enormous complexity, then proceed to create an individual figure, endowing it with all the appropriate details down to the telling small touches needed to give it full reality. That figure has to be an abstraction, yet look like a concrete; it has to have the universality of an abstraction and, simultaneously, the unrepeatable

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5 "Since a plot is the dramatization of goal-directed action, it has to be based on conflict; it may be one character's inner conflict or a conflict of goals and values between two or more characters." [Ref. 2.13]
uniqueness of a person.

In real life, we have only two sources of information about the character of the people around us: we judge them by what they do and by what they say (particularly the first). Similarly, characterization in a novel can be achieved only by two major means: action and dialogue. Descriptive passages dealing with a character's appearance, manner, etc, can contribute to a characterization; so can introspective passages dealing with a character's thoughts and feelings; so can comments of other characters. But all these are merely auxiliary means, which are of no value without the two pillars; action and dialogue. To re-create the reality of a character, one must show what he does and what he says.

...There is no rule about which of these three attributes should come first to a writer's mind and initiate the process of constructing a novel. A writer may begin by choosing a theme, then translate it into the appropriate plot and the kinds of characters needed to enact it. Or he may begin by thinking of a plot. that is, plot-theme, then determine the characters he needs and define the abstract meaning his story will necessarily imply. Or he may begin by projecting certain characters, then determine what conflicts their motives will lead to, what events will result, and what will be the story's ultimate meaning. It does not matter where a writer begins, provided he knows that all three attributes have to unite into so well integrated a sum that no starting point can be discerned.

As to the fourth major attribute of a novel, the style, it is the means by which the other three are presented.

**Style.** A literary style has two fundamental elements (each subsuming a large number of lesser categories): the "choice of content" and the "choice of words." By "choice of content" I mean those aspects of a given passage... which a writer chooses to communicate... By "choice of words" I mean the particular words and sentences a writer uses to communicate them.

For instance, when a writer describes a beautiful woman, his stylistic "choice of content" will determine whether he mentions (or stresses) her face or body or manner of moving or facial expression, etc; whether the details he includes are essential and significant or accidental and irrelevant; whether he presents them in terms of facts or of evaluations; etc. His "choice of words" will convey the emotional implications or connotations, the value-slanting, of the particular content he has chosen to communicate. (He will achieve a different effect if he describes a woman as "slender" or "thin" or "svelte" or "lanky" etc.)

As one may readily notice, there is enormous commonality and agreement between the various writers we have seen. But there are certain distinctions one may notice. To
see this we have to differentiate between the following three kinds of human creations:

1. Purely Artistic Designs(n): Designs(n) that address purely our inner psychosocial needs (for example, a novel).

2. Purely Non-Artistic Designs(n): Designs(n) that address purely our non-artistic needs. Thus designs such as those that meet our physical/material needs (for example, a butchers knife made purely to cut meat efficiently).

3. Mixed Designs(n): Designs(n) that address both our artistic as well as our non-artistic needs (for example, Sullivan's skyscraper).

The first design trace would consist of purely an aesthetic design trace; the second, purely a "functional" or non-aesthetic design trace. The mixed design (such as Sullivan's Skyscraper) would have both the aesthetic as well as the non-aesthetic design traces interacting in some intimate fashion. In each case design(n) follows function. But the form of the design trace would be different. Thus the form of the "pure" design trace would be a single arch; but the form of the "mixed" design trace would be two design traces, one modifying the other. These are as shown in Fig. 2.6. The notation is similar to that which we have used before, except that we have added the nodes "MP" for metaphysical value judgements, and "PE" for the psycho-epistemological of the artist (indicated by the star node with PE beside it: star to represent the implicit nature).

The non-aesthetic trace is exactly same as the one in Fig.1.6. The aesthetic trace on the other hand, is different from its non-aesthetic counterpart. If we illustrate it with the design of the novel, we would observe the artist select the subject (denoted by S) based on his metaphysical value judgements (MP). To a certain extent, this is a deductive problem statement derived from one's position on MP. But to the extent that one selects something germane to the author, something which (as Sullivan would say) does not lack in "identity:" it will then have to partake in problem abstraction, i.e., fresh inductions from real-life experiences. The authors style is implicit in the workings of his psycho-epistemology; it thus influences every single decision; decisions both in the large as well as in the minutiae. We indicate this with the boomerang shaped arch that descends from the style node (star with an s) on the actual design(n). Having selected the subject, and knowing one's own style, the author posits the fundamental "why" of the novel, namely the theme T. We thus now have a theme (such as "[Need to portray] the injustice of society towards its lower classes" in Victor Hugo's Les Miserables). With this in hand, Hugo then selects the plot-theme (PT), namely "[I shall use] the life-long flight of an ex-convict from the pursuit of a ruthless representative of the law." He then systematically develops his plot around this plot-theme, while adding the necessary characterization around the plot. Both plot (P) as well as the characterization (C) are shown as envelopes under the plot-theme. The psycho-epistemological style of the author influences each and every one of these selections.

Regarding the mixed trace, both the components (aesthetic/non-aesthetic) have been abstracted to supress the details, and thus looks very similar to the mixed
Purely Artistic Design Trace (A Novel)
M: Metaphysical Value Judgements
PE: Psycho-Epistemology
S: Subject
St: Style
T: Theme
TP: Theme-Plot
P: Plot
Ch: Characterization
CL: Creative Leap
MF: Market Feedback

Purely Non-Artistic Design Trace
NAR: Non-Aesthetic Requirement
NAD: Non-Aesthetic Design
CL: Creative Leap
MF: Market Feedback

The Mixed Trace
NAR: Non-Aesthetic Requirement
NAD: Non-Aesthetic Design
CL: Creative Leap
AR: Aesthetic Requirement
AD: Aesthetic Design
M: Metaphysical Value Judgements
PE: Psycho-Epistemology
MF: Market Feedback

Figure 2-6: The Three Basic Kinds of Design Traces
trace presented in Fig. 1.6. The addition is the metaphysical and the psycho-
epistemological nodes.

Given the above framework, what is the role of emotions in the process of artistic
creation. Elaborating on this, Rand writes [Ref. 2.13]:

As to the role of emotions in art and the subconscious mechanism that
serves as the integrating factor both in artistic creation and in man's
response to art, they involve a psychological phenomenon which we call a
sense of life. A sense of life is a pre-conceptual equivalent of metaphysics,
an emotional, subconsciously integrated appraisal of man and of existence.

It is the sense of life we denote as PE (the psycho-epistemological perspective) in our
above framework.

Elaborating still further on the role of emotions, Rand writes [Ref. 2.13]:

It is the artist's sense of life that controls and integrates his work, directing the
innumerable choices he has to make, from the choice of subject to the sublest
details of style. It is the viewer's or reader's sense of life that responds to
a work of art by a complex, yet automatic reaction of acceptance and
approval, or rejection and condemnation.

In all of this, one might ask, why does one have to go in such a round-about way in
trying to convey high-level abstractions such as the metaphysical value-judgements?
Why not simply communicate in a conceptual form things that may be rendered in
concepts? For example, mathematicians are able to convey fairly high-level concepts
that subsume a "long chain of concepts". Is not the very function of higher level
abstractions to help "hold in focus" the long chain of concepts that it subsumes. If
so why not then artists? Or in other words, why not simply write a whole story in
just a single Theme(T)/Theme-Plot statement such as:

T: The story is about the injustice of society towards its lower classes.

TP: The story is the life-long flight of an ex-convict from the pursuit of a
ruthless representative of the law.

Or to put it another way, why not simply have abstract art? The answer to this
is that this approach misses the issue at hand. For the root function of art is not
directed at the conscious faculty, but instead at the sub-conscious. And the human
sub-conscious has a certain nature; it is inductive and assimilative in nature. It thus
can be addressed and influenced only in a certain way, namely the (-in the case of
the novel) bottom-up, event-driven inductive mode. Rand elaborates on this in her
thoughts about the process of communication that takes place between the artist and
the viewer [Ref. 2.13]:

The psycho-epistemological process of communication between an artist
and a viewer or reader goes as follows: the artist starts with a broad ab-
straction which he has to concretize, to bring into reality by means of the
appropriate particulars; the viewer perceives the particulars, integrates
them and grasps the abstraction from which they came, thus completing the circle. Speaking metaphorically, the creative process resembles a process of deduction; the viewing process resembles a process of induction.

Of course Rand is fundamentally wrong in stating that "the creative process resembles a process of deduction"; but here she is selectively focusing on the right-arch of the overall design trace. Viewed as a whole, the creative process is far more inductive rather than deductive; and thus dominated by the left-arch.

Earlier, in connection with Sullivan's writings we had asked the following question:

Is there any relation between the levels of abstraction involved in the design versus the acuteness of the need for aesthetic accompaniment?

Rand answers in the positive: higher the levels of abstraction involved in the context of metaphysical value judgements, greater is the need in the subconscious for aesthetic reductions [Ref. 2.13]:

Metaphysics... involves such a long chain of concepts that no man could hold it all in focus of his immediate conscious awareness. Yet he needs that sum and that awareness to guide him—he needs the power to summon them into full, conscious focus.

That power is given to him by art.

The above comment is only in the context of metaphysical value judgements. But it is the authors firm conviction that such is also the case for other kinds of abstract thought: the sub-conscious needs aesthetic-like reductions to help it "hold it in focus of [the] immediate conscious awareness." This, for example, is the main function of the varios problem sets and exercises that a student needs to solve in fully grasping a mathematical treatise. Thus aesthetics is to metaphysical values as problem sets and exercises are to a mathematical treatise.

Let us close this section by indicating Rands views on the two fundamental modes (the contemplative versus the projective) for the experience of art:

1. "It is not journalistic information or scientific education or moral guidance that a man seeks from a work of art (though these may be involved as secondary consequences), but the fulfillment of a more profound need: a confirmation of his view of existence—a confirmation, not in the sense of resolving cognitive doubts, but in the sense of permitting him to contemplate his abstractions outside of his own mind, in the form of existential concretes." [Ref. 2.13]

2. "Since man lives by reshaping his physical background to serve his purpose, since he must first define and then create his values—a rational man needs a concretized projection of his values, an image in whose likeness he will re-shape the world and himself. Art gives him that image; it gives him the experience of seeing the full, immediate concrete reality of his distant goals." [Ref. 2.13]

The contemplative value is the primary experience the artist intends; the projective value is a consequence of the primary experience (as and when the viewer sees the
metaphysical value-judgement implicit in the art work, apply in the context of his own life). Thus there is a fundamental difference between these two modalities; for while the final cause of the contemplative value of art resides in the artist; the final cause of the projective value resides in the viewer. The latter intimately involves the personal vision-statement of the viewer.

Writings by others corroborate with Rands view about the contemplative value of art. Thus for example, as we saw in Wrights discussion on the art of expression [Ref. 2.8]:

And while it speaks to you of all those important matters, it leaves you imbued by dignity, grace, repose, gaiety, strength, severity, delicacy and of rhythmical order...

This completes our brief excursion into philosophy. We now turn to the contemporary developments in design and design methodologies as a discipline.

2.4 Design Methodologies as a Discipline

The history of design and design methodology as an intellectual academic discipline is a more recent occurrence. The First Conference on Design Methods was held in London. in 1962. Since then, the design “movement” has undergone some major transitions. Specifically it could be broken up into four major phases [Ref. 2.14]:

1. The Prescriptive Phase (1962-1967): prescribed methodologies based on the post-World War II Systems Approach for the efficient management of the design activity (Christopher Jones, Christopher Alexander, Bruce Archer). Bruce Archer identified for the first time the division of labor that is proper between the human and the computer (i.e, conceptual versus detailed). He also identified six stages in design; half of which are on the left arch of our design trace (programming, data collection, analysis); half on the right half (synthesis, development and data communication); and sandwiched between is the creative leap.

2. The Descriptive Phase (1967-1973): the realization that the application of the Systems Approach requires that the real world problem be well structured; but in fact that most real world problems (when we start describing these) are rather ill-structured and thus not amenable to the systems solution (Horst Rittel, Herb Simon).

3. The Observation Phase (Late 70’s): the observation of the designer behaviour using controlled experiments, open-ended interviews, etc. (Omer Akin, Bryan Lawson)

4. The Reflective Phase (1972-82): arguments for (and against) using modern developments in Philosophy of Science (by philosophers such as Karl Popper, Thomas Kuhn, and imre’ Lakatos) for the purpose of providing a philosophic basis for design methodologies (Bill Hillier, Lionel March, Geoffrey Broadbent).
Today the founding members of the field (Chris Alexander, J. Christopher Jones and others) view with disillusionment and regret the apparent contradictions in the field they helped found. The following remark by Christopher Jones captures the current mood tellingly [Ref. 2.14]:

In the sixties...there were many conferences on design methods, environmental systems and related topics. I wrote the book Design Methods, a review of the literature, and I became a teacher of design... I was seeking to relate all the design methods to each other, and to experience. [With time] I found a great split had developed between intuition and rationality, reason. There were black box methods like synectics which worked well, but nobody knew why. And glass box methods, like decision theory, which were logically clear, but which didn't work...In the seventies I reacted against the design methods. I dislike the machine language, the behaviourism, the continual attempt to fix the whole of life into a logical framework. Also there is the information overload which swamps the user of design methods (in the absence of computer aids that really do aid designing). I realize now that rational and scientific knowledge is essential for discovering the bodily limits and abilities we all share. But that mental process, the mind, is destroyed if it is encased in a fixed frame of reference.

Given the Organic Theory context that we have, it is not too difficult to see what went wrong. Re-quatizing Sullivan [Ref. 2.3]:

A: But cannot everything be reduced to the syllogism?

S: So the text books would seem to claim; yet I should not wish to see a rose reduced to syllogism; I fear the result would be mostly syllogism and that poetry would "vanish with the rose." Formal logic cannot successfully deal with the creative process, for the creating function is vital, as its name implies, whereas the syllogism is an abstraction, fascinating as a form of the function, so-called pure reason; yet when subordinate to inspiration, it has a just and high value. I say there is a logic over and above book-logic, namely, the subconscious energy we call imagination. Nevertheless, formal logic has its purpose and its place.

A: Then you do prize logic?

S: I surely do. It is a power of the intellect; but it has its limitations. It must not play tyrant.

And re-quatizing Wright [Ref. 2.8]:

Styles in architecture are part and parcel of this standardization. During the process of formation, exciting, fruitful. So soon as accomplished—a prison house for the creative soul and mind.
But more specifically, apparently the reason why the various methodologies failed
to capture the essence of design was because of the missing element of human cognition
in their (deterministic) behaviouristic frameworks. As Sullivan rightly foresaw, the
real issue at hand is the need to understand "logic over and above book-logic," the
logic of the subconscious.

Since the 1950's there has happened a cognitive revolution in psychology [Ref.
2.15] which is slowly making inroads in the arena of the logic of the subconscious. This
will have a major impact in the field of design. Examples of it may already be noticed,
for example in Prof. Donald Norman's "The Design of Everyday Things" [Ref.2.16].
Cognitive Science is an interdisciplinary fusion of disciplines (philosophy, psychology,
linguistics, sociology, artificial intelligence, and anthropology) centered around the
study of human cognition. Cognitive Engineering is the application of these and
other findings (such as ergonomics and human factors) towards the enhancement of
human cognition. The current state of basic knowledge is such that the upcoming
field is expected to be practice driven. As Donald Norman puts it in Cognitive
Engineering-Cognitive Science [Ref. 2.17]:

In fact, for the applications of the science, the cognitive engineering needs
so much from cognitive science that it is tempting to say that the science
is a subset of the engineering, a statement somewhat at odds with con-
ventional wisdom that suggests it is the other way around. But, actually,
this will come as no surprise to any practitioner of a field: the breadth of
knowledge required of a practitioner always exceeds that of the science.

Research being done in the areas of Cognitive Science and Cognitive Engineering, it
has special relevance in the context of design. Especially in regard to resolving the
seeming logjam between human creativity and the "standardized rational approach"
that Sullivan, Wright, Christopher Jones and others finds disheartening. We shall
return to this in our final chapter where we sketch the role of Cognitive Tools.

We now complete our historical survey with a word on the development of the ax-
iomatic approach. As we mentioned earlier, during the 1980s at M.I.T, there began a
concerted effort by Prof. Nam Suh et. al. [Ref. 2.18] to induce out fundamental prin-
ciples of design based on original design experiences in the mechanical/manufacturing
domain. Prof. Suh's approach is a return to the Aristotelian teleological approach to
design. The framework consists of viewing the proces of design in a bicameral sense.
As Prof. Suh puts it [Ref. 2.18]:

Everything we do in design has a hierarchical nature to it. That is deci-
sions must be made in order of importance by decomposing the problem
into a hierarchy... Design involves a continous interplay between what we
want to achieve and how we want to achieve it. For example, on a grander
scale, we may say "what we want to achieve" is to go to the Moon, whereas
the "how" is the physical embodiment in the form of rockets and space
capsules. On a smaller scale, "what we want to achieve" may be the mea-
urement of a minute amount of moisture in plastic pellets, and "how"
may be the special titration instrument... These examples of design show
that the objective of design is always stated in the *functional domain*, whereas the *physical solution* is always generated in the *physical domain*. The design procedure involves interlinking these two domains at every hierarchical level of the design process. These two domains are inherently independent of each other. What relates these two domains is the design. ...The design process involves relating...(Functional Requirements) FRs of the functional domain to the (Design Parameters) DPs of the physical domain....

Design may be formally *defined* as the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through the *mapping* between the FRs in the functional domain and the DPs of the physical domain, through the proper selection of DPs that satisfy FRs.

As we earlier saw, there is lot that is common between Prof. Suh’s framework and Sullivan’s approach. For example, regarding the hierarchy of design that Prof. Suh mentions. here we re-quote Sullivan on the same issue (written at the turn of the century) [Ref. 2.3]:

> Functions are born of functions, and in turn, give birth or death to others. Forms emerge from forms, and others arise or descend from these. All are interrelated, interwoven, intermeshed, interconnected, interblended. They exosmose and endosmose. They sway and swirl and mix and drift interminably. They shape. they reform. they dissipate....

While there are crucial differences between the two approaches, the similarity between the two is unmistakable.

Let us now consider the definition of design as a process. Compare Prof. Suh’s definition of design [Ref. 2.18]:

Design may be formally *defined* as the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through the *mapping* between the FRs in the functional domain and the DPs of the physical domain, through the proper selection of DPs that satisfy FRs.

with the definition we had put forth earlier (in Chapter 1):

Design is the cognitive thought process that transforms abstract human needs into an organization of artifacts that satisfy those needs.

While both these definitions agree upon the central Aristotelian issue namely, the normative mapping between that which is and that which ought to be, there are significant departures that need to be noted. The first is the importance of providing the genus (which is missing in Prof. Suh’s definition). Design is a process. Every process occupies a certain space and time. Design is a creative cognitive process. Its root location is the human mind. So the genus of the definition is that design is a cognitive thought process. The second is that the needs are not left at the perceptual stage. but instead have to be abstracted out into the conceptual realm.
This is unfortunately implicit in Prof. Suh’s definition. Without this there cannot be the process of thought, nor the hierarchical development of design. It is the hierarchy of concepts that provides the means by which designs are decomposed. The third significant difference is that in Prof. Suh’s definition, artifacts are primarily physical artifacts. Thus the design involved in the mental realm (for example design of a mental representation) or in the social realm (for example the design of a business organization) is left out of the overall scope of design. Despite these differences, the two definitions are fundamentally similar, primarily because of the Aristotelian basis they share. In fact our [Chapter 1] definition was built from the material provided by both Prof. Suh’s framework as well as Sullivan’s Organic Theory.

This completes our review of the design literature. We now turn to the literature on innovation.

2.5 Innovation Literature Review

The first hints on the role of the professional innovator may be witnessed in Adam Smith’s mention of it in the Wealth of Nations [Ref. 2.19]:

All the improvements in machinery, however, have by no means been the inventions of those who had occasion to use the machines. Many improvements have been made by the ingenuity of the makers of the machines, when to make them became the business of a peculiar trade; and some by that of those who are called philosophers or men of speculation, whose trade it is not to do anything, but to observe everything; and who, upon that account, are often capable of combining together the powers of the most distant and dissimilar objects.”

These “philosophers or men of speculation” perform the primary integration of labour (IOL) function; Adam Smith’s division of labour (DOL) principle is a secondary and corollary function. Without IOL there can be no DOL. The act of innovation falls under the purview of IOL. An innovator-entrepreneur such as Edison was primarily engaged in the integration of labor function when he set up his first large-scale electrical system: the Pearl Street Station enterprise in New York City. Fundamentally the innovator-entrepreneur is a visionary, capable of integrating (across multiple domains and concerns) and projecting a complex of activities targetted towards alternate means of solving pressing problems. Without such a visionary leadership, no division of labor can take place to deliver on the vision. In fact the fundamental problem of management is to provide such a visionary leadership.

Unfortunately, until recent times, seldom throughout the history of economics as a subject has there been a thought or concern raised on behalf of the integrators of labor. Until recent times, economics has chosen to treat sources of innovation as exogenous to the economy. Yes, there is a fundamental reason why earlier literature is silent on this matter. It has to do with the fact that until innovators like Edison set up dedicated and professional research and development laboratories (as in Menlo Park, New Jersey), it was difficult to see that the act of innovation could be deliberately
pursued. The idea that scientific knowledge and experience could be systematically and deliberately mined was itself an innovative concept on its own. One needs a certain critical mass of such experiences before economists could indenficate out causal economic relationships involved both within and without. Until then the literature on innovation had to remain anecdotal and biographical.

One of the first to hint at the conceptual basis of innovative developments was William Graham Sumner who published his seminal work *Folkways* in 1911. No matter how primitive or advanced a society, folkways are the “customary or habitual ways a people had devised ways for living together...As a society evolves to reach the stage of conscious reflection...the folkways become mores [Ref. 2.20].” Elaborating on this Sumner writes:

The folkways are the “right” ways to satisfy all interests, because they are traditional, and exist in fact. They extend over the whole life... The “right” way is the way which ancestors used and which has been handed down. The tradition...is its own warrant... The notion of right is in the folkways. It is not outside of them, of independent origin, and brought to them to test them. In folkways, whatever is, is right. ...

When the elements of truth and light are developed into doctrines of welfare, the folkways are raised to another plane. Then they become capable of producing inferences, developing into new forms, and extending their constructive influence over men and society. Then we call them the mores. The mores are the folkways, including the philosophical and ethical generalizations as to societal welfare which are suggested by them, and inherent in them. as they grow...

They [the mores] are the ways of doing things which are current in a society to satisfy human needs and desires. together with the faiths, notions, codes and standards of well being which inhere in those ways, having a genetic connection with them. By virtue of the latter element the mores are traits in the specific character (ethos) of a society or period. They prevail and control the ways of thinking in all the exigencies of life, returning from the world of abstractions to the world of action, to give guidance and to win revivification.

It is again the conceptual standardization, the mental ossification that Wright warns us against. And it is this conceptual basis or mores that shift when society suffers an innovation by stepping outside the accepted folklores/mores. We shall be pursuing this at greater length in Chapter 3. But one may see that Sumner anticipated Prof. Kuhn [Ref. 2.21] in regard to the manner by which Kuhn’s “normal” science gets done. In our final chapter we shall re-visit the concept of folkways/mores in the form of the cogenring.

The first major economist to formally study the problem of innovation was the Viennese economist Joseph A. Schumpeter. According to Schumpeter, in a capitalist society. “innovation is the prime mover”. In his approach to the problem of innovation, Schumpeter writes [Ref. 2.22]:

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Economic historians and economic theorists can make an interesting and socially valuable journey together, i.e. they will. It would be an investigation into the sadly neglected area of economic change.

Whenever an economy or sector of an economy adapts itself to a change in its data in the way that traditional theory describes, whenever, that is, an economy reacts to an increase in population by simply adding the new brains and hands to the working force in the existing employments, or an industry reacts to a protective duty by expansion within its existing practice, we may speak of the development as adaptive response. And whenever the economy or an industry or some firms in an industry do something else, something that is outside of the range of existing practice, we may speak of creative response.

Creative response has at least three essential characteristics. First, from the standpoint of the observer who is in full possession of all relevant facts, it can always be understood ex-post; but it can practically never be understood ex-ante; that is to say, it cannot be predicted by applying the ordinary rules of inference from the pre-existing facts... Secondly, creative response shapes the whole course of subsequent events and their "long-run" outcome. It is not true that both types of responses dominate only what the economist loves to call "transitions," leaving the ultimate outcome to be determined by the initial data. Creative response changes social and economic situations for good, or, to put it differently, it creates situations from which there is no bridge to those situations that might have emerged in its absence. This is why creative response is an essential element in the historical process; no deterministic credoavails against this. Thirdly, creative response—the frequency of its occurrence in a group, its intensity and success or failure—has obviously something, be that much or little, to do (a) with quality of the personnel available in a society, (b) with relative quality of the personnel, that is, with quality available to a particular field of activity relative to quality available, at the same time, to others, and (c) with individual decisions, actions, and patterns of behaviour. Accordingly, a study of creative response in business becomes coterminus with a study of entrepreneurship.

Let us stop and make a few observations here. Firstly, the definition of creative versus adaptive response fits in well with our earlier distinction between innovation in the strong versus weak sense. Secondly, regarding the point Schumpeter makes (the first point) regarding absolute unpredictability of the creative response, it would be in conflict with the third point Schumpeter posits, namely that a causal study of entrepreneurship is a possibility along the lines that he suggests. The resolution to this apparent paradox is in realising that while it is true that any human action that involves the free choice of "individual decisions, actions, and patterns of behaviour." is unpredictable on account of its normative content, it is definitely possible to induce out from ex-post analysis, normative principles and guidelines to aid its future course. This in essence is what we intend to do in this thesis. Thus if we treat innovation
as a random "natural" process, then nothing can be said, except that it happens occasionnally. But the moment we say that it is a purposeful, goal-directed human action, we can analyse the fundamentals and uncover normative principles to guide the process. And if we were to combine this with Sullivan's principle, namely, that "every problem contains and suggests its own solution," we definitely ought to be able to define the problem of innovation and approach it with deliberation. As we proceed, we shall see how this can be done.

But continuing on Schumpeter, here is another facet where we agree with Schumpeter regarding the relative sense in which we earlier defined the term innovation [Ref. 2.22]:

...the entrepreneur and his function are not difficult to conceptualize: the defining characteristic is simply the doing of new things or the doing of things that are already being done in a new way (innovation). It is but natural, and in fact it is an advantage, that such a definition does not draw any sharp line between what is and what is not "enterprise." For actual life itself knows no such sharp division, though it shows up the type well enough. It should be observed at once that the "new thing" need not be spectacular or of historic importance. It need not be Bessemer steel or the explosion motor. It can be the Deerfoot sausage. To see the phenomenon even in the humblest levels of the business world is quite essential though it may be difficult to find the humble entrepreneurs historically.

It might be difficult to find the "humble entrepreneur historically." But nothing stops us from considering the same phenomenon in recent times. The advantage is that if the phenomenon of innovation is indeed generic, it would share its basic architecture amongst diverse instances, both large and small. And if we can study it in the small, it should apply in the large too.

Schumpeter's own theory of innovation was put forth as a means towards explaining the (Kondratiev type of) business cycles phenomenon. Over time it matured from a strictly exogenous framework (Model I, Fig.2.7) to that of a mixed endogenous-exogenous one (Model-II, Fig.2.7). Summarizing Schumpeter's progression of thought, Prof. Christopher Freeman writes [Ref. 2.23]:

The pattern postulated by the Schumpeter-I model...may be summarized as follows:

1. There is a (discontinuous) flow of basic inventions related in an unspecified way to new developments in science. These are largely exogenous to existing firms and market structures, and hence to any measureable type of 'market demand', although they may certainly be influenced by the belief in a potential demand or concept of unmet need, or shortages of existing products.

2. A group of entrepreneurs (who in Schumpeter's view are responsible for the main thrust in capitalist economies) realize the future potential of these inventions and are prepared to take the risk of developing
Figure 2-7: Schumpeter Model I & II [Source: Ref. 2.23]
and innovating. This hazardous activity would not be undertaken by
the average capitalist or manager but only by exceptional individuals.
whom he defines as entrepreneurs.

3. Once a radical innovation had been made, it would disequilibrate
existing market structures and reward the successful innovator with
exceptional growth and temporary monopoly profits. However, this
monopoly will be later whittled away by the entry of swarming sec-
ondary innovators giving rise to the cyclical phenomena...

The main difference between Schumpeter II and Schumpeter I are in the
incorporation of endogenous scientific and technical activities conducted
by large firms. There is a strong positive feedback loop from success-
ful innovation to increased R&D activities setting up a ‘virtuous’ self-
reinforcing circle leading to increased market concentration. Schumpeter
now sees inventive activities as increasingly under the control of large
firms and reinforcing their competitive position. The ‘coupling’ between
science, technology, innovative investment and the market. once loose and
subject to long time delays. is now much more intimate and continous.

Note the decoupled status in Schumpeter I. between the early stage “discovery or
invention push” and the later stage “market demand or market pull.” By coupling
the inventive technology unit with the market demand structures. we now have a
feedback system that over time can develop normative capacities to strategically and
deliberately pursue the process of innovation. Schumpeter placed the importance
on “autonomous invention and entrepreunership.” Others (like J. Schmookler [Ref.
2.24]) have placed the emphasis on “market demand.” giving it thus the central role.

The next development relevant to our context is the work by Jewkes et. al. on
The Sources of Invention (1959) [Ref. 2.25]. The argument here is that invention is
spontaneous: that it cannot be predicted:

There is nothing in the history of technology in the past century and a
half to suggest that infallible methods of invention have been discovered or
are. in fact. discoverable... In many fields of knowledge, discovery is still a
matter of scouting about on the surface of things where imagination and
acute observation...are likely to bring rich rewards.

Regarding predictability, Jewkes et.al. write:

There is nothing...which lends support to the view that inventions can
be predicted or that forecasts of their consequences can provide secure
grounds for anticipatory social action....the claim that there is. or can be.
a ‘science of prediction’ might easily do more harm than good.

Experience suggests that most specific inventions were not foreseen: they
had an element of the accidental in them. they represented the last. and
therefore the crucial. step between the uncertain and the certain....
But if the details of the future are hidden, are there reasons for believing that it is still possible to perceive that it is still possible in a broader way what is to come? Is there a valid parallel, for example, between plotting the broad surge of technology and drawing up (say) a table of the movements of the tide?

Following are four reasons that were examined (summarized below) and found wanting. To Jewkes's counter-arguments, we have supplied our own "counter-counter":

1. **Argument:** Each new scientific discovery throws open new technical possibilities. Thus even though the scientific discovery is not predictable, the ensuing technology is. **Counter Argument:** Making a scientific discovery is remote from figuring out where all it could be used. Many are the scientists who have failed to recognize the practical implications of their discoveries. **Counter-Counter:** That there was no deliberate connection in the past is no indication of things in the future. With better understanding of the underlying creative process, one could perhaps discern profitable approaches to innovative decision making.

2. **Argument:** How would one explain the well documented phenomenon of simultaneous inventions? Clearly this suggests that there are times when the context is ripe for a given invention. **Counter Argument:** This is a plausible argument. However, too many counter examples that do not fall in this category. Also quite a few inventions made far ahead of their times. **Counter Counter:** Perhaps the context or underlying factor is the state of published or shared knowledge that is prevalent. Thus plotting the patterns of knowledge dynamics might provide clues and guidelines to its deliberate pursuit.

3. **Argument:** There is a time lag between the conception of the invention and its full scale adoption. One could profitably use this time to research out the possible implications. **Counter Argument:** Here we have dropped the invention/prediction line; we are now looking at merely market response. Adoption process could be slow or fast. If fast, then no time to predict the response. If slow, then too many uncertainties. **Counter Counter:** This is merely a repeat of the first argument at a different level.

4. **Argument:** All that we really need is to know is the market demand in a given context; we are technologically capable of finding a solution once the market demand has been identified. **Counter Argument:** But picking out those viable market needs is again speculative. **Counter Counter:** Again this is a repeat of the first argument, but now in the context of the market factors.

In a fundamental sense Jewkes et. al. are right when they claim that there is no sure silver bullet to innovation. But this does not at the same time mean that the act of innovating is purely random: that there are no discernable patterns to it. Later researchers started inducing out patterns of innovation, which then provide a useful basis for guiding it. We now turn to this.
The "Life-Cycle Model" (also called the A-U Model) that Abernathy and Utterback presented in the paper *Patterns of Industrial Innovation* (1978) [Ref. 2.26] established some of the major themes of current research on Innovation Management. At the core of the model is a temporal framework that tracks an innovation from its inception to its growth, maturity, and (sometimes) collapse. The initial stage is a fluid state; it then goes through a period of transition; then comes the period of standardization. This is the same distinction that Wright described between the fluid, elastic period of becoming...when possibilities are infinite versus the period when the form has set [and is] past redemption and the creative matter [is essentially] found dead. During the fluid-stage the program suffers from both market as well as technical uncertainties. With experience, we enter the transition stage where uncertainties are dissolved away and there emerges a dominant design concept (such as the Ford-T model) which then sets the stage for future standardization in the industry.

In this paper we also see that Schumpeter's concepts about adaptive change versus creative change are now cast as radical versus incremental innovation [Ref. 2.26]:

...accumulating, incremental developments in petroleum refining processes resulted in productivity gains which often eclipsed the gain from the original innovation. Incremental innovations...resulted in dramatic reductions in cost... 200z ...major systems improvements [radical innovations] have been followed by countless minor product and systems improvements, and the latter account for more than half of the total ultimate economic gain due to their much greater number.

As we suggested in our introductory chapter, perhaps a better terminology would be to call incremental innovation as *ensemble innovation* because it is the whole series of minor innovations we are talking about rather than each minor one stand alone. Also it is a bit unfair to suggest that the "ensemble innovation" is economically more or less on the same level as the radical innovation. For we forget that the ensemble innovation is taking place within the economic potential established by the radical innovation. As Schumpeter rightly saw [Ref. 2.22]:

...creative response [radical innovation] shapes the whole course of subsequent events and their "long-run" outcome.

Seeing the link between radical and the incremental helps us keep the proper perspective between the two.

One of the major problems of this paper is the mixed-level approach to studying innovation [Ref. 2.26]:

..the questions raised in this article require that a product line and its associated production process be taken together as the unit of analysis. This we term a "production unit."

Thus the hierarchy between products and processes in the partial system "(process (products (markets)))" has been collapsed. A mixed-level approach may be represented as (economic/political system (public), (Production Unit [processes, products])
The consequence of this approach is that the very identity of the innovation under study is lost. This leads to problems in identifying the evolutionary transitions between the levels. Even the authors confess, "identifying the evolutionary transitions from product to process innovation is sometimes troublesome." A mixed-level approach to studying innovation occurs whenever multiple contexts and levels are fused together with the primary focus on some one innovation; and all other innovations take second place to this. While such approaches are certainly useful at a later stage; the preliminary analysis ought to focus on uni-level/uni-context types of analysis. It is out of such uni-level transformations that more elaborate transitions could be articulated.

Despite the above problems, the authors do recognize the significance of the underlying hierarchy when they write [Ref. 2.26]:

Major change at one level works its way up and down the chain, because of the interdependence of product and process change within and among productive units.

As we saw in the James Watts Steam Engine case, this innovation penetrated all the way into the foundations of the British Economy.

A crucial insight that Abernathy and Utterback provide relates well to the "mental lock" problem we encountered in our design literature review:

Major new products do not seem to be consistent with the pattern of incremental change. New products which require reorientation of corporate goals or production facilities tend to originate outside organizations devoted to a "specific" production system; or, if originated within, to be rejected by them.....

Eight of the 13 product innovations [that John Tilton's study on semiconductor industry] considers to have been most important during [the period from 1950 to 1968] occurred within the first seven years, while industry was making less than 5 per cent of its total 18-year sales. Two types of enterprises can be identified in this early period of the new industry—established units that came into semiconductors from vested positions in vacuum tube markets, and new entries such as Fairchild Semiconductor, I.B.M., and Texas Instruments, Inc. The established units responded to competition from the newcomers by emphasizing process innovations. Meanwhile, the latter sought entry and strength through product innovation. The three very successful new entrants just listed were responsible for half of the major product innovations and only one of the nine process innovations which Dr. Tilton identified in the 18-year period, while three principal established units (divisions of General Electric, Philco, and R.C.A.) made only one-quarter of the product innovations in the same period. In this case process innovation did not prove to be an effective competitive stance; by 1966 the three established units together held only 18 per cent of the market while the three new units held 42 per cent
Apparently the established firms were unable to recover from the conceptual process-framework (wherein they were located) back to the product-framework from their earlier days. The conceptual front wherein a company currently operates places a "mental lock" on its options and flexibilities to act. Thus they were technically unable to "throw away" the current game plan and look at the problem afresh.

Building on the theme in the A-U Model, Abernathy and Clark put forward the Transilience Map model in their paper *Innovation: Mapping the Winds of Creative Destruction* [Ref. 2.27]. Transilience is the "capacity of an innovation to influence the established systems of production and marketing." The model is a product-focussed mixed-level [technology, markets] analysis. Here the term technology is again a mixed-level smeared concept which includes both production and operations (i.e., [firm(s), processes, products]). The model attempts to classify innovations into four major types (Fig. 2.8):

1. **Architectural Innovation**: This type of innovation departs fundamentally from the current practices and (re-)establishes the overall architectural framework for products, processes and marketing developments. It thus lays down the architecture of the industry. There is thus a definite transilience both in the technology (i.e., productions/operations) as well as in the marketing networks. Examples include innovations such as xerography and radio. The best way to stimulating architectural innovations "seem to hinge on the juxtaposition of individuals with prior experience in relevant technologies and new user environments latent with needs." From a management perspective, this type of innovation requires skills in the "management of creativity with a keen insight into business risk."

2. **Niche Market Innovation**: Here the transilience is mainly in the markets. Examples include fashion apparel and consumer electronics. The products definitely change, reflecting the transient niches in a fast-moving market. But the "technology" is basically constant. Here the requirement is that the manufacturing/management system ought to be well coordinated to detect and re-configure in order to quickly respond to the fast moving market.

3. **Regular Innovation**: Here the innovation conserves and preserves and builds on the existing markets and technologies. Thus "refinements in product design and processes reinforce increases in scale economies," bringing about "dramatic effect[s] on product cost, reliability, and performance." For example, improvements in the making of the Ford Model T between 1908 and 1926 enhanced its reliability while at the same time reducing the price of the car from $1200 to $290. Specific examples include the moving assembly line by Ford in 1913 and automatic welding by Budd in 1925. Regular mode innovation requires sustained and systematic improvements on the existing products, processes and markets. From an organizational perspective, "this is the work of the administrator and the functionally oriented engineer."

4. **Revolutionary Innovation**: Here the transilience is mainly in the "technology" which then gets "applied to existing markets and customers." For example,
Figure 2-8: Clark and Abernathy's Transilience Map [Source: Ref. 2.27]
the introduction of the closed steel body car (as compared to the earlier open wooden body models) in 1921 by Hudson. Chevrolet, GM and others strengthened existing "market linkages, but its impact on manufacturing was disruptive." Elsewhere [Ref. 2.28] Clark writes that "revolutionary changes mark a reversal in the classic pattern of evolution and may be a prelude to the redefinition of the product and the eventual reemergence of an "architectural" period of activity."

Having laid out the framework, the authors then map it onto a A-U kind-of life-cycle model and show how the industry cycles between architectural, to regular to revolutionary and niche modes (often the product versatility provided by the later-stage flexibility in the regular mode can address niche-markets). The link between revolutionary and architectural modes is left rather ambiguous. On account of the mixed-level analysis, innovations such as the transfer-line production system is treated as a regular innovation despite the architectural changes (such as pacing) it brought about in the organizational structures. Here one sees the importance of definitions, of being precise about the relative sense in which the term "innovation" ought to be used.

Two significant insights that Clark and Abarnathy provide relate to the role of knowledge in the context of radical versus conservative innovations, and with respect to technology: customer knowledge and customer communications:

1. Technology/Production:

   (a) **Conservative:** Impact of innovation such that the "knowledge and experience [gained in this context] builds on and reinforces applicability of existing knowledge."

   (b) **Radical:** Impact of innovation such that the "knowledge and experience [gained in this context] establishes links to whole new scientific discipline/destroys value of existing knowledge base."

2. Market/Customer Knowledge:

   (a) **Conservative:** Impact of innovation such that the "customer knowledge [gained in this context] uses and extends customer knowledge and experience in established product."

   (b) **Radical:** Impact of innovation such that there is an "intensive new knowledge demand [by the] customer: [it] destroys value of [earlier] customer experience."

3. Market/Customer Communication:

   (a) **Conservative:** Impact of innovation such that it "reinforces existing modes/methods of communication."

   (b) **Radical:** Impact of innovation such that there is a need for "totally new modes of communication... (e.g., field sales engineers)."
The significance of the knowledge shift is critical. As we shall see, fundamentally, it is this knowledge shift which is the efficient cause behind the various styles of innovation. Also just as the customer communication channels are disrupted during a radical innovation, so also the communication channels are disrupted within the firm level giving rise to the “old-guard/new-guard” politicking.

The final paper we shall review is by Prof. Kim Clark on *The interaction of design hierarchies and market concepts in technological evolution* [Ref. 2.28]. Of the various researches on innovation, this approach is most closely aligned with our framework. For it studies innovation at the micro-level of design. We shall therefore be considering it in greater detail. Prof. Clark is explicating the conceptual hierarchies (both in technology and customer understanding) and patterns involved in incremental innovation. Central to the discussion are the concepts of design(n) form, and problem context and the fit or mapping between the two. Introducing the theory, Prof. Clark writes [Ref. 2.28]:

I argue that the logic of problem solving in design and the formation of concepts that underlie choice in the market place impose a hierarchical structure on the evolution of technology. The pattern of innovation, the kinds of design changes introduced and their timing and sequence, not only depend on the technical alternatives but on the interaction between the internal logic of the product and the evolution of customer requirements....

[The question here is]... is there a pattern to the narrowing of approach in some dimensions and the emergence of new approaches in others? And if so, what is the logic behind the sequence of developments? These questions are central to an understanding of the changing focus of customer valuation and innovative effort, and thus of the forces driving evolution. The logic of design... suggests that answers to these questions must be found in the interaction between [design] form and [problem] context.

One of the patterns cited (from the automobile industry) is that of the “precedence of innovation in engines over transmissions up until the the late 1920s and then the dominance of transmission innovation during the decade of the 1930s.” This was true even though “the scientific and engineering principles embodied in the semi-automatic and transmissions of the 1930s were available at least by 1920s.” Also, “within the engine category, the number and configuration of cylinders and the starting/firing of the engine were the focus of significant effort over several years, while other parameters within the engine were subject of little innovation until well into the 1920s.”

As an explanation of these patterns from the technology side, Prof. Clark writes [Ref. 2.28]:

Patterns of innovation like those observed in early automobiles are the result of two related processes. The first is the logic of problem solving in design; the second is the formation of concepts that underlie customer choice. Both processes impose a hierarchical structure on the evolution of technology....

It is inherent in the nature of an hierarchy that the various functional parameters are of unequal significance. At each level in the hierarchy
competing alternatives have implications for subsequent decisions, but choice at the apex has ramifications throughout the hierarchy. Within a given functional domain like an engine in an automobile, the structure of associated parameters is hierarchical. One parameter sits at the apex, and is particularly trenchant in its impact on other aspects of the domain. Such concepts are central or “core” in the sense that the choices they represent dominate all others within the domain. That domination arises from the fact that the choice of a core concept creates a set of given conditions with which other parameters must deal. Said another way, choice of a core concept establishes the agenda for a product’s technical development within a particular functional domain.

...The central functional problem in the evolution of the engine was the choice of fuel and the principle of energy transmission. In the very early days of the industry it was not clear whether steam or electricity or gasoline would dominate. Indeed before 1900, steam and electricity powered vehicles were more reliable. By 1902, however, the dominance of the gasoline engine was largely established. Once the core concept became internal combustion based on gasoline, the technical agenda was set for a variety of subsidiary problems and choices. Starting and firing the engine, size and configuration of cylinders, placement of valves and camshafts, and so forth, were examined and approached in subsequent years...

Given the logic of problem solving, “working through” a particular technical agenda entails a hierarchical exploration of alternative concepts. Thus, even without any changes in context, one would expect to observe a conceptual hierarchy in the sequence of design decisions embodied in successive generations of a new product.

The developments cited above are along the right-arch of the design trace [Fig. 2.9(a)]. The envelope of design-traces (the two inner arches) is the ensemble of all the historical developments. This provides the overall context. The market feedback loop has been omitted for purposes of clarity. Also the left arch contains not just the problem abstraction phases of the various design traces, but also all the various nested problem abstraction phases too. Prof. Clarks’s concept of the “core concepts” agree well with our concept of the innovation axis. When there takes place a shift in the core concept, there is an architectural shift at that level.

Within the ensemble of design-traces is shown the level at which the problem of the engine was posed and solved. There is a bunching up of the various options, making a conceptual nodule at this level. As soon as a dominant concept emerges at this level, the nodule shifts downward to find the dominant concepts at a lower level. This is shown in Fig.2.9(b).

To understand the patterns from the market side, Prof. Clark writes [Ref. 2.28]:

[But].. to understand the hierarchy of design as it emerges in the sequence of design choices over time one must understand not only the internal logic of the product. but the evolution of the requirements of customers....
Figure 2-9: Hierarchical Evolution on the Right Arch

Figure 2-10: Conceptual Hierarchy related to Asparagus [Source: Ref. 2.29]
Research on the role of information processing in marketing suggests that customer problem solving is closely related to language and memory and their interaction. Two aspects of that process are critical. The first is grouping, in which the unfamiliar product is associated with other known product concepts to which it is similar or related. The second is distinguishing, that is, identifying those dimensions of the product that differentiate it from the group in which it has been placed.

The process of grouping and distinguishing can be illustrated with a relatively trivial example. Fig. 2.10 depicts a set of concepts related to a type of vegetable—asparagus. This set of concepts is hierarchical in nature with the more inclusive, abstract concepts located higher in the order of things. Suppose that a set of customers had never before encountered asparagus. Faced with the problem of evaluating the product, the customers might first group it with other plants simply on the basis of observation. Observation might also provide enough information to permit the customer to make finer distinction (green vegetable). But further refinement and development of the meaning of asparagus would depend on experience in use. One can imagine further distinctions based on taste, texture and interaction with other foods that would further establish the product’s identity within the customer’s conceptual framework.

The early history of semiconductors illustrates the important role of established and closely related products to the conceptual development of one that is new. The first transistors, for example, were evaluated in the language and context of vacuum tubes. Scientists at Bell Labs thought of the transistor as a substitute for the tube, and subsequent development proceeded in those terms, at least for a while... It was not until experience with transistors had deepened understanding of the possibilities of semiconductors that new concepts like the integrated circuit emerged. What happened in transistors seems to be a general property of new products: in the early stages, the new product is defined largely in terms of the old; as learning occurs, it develops a meaning and definition of its own.

Clearly, the working out of the conceptual definition occurs through use and experience with the product... [But].. development of a new product concept is a market process and thus involves learning and problem solving on the part of the customer group. In this situation communications between customers (e.g., word of mouth) will be important in the diffusion of the product and the crystallization of concept...

Problem solving on the customer side, thus follows a hierarchy of concept. What the product is, how it meets needs, how it functions in different situations, and so forth, is not defined in one swell swoop. Nor are the different aspects of the product of equal significance. Understanding and

\[\text{Ref. 2.29}\]
insight develop over a period of time...

Prof. Clark then shows the development of customer related concepts in the automobile industry:

1. **Horseless Carriage versus Carriage with a Horse:** The first customer decisions were framed in the vocabulary of the horse drawn carriages. It was perceived that the new contraption was merely replacing the function of the horse-drawn carriages. It was in this context that the primary innovations in the engine design happened. As Prof. Clark puts it [Ref. 2.28]:

   The engine was the most immediate and distinctive feature of the new product. Indeed, one can see in photographs of early cars that a good deal of the preceding product (the carriage) was carried over almost intact. There was little distinction in the seats, or the body or even the tires and the frame. The engine gave the new product its character, and provided the greatest source of potential misfit... Once choices about core concepts in engines were established, innovative effort moved down into subsidiary parameters...

2. **Automobile versus Horseless Carriage:** With added functionalities (“speed, mobility, endurance, payload.”) there arose a plethora of concepts: “roadster, touring car, coupe.”

3. **Basic Transportation:** With the arrival of the dominant design, Model T, these concepts converged to become the “basic transportation,” meaning “rugged, durable, reliable, easy to maintain, low cost.” The customer base was predominantly rural.

4. **Rolling Living Room (the all purpose road cruiser):** With innovations by GM, Chevrolet, and others, and a shift in the customer base (from rural to urban users who were “less mechanically sophisticated, less tolerant of inconvenient operation”), the context was set for innovations in automated engine transmission.

As the needs and priorities of the customers shift, as new customers enter the market and make their needs felt, the problem context shifts. The shifts lead to an upward shifting of the market-feedback loop. This is depicted in Fig. 2.11. There is an approximate correspondence between the market feedback loop and the main design trace. It is important to map and closely follow the changing dynamics between the two. Thus the arrival at a dominant design on the main design trace might be detectable by the stabilization that happens at the corresponding level on the market-feedback loop. These are intriguing options that need to be researched out in the future. But we now return to Prof. Clark.

As a final capstone. Prof. Clark applies the concept of design hierarchies in the context of process innovations (in the framework of the A-U model). He thus says [Ref. 2.28]:

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Figure 2-11: Dynamics of the Market Feedback Loop
It is reasonable to expect to observe a hierarchy of design on the process side as well.... the evolution of process design is driven by the same forces that drive product development.

One finds in the A-U model that product innovation is much more frequent in the fluid stage of development compared to innovation in processes. But frequency is not the same thing as significance. While it is true that stability in core concepts and major functional product parameters is an essential prelude to a high rate of process innovation, there are two kinds of process change that may grow out of and interact with the development of product design... The first takes the product and its design as given, and introduces new ways of organizing and coordinating production. The second introduces new process capabilities and changes the characteristics of the product.

Prof. Clark then illustrates this with examples in the automobile (the V-8 engine from innovations in casting technology) and in semiconductors (doping in crystal growing versus alloying versus jet etching, etc). By distinguishing between frequency and significance, Prof. Clark is alluding to the difference between innovation in the strong versus weak sense (i.e., architectural versus non-architectural).

If we were to map all this into the multi-knowledge humps that pertain to each domain (customer problem solving, product design, process design, etc) we would arrive at the multi-hump diagram shown in Fig.2.12. Here the problem solving at various levels has been separated out. One design trace feeds into another, providing the context for developments in that domain.

In his concluding remarks, Prof. Clark makes two major distinctions:

1. **Vertical Movements**: Innovative developments along the knowledge hierarchy could be mapped as a vertical movement (Fig.2.13(a)). As Prof. Clark puts it [Ref. 2.28]:

   [The first distinction involves..] movements up and down the hierarchies of design and customer concept. Movement down the hierarchy are associated with refinement or extension of higher order concepts. Innovation of this kind strengthens and reinforces existing commitments. It is conservative in nature; it strengthens and improves the fit between form and context and thus entrenches the established approach.

   Movements up the hierarchy are associated with departure from existing approaches. Such innovation is most dramatic when it involves core concepts, but it may occur within lower order concepts and yet have significant impact.

2. **Horizontal Movements**: Here Prof. Clark distinguishes between changes that happen on the left versus the right arch of the design trace (Fig. 2.13(b)):

   The second distinction is between hierarchies and associated skills and resources linked to product and process technology, and those linked...
to customers and markets. The importance of that distinction lies in the fact that a given innovation need not affect the two hierarchies in the same way. What may be a movement down the design hierarchy, may open up new channels of distribution and draw in new customers with different uses and needs. Conversely, an innovation that departs from previous design concepts, may be applied to an unchanging set of customers with unchanging conceptual hierarchy.

Prof. Clark then uses this left/right distinction to match his framework with the Abernathy-Clark Transilence model we saw earlier. Thus change versus no-change on the left versus right limbs correspond to the radical versus conservative axis on the market versus technology axis. The improvement this has over the Abernathy-Clark paper is that here the levels are no longer smeared between products and processes.

We have now completed our innovation literature review. We shall later see how the same knowledge hump diagram which we used to study incremental innovation (as above), could also be used to map and "suggest" places to seek for radical innovations.
2.6 Conclusion

We started off with a historical review of Sullivan's Organic Theory of Design. From this we gained valuable insights both in the context of design as well as innovation. Sullivan's case provided us with two fundamental principles of design, namely:

1. The Direct Principle: Design(n) follows function.

2. The Indirect Principle: Design(n) of design follows function.

He also gave us the fundamental manner in which aesthetic requirements have to be integrated into the design(n) that is based on non-aesthetic requirements.

On a different level, his case also gave us illustration of the inductive style archstand based innovation in the realm of architectural design. For he induced out his principles based on observations of design(n) in nature. He then applied it in the context of the cascade innovation (cascade from cheap steel manufacture and elevator technology) in the architectural design of skyscrapers. In doing so he provided us illustration of Prof. Suh's "square-one" (Theorem 5) principle of innovation.

Prof. Suh provided us the ways and means by which one could more clearly study the mapping between function and design(n). His approach provided us the needed rigour in studying design.

Our analysis of the writings by Wright gave us fundamental insights into the challenges posed by the machine, and into the problem of "mental standardization." He also provided us valuable insights into the role of aesthetics in design.
Our excursion into philosophy provided us the needed basis in integrating the aesthetic requirements into our design framework. Without this, our design framework would have been only partial in scope.

Our review of the literature on innovation brought together the full context in which Prof. Clark presented his framework on innovation based on design hierarchies. Prof. Clark applied this in the context of innovations that build upon existing architectures. We are now ready to extend it into the study of innovations that bring about fundamental shifts in the architecture of existing systems.

2.7 References


Chapter 3

The Archstand Theory of Innovation

3.1 Introduction

In this chapter we first study the structure and nature of human knowledge design(n) and the resulting knowledge dynamics. The premise is that human knowledge has a certain structure that is derived from the human condition, i.e., the nature of the human consciousness and its limitations. We first look at the philosophic reasons why this is so. Here we look at human knowledge from a design perspective and contrast the various historical approaches to the study of the "making" of human knowledge.

Having looked at the static structures of human knowledge, we then look at the dynamics of human knowledge. From a philosophical perspective, we look at the ways and means by which knowledge structures could shift and move and transform and be modified.

We then try to see if indeed the theory meets the data. In order to do this we illustrate the phenomenon with various examples from the history of science. These examples are excerpted from Prof. Thagard's seminal work Conceptual Revolutions [Ref. 3.1]. We then contrast the Thagardian cognitive framework against the Kuhnian analytic-synthetic framework and show what it means in the context of the study of innovations.

We then integrate it all in the context of innovation and "design(n) for innovation" in our final section on the Archstand Theory of Design(n) for Innovation.

3.2 Knowledge Architectures and Knowledge Dynamics

Human knowledge is a human creation. Like every other human artifact, human knowledge too is designed to satisfy certain functions. What are these functions? And what is the design(n) (if any) in what we call knowledge? In this section we inquire into this. As humans, we create knowledge for certain purposes. And when it doesn't satisfy those purposes any more, we demolish or rebuild our knowledge architectures. What function does human knowledge serve? And what could it tell us about knowledge dynamics?

Before we begin, let us take stock of things we already know. As we saw in our
introductory chapter, human knowledge definitely does have a hierarchical structure to it. Knowledge as concepts display kind hierarchies and part hierarchies. One gives the causal link; the other the compositional link. Thus humans belong to the animal kingdom because humans share in the animal nature thus differentiating them from plants (heterotrophism versus autotrophism); while the beak is part of the bird.

Propositional knowledge too displays logical hierarchies. Thus, for example, we have the Newtonian mechanics logically being deduced from the Newtonian principles (in our next chapter we shall see a similar structure in Euclidean Geometry). Things that are more specific are deduced from things more general.

In our last chapter, we saw a simple example of how a customer went about classifying a new existent, asparagus, into its proper location along his existing knowledge hierarchy. If however it somehow did not fit into existing architectures (for example, the discovery of AIDS), we induce out new categories to accommodate our discovery. We induce out concepts based on similarities and differences [Ref. 3.19]. Thus the existents milk, water orange juice,.. are sufficiently different from existents rock, wood, sand: but they are sufficiently similar between them that we feel the need to create concept fluid as opposed to solid in order to identify between them correctly. Our consciousness is a living process. And in its fundamental elements, it basically consists of just these two processes: finding differences and similarities (or differentiating and integrating).

Historically, there have been three positions taken regarding the fundamental cause for concepts (and thus knowledge) [Ref. 3.2]:

1. The Intrinsicist: The Intrinsicist (or the realist) approach (as advocated by Plato, St. Augustine, etc.) holds that conceptual essences (or platonic forms) are universals that belong to a different world; and things in reality part-take in these essences; and we are able to "intuit" (intuition: the faculty of attaining direct knowledge or cognition without rational thought and inference) out these essences because we somehow knew them prior to this life. A personal encounter with the existent merely gives us the needed cue to become explicitly aware of what we already knew. Humans differ regarding how well they might intuit. Philosophers on account of their impressive mental constitutions, are better equipped to take the "wax imprint" the universals leave behind. Thus they are most suited to be leaders (hence Plato's ideal of the philosopher-king).

In this system, the problem of design of knowledge never does arise. For knowledge is not a human creation. Knowledge is gained thru intuition during which reality writes itself directly onto our impressionable minds. Thus the protagonist in the context of knowledge aquisition is reality; we are merely passive witnesses to the various manifestations of the universal forms.

In this framework, the problem of knowledge dynamics also does not arise. For knowledge as such neither grows nor gets destroyed. All that that changes is how much of it are we currently exposed to.

2. The Subjectivist: The Subjectivist (or the nominalist) approach (as put forth by Immanuel Kant, John Dewey, Georg Hegel, Thomas Kuhn) is a skeptical
reaction to the intrinsic “intuitive” approach. They hold that knowledge is purely an arbitrary human (or social) construct; that there is “really” no basis in reality as allegedly claimed by the intrinsic theorists. For on account of our peculiar mental constitutions, we are fundamentally cut off from the “phenom-
enal world” that pertains to the real world out there (i.e., that our senses are invalid). We are thus confined to our mentally created “noumenal worlds”.

In this world-view, there is a definite problem of knowledge design as well as knowledge dynamics. Hegel, for example, put forth his dialectic approach (of thesis, anti-thesis and synthesis) for knowledge creation. Dewey’s pragmatic school rejected the correspondence theory of truth and instead put forth the pragmatic ideal that truth is that which works. And “that which works” keeps shifting as the pragmatics of the moment dictate.

3. The Objectivist: The Objectivist school [Ref. 3.2] is a modern development which has many parallels in the current cognitive psychology developments we mentioned earlier. Perhaps the best way to follow these developments (against the historic context) is to cast the various approaches onto our design framework. We undertake to do that immediately.

To understand the functional requirements for knowledge design, let us inquire into its fundamental purpose and what it entails. The final purpose of knowledge is to apprehend reality that exists independent of human consciousness. This purpose is born out of the fact that in order to live we need to act in a goal-directed fashion and design artifacts that aid us in life. We design these artifacts based on things we find in nature. In order to come up with proper designs, we need to understand the operative laws in nature. Or to put it in Baconian terms, “nature to be commanded must be obeyed.” This then is the final cause for our quest for knowledge. Knowledge essentially is the understanding or grasp of the causal laws operative in nature in order to help us “command” nature to meet our existential needs.

But as humans we have a limited nature. We are definitely not omniscient; for we do not grasp all of reality all at once. We thus have to build our understanding in stages while all the time making sure that that which we build does indeed correspond to the reality that we perceive thru our senses that interface with the world at large. Contrary to Kant, our senses are indeed valid. They might give us a distorted view of the world at large; we then correct it by understanding the physics behind it; for example, corrective glasses for myopic distortions. But our senses are valid automatically—for they give us the total information available, including the facts about our weakening eye-lenses. It is up to our conceptual faculties to make “sense” out of all this and to make judicious use of it (for example, entering the lucrative practice of optometry). The “problem” of validity (or correspondence to reality) arises only at the conceptual level.

We are not omniscient beings. Our sensory apparatus is capable of attending to only parts of the world at large. Yet out of these partial views we need to build a more comprehensive understanding. So we observe the world at large and try to put together the various facts into a more comprehensive understanding. Thus we observe
Tycho Brahe's multitude of observations, we visit Galileo's free fall experiment, we observe the trajectory of the apple's fall, etc. We then try to put together out of this, a sort-of collage of the world at large. But in trying to do so, we come up against yet another limitation (but this time an internal cognitive limitation). For our internal apparatus wherein we could put together such a comprehensive understanding is also limited. Here it is not just that we have limited memories (for to overcome that we could use external aids); more fundamentally, the problem is that in order to relate the various facts, we do need to grasp them in a single instance (or at best a few contiguous instances). Hence arises the need to be selective in our partial views. Hence arises the need to focus on the essentials (essentials, based on the problem of design we are faced with; for example, in the context of the myopic eye-lens problem, essentials are facts that relate to the myopic distortions, and possible ways to correct it). Hence arises the need to be conceptual rather than merely perceptual. Hence arises the need to induce out concepts, as we did in the case of the "asparagus." Hence arises the hierarchical structure to human knowledge. Hence arises the need to induce out propositions (out of these building-block concepts) in order to assert and validate statements about our understanding of, say, the natural mechanics in terms of Newtonian laws. Causal laws are essentially the links that connect our partial views as captured in the essential terms of concepts and ground propositions. And once we have these, we are able to predict the eclipses, the motions of the planets, the cause behind the seasons, the rise and fall of the tides, the trajectory to reach the moon...

So all said and done, the fundamental purpose and design(n) of the human knowledge is as follows1:

- \( FRO1_{(1,0)} \): In order to meet our human needs, we need to grasp the nature of reality that exists independent of us, given the limitations of our human cognition.

- \( DPO1_{(1,0)} \): Human knowledge is the manner or tool by which we grasp reality that exists independent of us, given our cognitive limits.

If we then decompose the problem as per our decompositional analysis (see Section 1.3.2) \( A_d \) analysis, we come up with the following two requirements and the corresponding design(n):

- \( FRO2_{(2,1)} \): In order to accomodate to our cognitive limits while engaged in our knowledge pursuit, we need cognitive ways and means to focus on essentials, synthesize concepts and propositions based on the facts we have observed.

---

1Note: Here the notation we have used is as follows. \( FRI_{(m,n)} \) means l-th FR (with all FR's sequentially ordered), at the m-th level of design, and derived from the n-th FR from higher levels. Thus \( FRO_{(3,2)} \) means the 5th FR in the sequence, encountered at the 3rd level of design, and derived from the 2nd FR in the sequence. Here the O in the \( FRO5_{(3,2)} \) denotes the Objectivist version versus I for the Intrinsicist and S for the Subjectivist.
- \(FRO3_{(2,1)}\): In order to accommodate to the need that what we have does indeed correspond with reality, we need cognitive ways and means to analyse and validate our knowledge.

- \(DPO2_{(2,1)}\): Methods of Knowledge Synthesis.

- \(DPO3_{(2,1)}\): Methods of Knowledge Analysis.

The fact that knowledge is hierarchical can give rise to two kinds of analytic problems and their corresponding designs(n):

- \(FRO4_{(3,3)}\) (Problem of the Proof (or Vertical Support)): We need to ultimately ground the propositional structures with our sensory data.

- \(FRO5_{(3,3)}\) (Problem of Consistency (or Horizontal Support)): We need to check the integrity or knowledge consistency between existing knowledge structures, thus keeping the full context. We need to keep the full context because reality is an integral whole. Reality is an integral whole in the sense that everything is causally connected with everything else (some mediatly, some immediately). Our knowledge thus has to reflect this integrity. Vertical support is mainly concerned with piece-meal validity. Horizontal support makes our knowledge architectures holistic.

- \(DPO4_{(3,3)}\): Proof (both inductive as well as deductive) as the method of Knowledge Reduction.

- \(DPO5_{(3,3)}\): Knowledge integration as the method of keeping the full context.

While there exists excellent treatise on methods of proof [Ref. 3.3], there exist very few well grounded techniques for knowledge integration. There is however a burgeoning interest in the realm of inter-disciplinary research [Ref. 3.4]. But the work being done in this area is mainly heuristic and preliminary in nature. Here then we have a challenging problem for modern epistemologists. And it corroborates with what we have said (in our last chapter) regarding the missing half of economics research namely, on the integration of labor.

Fig. 3.1 gives the architecture of the above knowledge design against the background of our “implicit” knowledge hump; implicit because the rules of knowledge explication are being formulated right here. Analytically, we may represent the above design(n) as follows\(^2\):

\[
\begin{align*}
\{ FRO3_{(2,1)} \} &= \left[ \begin{array}{ccc}
\oplus_2 & O & O \\
O & \oplus_3 & O \\
O & O & \oplus_3 \\
\end{array} \right] \left\{ DPO3_{(2,1)} \right\} \\
\{ FRO4_{(3,3)} \} &= \left\{ DPO4_{(3,3)} \right\} \\
\{ FRO5_{(3,3)} \} &= \left\{ DPO5_{(3,3)} \right\}
\end{align*}
\] (3.1)

The natural question we need to ask here is, how well does this architecture accommodate to change and knowledge dynamics? For as we focus on and identify fresh

\(^2\)The subscripts on the design(n) matrix elements represent the level of the design(n) along the row
Figure 3-1: Design Trace for the Design of Human Knowledge
exists in reality, then as per our $\text{FRO5}_{(3,3)}/\text{DPO5}_{(3,3)}$ design(n), the new set of concepts and propositions that we induce (out of our novel experiences), these have to be integrated with the knowledge that we already possess. If there exists a contradiction between the two sets of knowledge, then we have to resolve the contradictions by referring back to reality as the standard of reference. We thus design experiments to emphasize the predictive inconsistency between the two.

We ought to remember time and again that we are not omniscient; that our senses are not picking up signals from every single existant at every single instant. Thus at any given time, the knowledge that we possess is built upon a limited amount of experiences. The certainty that we possess is built upon this limited context. Whenever we come across an existent that does not fit in into our existing architectures, we then have to decide between the two. We thus conduct carefully engineered experiments (again a problem of design) to decide between the two sets of concepts and propositions that we have. And depending upon what results we get, we might have to modify our existing knowledge architectures. For what we possess now is more comprehensive, more complete. And it reflects our above $\text{FRO3}_{2,1}/\text{DPO3}_{2,1}$ holistic design. In the next section we look more closely at the various kinds of changes we might have to make in our knowledge architectures. But here let us briefly ask a fundamental question: given the hierarchic nature of human knowledge, is change likely at all levels in a homogeneous sense? Is our knowledge a constant shifting “heraclitian” flux at every level? Or is there a gradation along the hierarchy? Or to put it differently, are there differences in the rates of change across the knowledge hierarchy? Let us look at the various levels of the knowledge hierarchy to see what we might expect. At the bottom rungs of the knowledge hierarchy we find concrete instances such as the bird Tweety we encountered in our introductory chapter. In the middle layers we find the laws and propositions of various disciplines (such as the Newtonian principles of mechanics, or Mendels laws of genetic inheritance). At the highest levels we find the metaphysical axioms that identify the fundamental nature of existence (such as the Aristotelian axioms of existence and identity). Let us observe now the rates of change. Tweety the bird is constantly suffering the onslaught of change. It hatches from its egg, it grows, it dies. But the concept bird that subsumes Tweety remains relatively constant. Of course, the concept too could suffer change, especially when it gets redefined based on a more precise and refined ousia (οὐσία) or the essential characteristic. At a higher level are the laws such as Mendel’s laws. Of course Mendels laws too could suffer change in the sense of becoming more precise and refined (based on larger and more precise observations. So already we notice a couple of things about this rate of change:

1. That there is a decreasing rate of change as we go higher up the knowledge hierarchy.

2. That the changes are such that the new knowledge subsumes the old context (definitely the context of concretes, and sometimes the context of the earlier theory too) in the sense that the change is towards greater precision. Thus Einsteins laws subsume Newtonian mechanics when the velocity of the object has yet to approach the speed of light.
Figure 3-2: The Rate of Change along Knowledge Hierarchies

At the highest levels of our knowledge hierarchy are our metaphysical axioms of existence and identity. These are so fundamental that they remain constant. Thus if we were to plot the rate of change along the knowledge hierarchy, we would arrive at the diagram shown in Fig. 3.2. It is this differential rate of change (and at the fundamental level, the constancy) that provides the continuity of conceptual architectures between various stages of development, regardless of the incessant change. The issue of knowledge continuity is crucial in trying to understand conceptual evolutions. It is these continuing conceptual structures that provide us the context to even detect that change has occurred. And this continuity (as we just saw) is an outcome of the knowledge hierarchy. If we fail to recognize the knowledge hierarchy, we also fail to recognize the knowledge continuity. We shall take up the specifics about knowledge dynamics in the next section. For the moment let us now look at the alternate design(n)s that were proposed for knowledge.

Given the above objectivist design(n), we may now contrast this with the default intrinsicist/subjectivist design(n)s. The coupled intrinsic design(n) is as follows:

- **FRI**: In order to grasp reality, we need to know the universal forms that exist intrinsically within the object to be grasped.

- **DPI**: Use the method of intuition whereby reality writes its universals upon impressionable minds.

Cast against the true nature of the problem (i.e., the left-hand side of equation 3.1),
we have a coupled design(n):

$$\begin{align*}
\{ & FRO3_{(2,1)} \} = \left[ \begin{array}{ccc}
\oplus & O & O \\
O & O & O \\
O & O & O \\
\end{array} \right] \{ DPI \} \\
\{ & FRO4_{(3,3)} \} \equiv \\
\{ & FRO5_{(3,3)} \}
\end{align*}$$

(3.2)

As we mentioned earlier, in this framework, the problem of knowledge dynamics simply does not arise. For knowledge exists independent of us, as universals in a changeless domain. Here we do not encounter the need for proper methods of knowledge synthesis nor analysis.

The subjectivist approach in contrast recognizes the need for knowledge consistency, but not the need for ground support. Also the need for knowledge consistency is not in a rigourous sense (i.e., all of knowledge), but in a rather compartmentalized, limited context. The coupled subjectivist design(n) is as follows:

- **FRS1**: We need ways and means by which we may synthesize our internal noumenal world(s).

- **FRS2**: We need ways and means by which we may analyse the consistency of our noumenal world(s).

- **DPS1**: Subjectivist methods of world (view) creation.

- **DPS2**: Subjectivist methods of world-view analysis.

The design(n) mapped against the true nature of the problem presents a coupled architecture:

$$\begin{align*}
\{ & FRO3_{(2,1)} \} = \left[ \begin{array}{ccc}
\oplus & O & O \\
O & \oplus & O \\
O & O & O \\
\end{array} \right] \{ DPS1 \} \\
\{ & FRO4_{(3,3)} \} \equiv \\
\{ & FRO5_{(3,3)} \}
\end{align*}$$

(3.3)

Since most modern and post-modern philosophies are Kantian and subjectivist in nature, the result is the modern balkanization of human knowledge. Thus epistemologically, one of the poorly developed methods of research is the inter-disciplinary research. In a world with human needs becoming more and more large-scale and global, and human knowledge becoming more and more fragmentary, specialized, and therefore isolated, we find ourselves unable to comprehend not just the operative laws in nature; we are fundamentally at a loss to understand and control our own man-made creations. Examples include the Three Mile Island Reactor accident, Union Carbide disaster in Bhopal, O-ring failure in the Challenger space shuttle, the New York City Blackout, etc. The fundamental fault in this regard lies with modern philosophy in perpetrating the above described coupled design(n)s. What is desperately needed today is a proper epistemology that brings back the renaissance perspective that reality is an integral whole: thus human knowledge that describes it also ought to be an integral whole.
3.3 The Thagardian Archstand: Background

In his seminal work, *Conceptual Revolutions* [Ref. 3.1], Prof. Paul Thagard has provided us a sorely needed rejoinder to Prof. Kuhn's historical sketch regarding the "irrationality" of the revolutionary changes that visit science (and scientists) in general from time to time. Reviewing this work, Prof. Rattansi writes [Ref. 3.1]:

Thomas Kuhn's *The Structure of Scientific Revolutions* (1962) familiarized a wide public with the idea of revolutions as the inevitable result of the development of 'normal science.' It also made them seem irrational, the outcome of processes which were compared to Gestalt-switches and religious conversions. Thagard seeks to reinstall reason at the core of science.

As we saw earlier, at the core of the issue is the problem of knowledge continuity. For without it, we fall into the Kuhnian trap of "religious" or "total" conversions or "belief" revisions.

While we will have reason to disagree with Prof. Thagard (which we shall soon see), the data he provides is quite valuable. But let us first consider what Prof. Thagard has to say regarding conceptual dynamics [Ref. 3.1]:

If a conceptual system consists of a network of nodes with links..., then conceptual change consists of adding or deleting nodes and links. The most common changes involve the addition of:

1. New concept nodes. Example: new concept *ostrich*.
2. New kind links between concept nodes. Example: canaries are reptiles.
3. New rule links between concept nodes. Example: canaries have color blue.

Changes often come in groups rather than in isolation. For example, addition of the concept node for ostrich will be accompanied by addition of a kind link from *ostrich* to *bird*, addition of instances links from *ostrich* to various object nodes representing particular ostriches, and addition of rule links between *ostrich* and concept nodes such as *long-legged*.

But not all additions and deletions are equally serious. The most dramatic changes involve the addition of new concepts as well as new rule and kind links, where the new concept and links replace ones from the old network. We can distinguish replacement of a conceptual system from simple deletions and additions if some of the previous links remain, indicating that the new concepts and links have a place in the new system similar to those in the old system. Although a conceptual revolution can involve dramatic replacement of a substantial portion of a conceptual system, continuity is maintained by the survival of links to other concepts.
Thus in the Thagardian view, the links are the primary; and it is these links that provide the sense of continuity. Concepts may come and go; but the “scaffolding” that the links provide, remain. Now on its own, this is rather arbitrary. Here the fundamental is being missed. It is the hierarchy of concepts and the resulting hierarchy of propositions that provides the differential rate of change across the knowledge architecture. And it is this differential rate that acertains that “some” of the concepts remain, hence “some” of the links remain. It is the concepts that are the primary. Links are links relating these concepts.

In general, knowledge architectures change whenever nodes and links within given knowledge architectures are added or deleted (Fig. 3.3) [Ref. 3.1]. According to Prof. Thagard, there are nine hierarchically organized (in the order of increasing significance) degrees of conceptual change (Fig. 3.3) [Ref. 3.1]:

1. Add a new instance: Here we identify a new instance. Thus for example, that Shamu is a whale (Fig. 3.3(a)).

2. Add a new weak rule: Thus for example, that there are some whales to be found in the Arctic ocean (Fig. 3.3(b)). This is a “particular” statement.

3. Add a strong rule: Thus for example, that all whales eat sardines (Fig. 3.3(c)). This is a “universal” statement.

4. Add a new part relation: Here we decompose and add a new part-relation. Thus for example, that all whales have spleens (Fig. 3.3(d-e)).

5. Add a new kind-relation: Thus for example, that the dolphin is a kind of a whale (Fig. 3.3(f)).

6. Add a new concept: Until now we have merely added or deleted links along existing conceptual hierachies. But now we can add a new concept, for example the concept of a narwhal, a cetacean that has an ivory tusk (Fig. 3.3(g-h)).

7. Collapse part of a kind-hierarchy: Thus for example, Newton “abandoned the Aristotelian distinction between natural and unnatural motion” (Fig. 3.3(i)).

8. Branch Jumping: This involves shifting a concept from one branch of the tree to another. For example, the Copernican theory reclassified earth from a special sui generis status to that of a planet (Fig. 3.3(j-l)).

9. Tree Switch: Here the very organizing principle of a hierarchical tree changes. Thus Darwin reclassified the natural order from one that was based on similarity (in form, behaviour), to one that was based on evolutionary links (Fig. 3.3(m-n)).

Except for the first and the last items (where incidently, the knowledge hierarchy is implied: the bottom-most rung (add new instance) versus changing the overall architecture), those in between seem rather arbitrary in the significance hierarchy. There is simply no context provided to evaluate the so called “significance or severity
Degrees of Conceptual Change:

1: Add a new instance: Shamu is a whale

2: Add a new weak rule: Some whales can be found in arctic ocean.

3: Add a strong rule: All whales eat sardines.

4: Add a new part relation: All whales have spleens (decomposition).

5: Add a new kind-relation: Dolphin is a kind of a whale.

6: Add a new concept: Narwhal

7: Collapsing part of a kind-hierarchy, abandoning a previous distinction.

8: Branch jumping: shifting a concept from one branch of the tree to another.

9: Tree Switching: Changing the organizing principle of a hierarchical tree.

Figure 3-3: Degrees of Conceptual Change [Source: 3.1]
of conceptual change." The question is, severe with respect to what? For example, it is purely arbitrary to say that adding a new concept is more severe than say adding a new kind relation. One could easily imagine instances where just the opposite is the case. For example, if the context is that of a slave, adding the kind relation, "those forced into slavery are also human (and thus have certain inalienable rights)," could potentially gain him his freedom. Whereas, adding a new concept into his vocabulary such as say "penguin" gains him practically nothing. As stand-alone changes, it is impossible to produce a hierarchical order between them. It is within a given context (i.e., the knowledge hierarchy) that these changes have different impacts. Depending upon where along the hierarchy, the nodes and links are added/deleted, we have different degrees of knowledge dynamics (Fig. 3.4). It is knowledge hierarchy that provides the context for judging the significance of conceptual change: specifically at what level is the change being introduced. Having said this, nevertheless, the above classification, is an excellent description of the kinds of changes one might see. Furthermore, as we shall see, Prof. Thagard does subscribe (although implicitly) to this hierarchy based approach to judging conceptual change. In the next section we consider Lavoisier's theory of oxidation that overthrew Stahl's phlogiston theory.

3.3.1 Lavoisier's Theory of Oxidation

During the years 1772 and 1778, there took place a revolution in the chemistry of combustion which in turn became the basis for modern chemistry. The accepted view
on combustion then was by Georg Stahl's. In 1723, Stahl put forth the phlogiston theory which held that compounds such as sulphur burn because they contain the inflammable element phlogiston (Fig. 3.5(a)). Describing the Phlogiston theory, Prof. Thagard writes [Ref. 3.1]:

In contrast to our current view that metals combine with oxygen to produce metallic ores (oxides), the phlogiston theory said that ores are simpler than metals. When ores are heated, the phlogiston from the burning charcoal combines with them to produce metals. Calcination, such as the rusting of iron, is the result of the metals losing their phlogiston. Respiration has the effect of removing phlogiston from the body into the air. so that if air is saturated with phlogiston by combustion or breathing, further respiration becomes impossible. Stahl discussed, for example, the philosopher's stone of the alchemists. His conceptual system suggests that the convertibility of compounds like lead into mixts\(^3\) like gold should be merely a matter of getting the right combination of principles.

In 1772, Lavoisier made note of two crucial observations that were not explainable by the phlogiston theory (Fig. 3.5(b)):

1. That metallic calxes (or salts) when placed in acids effervescence. This suggested that air was contained within the calx.

2. That objects gain weight during calcination (i.e., oxidation).

Depicting this on the conceptual system of Fig. 3.5(b), Prof. Thagard writes [Ref. 3.1]:

Air, calxes, and metals are three kinds of substances. Curved lines represent the rules that effervescing calxes (later: oxides) produce air and that metals gain weight when they become calxes. To explain these rules, Lavoisier conjectures that calxes might contain air. forming the rule labeled "contain?" The dotted lines show an explanatory relation, indicating that the hypothesis that calxes contain air might serve to explain both why calxes effervescence and why metals gain weight in calcination....Lavoisier did not possess a theory of oxygen at this point, only a vague idea that the presence of air in minerals might explain some puzzling phenomena.

In September of 1772, Lavoisier conducted experiments on the combustion of sulphur and phosphorus, confirming that in combustion they too gain weight Fig. 3.5(c). Regarding these experiments, Prof. Thagard writes:

In January of 1774 Lavoisier published a detailed report [in which he discusses his] experiments involving calcination, combustion, and dissolution of earths such as chalk that support the existence of an "elastic flexible

\(^3\)A "mixt" is a body that consists of simple principles, whereas a compound may consist of mixts [Ref. 3.1]
Figure 3-5: Conceptual Revolution in Chemistry (1772-1778) [Source: Ref. 3.1]
fluid" ir. chalk, alkalis, and metallic calxes. He is not at all clear whether this fluid is part of air or air itself: he speaks of an "an elastic fluid of a particular kind which is mixed with air", but suspends judgement on the relation of this fluid to atmospheric air.

At this stage Lavoisier is not clear what the nature of the "elastic" fluid is. Commenting on this, Prof. Thagard writes:

[At this point, Lavoisier] still lacked a clear idea of what that air is. Moreover, he was not yet confident that he had a sharp alternative to the phlogiston theory of Stahl, saying of calcination and reduction that the present state of knowledge did not permit deciding between his phlogiston interpretations and that the opinions of Stahl was perhaps not incompatible with his. In 1776 Lavoisier admitted in correspondence that he often had more confidence in the ideas of the eminent British phlogiston theorist Joseph Priestly than in his own.

By 1777, Priestly had isolated the element oxygen, naming it the "dephlogistacted air". But Lavoisier saw in it that "pure and eminently respirable air" responsible for the anomalies [Ref. 3.1]:

"...that the principle that unites with metals during their calcination, that increases their weight and constitutes them in the state of calxes, is nothing but the portion of air the most salubrious and the most pure."

Summarizing the conceptual changes (Fig. 3.5(d)), Prof. Thagard writes [Ref. 3.1]:

Lavoisier listed four kinds of air: eminently respirable, atmospheric, fixed, and mophette (nitrogen). Lavoisier described how combustion and calcination are subject to the same laws and how they can be given a common explanation by considering pure air as the real combustible body... Although he criticised the followers of Stahl for failure to isolate phlogiston, and suggested that the existence of an alternative hypothesis might shake the system of Stahl to its foundations, he did not feel sufficiently sure to reject the phlogiston theory out of hand. He concluded by saying: "In attacking here the doctrine of Stahl, it is not my purpose to substitute for it a rigourously demonstrated theory, but only an hypothesis which seemed to be more probable, more in conformity with the laws of nature, and one which appeared to involve less forced explanations and fewer contradictions".

By 1783, Lavoisier had a fully complete theory. Summarizing this finale (Fig. 3.5(e)), Prof. Thagard writes [Ref. 3.1]:

---

*Note here the usage of Aristotle's axiom of identity in the law of contradiction format. Here one may see that it is the highest level abstractions that is forcing the conceptual systems at lower levels to shift, while itself remaining constant.*
By 1783, however, the gloves were off, and Lavoisier demolished the doctrine of Stahl in his "Reflexions sur le Phlogistique". Using the term he coined in 1780, Lavoisier now referred to pure or eminently respirable air as principle oxygine. Lavoisier's position is presented in his opening paragraphs:

In the series of memoirs that I have communicated to the Academy, I have reviewed the chief phenomenon of chemistry; I have stressed those that accompany the combustion and calcination of metals, and, in general, all the operations where there is absorption and fixation of air. I have deduced all these explanations from a simple principle, that pure air, vital air, is composed of particular principle belonging to it and forming its base, and that I have named principe oxygine, combined with the matter of fire and heat. Once this principle is admitted, the chief difficulties of chemistry seemed to fade and dissipate, and all the phenomena were explained with an astonishing simplicity. But if everything is explained in chemistry in a satisfactory manner without the aid of phlogiston, it is from that alone infinitely probable that this principle does not exist.

This quotation shows that Lavoisier had completely rejected the phlogiston theory, but his concept of oxygen clearly differs from ours in that oxygen gas was not itself an element. Rather, it was a compound of principe oxygine (as for Stahl, "principle" here means basic and original) and of the matter of fire and heat [i.e., caloric]...[Thus] air rather than the combustible substances, was the source of heat. The substance caloric was accepted until the development of kinetic theory of heat in the next century.

Prof. Thagard then uses the above material to build his theory of conceptual change.

3.4 Thagardian Cognitivist Archstand on Conceptual Revolutions

Setting the broad mandate for a theory of conceptual change, Prof. Thagard writes [Ref. 3.1]:

1. Development by Discovery: The theory should "describe the mechanisms by which discoverers of new conceptual systems such as Lavoisier can build up their new systems by generating new nodes and links."

2. Replacement by Discover: "The theory must also explain how the new conceptual system can come to replace the old, as the oxygen theory replaced the phlogiston theory."
3. Development & Replacement by Instruction: "Finally, the theory must provide an account of how additional members of the scientific community can acquire and accept the newly constructed conceptual system."

We will consider the first two issues. The third issue is fairly straightforward; for having brought back rationality once again into the profession of science, we can now presume the method of rational discourse to effect the social change.

Before we take up the above issues, let us contrast the Thagardian versus the Kuhnian approach. Critiquing Kuhn's *gestalt* theory of scientific change, Prof. Thagard writes [Ref. 3.1]:

...Kuhn [Ref. 3.5] likened conceptual change to gestalt switches of the sort that occur in perceptual phenomena like the Necker cube... He used the fact that Priestly never accepted the oxygen theory as evidence for the incommensurability of paradigms.

Thinking of changes as gestalt switches...makes it hard to see how conceptual change can take place. We saw that Lavoisier did not completely make the shift over to the new framework until around 1777....Looking only at Stahl's conceptual system and Lavoisier's final one, it does appear that something like a gestalt switch has occurred. But understanding how Lavoisier got to his fully developed view requires consideration of the smaller steps that took him through the stages of 1772, 1774, and 1777.

Simple... gestalt theories also have difficulty accounting for conceptual change in those who follow the discoverer in accepting a new conceptual framework. In the chemical revolution, radical conceptual change took place not only in Lavoisier, but in most chemists and physicists. By 1796 most scientists in Britain as well as in France had adopted the oxygen theory (Perrin Ref. 3.6; McCann Ref. 3.7). Priestly, who maintained the phlogiston theory until his death was exceptional. Kuhn suggested [Ref. 3.5], following a remark of Planck, that a revolutionary scientific view only triumphs because its opponents die. But Perrin's thorough chronicle shows that in the twenty years after 1775 virtually the entire scientific community converted over to Lavoisier's new system.

One of the last major proponents of the phlogiston theory was Richard Kirwan, who published a defense of the phlogiston theory in 1784. The French translation of Kirwan's *Essay on Phlogiston* was published in 1788 with responses by Lavoisier and his collaborators interspersed among its chapters (Kirwan Ref. 3.8). These responses are fascinating, because they show Lavoisier and others systematically criticizing the attempts by Kirwan to defend the phlogiston theory. Rational dispute was clearly possible, and by 1792 Kirwan also had gone over to the oxygen theory. Radical conceptual change is not easy, but it is not impossible either.

These are refreshing advances over the Kuhnian framework that has until recently placed such a crippling mental gridlock on any rational discourse on how change occurs
in our knowledge architectures. And as we shall see, this has significant implications regarding the research on innovation, including technological innovation.

In a different context, Prof. Thagard elaborates on the cognitive perspective that he is bringing to the problem at hand:

Kuhn's claims about scientific revolutions have caused great consternation among philosophers of science because of their apparent implication of irrationality. Kuhn so stressed the dramatic and noncontinuous nature of scientific change that transitions in scientific theories or "paradigms" took on the appearance of cataclysmic, nonrational events. According to Kuhn's early statements, later moderated, a scientific revolution involves a complete change of standards and methods, so that rational evaluation of competing views using external standards appears impossible. He even said that when one theory or "paradigm" replaces another, scientists work in a different world.

Although Kuhn's emphasis on revolutionary change was an antidote to the simplistic models of the logical empiricists, a finer-grained theory of revolutionary change than Kuhn presented need not succumb to irrationalism. To develop such a theory, however, we need tools different from both the formal ones of the logical empiricists and the vague historical ones of Kuhn...[Using the cognitive science perspective]...we can begin to characterize the structure of conceptual systems, before, during, and after conceptual revolutions; and we can investigate the cognitive mechanisms by which conceptual changes occur.

There is a fundamental epistemological reason why Kuhn held that "when one theory or "paradigm" replaces another, scientists work in a different world." And it has to do with the Kantian analytic/synthetic dichotomy that prevades modern philosophy of science. We touched upon this in our section on subjectivism. We shall take it up in section 3.5. It will help us clarify some of the deeper issues about the role of concepts in the context of change.

In the next subsections we take up the various issues regarding the role of a proper theory of scientific change.

3.4.1 Development of Conceptual Systems by Discovery

How might one explain the conceptual process by which a system such as Lavoisier's oxygen theory was formulated? Lavoisier had to come up with new concepts and formulations that explain both the earlier existents (such as the phenomenon of combustion) as well as the anomalies such as the weight gain.

\^5"Exemplified by such philosophers as Carnap and Hempel, the logical empiricists used the techniques of modern formal logic to investigate how scientific knowledge could be tied to sense experience. ...[they] emphasized the logical structure of science rather than its psychological and historical development."[Ref. 3.1]
Prof. Thagard asserts that in general there are three ways by which revolutionary discoveries are made, namely, the data-driven, the explanation based, and the coherence-driven. These may be mapped into our framework of the archstand (Chapter 1, Section 2.4) wherein we spoke of the inductive, the abductive and the integrative approaches. These approaches were partly formulated based upon Prof. Thagard's work. But partly they were arrived at independently (i.e., the inductive and the abductive\textsuperscript{6} modes.

Although Prof. Thagard does not speak of an external perspective, it is easy to see that one needs an integrated external perspective from which one might challenge the existing architectures. For if it were otherwise; if it were a diffuse set of facts and propositions, one would be hard-pressed to challenge a well entrenched framework. The premise here is that human knowledge in a given domain is an integral whole (or tends towards that state). This is so because the reality that it tries to model is an integral whole\textsuperscript{7}. Now the fundamental problem of innovation is to cause a shift in the given knowledge architectures. Thus in order to cause this shift, the innovator needs an integrated external perspective from where to architect this shift. Thus the fundamental problem of innovation is then to establish an integrated external perspective (or the archstand) to the current knowledge architectures in order to systematically innovate in a given domain. It is from this context that we view the three modes of discovery that Prof. Thagard induces out and explicates.

To recollect once again the basic three approaches to finding an archstand (Fig. 3.6):

1. Methods that are data-driven or inductive (based on inductive generalizations from observations and experiments) (Fig. 3.6(c)). Thus the evidence provided by the weight gain by sulphur and metals is used to gather a critical external perspective on the current framework. It might be stated in Lavoisier's own words as:

   "..my purpose [was] to [formulate] an hypothesis which seemed to be more probable, more in conformity with the laws of nature, and one which appeared to involve less forced explanations and fewer contradictions."

The hypothesis or the archstand here is the hypothesis of the principe oxygine which went thru the following transformations:

(a) 1772: "vague idea that the presence of air in minerals might explain some puzzling phenomenon [Ref. 3.1]."

\textsuperscript{6}C.S. Pierce's abductive mode [Ref. 3.12] is a mixture of the inductive and the deductive modes of thought. This again is our interpretation. See Lavoisier's use of the effervescence evidence as explained in text that follows

\textsuperscript{7}In the final section in this chapter we elaborate on this by integrating it with the theory of knowledge we set out with in the beginning.
Figure 3-6: Framework of the Archstand

(b) 1774: "that the principle that is united to metals during their calcination, which increases their weight, and which constitutes them in the state of a calx. is... the air itself undivided [Ref. 3.1]"

(c) 1777: "that the principle that unites with metals during their calcination, that increases their weight and constitutes them in the state of calxes, is nothing but the *portion of air the most salubrious and the most pure* [Ref. 3.1]"

(d) 1783: "I have deduced all these explanations from a simple principle, that pure air, vital air, is composed of a particular principle belonging to it and forming its base, and that I have named *principe oxygene* [Ref. 3.1]"

Note how the perspective changes from a vague notion to that of a definitive statement.

2. Methods that are explanation driven or abductive (abduction is a mixture of inductive and deductive reasoning) (Fig.3.6(d)). Here the discovery process is partly deduced from what we already know; and partly it is based on data we are trying to explain. Thus Lavoisier uses the fact that oxides effervesce when placed in an acid, along with the existing phlogiston-type theory (that during combustion, phlogiston is being given up) to hypothesize that perhaps air contained in the oxide is being given up. Thus in August of 1772, Lavoisier wrote: "An effervescence is nothing but a disengagement of the air that was
Figure 3-7: Modes of Discovery \[Source: \text{Ref. 3.1}\]

3. Methods that are coherence driven or integrative (Fig. 3.6(e)). For example, “the major impetus to discovery” for Copernicus and Einstein “came from incoherencies in existing views [Ref. 3.1]”

Fig. 3.7 gives the summary of Prof. Thagard’s findings regarding the various modes of discovery for nine major conceptual revolutions (taken from diverse fields). Fig. 3.8 gives the summary of the conceptual changes that took place. In some of these cases, the single concept that gets added is indeed the archetypal for the revolution. For example, in Lavoisier’s case, it was the hypothesis of oxygen that provided the integratively archetypal. In the case of Darwinian revolution, it was the Mathusian principles on the struggle for existence that abductively provided Darwin the needed archetypal namely, the principle of natural selection.

In the context of 1960s development of Plate Tectonics, it was Alfred Wegener’s earlier (1915) theory on Continental Drift (based on approximate coastline fit between various continents, supported by paleontological and geological evidences) that provided part of the external perspective to challenge the shrinking earth theory. The other part, of course was the seafloor spreading hypothesis that Harry Hess and Robert Dietz induced out of the information that the explorations by U.S Navy provided re-
<table>
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<tr>
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<tr>
<td>Lavoisier</td>
<td>oxygen</td>
<td>phlogiston</td>
<td>metal APO calx</td>
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<td></td>
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<td>gold AKO element</td>
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<td>Darwin</td>
<td>natural selection</td>
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<td>humans AKO animal</td>
<td>kind: historical</td>
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<td>Geology</td>
<td>plate</td>
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<td>Copernicus</td>
<td></td>
<td></td>
<td>earth AKO planet</td>
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<tr>
<td>Newton</td>
<td>force of gravity</td>
<td>vortex</td>
<td>motion AKO state</td>
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<tr>
<td>Einstein</td>
<td>relativistic mass</td>
<td>aether</td>
<td>mass and energy equivalent</td>
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<td>Quantum</td>
<td>light quantum</td>
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<td>wave and particle related</td>
<td>indeterminacy</td>
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<td>Behaviorist</td>
<td>mind</td>
<td></td>
<td>thinking AKO response</td>
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<td>Cognitivist</td>
<td>information</td>
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<td>thinking AKO computation</td>
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Note: AKO means "becomes a kind of." APO means "becomes a part of."

Figure 3-8: Kinds of Conceptual Change [Source: Ref. 3.1]
garding the mid-atlantic ridge. F. Vine and D. Matthews then used the sea-floor spreading hypothesis to predict magnetic anomalies parallel to the oceanic ridges. Confirmation of this in 1965 led to the rigourous development of Plate Tectonics and the rejection of the cooling and shrinking earth theory.

The Copernican revolution was essentially based on an epistemological archstand regarding the need for simplicity in description as idealized by Aristotle (in his uniform circular motion postulate) but lacking in the Ptolemaic confusion of epicycles. As Prof. Thagard remarks [Ref. 3.1]:

Although the details of Copernicus's discovery are not known, it seems that it is better characterized as coherence-driven than as data-driven or explanation-driven. To be sure, Copernicus wanted better accounts of the observations of the sun and moon, but most of all he wanted accounts that did not violate Aristotelian principles of uniform circular motion. For Copernicus, the Ptolemaic system had an internal contradiction, exalting the perfect motion of the heavenly spheres while postulating epicycles and other deviations from perfection.

The Newtonian revolution is far more difficult to incorporate into an archstand approach mainly because Newton did not leave behind a trace of his conceptual development during the eighteen months (mid-1680s) it took him to produce his magnum opus, the Principia. However the fundamental role that differential mathematics (which he developed during the 1660s) plays in the Newtonian system building makes one suspect that this perhaps was his organizing principle.

Einstein had a clearly formulated integrative (or coherence-based) archstand, namely, the rejection of the concept of simultaneity [Ref. 3.1]:

In his autobiography, Einstein said that [the special theory of relativity] resulted from a paradox that he had constructed at the age of sixteen about what would happen if he were to pursue a beam of light with the velocity c. Intuitively, he would expect to perceive the beam of light at rest, since he would be traveling at the same speed, just as two cars on the highway at the same speed seem to each other not to be moving. But Maxwell's equations did not allow the possibility of an electromagnetic field at rest. The key to resolving the tension between Maxwell's laws and the thought experiment was to reject the standard concept of simultaneity that presupposes a concept of absolute time. On the new account, every reference body has its own particular time, so nothing is absolutely at rest.

Hal Hargreaves in his work Visions and Discoverers writes on a similar theme [Ref. 3.9]:

In his autobiographical notes, [Einstein] modestly recalls that at this age, sixteen, he hit upon the vision that would eventually blossom into special relativity. "If I pursue a beam of light with the velocity c (velocity of light in a vacuum), I should observe such a beam of light as a spatially oscillatory electromagnetic field at rest. However, there seems to be no such thing..."
In regard to Fig. 3.8, note the “relative significance” of the “concepts being added” and that of say “tree-jumping.” For example, in the Lavoisier case, the addition of the concept oxygen is far more significant than say the branch jumping that a metal is now “a part of” (APO) calx. For the former is more fundamental; the latter is derived from the first. We make this point in order to bring home the point we made earlier (in connection with Fig. 3.3) regarding the importance of specifying the context of knowledge hierarchy in judging the significance of the conceptual change. Thus Prof. Thagard’s own data contradicts his theoretical hierarchy regarding “severity of conceptual change” we had analysed in section 3.3. This will prove of crucial value when considering the dynamics of change in the next section. For by grasping that knowledge hierarchies have a definite structure, we are able to see more clearly how exactly the change is being wrought.

To summarize the various archstands we have encountered so far (Fig. 3.9):

1. **Louis Sullivan (Inductive):** Design(n) principle (that designs(n) follows function) induced from multitude of examples of design(n)s in nature (Fig. 3.9(a)).

2. **Lavoisier (Inductive/Abductive):** Hypothesis of oxygen to replace phlogiston (Fig. 3.9(b)).

3. **Darwin (Abductive/Inductive):** Principle of natural selection abduced using Malthusian struggle for survival principle (Fig. 3.9(c)).

4. **Plate Tectonics (Abductive/Inductive):** Hypothesis of the spreading seafloor partly abduced from Wegner’s Continental Drift theory; also partly induced out of U.S. Navy data about the mid-atlantic ridge (Fig. 3.9(d)).

5. **Copernicus (Integrative):** The epistemological ideal of simplicity in nature (specifically that of Uniform Circular Motion) (Fig. 3.9(e)).

6. **Newton (Abductive):** Perhaps the differential calculus that Newton developed (Fig. 3.9(f))?  

7. **Einstein (Integrative):** The rejection of the concept of simultaneity (Fig. 3.9(g)).

In addition we have also included the Thagardian archstand ((Fig. 3.9(h)) in bringing to bear the Cognitive Revolution in psychology while formulating his theory of conceptual revolutions as against the Kuhnian gestalt-switch theory. We think that this framework cuts right through to the core of much that is flawed in the current Kuhnian gestalt-switch approaches. We will have more to say on this in the coming sections.

### 3.4.2 Replacement by Discovery

We now consider the problem of how one conceptual system replaces an existing one? In Fig. 3.5(g). Prof. Thagard provides a framework by which these changes could take places [Ref. 3.1]:
Figure 3-9: The Archstarks of Various Revolutions
Stage [g-1] shows a conceptual system 1 with links to other concepts. Stage [g-2] shows a new conceptual system partially formed in the background, also with links to other concepts. That the other concepts are linked to both systems runs counter to Kuhn's suggestion that in scientific revolutions the world changes. Although Priestley and Lavoisier had very different conceptual systems in 1777, there was an enormous amount on which they agreed concerning many experimental techniques and observations. Thus even revolutionary conceptual change occurs against a background of concepts that have relative stability. Finally, stage [g-3] shows system 2 fully developed and coming into foreground so that system 1 fades back. It does not disappear: Lavoisier could talk phlogiston-talk when required.

Now clearly what is meant by the term "background of concepts" is fundamentally the concepts and propositions that lie at a hierarchical level above the level of change. For example, the concept substance (or "body" in Stahl's framework still refers to the same set of entities in Lavoisier's conceptual hierarchy. Its subdivisions have suffered change: but it itself points to the same overall set of existents both Stahl and Lavoisier were trying to classify.

Also in a more fundamental sense, when Prof. Thagard mentions that there is concurrence in the "experimental techniques" and the "observations" that result, this is agreement at the two extremes of the knowledge hierarchy. Concurrency in experimental techniques refers to the epistemological agreement at the highest levels. Concurrency regarding the data is again because of the metaphysical "primacy of existence" principle that scientists agree upon as a principle of science. So from the examples that Prof. Thagard suggests, it is probable (at least in an implicit) sense that he does see the "background of concepts" as those at the higher rungs.

Now this does not mean that concepts at the levels lower to the perturbed conceptuals always has to suffer change. This does not have to be true. For example, if these lower-level concepts belong to a different branch. they could continue to enjoy their tenure with relative stability.

Now we come to the crucial issue of the innovation axis. Earlier we posited that the innovation axis is the core set of concepts which when it suffers a shift, shows up as an architectural shift. Again we have evidence for it in the data that Prof. Thagard provides. For as we just saw, the oxygen principle does not cause changes in the existing knowledge architecture, everyday and all over. The changes are rather localized within certain levels. In trying to more carefully model the world at large, the oxygen premise clashes with certain regions of the existing knowledge architectures, specifically the nodes and links derived from the phlogiston premise. And in the context of our understanding the phenomenon of combustion, the phlogiston premise was a central premise. It was thus part of the core set of concepts used to explain many of the then known chemical and biological transformations (such as why respiration becomes increasingly harder in a closed room). In general, the centrality of a premise may be judged based upon how many other propositions subsequently refer back to it for support. Given the centrality of a certain premise, one may also deduce
that it would be situated close to the shortest conceptual path from the highest abstractions (in a given knowledge context) down to the ground perceptuals. For given the tapering architecture of the knowledge structures, to be maximally connected, a premise has to be closely located to this shortest path. Thus explicitly mapping the knowledge architectures of an existing domain can be an extremely valuable exercise. For knowing the explicit structure of the knowledge architecture provides us clues regarding what kind of changes would be radical. We now have a metric on the potential changes that are radical versus things that are not.

We shall take up these issues in our next chapter on the Non-Euclidean revolution. But for now we go back to our earlier problem regarding the fundamental epistemological reason why Prof. Kuhn held that "when one theory or "paradigm" replaces another, scientists work in a different world." Also what the acceptance of such a world-view does to any research that is focussed on understanding and bringing about change in a directed fashion. The thesis here is that unless the flaw in the Kuhnian framework is grasped in its epistemological roots, it places a fundamental limit on any rational discourse on understanding and bringing about change in a directed fashion. To understand the Kuhnian flaw, one has to disect the Kantian analytic/synthetic dichotomy from which it derives.

3.5 The Analytic/Synthetic Dichotomy as central to the Kuhnian Worldview

Regarding the current state of modern philosophy, Prof. Hobhouse writes [Ref. 3.10]:

..philosophy itself, once the appointed guardian and advocate of reason, shares in the irrationalist tendency. We shall end by defining man as the irrational animal, and the modern philosopher as his prophet.

One of the fundamental epistemological errors in modern philosophy is the Kantian analytic/synthetic dichotomy. This dichotomy is accepted by every contemporary philosopher—pragmatist, logical positivist, analyst, existentialist alike [Ref. 3.11].

Historically, the analytic/synthetic dichotomy has its roots in Plato’s theory of universals. It was however given its explicit modern form by Immanuel Kant. According to Kant, the whole of human knowledge is fractured into two non-intersecting kinds of propositions. This divide is based on the manner by which the propositions are validated. Analytic propositions are validated by analysing the meaning of its building blocks. One thus validates $2 + 2 = 4$ by showing that its negation would imply a self-contradiction: $1+1+1+1 \neq 1+1+1+1$. Synthetic propositions such as "Salt dissolves in water," cannot be validated by a similar analysis of its constituent parts. The predicate (dissolves in water) cannot be logically deduced by considering the definition of the subject (Salt: crystalline compound NaCl). The proposition is the synthesis of the subject with something outside its definitional scope. Thus Kant

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8For a fuller discussion on this please refer to Prof. Peikoff in Ref. 3.11.
asserts that it is not a self-contradiction to deny that salt dissolves in water. It is perhaps factually wrong, but not so on grounds of logic. Analytic propositions, it is claimed, are necessary—because by linguistic convention we make them so; their denial is self-contradictory and therefore unimaginable (example, a square-circle). Synthetic propositions on the other hand, are merely contingent; they could have been otherwise (salt remains intact in water). Analytic propositions are supposed to be a priori (independent of experience); synthetic propositions, a posteriori (dependent upon experience). Analytic propositions are supposed to be non-ontological; they have nothing to do with reality and its experience, and are therefore immune from it. Synthetic propositions are factual; they pertain to reality and its "blooming, buzzing, confusing" experience. Now this Kantian divide between the analytic and the synthetic, cuts right thru the whole of human knowledge and renders it dysfunctional. The implications are enormous. It is therefore important to discover why Kant made such a fundamental distinction.

The root of the problem goes back to Plato’s intrinsic theory of concepts we saw earlier. The fundamental question is the following: what does a concept include? Does it include all or only certain essential characteris.ics of the existents it subsumes? And of these, does it include only those characteristics currently known, or also those yet to be discovered? It is in the context of this last question that current evolutionary epistemologists (such as Prof. Kuhn) cash-in on the analytic/synthetic dichotomy.

For example, when we define man as a rational animal, do we include only his rationality and animality, while excluding his anatomical, physiological and psychological characteristics (known and those yet to be discovered)? When we define common salt as the crystalline compound NaCl, do we include only its physical form and composition while excluding its behaviour (known and those yet to be discovered)? When we define table as furniture consisting of flat slab fixed on legs, do we include only its genus class and its form differentia while excluding its function (known and those yet to be discovered)? According to Plato’s intrinsic theory, concepts designate the essence or the ousia (οὐσία) that exits in a supernatural world of universals. And existents in our natural world are but a poor reflection of these essentials. For they exist alloyed with other accidental material corruptions that are in constant flux. Our senses perceive this changing reality, while our thoughts partake in the abiding world of universals. Thus according to Plato, the concept of an entity includes its essential characteristics, while excluding its accidentals. This exclusion is the fundamental historic error that has given rise to the devastating analytic/synthetic dichotomy.

The modern nominalists (Kant, Dewey) have unquestioningly accepted the above distinction with peripheral modifications. To understand these modifications, one needs to consider the basis by which we as humans, make the distinction between the essential and the accidental. Plato answers that it is by an act of intuition that one attains direct knowledge from the world of universals. The moderns reject such intuitive insights as being mystical and thus implicitly subjective. They reject the implicit version and substitute instead, an explicit version: the essences are not obtained by some mystic insight, but are arbitrary and socially determined; they have no objective basis in reality. People have been using concepts in a certain way, and that is that. One does not ask how and why these concepts were formed to mean
such and such. There is no objective basis to answer such questions, they say. This then is the secularized modern version of Plato’s theory with its erroneous distinction between the essential and the accidental intact.

In order to correct this error, one needs a proper theory of concept formation. We need the how and why of concept formation. And this is what Rand has provided for the first time in her work *Introduction to Objectivist Epistemology* [Ref. 3.19]. According to Rand, concepts are not arbitrary social constructs. They have an objective basis. If we had unlimited capacities (mental/physical) to observe the universe in all its vast complexity, we simply would not need any concepts whatsoever. An omniscient mind has no need for concepts. It is because we have limited capacities that we face the need to reduce the vast array of observables into manageable units. This is the fundamental reason why we form concepts. Concept formation is an individual conscious act. It is an inductive process that involves both an act of differentiation as well as integration. We first mentally differentiate a group of concretes from all other known concretes, based on observed similarities. Two or more things are similar if they have the same characteristic but perhaps to different degrees. A piece of chalk, a ruler, a pointer...they all have the attribute length, but in varying degrees. Having observed this common characteristic, we then integrate the similarities into a new mental unit: the concept length. We do this by a process of measurement omission. Existents that possess length must have some length, but may have any length. Concept-formation is complete when we assign a perceptual symbol “length” to the concept. The concept now applies to any existent (past, present or future) that possesses (in any measure) the characteristic length. We now have a basis for grasping the immense expanse of the universe and bringing it down to our reach. When in future, we encounter a new entity that possesses length, we do not have to engage in concept formation afresh: but simply apply the concept already induced. This process applies to all concepts no matter how abstract. For example, when we form the concept chair for the first time, we differentiate two or more chairs from other objects on the basis of their similar shapes. Their actual shapes may vary between them, but they have something in common: a seat with four legs and a back.

We have answered the why and the how of concept formation. We are now in a position to correct the false alternative between analytic v/s synthetic (or essential v/s accidental). Earlier we asked, what does a concept include? Both intrinsicist’s as well as subjectivist’s have answered that it includes only the defining essential characteristic. The truth of the matter is that a concept includes all the characteristics of the units it integrates. The function of a concept is unit reduction. But having successfully abstracted out the common defining characteristic between various units, one does not exclude out the remaining characteristics. Otherwise, the very purpose of unit-reduction is lost in the process. The concept man includes not just his rationality and his animality, but also his anatomical, physiological and psychological characteristics (known and those yet to be discovered). The concept salt includes not just the physical form and composition, but also its behaviour (known and those yet to be discovered), such as “that it dissolves in water”. The concept table includes not just the genus class and its form differentia but also its function (known and those yet to be discovered). One may ask, why include those yet to be discovered? Because a con-
cept means the existents it subsumes, and existents follow their identity, regardless of the state of human knowledge. We may make radical changes in our conceptual and propositional hierarchies depending upon our changing context. But the reality it refers back to remains what it is. Contrary to Kuhn, it does not move lock-step with our changing world-views. It has its own independent identity. It is up to us to make sure that our conceptual models are in lock-step with the world at large, not the other way round. It is in trying to do this “lock-step”, to more closely model the world at large that we change our conceptual architectures (and not in any “gestalt” holistic sense: but in a localized manner that retains the higher level conceptual context along the knowledge hierarchy). And in trying to more closely model the world at large, we may redefine the essential v/s the accidental. Thus our current definition of say “common salt” may be radically different from say what the ancient Arab merchants used a thousand years ago (in the context of their salt trade). For we have a better grasp of the underlying chemical constitution.

Fundamentally, the widest conceptual abstraction, namely, the concept thing, has not changed since whenever it was first formulated. It still enjoy the same breadth. What has been augmented is the knowledge of the things underneath this highest level abstraction.

With this background, we are now in a position to consider the problem of change induced from observations that conflict with a given theory (such as Lavoisier’s weight gain in metals during combustion).
3.5.1 Dynamics of the Theory/Observation Dichotomy

A theory is a set of abstract integrated principles. A theory is validated by how well it corresponds with reality. This implies the logical application and reduction of a theory to match observations. Observation is an act of recognizing and noting a fact or occurrence often involving measurement with instruments. When a theory/observation dichotomy arises, what could be the causes for it, and what needs to be done? There could be the following cases:

1. The theory is wrong and needs to be changed. Here is an example: Samuel Johnson and James Boswell were once talking about Berkely’s theory of the nonexistence of matter. Boswell recounted that he was convinced on the bishop’s theory being false, but found it impossible to refute it. Johnson immediately walked up to a large nearby stone, struck his foot against it and fell down exclaiming—“I refute it thus”.

2. The logical application of the theory might be wrong and needs modification. When Newton’s prediction of the moon’s perigee was half the observed value, some proposed a modification on the inverse square law. Considering the seriousness of the change, others held on. It took 60 years to show that the problem was not with the theory, but with its mathematical application.

3. The observation is inaccurate and needs better precision. When D.C. Miller tried to repeat the Michelson-Morley experiment, he found that his observations were at variance. It took all 25 years to bring about the necessary precision.

4. The observations are fundamentally coupled with the theory; i.e., they are “theory-laden,”; thus they refer to incommensurate world-views. A fundamental “gestalt” or paradigm shift is needed to bring about a resolution.

The first three approaches are the normal ways by which a theory and the observations that validate it are brought to agree. The last alternative is the Kuhnian/Kantian approach and is based on the analytic/synthetic dichotomy. For example, in the context of discovery of the planet Uranus [Ref. 3.5], Kuhn first engages in an elaborate equivocation between the act of “seeing” and “interpreting”. He then focusses on the changes brought about when a given entity gets reclassified (e.g., Uranus identified first as a star, then as a comet, then as a planet). As a nominalist, by redefining the essential characteristic of a certain entity, he now thinks he deals with a different entity. He then combines these two and calls the total a metaphysical paradigm shift. Kuhn is wrong. The entity remains the same (uranus remains uranus whether interpreted as a star or as a planet). The change is at the epistemological level (not metaphysical); given the greater context of human knowledge, the distinguishing characteristic of the entity has undergone change.

3.5.2 Implications in the Context of Innovations

Rejection of the Kuhnian approach has major benefits in the context of research on innovation. Firstly, it prompts us to demystify the innovation process (especially of
the radical kind; for there currently exists a stultifying self-imposed taboo on questions regarding radical innovations) by asking for the cognitive processes by which innovations are wrought. As Prof. Thagard rightly points out, revolutionary conceptual changes are not "gestalt" switches; they do have an underlying cognitive process. Having set forth the conceptual patterns by which change is wrought, one may then look for underlying structures (those such as our hypothesis about the innovation axis and the archstand induced axis-shift). Or the fact that change is happening within the broader context as established by the higher level conceptual architectures. Finally in the context of management of innovation, rejection of the Kuhnian framework opens up significant research frontiers such as what fundamentally does it mean to assert "management of innovation?" One answer could be that fundamentally it means mapping the conceptual architectures of existing knowledge domains, locating its innovation axis, strategically locating innovative archstands, then projecting the vision of what it means to sufficiently shift the innovation axis in order to realize greater economic value. We take this up in our next section on the archstand Theory of Innovation.

3.6 The Archstand Theory of Innovation

In the Archstand Theory of Innovation (as described above in Sec. 3.4.1) we said that the innovator needs an external perspective, an integrated external perspective from where one might challenge the existing knowledge architectures. And we defined this as the archstand. We also held that without such an integrated perspective, the innovator would be hard-pressed to challenge a well entrenched framework. Thus if the perspective the innovator brings to bear is a non-integrated diffuse set of facts and propositions, the prospects for engaging and successfully challenging the existing architectures is rather dim. The various operative causes for this might be as follows:

1. In a sociological sense, a meaningful dialogue with the proponents of the entrenched framework is difficult because each non-integration is perceived as a major weakness.

2. In a more fundamental psycho-epistemological sense, the innovator himself is unable to see what the change entails.

3. In a still more fundamental metaphysical/epistemological sense, the reality that the innovator is trying to model more accurately is in fundamental disagreement with any non-integrated frameworks. For the reality is an integrated whole. And the human knowledge of it also ought to be integrated.

It is this last fundamental cause we wish to explore here. The premise here is that human knowledge in a given domain is an integral whole (or tends towards that state). This is so because the reality that it tries to model is an integral whole. Here we elaborate on this by integrating it with the theory of knowledge design(n) we set out with in the beginning.
In our knowledge design(n) we set our $DPO_{32}$ to perform this integrative function. This then is the fundamental reason why the innovator needs an integrated perspective. For otherwise it is impossible to make good on the Baconian dictum, that "nature to be commanded must be obeyed." For context, the full third-level design is recalled as below:

- $FRO_{3(2,1)}$: In order to accommodate to the need that what we have does indeed correspond with reality, we need cognitive ways and means to analyse and validate our knowledge.

- $FRO_{4(3,3)}$ (Problem of the Proof (or Vertical Support)): We need to ultimately ground the propositional structures with our sensory data.

- $FRO_{5(3,3)}$ (Problem of Consistency (or Horizontal Support)): We need to check the integrity or knowledge consistency between existing knowledge structures, thus keeping the full context. We need to keep the full context because reality is an integral whole. Reality is an integral whole in the sense that everything is causally connected with everything else (some mediately, some immediately). Our knowledge thus has to reflect this integrity. Vertical support is mainly concerned with piece-meal validity. Horizontal support makes our knowledge architectures holistic.

- $DPO_{3(2,1)}$: Methods of Knowledge Analysis.

- $DPO_{4(3,3)}$: Proof (both inductive as well as deductive) as the method of Knowledge Reduction.

- $DPO_{5(3,3)}$: Knowledge integration as the method of keeping the full context.

Analytically, we may represent the above design(n) as follows (repeat of Eq. 3.1)$^9$:

\[
\begin{align*}
\begin{bmatrix}
FRO_{3(2,1)} \\
FRO_{4(3,3)} \\
FRO_{5(3,3)}
\end{bmatrix}
&= \begin{bmatrix}
\oplus_2 & O & O \\
O & \oplus_3 & O \\
O & O & \oplus_3
\end{bmatrix}
\begin{bmatrix}
DPO_{3(2,1)} \\
DPO_{4(3,3)} \\
DPO_{5(3,3)}
\end{bmatrix}
\end{align*}
\]

(3.4)

Here is some evidence to support the validity of the above design(n) (in a post-hoc sense), that human knowledge in a given domain is an integral whole (or tends towards that state). In a scientific context one may witness this in the attempts to unify diverse phenomenon under a common ruberic. Thus for example the integration by Maxwell of the two fields, electricity and magnetism under the single explanation, electromagnetism. In an industrial/economic context one may witness the same phenomenon in two pradoxically opposing trends (but actually reflecting the larger reality more truely). One trend that is noticed (often by business historians such as Alfred Chandler [Ref. 3.13]), the "vertical integration" achieved by firms

$^9$The subscripts on the design(n) matrix elements represent the level of the design(n) along the row
such as Standard Oil and GM. The other trend is the more recent need to balance the centrality (as imposed by the first trend) by "franchising" and de-centralizing away the various human activities in order to better reflect the autonomy of the human condition [Ref. 3.14-15]. This set of "conflicting" trends (that attempts to achieve a proper balance) too is an example of the proper “conceptual integrations” being made regarding the true nature of the human condition (i.e., upholding the impossibility of any “centralized” decision-making that negates human volition) versus the need to coordinate and do the proper integration of labor involved in an industrialized economy. The second “decentralizing” trend is of a more recent origin and could be traced to the cognitive revolution in psychology (especially to the two publications, one by George Miller [Ref. 3.16] and the other by Card et. al. [Ref. 3.17]) and how it transformed the computer industry with the beginings at Xerox. Parc. [Ref. 3.18]. The proper balance between these two needs has yet to be achieved. But the continuing revolution in Cognitive Science is a promising trend towards a final resolution.

To summarize the archstand theory, we see the problem of innovation as follows (Fig. 3.11):

- \( FR_1(1,0) \): The human knowledge in a given domain is an integral whole (or tends towards that state). The problem of innovation is to cause a fundamental shift in the given knowledge architecture/design trace. To cause a fundamental shift, the innovator has to shift the core set of concepts and propositions (i.e., the innovation-axis) of the domain knowledge/design trace. In order to architect this shift, the innovator needs an integrated external perspective from which to architect this shift.

- \( DP_1(1,0) \): The fundamental solution to the problem of innovation is to establish an integrated external perspective (or the archstand) to the current knowledge architectures in order to systematically innovate in the given domain.

When we decompose our design(n) to see what it really means in order to achieve it, we come up with the following set of sub-functions

- \( FR_2(2,1) \): In order to establish the archstand, we need to conceptually map the existing (domain and allied) knowledge architectures and practice design traces. At a minimum, one ought to do this at least for the major trunks of the innovation-axis.

- \( FR_3(2,1) \): We need to discover viable archstand(s) (i.e., those that are conceptually central enough to perturb the innovation-axis).

- \( FR_4(2,1) \): We need to shift the innovation-axis of the existing knowledge architecture/design trace.

- \( FR_5(2,1) \): We need to shift the innovation-midwife of the existing knowledge architecture/design trace.
Figure 3-11: The Archstand Theory of Design for Innovation
• \( DP_2 (2,1) \): In order to meet the \( FR_2 (2,1) \) requirement, our design (n) is to basically engage in the process of mapping the knowledge/design trace hierarchies. This might involve interviewing, scanning for recent developments, collating and conceptually organizing the essential information in a manner that reveals the underlying architecture. We might be able to use some of the AI tools in this regard. However most of these tools are fundamentally flawed in the same sense as Prof. Kuhn’s “gestalt-switch” theories. Both approaches share in the analytic/synthetic dichotomy. The fundamental tools we need in this regard are not AI-based tools and techniques, but cognitive tools and techniques. We will have more to say on this in our final chapter.

• \( DP_3 (2,1) \): In order to meet the \( FR_3 (2,1) \) requirement, we study the explicated knowledge hierarchies and see if they might yield a viable archstand based on our archstand discovery methods (i.e., the inductive, the abductive, and the integrative). We judge the viability of the archstand based upon whether it can dislodge concepts and propositions along the existing knowledge hierarchies.

• \( DP_4 (2,1) \): Having found a viable archstand, we then shift the innovation-avis by substituting the results based on the archstand and deleting those that do not fully conform to reality as the standard.

• \( DP_5 (2,1) \): Having shifted the axis, one then systematically traces the consequences through the rest of the knowledge architecture/design trace. Contrary to the “incrementalists” and the “regular innovators,” this phase is not something made-to-order for the “organizational man” with no demands on human creativity. The truth of the matter is that it is from improper integrations in these outliers that one might expect future archstands. Or in general there is really nothing called “incremental innovations”. Every “innovation” by its nature is radical: what is different though is the level at which these changes are being made. But the mechanics of innovation remain exactly the same.

We may represent this final design (n) as follows:

\[
\begin{align*}
\left\{ FR_2 (2,1) \right\} & = \left[ \oplus_2 \ 0 \ O \ O \right] \left\{ DP_2 (2,1) \right\} \\
\left\{ FR_3 (2,1) \right\} & = \left[ + \ \oplus_2 \ O \ 0 \right] \left\{ DP_3 (2,1) \right\} \\
\left\{ FR_4 (2,1) \right\} & = \left[ + \ + \ \oplus_2 \ 0 \right] \left\{ DP_4 (2,1) \right\} \\
\left\{ FR_5 (2,1) \right\} & = \left[ + \ + \ + \ \oplus_2 \right] \left\{ DP_5 (2,1) \right\}
\end{align*}
\]  

(3.5)

The design (n) is a lower-triangular design (n) and represents temporal sequencing. Thus if one is unable to find a viable archstand, one cannot proceed any further. One instead has to go back and re-iterate.

This concludes our archstand theory of design/design (n) for innovation. In our next chapter we take up the explication of the Euclidean/non-Euclidean world.
3.7 Conclusion

In this chapter, we first considered the fundamental psycho-epistemological reasons why knowledge structures have a certain hierarchical architecture. We then investigated into the manner in which philosophy considers the fundamental problem of the design(n) of human knowledge. We then considered the problem of dynamics in knowledge hierarchies.

Having set the stage from a philosophic perspective, we then looked more closely at the conceptual revolutions as described by Prof. Thagard in his seminal work on *Conceptual Revolutions*. In contrast to Prof. Thagard, we asserted that the “innovative significance” of a certain conceptual change has to be judged not on a “stand-alone” basis, but in relation to the overall knowledge architecture. Having stated this, we then looked at the data Prof. Thagard provides to see that in fact his data does agree with our contextual approach rather than his (implicit) “stand-alone” approach.

We then contrasted the Thagardian cognitivist approach versus the Kuhnian nominalist approach. We saw the various ways and means by which the Thagardian approach more closely fits the data of scientific revolutions rather than the crippling “gestalt-switch” approach as set forth by Prof. Kuhn.

In the context of our main thesis regarding design(n) for innovation, we then collected insights regarding the archstand of the various revolutions. We also elaborated on the concept of the Innovation Axis and its central location.

We then returned to our philosophic discussion of the Kuhnian world-view and framed it in the analytic/synthetic framework as set forth by Immanuel Kant. Having demolished this flaw, we then sketched what it all means for serious research on innovation and the management of innovation. This then is our anti-Kuhnian archstand. In retrospect one notices that an archstand is essentially a visionary statement of what things ought to be. Our anti-Kuhnian archstand is indeed such a visionary statement for future research on innovation.

Having sketched the underpinnings of the theory, we then finally explicated the Archstand Theory of Design for Innovation. As per our design process trace, we abstracted out the fundamental problem of innovation as the problem of establishing an integrated external perspective from where to architect the innovation axis-shift. We then systematically decomposed this to show what it really means to achieve this in real-life. We then set up the design(n) which could achieve these sub-requirements. In Chapter 5 (on design for innovation) we illustrate various facets of this framework with historical examples. But in our next chapter we map out the Euclidean/non-Euclidean worldviews.

3.8 References


Chapter 4

Non-Euclidean Geometries

4.1 Introduction

This chapter is a case study of the revolution that happened 150 years ago in the discipline of geometry. It will help us ground some of our elementary notions from the last chapter. We start with a historical sketch of these developments. We then systematically structure the Euclidean Geometry and explicate the intricate relationships that exist between conceptual and propositional hierarchies.

Having set the stage, we then show the manner by which the Non-Euclidean Geometries were discovered. Apart from the drama that is involved, it also provides enough context to study the conceptual shift that took place. We then map out some of the salient components of both the hyperbolic geometries as well as the elliptic geometries. All of this provides rich context for us to make some extremely valuable generalizations.

4.2 Historical Background to Euclid

Western traditions on Geometry started on its course when Thales (640-546 B.C.) of Miletus (one of the seven wise men of ancient Greece) travelled to Egypt and brought back with him insights on how to re-map and stake out property boundaries that were constantly inundated by the flooding Nile. Pythagoras (580-500 B.C.) too visited the temples of Egypt to learn first hand from temple priests, their closely guarded geometric secrets [Ref. 4.1]. These secrets were empirical rules that the Egyptians had gathered over countless years of monument building and battling with the Nile. For example, analysis of the Moscow papyrus shows that the Egyptians knew the following algebraic formula for the volume of the frustum of the pyramid at least as far back as 1580. B.C. [Ref. 4.2]:

$$V = \left( a^2 + ab + b^2 \right) \frac{h}{3}$$  \hspace{1cm} (4.1)

An example on the papyrus shows how to use this formula. Thus if the base dimension $a = 4$, the top dimension $b = 2$, and the height $h = 6$, then the papyrus says:
"Combine this 16 with this 8 with this 4, and one obtains 28. Take \( \frac{1}{3} \) of 6, giving 2; take 28 twice, giving 56. You see, it is 56, you have it correctly."

Yet despite such practical knowledge, the Egyptians were not able to systematize and bring their various results into an integrated conceptual framework. And this is what the Greeks achieved between the years 600-300. B.C. For by 300 B.C, the Geometric system was so well articulated that Euclid could systematize it into a single master treatise, the Elements, consisting of 5 common notions (or general axioms), 5 postulates, 131 definitions, and 465 propositions. The 5th postulate of course is the parallel postulate which for 2000 years suffered various unsuccessful attempts to be deduced within the rest of the system. And it was only in the 1820s that it was granted the full status of a postulate, affirming Euclid's insight into the true nature of the problem.

The whole Geometry is organized into thirteen books that covered the following topics [Ref. 4.3]:

- Books I and II: Plane Rectilinear Geometry
- Book III: The Circle
- Book IV: Regular Polygons
- Book V: The Theory of Proportions
- Book VI: Plane Geometry with Proportions
- Books VII-IX: Irrational Lines
- Book XI: Elementary Solid Geometry
- Book XII: The Method of Exhaustion
- Book XIII: Regular Polyhedra

The text we shall analyse is the English translation of Heiberg's text by Sir Thomas L. Heath [Ref. 4.4]. Prefacing the text, Sir. Heath writes:

It is one of the noblest monuments of antiquity; no mathematician worthy of the name can afford not to know Euclid, the real Euclid as distinct from any revised or rewritten versions which will serve for schoolboys or engineers...¹

...so long as mathematics is studied, mathematicians will find it necessary and worth while to come back again and again, for one purpose or another, to the twenty-two-centuries-old book which, notwithstanding its imperfections, remains the greatest elementary mathematics that the world is privileged to possess².

¹Preface to first edition.
²Preface to second edition
These are well-deserved comments from a sympathetic voice. But the most touching comments are from those who played historical roles in advancing geometries contrary to Euclid. Thus Sommerville who systematized the nine non-Euclidean geometries writes [Ref. 4.5]:

...so great was [Euclid's] prestige that he acquired, like Aristotle, the reputation of infallibility, a fact which latterly became a distinct bar to progress....

It seems impossible to suppose that Euclid ever imagined [the 5th postulate] to be self-evident, yet the history of the theory of parallels is full of reproaches against the self-evidence of this "axiom." Sir Henry Savile referred to it as one of the great blemishes in the beautiful body of geometry; D'Alembert called it "l'écueil et le scandale des éléments de Géométrie."

[But] modern research has vindicated Euclid, and justified his decision in putting this great proposition among the independent assumptions which are necessary for the development of the euclidean geometry as a logical system.

With this brief introduction, we now look into the structure of Book I of Euclid.

### 4.3 Elements (Book-I): The Conceptual Hierarchy

Book I consists of 5 common notions, 5 postulates, 23 definitions and 48 propositions. The propositional hierarchy is deductively organized in the center of Fig.4.1. At the bottom left is placed the 23 definitions organized from top to bottom to show that these are the terms that the geometry will be using after demonstrating their existence. The crucial definitions d1-d4, d10 and d23 are organized bottom to top (on the right side) with interpretive figures attached.

The conceptual hierarchy between the various terms is as shown at the bottom of the figure. Geometric forms may be divided up into atomic (or monadic) forms and composite forms. The "point" is merely an epistemological "notation" for our representational convenience. But the "line" and "angle" does have physical basis. The non-Euclidean revolution was based on an integrative archstand that arose out of the impossibility of proving the 5th postulate and led to the re-definition of the atomic units of the system, namely, the line and the angle. Changing the definition of these two concepts immediately leads to changing the architecture of every single composite unit. The non-Euclidean archstand is shown in the bottom right of Fig. 4.1. Even today the physical basis of the atomic units is still unclear. But this does not matter much to geometers. For their main concern is developing the various logical possibilities.

The propositional hierarchy (as shown in the diagram) would be build out of (and therefore remain true to) the underlying conceptual hierarchies. Much of the two-thousand year struggle with the parallel postulate could be traced to the circularities that people ran into on account of the vagueness of Euclid's definition of the atomic
1. P32: Exterior/Interior Angle Theorem (Fig. 4.2g): In any triangle, if one of the sides be produced, the exterior angle is equal to two interior and opposite angles, and the three interior angles of the triangle are equal to two right angles.

2. P45: Area Application Theorem: To construct, in a given rectilineal angle, a parallelogram equal to a given rectilineal figure.

3. P47: The Pythagorean Theorem (Fig. 4.2h): In right-angled triangles, the square on the side subtending the right angle is equal to the squares on the sides containing the right angle.

The following are some of the commonly known propositions (proofs diagrammed in Fig. 4.2 left column):

1. P4: The Side-Angle-Side (SAS) Theorem (Fig.4.2 (a)).

2. P8: The Side-Side-Side (SSS) Theorem (Fig. 4.2 (d)).

3. P26: The Angle-Side-Angle (ASA) Theorem (Fig. 4.2(f)).

The propositions, postulates, and common notions that are directly premised by each theorem is indicated in the bottom bar in each box (of Figs. 4.2(a-h)). At the bottom right of each inset is the inset identifier (such as a, d, f for the above three theorems).

Postulate 5 is the parallel postulate and asserts that:

That, if a straight line falling on two straight lines make the interior angles on the same side less than two right angles, the two straight lines, if produced indefinitely, meet on that side on which are the angles less than the two right angles.

Postulate 5 is brought to bear for the first time only when proving proposition 29 which asserts that:
Figure 4-1: Euclid's Elements
Figure 4-2: Euclidian/Non-Euclidean Geometries
A straight line falling on parallel straight lines makes the alternate angles equal to one another, the exterior angle equal to the interior and opposite angles, and the interior angles on the same side equal to two right angles.

Let us now use this architecture for process mapping in a real problem context: the construction of the gnomon (a vertical-staff sun-dial used to measure time). As we mentioned in chapter 1, every problem solving context may be broken into the following generic stages:

1. Problem Perception.
2. Problem Abstraction.
3. The Creative Leap.
4. Design Synthesis.
5. Design Analysis.
6. Design Implementation.

Let us now demonstrate the design-trace along the conceptual architecture (Fig. 4.2) using the example of the gnomon. Suppose like the Greeks, we had the need to coordinate and organize our activities through the day. For otherwise we find it impossible to coordinate between people and between events. This is problem perception. We then study this and abstract out the need to measure time: we need some means to measure time across a given day. We recognize that at the most general level, we have the passage of the sun across the sky to mark the day. The problem now is to break this interval into smaller units. From our experience, we recall that trees and other upright structures create moving shadows as the sun passes above. We then make the creative connection between the market need and our technological experience, the creative leap, namely to mark time using moving shadows made by vertical elements. Now we are in the realm of geometry. We need a means to construct a vertical line or a gnomon. Proposition 12 (P12) tells us how to construct a gnomon, a line perpendicular to another. We analyse its validity by tracing it back to the fundamentals. So this is the design trace. We have used the architecture to help us locate ourselves on the cognitive plane in a rather simplistic problem solving context. But this in principle is what is happening in every problem solving context, be it the solving of high-school geometry or the design and analysis of United States Constitution. We might not follow the exact chronological order as depicted above; for each of us have our own unique problem solving styles. But when everything is said and done, there will be a logical conceptual order between the various problem solving elements as captured along the design trace. The real power of the “St. Louis” type design-arch is its generic property, whether in demonstratating high-school geometry, or while brain-storming about advanced engineering design problems. In other words, this framework is scalable. It is scalable and generic because it is fundamental to the human condition, the need to abstract and create concepts.
We now analyse the role of various items in the above knowledge architecture. Aristotle had a major influence on Euclid in organizing the Geometric subject matter. Sir Heath summarizes this influence while elaborating on the architecture of the Euclidean geometry [Ref. 4.4]:

Every demonstrative science, says Aristotle, must start from indemonstrable principles: otherwise the steps of demonstration would be endless. Of these indemonstrable principles some are (a) common to all sciences, others are (b) particular, or peculiar to the particular science; (a) the common principles are the axioms, most commonly illustrated by the axiom that, if equals be substracted from equals, the remainders are equal. Coming now to (b) the principles peculiar to the particular science which must be assumed, we have first the genus or subject-matter, the existence of which must be assumed, viz. magnitude in the case of geometry, the unit in the case of arithmetic. Under this we must assume definitions of manifestations or attributes of the genus, e.g. straight lines, triangles, deflection, etc. The definition in itself says nothing as to the existence of the thing defined: it only requires to be understood. But in geometry, in addition to the genus and the definitions, we have to assume the existence of a few primary things which are defined, viz. points and lines only: the existence of everything else, e.g., the various figures made up of these, as triangles, squares, tangents, and their properties, eg., incommensuability etc., has to be proved (as it is proved by construction and demonstration)...We have then clearly distinguished, among the indemonstrable principles, axioms and definitions. A postulate is also distinguished from a hypothesis, the latter being made with the assent of the learner, the former without such assent or even in opposition to his opinion.....[this] seems to fit Euclid’s Postulates fairly well, not only the first three (postulating three constructions), but eminently also the other two, that all right angles are equal, and that two straight lines meeting a third and making the internal angles on the same side of it less than two right angles will meet on that side.

...Proclus\(^3\) remarks that, according to Aristotle and the geometers, axiom and common notion are the same thing.

Aristotle discusses the indemonstrable character of the axioms in the *Metaphysics*. Since all the demonstrative sciences use the axioms, the question arises, to what science does their discussion belong? The answer is that, like that of Being (*οὐσία*), it is the province of the (first) philosopher. It is impossible that there should be demonstration of everything, as there would be an infinite series of demonstrations: if the axioms were the subject of a demonstrative science, there would have to be here too, as in other demonstrative sciences, a subject-genus, its attributes and corresponding axioms; thus there would be axioms behind axioms, and so on

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\(^3\)Major 5th century A.D commentator on Euclid

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continually. The axiom is the most firmly established of all principles. It is ignorance alone that could lead any one to try to prove the axioms; the supposed proof would be a *petitio principii*. If it is admitted that not everything can be proved, no one can point to any principle more truly indeemonstrable. If any one thought he could prove them, he could at once be refuted...

Let us now focus on the following definitions in order to validate the conceptual hierarchy in Fig. 4.1./Ref. 4.4:

- **d1-Point**: A point is that which has no part.

- **d2-Line**: A line is a breadthless length.

- **d3-Connection between line and a point**: The extremities of a line are points.

- **d4-Straight Line**: A straight line is a line which lies evenly with the points on itself.

- **d13-boundary**: A boundary is that which is an extremity of anything.

- **d14-figure**: A figure is that which is contained by any boundary or boundaries.

- **d19-Rectilineal figures**: Rectilineal figures are those which are contained by straight lines. *Trilateral* figures being those contained by three, *quadrilateral* those contained by four, and *multilateral* those contained by more than four straight lines.

- **d20-Trilateral figures**: Of trilateral figures, an *equilateral triangle* is that which has its three sides equal, an *isosceles triangle* that which has two of its sides alone equal, and a *scalene triangle* that which has its three sides unequal.

As we saw in our introductory chapter, there are two basic kinds of hierarchies: kind-hierarchies and part-hierarchies. The former makes the primary causal (final, formal, efficient) identification; the later the secondary causal (material) identification. Thus when we define man as a rational animal, we are focusing on the efficient cause (i.e., that faculty in man as an "efficient agent" that differentiates him from other animals in dealing with the problem of existence). In doing so we are using kind-hierarchies (such as the genus animal). On the other hand we may describe man as an entity materially consisting of part-hierarchies such as arms and wrists and fingers. The first is a definition, the second is a description. In the context of geometry, the causal identification is on the basis of the formal cause, i.e., the family of forms that the geometric entities belong to. Thus compositions such as circles and triangles and rectangles belong to the family of figures, for they are closed forms. Composites such as the arrangement of parallel lines—these are non-figures, for they are open forms.
Monads are the ultimate part-hierarchies; the manner in which these are defined could fundamentally alter the geometries. Euclid's conceptual hierarchy is thus clear: (forms(composites(figures, non-figures), monads)). The details are as shown in the Fig. 4.1.

By studying Euclid's propositional knowledge structure (Fig. 4.1 center) we notice the following:

1. That the propositional structure is definitely hierarchical and pyramidal in nature. Thus the density of propositions increases as we move from the more general to the more specific results.

2. That certain of these propositions are far more centrally located and richly networked than others.

3. That these centrally networked propositions are also more richly vertically networked.

4. That most of the axioms and common notions are immediately put to use right at the very top.

5. That there are more outliers as we move down the propositional hierarchy.

By studying Euclid's conceptual knowledge structure (Fig. 4.1 bottom center) we notice the following:

1. That the composites are defined based upon the manner in which certain key monadic elements in the composition are related. Thus the equilateral triangle is defined by equality in magnitude of the lines that compose the triangle. This is true of every other composite definition. Thus the conceptual hierarchy is actually based on two sub-hierarchies, the monadic tree playing a key role in the definition of the composite tree. This type of overall conceptual dependency between two trees is not something new. For we briefly saw this in our study of cascade innovations. "Any" slight change along one can have a major impact on the other. If we instead choose to plot the knowledge hump as a single architecture, we would have to place all of the monadic architecture right within the innovation axis, and often at the very top.

Here is another way to look at it. In the above context, the defining monadic elements proved to be of central importance in shifting the composite structure. Such is also the relationship between the conceptual hierarchies and the propositional hierarchy. Conceptual hierarchies identify the fundamental nature of the entities in the given system under study; propositional hierarchies are used to build the behaviour of the overall system. Conceptual hierarchies provide the elements out of which the system is built. Thus the analogy is as follows: the monadic elements are to the composite entities as the conceptual hierarchy is to the propositional hierarchy.
2. At the very top of the propositional hierarchy, the propositions and postulates are primarily about the translation and bisection of the monadic elements. As we traverse down the propositional hierarchy, we starts dealing with the composite elements (from the more general to the more specific). We thus see that the propositional hierarchy and the conceptual hierarchy, these are intimately related, and go hand in hand.

4.4 The Non-Euclidean Revolution

Having seen the above conceptual architectures, the question now arises, where exactly is the non-Euclidean archstand located; is it in the conceptual hierarchy, or is it in the propositional hierarchy? And the answer is that it could be either. One has to recognize that the conceptual hierarchy is a kind of propositional hierarchy that identifies the fundamental nature of entities. Thus when we define circles as “figures” of a certain kind, it in itself is a proposition too. It is thus possible to make a composite knowledge architecture of a system; one that contains both the nature and behaviour of the entities under study. And if one were to do that, one would see that the conceptual hierarchy is central to the innovation axis itself. It thus constitutes the core of the innovation axis. And a radical shift often involves addition and deletion of nodes and links at this innovative core.

But from an historic perspective, the archstand is often discovered at the propositional levels before it percolates into the central core. Thus the first insight towards the non-Euclidean revolution was in regard to perturbing the parallel postulate. Thus we have the initial perturbations by Saccheri in 1733; and the more rigorous ones by Gauss, Bolyai and Lobachevsky (in the 1820s). This gave birth to the Hyperbolic geometry which ruled for approximately 40 years as the sole non-Euclidean geometry. It was only later-on that the conceptual hierarchies (and especially the monadic elements) were explicitly identified as the root location where the changes were implicitly being made by Reimann (founder of the elliptic geometries in 1860s), Cayley and Klein (1860s-1920s).

We now look into some of the patterns of knowledge dynamics created by the hyperbolic non-Euclidean revolution. In Fig. 4.2 we map the propositions that either suffer (-shaded circles) or do not suffer (-plain circles) knowledge dynamics based upon their location on the knowledge hierarchy with respect to the archstand induced shift (by Gauss, Bolyai and Lobachevsky in the 1820s) of the propositional hierarchy. Here the non-Euclidean archstand is fundamentally impacting the propositional hierarchy at the levels below the 5th-postulate perturbation. Thus propositions such as the SAS (P4), the SSS (P8), the ASA (P26); these do not change in their assertions (although the assertions are about different kinds of triangles). But propositions such as the Exterior/Interior Angle Theorem (P32), and the Pythagorean Theorem (P47); these are fundamentally altered (Fig. 4.2(m)). For example, the Angle Sum theorem in

\[ \text{\footnote{However, this might all change given the material presented here; we could witness a deliberate approach that uses the knowledge architecture to strategically loate the necessary archstand.}} \]
hyberbolic geometries asserts that the angle sum of every triangle is less than 180 degrees. The first row in table at the bottom (Fig.4.2(n)) shows the analytical form that the pythagorean theorem takes. The sides of the triangle are respectively a, b, and c. The corresponding angles are A, B, and C. The last row is the angle sum theorem (here the angle A is the external angle). The central column contains the Euclidean results (also called Parabolic); the left column contains the Reimann's elliptic results; the right column, the hyperbolic results. We again see that the changes are happening at a given level in a given context. Above the perturbation level, there is practically no change in the results. But below the perturbation level, things fundamentally change.

4.5 Conclusions

The above analysis provides us corroborative evidence for what we have been asserting, namely, that:

1. That human knowledge has a hump-shaped hierarchical architecture, stout at the base, tapering towards the top.

2. That this tapering architecture creates a central bias (or the innovation axis), the concepts and propositions along which, if perturbed, can cause fundamental changes in the overall architecture.

3. Such a change is often initiated by perturbing a few key concepts (in the context of non-Euclidean geometries, the definitions of line and angle): the new configuration of these concepts being termed the archstand.

4. That the perturbation of the knowledge hierarchy is minimal at the axiomatic level; maximal at the basal level.

One might ask, what is the difference between the revolution here in geometric systems versus that which we saw in the last chapter in regard to the scientific revolutions? In the scientific revolutions we saw earlier, it ended up asserting one worldview (at a given conceptual level) against the other. The fact that we have a single world that is being modelled, forces a unified worldview. But in the geometric revolutions we studied here, the mathematical privilege of assuming abstract world models, allows for multiple worldviews. When we apply these geometric results to the study of actual physical space, we would have to integrate between the two. As of today, the experimental corroboration is not conclusive. The truth is that just as Einsteins theories contain the Newtonian worldview with restrictions on the velocities involved, so also the geometries involved contain one within the other (like a Russian doll), and needs to be particularized for local conditions.
4.6 References


Chapter 5

Archstands for Visionary Leadership in Business

5.1 Introduction

In this chapter we give historical examples of visionary leadership in business, and then cast these in the archstand framework. Examples include:

1. **James Watt**: Steam Engine.

2. **Gustavus Swift**: Meat Packing/Refrigerated Car for Shipping.

3. **Andrew Carnegie**: Transformation of the Steel Industry from a Railway Systems Perspective.

4. **King Gillette**: Disposable Safety Razor.

5. **Lee Cole**: Liquid Yield Options Note (LYONS).

In essential terms, the establishment of the archstand is also the establishment of the statement of vision. The archstand approach could thus fundamentally help establish and project the overarching statement of vision. It is the study of visionary leadership we wish to undertake in this chapter.

5.2 Review of Theory

In our introductory chapter we set up a design framework and defined the design circuit as consisting of the following activities [Fig.5.1]:

1. Problem Perception

2. Problem Abstraction
   
   (a) Problem Abstraction Synthesis
   
   (b) Problem Abstraction Analysis
3. Design Proper

(a) Creative Leap
(b) Design Synthesis
(c) Design Analysis
   i. Validity Analysis
   ii. Decompositional Analysis

4. Design Communication

5. Market Feedback

In Chapter 3, we set up the broad design(n) for innovation (here modified to fit the context of design practice) as follows [Fig. 5.2]:

- $FR_{2(2,1)}$: In order to establish the archstand, we need to conceptually map the current-practice design-traces. At a minimum, one ought to do this at least for the major trunks of the design-trace innovation-axis.

- $FR_{3(2,1)}$: We need to discover viable archstand(s) (i.e., those that are conceptually central enough to perturb the innovation-axis).

- $FR_{4(2,1)}$: We need to shift the innovation-axis of the existing design trace.

- $FR_{5(2,1)}$: We need to shift the innovation-midwife of the existing design trace.

- $DP_{2(2,1)}$: In order to meet the $FR_{2(2,1)}$ requirement, our design(n) is to basically engage in the process of mapping the design trace hierarchies. This might involve interviewing, scanning for recent developments, experimenting, collating and conceptually organizing the essential information in a manner that reveals the underlying architecture. Here we might be able to use some of cognitive tools and techniques currently being developed [see next chapter].

- $DP_{3(2,1)}$: In order to meet the $FR_{3(2,1)}$ requirement, we study the explicated knowledge hierarchies and see if they might yield a viable archstand based on our discovery methods (i.e., the inductive, the abductive, and the integrative). We judge the viability of the archstand based upon whether it logically can dislodge concepts and propositions along the existing design trace hierarchies.

- $DP_{4(2,1)}$: Having found a viable archstand, we then shift the innovation-axis by substituting the results based on the archstand and deleting those that do not fully conform to reality as the standard (in the case of design, this includes the left-arch normative design standards).

- $DP_{5(2,1)}$: Having shifted the axis, one then systematically traces the consequences through the rest of the design trace.
Figure 5-1: The Design Trace Along with the Axis Shift
We represented the lower-triangular design(n) as follows:

\[
\begin{align*}
\{ FR2_{(2,1)} \} &= \left[ \begin{array}{cccc}
\oplus_2 & O & O & O \\
+ & \oplus_2 & O & 0 \\
+ & + & \oplus_2 & 0 \\
+ & + & + & \oplus_2 \\
\end{array} \right] \{ DP2_{(2,1)} \} \\
\{ FR3_{(2,1)} \} &= \{ DP3_{(2,1)} \} \\
\{ FR4_{(2,1)} \} &= \{ DP4_{(2,1)} \} \\
\{ FR5_{(2,1)} \} &= \{ DP5_{(2,1)} \}
\end{align*}
\]  

(5.1)

This is the context we established in Chapter 3. Here we address the finer details of coupling design to innovation. How does the design-trace get modified in the context of the archstand based innovation? Specifically these are the issues we need to address:

1. How to conceptually map the knowledge architecture of the design trace?

2. Given the context of the design trace, where all might one scan and look out for discovering viable archstands? Given the nature of the design trace, what kinds of pro-active stances might one consider in undertaking this task? How might one judge the level at which potential changes are possible? How might one judge the axis-perturbation potential of these archstands? What techniques might one consider in validating the perturbation potential of the archstand?

3. How to systematically track the consequences of the shift along the design trace axis (i.e., the innovation axis)?

4. How to systematically track the consequences of the shift along the overall design trace (i.e., the midwife trace).

Solutions to many of these problems are contingent upon an exhaustive explication of knowledge architectures (similar to what we engaged in in the context of the non-Euclidean revolution). And as we mentioned earlier, some of the tools and techniques from artificial intelligence might prove useful. Future work needs to be done in the context of building a whole system of tools and techniques for mapping and tracking knowledge architectures. In this chapter we are more concerned with a qualitative mapping of the various business/financial innovations from a historical perspective.

### 5.3 Conceptual Mapping Using Historical Data

The problem of innovation is that of change. Thus the focus of the design-trace map ought to be to locate those segments that are changing in a fundamental sense. Thus the problem of mapping is not really that of exhaustively charting out every single bit of information that ever was transacted in the past (both remote and contemporary). The issue is to chart the changing patterns in its essential terms. Otherwise it is easy to lose ones perspective and suffer cognitive information-overload with the trivia.

Here the question then is, what constitutes the essentials of the design-trace? Also what about the changes that often seep in from the outlying peripheral regions of the design-trace architecture (i.e., that which constitutes the innovation midwife)?
Figure 5-2: The Archstand Theory of Design for Innovation
It is here that a good grasp of the existing knowledge hierarchy pays rich dividends in a given problem context. For as we earlier indicated, change is happening within the context established by the higher echelons of the knowledge hierarchy. One good way to identify the essential concepts in a given field is to study the history of the field in conceptual terms. For example, if the context is technical innovation, a good grasp of the history of the technology involved also provides valuable insights regarding that which is essential versus that which is peripheral; that which is changing in fundamental terms versus that which is not. In this context it is ironic that very few engineering schools provide a glimpse of the historic context while dealing with present day problems. Writing about this in Teaching the History of Civil Engineering, Prof. Hauck writes [Ref. 5.1]:

...How much do we really know... of those witnesses to earlier engineering genius? How familiar are we with the care and the inspiration and the devotion that went into the building of canals, roads, bridges, towers and harbours, of works now crumbled or even of those that still serve us? How often do we take advantage of past success or failure to guide us as we design for the future? Not much, not very, not often. And why not? Because no one taught us very much about our heritage, or even tried to convince us that it is worth studying...

...[But with so many changing issues, and so little time]. . . is it not.. [im- portant that] we should concentrate on facing the challenges of the present and future rather than bothering with those of the past? The answer becomes unmistakably clear if one realizes that, while certain aspects of our challenges are new, the essence of them are all old indeed.... An appreciation of the continuity of this experience provides perspective; familiarity with it invokes examples, guides thoughts, suggests ideas.

Prof. Huack is entirely right as regards history providing us the conceptual context and perspective we need for judging the patterns of change both in the current as well as into the future.

The fundamental problem of the "conceptual" design-trace mapping reduces then to that of mapping the essential components of the design-trace given the historical context. Knowing the history of the problem context, the ways in which the problem has been abstracted out, the kinds of designs that have been proposed, the technologies that have been brought to bear, the ways in which the markets have reacted--these when conceptually integrated provide a powerful perspective from which to judge both the essential core of the current design trace as well as the changing patterns. Knowing the history of the design-trace is the most important conceptual tool an innovator could bring to bear; for it provides him the rich conceptual context for every other decision he will be taking in the future. Proactively, this is the most important (currently untapped) asset a innovator could possess in regard to the problem of innovation.

In essential terms, the establishment of the archstand is also the establishment of the statement of vision. For entrepreuners, history serves as a powerful motivator as
well as a reference benchmark to call upon when conflicting sub-requirements need to be resolved. In the next few sections we look at various business/financial innovations from an archstand perspective.

5.4 James Watt: Steam Engine

In January of 1769 James Watt applied for and received the condensing steam engine patent. From a historical perspective, this is the single most invention that epitomises the birth of the Industrial Revolution. By designing a cheap source of mechanical power, Watt provided the means by which England could take the lead in mechanizing various production systems, thus transforming the economy from largely a home-manufacturing base to that of large-scale factory production. It is thus no accident that to commemorate the transformation wrought, the international unit of power is designated as watt.

In this section we look at how to apply the design and innovation framework along with the axiomatic framework (specifically the concept of the coupled design) in order to analyse the manner by which James Watt invented the steam engine with the separate condenser, and thus reduced the fuel consumption to less than one third of the prevalent Newcomen engine [Fig. 5.3].

If we were to analyse the Newcomen engine, in essential terms it has two functional requirements with regard to the steam chamber design:

- FR1: Keep expansion chamber hot to minimize heat losses.
- FR2: Cool and Condense steam during downward stroke to create vacuum.

But the engine had basically one and the same cylindrical chamber (the DP1) to accomodate both these functions. The design may thus be represented as follows:

\[
\{ FR1 \} = \begin{bmatrix} \oplus \\ \oplus \end{bmatrix} \{ DP1 \}
\]

(5.2)

As we may notice, this is a coupled design.

Watt recognized the coupled nature of the design and added the new design parameter, namely the condensor (the DP2). He also added a steam-jacket around the expansion chamber in order to trap and minimize the heat losses. The Watt design [Fig. 5.4] may thus be represented as follows:

\[
\begin{align*}
\{ FR1 \} & = \begin{bmatrix} \oplus_2 & O \\ + & \oplus_2 \end{bmatrix} \{ DP1 \} \\
\{ FR2 \} & = \begin{bmatrix} \oplus_2 \\
\end{bmatrix} \{ DP2 \}
\end{align*}
\]

(5.3)

Here we have an historic example of how one might decouple (or uncouple) existing designs that are coupled in order to bring about a fundamental shift in the industry. By grasping the fact that a drastic scale-down in the cost of mechanical power could result in a radical innovation in the industrial practice (thus bringing about rapid scale-up in the level of industrialization). Watt was able to take good advantage of
Figure 5-3: The Newcomen Engine [Source: Ref. 5.16]
-Watt's single-acting engine for pumping water for draining mines, 1788. The boiler c is placed in an outhouse, and the steam passes to the cylinder v, which is kept hot all the time by a separate steam jacket. v is the separate condenser and t an air-pump.

Figure 5-4: Watt's Engine [Source: Ref. 5.16]
his invention. While it is a matter of conjecture whether Watt was a-priori aware of the scale of transformation his invention would bring about (and thus worked towards it in a goal-directed sense), it is definitely possible for us to look back and make some conclusions:

1. This innovation is an example of axis shift generated by inducing out a archstand (namely separate condenser) by first analysing the nature of the current design as being coupled, uncoupled or decoupled. In order to grasp this fact, Watt had to experiment with a model Newcomen engine and arrive at the coupled nature of the design.

2. Not every decoupling of existing designs could lead to an innovative shift. Ultimately it is the comparative economic analysis of the cost differentials that could help one conclude the axis-shift potential of the decoupling archstand.

Given the above context, one might explicate the involved integrative archstand [Fig. 5.5] in Watt's steam engine as follows:

To de-couple the existing coupled design(n) (that entailed high fuel-consumption and engine fatigue damage), by providing a new design(n)-parameter dedicated to the function of cooling and condensing the steam during downward stroke to create the needed vacuum.

Here the archstand is nothing but the top-level design(n) (of the new design trace), the development of which brings about the design-trace axis-shift which then percolated into various other levels of the British economy as cascade innovations.

5.5 Gustavus Swift: Meat Packing/Refrigerated Car for Shipping

By mid-1820s, Boston's Frederic Tudor had established the ice-harvesting industry which in the 1870s gave birth to the meat-packing industry pioneered by Gustavus Franklin Swift. Tudor harvested his ice for 10 cents [Ref. 5.5] a ton in the Massachusetts ponds and sent it insulated to the tropical southern climates where he could fetch close to 10 cents a pound. The ice was being used for various purposes, including cold drinks, ice-creams, food-preservation, etc. By the end of the civil war, refrigeration by ice was slowly transforming the food habits of the nation. But it was the coming of the railroads that threw open far-flung markets and brought an urgency to the efficient distribution of packaged food products. Thus from the technology side, the double cascade innovations that heralded the birth of the meat-packing industry were:

1. The establishment of a well-articulated national railroad system that provided the potential for the marketing of goods on a national level.

2. The mass-production efficiency of the ice-harvesting industry that had brought prices sufficiently down to study the possibility of preserving perishable food products over the long railway haul.
1: James Watt [1769]  
FR1  
FR2  
Need a new DP  
James Watt's Design  
Integrative

2: Gustavus Swift [1875]  
Butchery at Place of Use  
-Huge Freight Cost  
-Transport Decimation  
-Spoilage  
-Gross Waste  
Meat Packing with Refrigerated Car Transport  
Integrative

3: Andrew Carnegie [1872]  
Disintegrated Steel Manufacture  
-Fragmented Processing  
Integrated Steel Manufacturing  
Integrative

4: King Gillette [1904]  
Straight Razor/Bearded Tradition  
- Took > 30min  
- Needed good hand skills  
- Not Safe  
- Not economical  
A Salesman Perspective on Trends in Disposable Goods ["Something that would be used and then thrown away"]

5: Lee Cole [1983]  
Inerest investments in risky options with principal in T-Bills  
Re-Channel Public Funds into Private Sector using Tools of modern finance.  
Abductive Untapped funds  
Abductive  
Inconvenience of Straight Razor

Figure 5-5: Archstand Profiles in Entrepreneurship
Gustavus Swift was not the first to attempt refrigerated meat-packing [that honor belongs to G. H. Hammond, 1871]; however he was the first to recognize the fundamentality of the challenge at hand and organize his efforts for the tremendous scale-up that took place.

It is fascinating to trace the step-by-step conceptual integrations made by Swift in transforming his 1855 ($25/-) stake in home-butchering when he was still a teenager at Cape Cod-Massachusetts, to a multi-million dollar global industry by the turn of the century. An excellent account of this history is given by Gustavus Swift's scn, Louis F. Swift [Ref. 5.6]. In mid-1870s, Swift (who then was heading a wholesale slaughter/meat dealership in New England) recognized the importance of buying his cattle near the source of supply, i.e., Chicago; for direct purchase in the cattle-hub of Chicago afforded choice selections for a fraction of the usual commissions. Thus in 1875, when he was thirty-six years old, Swift sold his dealership (for thirty-thousand dollars) to his partner J. A. Hathaway, and moved over to Chicago.

The prevailing conditions in the cattle-industry during this time were rather unsavory. With scaled-up industrialization and rapid urbanization after the civil war, growing populations in the urban centers of the north-east created an attractive market for shipping live cattle from the western states. The preservation of food using ice was not a prevalent practice. There was thus an urgency to sell the butchered parts soon after the slaughter. On account of the centrality of location, these local slaughterhouses were often located in downtown sections. But lacking well-developed methods of food preservation, meat spoiled quickly; thus creating health-hazards to the community. Even upper-class folk sometimes had to make-do with spoiled meat. All this was compounded with the fundamental fact that economically, the whole procedure gave rise to enourmous amounts of waste. As Louis F. Swift records [Ref. 5.6]:

The abattoir was literally a shambles. Meat and hides were the products. Livers, hearts, tongues all went unweighed to the meat market man who bought a whole carcass of beef. Everything else was waste, or at best was used as an unwholesome ration for a sty of “slaughterhouse hogs.”

Into this hodge-podge of small, dirty, wasteful local businesses came the Cape Cod Yankee who was to upset every idea which had been accepted in the trade since its inception...

At first he saw the waste of buying cattle which had passed through the hands of too many middlemen and against which too many charges had accumulated. He went west to buy the cattle nearer their sourc, to elimi-nate these extra charges.

Then he began to think about the waste of shipping the whole animal east instead of shipping only the parts which were needed there. It was not alone the freight on the sixty percent inedible portion—though that was a tempting saving if it could be attained. But also in shipping the cattle east they were bruised too much. They shrank in weight too much. The expense of feeding in transit was too much. It was all waste—and to my
father any waste was too much.

Father was the man who began to slaughter cattle at Chicago, and to ship the beef east. At first this was confined to the winter months. Then, through the refrigerator car’s development, it became an all-year business. And thereby the greatest saving possible in producing meat from animals had become a reality. This saving from that time on meant cheaper meat for the consumer, higher prices for the cattleman—and the birth of a great industry.

Given the above context, if one were to cast Swift’s achievement in an archstand framework, one might explicate the involved integrative archstand as follows [Fig. 5.5]:

To efficiently package and distribute meat products by establishing a total refrigerated car transport systems.

As we saw, the refrigerated car transport system that Swift established was a result of cascade innovations from the the railways as well as the ice-harvesting industry. But Swift also pioneered something fundamentally stand-alone and unique namely, the dis-assembly line, the corollary to Henry Ford’s assembly line concept. Marvelling at the “dis-assembly line” concept, historians Robert Sobel and David Sicilia remark [Ref. 5.5]:

Swift’s concern with efficiency was usually beneficial. He seems to have been the first of the large meat packers to utilize overhead conveyors to move carcasses from butcher to butcher. Instead of one worker butchering an animal and then dressing it, as was the prior practice, each man on the line made a single cut as the carcass moved to his section. Long before Henry Ford introduced the assembly line in the auto industry, Swift had perfected his “disassembly line”. That this cut cost and increased productivity was obvious.

This is an excellent example of the deductive use of Adam Smith’s division of labor principle in the context of meat packing. A study of Swift’s biography offers many more similar innovations, especially in the context of personnel management.

5.6 Andrew Carnegie: Steel Industry from a Railway Systems Perspective

Andrew Carnegie, the Pittsburgh steelmaster matured and worked his way up in the railroad industry between ages 15 and 36. He joined as a telegraph-boy in Pittsburgh (1850) and under the mentorship of Thomas (Tom) Scott (Head of Western Division, Pennsylvania Railroad-1852; Vice-President of the company-1864) graduated as the Superintendent of the Western Division of the Pennsylvania Railroad (1872) During these 21 years, Carnegie accumulated an in-depth appreciation of the scaled-up industrialization that was transforming the nation. Between 1856-1872 he invested in
various industries to earn an investment stake of $250,000. By then he had decided that his future lay in the manufacture of cheap steel; for railroads were converting their lines into steel. He had a solid investment capital. And the time was opportune. But more importantly, unlike his competitors, Carnegie had the key insights regarding how to run an integrated large-scale enterprise. Fundamentally, it was this external railroad perspective that Carnegie brought to bear in transforming the steel industry.

Commenting about his responsibilities as the Superintendent of the Western Division, Pennsylvania Railroad (1864-1871), historians Robert Sobel and David Sicilia write [Ref. 5.5]:

During the next seven years, Carnegie completed the education upon which he would draw in becoming the world’s greatest steel maker and its richest citizen. Under Scott, he had learned the importance of careful cost accounting, a practice in which the railroads had pioneered. With millions of dollars of moving stock, hundreds of employes, and thousands of passengers, the railroads—and the Pennsy was the largest—were impelled to keep careful records in order to make operations, investment, and personnel decisions or even to determine if profits were being made. This realization Carnegie would later forge into one of the basic rules of business: “Watch the costs and the profits take care of themselves.”

...His railroad experience told Carnegie that there were serious flaws in the way steel business was conducted. For one thing, different processes were fragmented: smelting was conducted at some facilities, forging and rolling at others, cutting and even founding elsewhere... Carnegie would integrate all the processes of steel manufacture under a single roof.

Given the above context, one may posit the integrative archstand that Carnegie built upon:

To integrate the fragmented steel industry using the tools of large-scale systems management as pioneered in the railway industry.

There were other pioneering steps Carnegie took, especially at the conceptual level. Thus remarking about the introduction of the science of chemistry in guiding the business strategy, Carnegie writes [Ref. 5.8]:

The next step was to find a chemist...We found the man in a learned German, Dr. Fricke, and great secrets did the doctor open up to us. Ironstone from mines that had a high reputation was now found to contain ten, fifteen, and even twenty per cent less iron than had been credited with. Mines that hitherto had a poor reputation we found to be now yielding superior ore. The good was bad and the bad was good, and everything was topsy-turvy. Nine tenths of all the uncertainties were dispelled under the burning sun of chemical knowledge....

What fools we had been! But then there was this consolation: we were not as great fools as our competitors. It was years after we had taken
chemistry to guide us that it was said by the proprietors of some other furnaces that they could not afford to employ a chemist. Had they known the truth then, they would have known that they could not afford to be without one. Looking back it seems pardonable to record that we were the first to employ a chemist at blast furnaces—something our competitors pronounced extravagant.

Under the guidance of such scientific precision, production for example, at the Lucy Furnace shot up from 13,361 tons to 100,000 tons per year. And between 1872 and 1900, the cost of production dropped from $56/- per ton to $11.50 per ton. No wonder Carnegie could retort to his competitors who were looking to establish a trade cartel with him [Ref. 5.7]:

“I can make steel cheaper than any of you and undersell you. The market is mine whenever I want to take it. I see no reason why I should present you all my profits.”

5.7 King Gillette: Disposable Safety Razor

At the age of thirty-six, King Camp Gillette joined the Baltimore Seal Company (later the Crown Cork & Seal Company) as a sales representative. The flagship product of the company was a cork-lined stopper (-invented by the president, William Painter) that enjoyed a good market amongst the brewers and bottlers of the nation. Over time Gillette and Painter became very close friends. And Painter inspired Gillette with his vision about the convenience and market potential of disposable consumer products. Re-creating the overall context for the invention of the disposable razor, business historian Russel B. Adams, Jr. writes [Ref. 5.9]:

As kindered spirits, Gillette and Painter struck up a close personal as well as business relationship, and their conversations frequently turned to the development of useful and novel products. Salesman that he was, Gillette could talk a good game, but it was Painter, the proven and prosperous innovator, who spoke from really hard experience. And one day, he said something that would always stick in Gillette’s mind.

“King,” said Painter, “you are always thinking and inventing something. Why don’t you try to think of something like the Crown Cork which, when used, is thrown away, and the customer keeps coming back for more—and with every additional customer you get, you are building a foundation of profit.”

...Gillette [took] William Painter’s advice to heart, and spent long hours mulling over lists of everyday items that might be improved upon, preferably with a throwaway substitute. It was a good way to pass the time while on selling trips, riding on Pullmans or overnighting in sparsely furnished hotels... Then one day in the spring of 1895—appropriately enough, while he was shaving—the idea popped almost idly into his mind. As
Gillette explained somewhat laconically in connection with a patent suit in early 1900s, “the thought occurred to me that no radical improvements had been made in razors, especially in razor blades, for several centuries, and it flashed through my mind that if by any possibility razor blades could be constructed and made cheap enough to do away with honing and stropping and permit the user to replace dull blades by new ones, such improvements would be highly important in that art.”

Perhaps the best way to capture the value of the safety-razor invention in contrast to the prevalent straight-razor practice is in the words of Harry Kellar, the renowned American-born magician [Ref. 5.9]:

“God bless the man who invented the Gillette Safety Razor. I have for years suffered torture at the hands of all kinds of barbers, as I have a very hard beard and shave every day, until I discovered your marvelous razor. With the Gillette razor, shaving is a luxury and I am able to shave my face as clean and smooth as a baby’s without irritating the skin. I want to thank you heartily for this priceless boon.”

As before, if we were to cast the birth of the safety-razor in the archstand framework, one might arrive at the following abductive archstand [Fig. 5.9]:

To solve the problems of “straight-razor” shaving (-it needed good hand-face coordination, was not safe, took more than 30 minutes, and was not economical), need a de-coupled design that separates and de-composes the various functions involved and relegates the inconvenient aspects (stropping, honing and finding the right body-contact) into the “disposable goods” paradigm.

In his own words, this is how Gillette analysed his invention [Ref. 5.9]:

It is manifestly true that no one—previous to the Gillette invention—had conceived the idea of producing a blade in which the purpose in view was to produce a blade that would be so cheap to manufacture that its cost to the consumer would permit of its being discarded when dull, thus avoiding the annoyance and difficulties of stropping and honing. Furthermore, it was true up to the time that the Gillette razor went on the market that there were hundreds of thousands of men who did not shave themselves, for the reason that they could not keep a razor in condition—they had not the knack or mechanical skill to strop and hone a razor, and there being no razor on the market that was of such low cost as to permit of the blade being discarded when dull and a new one substituted, they were obliged to be content to go to the barber, which involved large expense, annoyance and loss of time. It is to this fact that I the inventor attribute in large measure the instantaneous success of my razor.

The Gillette Safety Razor Company was incorporated in 1901. It went into production in 1903, selling 51 razors (priced at $5/-) and 168 blades. In 1904 the sales
were 90,000 razors and 12.4 million blades. The big boost came during World War-I when the army started furnishing convenience Gillette razor-kits to its soldiers and sailors. The purpose was multi-fold: a clean shaven face provided a close-fit for the wearing of gas-masks; it was more hygienic; it boosted the morale; and a clean-shaven face projecting alertness and character was definitely an asset while pursuing leadership roles. In 1918, the orders booked by the War Department orders were for 519,750 razors and 1,420,000 blades. By the end of the war 3.5 million razors and 32 million blades were in military hands—and the returning soldiers retained their razors in their civilian role. And with that the ritual of the morning shave became part of the daily life.

5.8 Trends in Modern Finance

Historically, modern finance was architected from a perspective of stochastic calculus and the random walk theory by pioneers such as the French mathematician Louis Bachelier [Ref. 5.10]. As a result, there has been a fundamental shift in the practice of finance away from the Technical Analysis of the Dow-Jones fame, to looking at it from the perspective of random signals and filter designs such as options. As a whole, the discipline has benefitted enormously from the infusion of concepts/mathematical rigour from the outside. Modern finance theory has thus served the role of the architect in bringing about the design and development of some of the major financial innovations. This combined with the on-going revolution in information technologies has made the finance industry a fast-moving target of opportunity. The following are some of the resulting major trends in finance that we wish to study from our design-trace perspective:

1. Financial Innovations: or the deliberate engineering of major innovations.

2. Human/Automated Financial Decision Making: or the problem of a proper division of labor between the human and the machine.


We begin our study by citing the innovation of LYONs by Merryl Lynch.

5.8.1 Financial Innovations

Let us first study the case of the Liquid Yield Options Note (LYON) at Merryl Lynch. Professors John McConnell and Eduardo Schwartz from Purdue and UCLA respectively, have given an excellent case study of the design process [Ref. 5.13]. The LYON is a combination of a zero-coupon, convertible, callable and puttable bond which is a time-dependent state contingent-claim. Between 1985 and 91, Merryl Lynch was the underwriter to 43 issues which raised about $12 billion dollar for corporate clients. Merrill Lynch earned about $248 million in the process. Regarding the actual conceptual design of the LYON, John and Eduardo write [Ref. 5.13]:

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On closer inspection..., the actual process of financial innovation turns out like most other human endeavors, to be a lot less tidy than economists's model would have it...

During mid-1980's. Merrill Lynch was the largest broker of equity options for retail (that is non-institutional) investors. During that period, owing to the success of its Cash Management Accounts, Merrill Lynch was also the largest manager of individual money market accounts. Individuals had over $200 billion invested in CMA's. CMA's are funds invested essentially in short-term government securities and, for this reason, are subject to little interest rate risk and virtually no default risk.

During 1983. Lee Cole was Options Marketing Manager at Merrill Lynch. Cole discerned... a pattern in the transactions of individual retail customers. As Options Marketing Manager. Cole observed that individuals primary activity in the options market was to buy calls on common stocks. The most active calls had a maximum term to maturity of 90 days and often expired unexercised. Viewed in isolation this strategy appeared to be risky.

In reviewing customers consolidated accounts however. Cole observed that many options customers also maintained large balances in their CMA accounts while making few direct equity investments. From these observations. Cole deduced a portfolio strategy: Individuals...were willing to risk a fraction of their funds in highly volatile options as long as the bulk of their funds were largely safe from risk in their CMA accounts. They also avoided direct equity investment. He leaped to the further inference that funds used to buy options came largely from their CMA accounts. In short, individuals were willing to risk all or a fraction of the interest income from their CMA's in the options market so long as their principal remained intact in their CMA account.

With these observations and deductions in hand. Cole drafted a memorandum describing in general terms a corporate security that would appeal to this segment of the retail customer market. In drafting the memo. Cole's intent was to design a security that would allow corporations to tap a sector of the retail market whose funds were currently invested in government securities and options. The security described therein turned out to be the LYON. Because it is convertible into the stock of the issuer. the LYON effectively incorporates the call option component of the portfolio strategy perceived by Cole. Because of the put option, the investor is assured his principal can be recovered by putting the bond back to the issuer at pre-specified exercise prices. The LYON thus approximates the features of the trading strategy.......

Having conceived the overall design Cole could then push forward both at the market side as well as at the analytical side to more sharply define the actual product [Fig. 5.6]. The numerical analysis can take off only after the product has been
Short Term 90 day Govt Treasuries

CMA Principal (P)

Interest (I)

OPTIONS

$200B
Largest Manager of CMA Accounts

Mid-80s: Largest broker of equity options.

MERRILL-LYNCH

Waste Management Inc.

1: Name Recognition
2: High Credit Rating.
3: Stock exhibits volatility.

Conversion (Call) Option

4.36
4.36x52 =226.72

S
L $250

Investor Limits Down Side Risk
Issuer Limits Upside Exposure
Put Option
Volatility of Stock
4.36 Conv

250
301.87
346.72

Issuer's Call Option

Interest investments in risky options with principal in CMAs

Re-Channel Public Funds Into Private Sector-using Tools of modern finance.

Abductive Untapped funds

Govt Treas
Brokers Fees
Corp Sec

Figure 5-6: The Origin of LYONs [Source: Refs. 5.13 & 5.17]
conceived. If one were to stand back and evaluate the overall process, one realizes that Cole had to look at the existing volume flow of funds in the short-term government-backed treasuries, and abstract out the idea that the same risk-return payoff could be engineered for the individual investors, but now in the context of corporate securities. If one were to capture this in the archstand framework, one could say that Cole was propelled by a vision that says:

Given the ability that modern finance provides, of replicating payoff patterns using substitute assets, how to re-channel funds locked in the public sector, into the private sector and thus realize brokerage fees at the corporate level.

Or to put it more succinctly,

To re-channel public funds into the private sector using the tools of modern finance.

Stating this explicitly, one then realizes that the LYON-like opportunities might exist in various other similar contexts.

In all of this, the critical step as we saw was in Cole inductively recognizing the business opportunity. This is the critical human input. The irony though is that it is difficult to convince a hard-core technologist about the critical human element in design. Yet this attitude-problem is slowly changing, mainly on account of the in-roads being made in cognitive engineering [see chapter 6]. The first steps were in the context of the human-computer interaction research at Xerox-Parc and others which then percolated into Apple; and it is now everywhere.

Somebody said, familiarity breeds contempt. If that is true, it must apply to us most acutely; the unmistakable conclusion is that we are most oblivious of our own cognitive faculties. We thus occupy our own worst blind spots, i.e., the self-blind-spot. And the irony is in the fact that it is the economies provided by the machine that is slowly but irrevocably displacing us in an economic sense, into the realm of inductive problem abstraction and conceptual design.

In his study of the subject of financial innovation, Nobel Laureate Merton Miller writes [Ref. 5.11]:

No word is more overworked these days than "revolution". Yet, in its original sense of a major break with the past, the word revolution is entirely appropriate for describing the changes in financial institutions and instruments that have occurred in the past twenty years.

As one small example of how far we have come, I can still recall the shock and incredulity of my Belgian colleagues at the University of Leuven in 1966 on learning that I, as an American citizen, could not then legally own monetary gold. Nowadays, of course, we can hold and trade not only gold coins, gold bullion, gold futures, and gold options, but literally hundereds of other financial instruments that either didn't exist in 1966 or existed only in rudimentary form. A partial list of major novelties would include, in no particular order: negotiable CDs, Eurodollar accounts, Eurobonds, sushi funds, floating-rate bonds, putable bonds.
zero-coupon bonds, stripped bonds, options, financial futures, options on futures, options on indexes, money market funds, cash management accounts, income warrants, collateralized mortgages, home equity loans, currency swaps, floor-ceiling swaps, exchangeable bonds, and on and on. The mind boggles.

Merton then goes on to discuss and ferret out the major causes in triggering many of these financial innovations [Ref. 5.11]:

The major impulses to successful financial innovations over the past twenty years have come, I am saddened to have to say, from regulations and taxes... The income tax system of virtually every country that is advanced enough to have one seeks to maintain...different rates of tax for different sources (and uses) of income—between income from capital and income from labor; between interest and dividends; between dividends and capital gains: between personal income and corporate income;...and so on. At the same time, modern finance theory assures us, as practitioners have known, that securities can be used to transmute one form of income into another—in particular, higher taxed forms to lower taxed ones.... [This creates an] endless sequence of [regulatory] action and [market] reaction [which] has been aptly dubbed the "regulatory dialectic" by Edward Kane of Ohio State University.

One can start hypothesising that major integrations in modern finance theory provided the needed archstand for contemporary financial innovations.

Merton distinguishes between transitory versus permanent innovations based on their enduring features. He then goes on to give examples of the latter [Ref. 5.11]:

Many instances of such nontransitory, significant innovations can be found among those on my earlier list. The Eurodollar market, for example, owed its origin to a curious US restriction known as Regulation Q. The regulation, among other things, placed a ceiling on the rate of interest that commercial banks could offer on their time deposits. Over much of the post-war period, that rate ceiling was, if not actually above, at least not drastically below the market clearing level. But that changed in the late 1960s and early 1970s with the rise in US and world interest rates. The US money-center commercial banks soon noticed that the restrictions of Regulation Q did not apply to the dollar-denominated time-deposits in their overseas, and especially Western European denominated time deposits in their Western European branches... The US banks did and their rivals could and did bid competitively for short-term dollar-denominated accounts; and they continue to do so on a huge scale today even though Regulation Q has long since become a dead letter.

The currently huge Eurobond market was set off by a tax rather than a regulatory change. It sprang up initially in response to the US government's institution in the late 1960s of a withholding tax of 30% on interest
payments on bonds sold in the United States to overseas investors. The locus of the market for dollar-denominated bonds for non US citizens thereupon moved from New York to London and other money centers of the continent. The withholding provision has since been repealed, but the Eurobond market it induced has continued to thrive, in part, no doubt because the cumbersome new issue prospectus requirements imposed by the SEC on public issues of securities by even the best known US firms....

The current vogue for “swaps” for example, was set in motion some years back by firms seeking ways to avoid British government restrictions on dollar financing by British firms, and on sterling financing by non-British firms....

In developing his theory on the causes of financial innovation, Prof. Miller leaves us with a seemingly unanswered question [Ref. 5.11]:

..what actually triggered the recent past surge. That the triggering had at least something to do with tax and regulatory changes is.clear... But of course, those triggers have always been with us. The process of adaptation and selective survival in response to tax and regulatory changes has been going on throughout recorded history... But something else seems to have happened about twenty years ago that shocked the system into a period of unprecedented rapid innovation.

I must confess that despite much pondering I have yet to come up with a completely satisfying first cause. There are certainly plenty of possibilities, both economic and technological, but, with the exception of the great oil shock of the 1973-4, most had obvious counterparts at times (and often at several times) in recent past history. And, as for the oil shock, many of the key developments were under way well before it occurred.

Perhaps, then, there was no single, easily pinpointed cause, but just the coincidental coming together of a whole set of seemingly unrelated...events and circumstances. Most of the critical tax and regulatory frameworks that supplied the motives for the financial innovations I have described were put in place in the 1930s. In that depressed and war-scarred period, and even more so during the war and slow recovery years that followed, there were better outlets for innovative talents. We were just too poor and too distracted with other, more pressing concerns. The regulatory and tax constraints were not the most seriously binding ones.

By the middle and late 1960s, however, the recovery in world wealth (and trade) had progressed so far that the taxes, interest rate ceilings, foreign exchange restrictions, security sales restrictions, and other anticompetitive controls slapped on in the 1930’s and 1940s were becoming increasingly onerous. It was not so much that new tax and regulatory burdens were being imposed (though that was happening too), but more that the existing burdens were increasingly binding, particularly so given the surges in
the level and volatility of prices, interest rates, and exchange rates that 
were erupting in those years. The innovative wave then triggered was 
much like a snake bursting through its old skin.

Here one may discern the earlier mentioned self-blind-spot in action. The main 
thing that happened since 1970s is the diffusion of ideas hammered down in the realm 
of modern finance, many of the main tenets Prof. Merton himself contributed. It is 
the earlier conceptual barrier of how one might trasmute one cash-flow stream into 
another, how one might price exotic derivative instruments, how one might architect complex instruments..., it is the breakdown of this conceptual barrier if anything else 
that gave birth to the recent wave of financial innovations. As mentioned earlier, 
modern finance was architected from the perspective of stochastic calculus and the 
random walk theory by pioneers such as the French mathematician Bachelier. As 
a result, there has been a fundamental shift in the practice of finance away from 
the Technical Analysis of the Dow Jones fame, to looking at it from the perspective 
of random signals and filter design such as options. Figure 5.7 captures some of the 
major integrations of modern finance. Each of these integrations could serve as points 
of departure for future innovations. In addition, the figure includes (top-right) the 
cutting edge frontier in finance. One of the main research fronts is the human process 
of financial decision making [Ref. 5.12]:

Arnold Sametz commented in 1964 that “we know very little about how 
the great nonroutine financial decisions are made.” That is no less true 
today. We know quite a bit about asset values, but we do not know 
very much about the decisions that give rise to these values. What is the 
process that causes one company to make major investment and another 
to reject it?...

Strategic planning is a “top-down” approach to capital budgeting: You 
choose the business you want to be in and make the capital outlays nec-
essary for success.... The trouble is we understand the bottom-up part of 
capital budgeting process better than the top-down part.

Top-down and bottom-up should not be competing approaches to capital 
budgeting. They should be two aspects of a single integrated procedure. 
Not all firms integrate the two approaches successfully. No doubt some 
firms do so, but we don’t really know how.

This comment is an extremely valuable insight into where future effort needs to be 
targetted: the human end of problem perception, problem abstraction (both bottom-
up) as well as (what the authors perceive as top-down) conceptual design. And it 
provides an excellent transition into our next section regarding human/automated 
financial decision making.

5.8.2 Human/Automated Financial Decision Making

Study of the design-trace framework gives us a fundamental insight regarding where 
exactly to draw the line between human decision making versus the machine. The
Figure 5-7: Modern Finance as the Major Archstand for Recent Innovations
fundamental question is what are the tasks that can be automated: and what cannot.

As we have indicated before (in the context of writings by Frank Lloyd Wright),
the divide is along induction versus deduction. Machine are excellent in the deductive
mode of moving down the knowledge hierarchy; while humans are far better in the
inductive mode of moving up along the knowledge hierarchy...ie., problem perception,
problem abstraction, the creative leap, and the initial stages of conceptual design.
This is where humans have the fundamental inductive advantage [Fig. 5.8]. The
machine on the other hand is an excellent tool in the deductive analytics, in the
logical execution of coded, pre-packaged algorithms and inferences.

Thus for example, if we look at the field of structural engineering, we may witness
the awesome power of the machine in displacing human labor at the details level,
forcing a conceptual re-tooling of the human potential more and more into the concep-
tual design and analysis realm. Until mid-80s. structural engineers were in high
demand: today with proliferating Finite Element Analysis packages, the demand is
less acute. The premium today is on people who can conceive and design structural
systems rather than in analysing existing systems.

Now what does this mean in the context of finance and financial decision making?
Just as in the case of structural engineering with its NASTRAN and other Finite
Element software packages, so also in finance: we will soon see the proliferation
of standard analytic packages that help price various financial instruments and do sen-
sitivity analysis. For example, J P Morgan recently made available some of its risk
metric analytics on the internet (http:www.jpmorgan.com). So just as in structural
engineering, so also in finance, the premium will be on those who can conceptualize
and conceive and deliver innovative financial products in a rapidly evolving market.
And we have looked at one such case in the context of the Merryl Lynch LYON’s. The
future belongs to those who can institutionalize such an innovative ethic. Curtesy
the psychological free time made available by automation, the design trace will inch
up more and more, becoming over a period of time more and more overarching and
rich in concepts that span the overall global context.

What do Knowledge-Based Systems have to offer in this regard? Certainly, KBES
systems have a place in the overall context: but as experience shows, not in the
inductive limb. If we try to make the total system purely machine based, we end up
with a brittle system. Consider the experience of Syntelligence from the commercial
banking industry [Ref. 5.14]:

Clearly something happened on the way to full-blown expert systems. The
systems were slow in coming, difficult to develop and very costly when they
arrived. Very few actually made it into the market. Of those, Syntelligence’s Lending Adviser became the best known, although it never pen-
etrated more than a handful of banks. Syntelligence filed for bankruptcy in December 1990....

Despite interest in expert technology, most banks continue to rely on
more conventional systems. These systems help lenders gather and or-
organize credit information and perform credit scoring, but leave the fi-
final risk analysis and judgement to the lender.... Riggs National Bank,
Figure 5-8: The Evolving Human/Machine Divide
for instance uses Credit Revue from Credit Management Solutions Inc. (CMSI), Columbia, Md., as the basis of its consumer risk management.

"We use the system to calculate key risk ratios like loan to value and debt to income, but we do the actual review manually," says Larry Grist, vice president.

To re-iterate, the main idea is that given the design-trace architecture, there is an elegant and symbiotic division of labor between the human and the machine. Initially, this divide will start off somewhere near the base [Fig. 5.8] It then tilts upwards until it saturates somewhere near the conceptual design level. For it will have reached levels of the inductive creative leap.

5.8.3 Mass Customization of Financial Products

Let us now study how the generic design-trace framework may be applied in the context of mass-customization of financial products and services. Information Technology has paved the way towards mass-customization in more than one field, including finance. Here are some representative quotes. For example. Fred Wheeler from Comerica is quoted as saying [Ref. 5.15]:

"We wanted to get away from a tightly defined loan product into an environment where officers could negotiate with their customers to customize every loan."

Sheila O’Heney in Bankers Monthly writes [Ref 5.15]:

"In the turbulent markets of the 1990s the customer is supreme. To delight customers today, services need to be tailored to their individual needs and delivered in "quantities of one." ...At the core of the movement is information—accurate, current, and easy to access... "Commercial bankers must be responsive to their customers," says Pat McCartney, First Union's senior vice president in charge of commercial automation. "Years ago, you would develop a system around a specific product line. Today, you have to develop a range of tools that enable the banker to respond to the demands of the customers within the time frames they, not the banker, set."

Until recently mass-markets and customized-markets were antithetical. But today with technology providing the ability to track individual customer's entire lending relationship, search for accounts with balancing cash flows, and built-in credit-check warnings, the opportunity to customize the financial service to each individual customer is a definite possibility.

We understand what the technology can offer in the context of mass-customization. But the real problem in mass-customization is when technology has to hand-shake with the human context. For the granularity of the problem is fundamentally different in a mass-market versus a mass-customized market.

There are two fundamental problems here:
1. **Mass-Custimized Marketing**: Given the fine-grained nature of the problem, how does the client/financial service identify each other in the huge signal/noise ratio that fine-grained markets are bound to create? How does one overcome the information overload such markets are bound to create?

2. **Customized Problem Solving**: Having made the customer/financial service identification, how does the organization efficiently tackle the human end of the customized problem solving? While the deductive loop may be automated, the human centered inductive loop could potentially end up as the major bottleneck in mass-customized decision making.

In order to tackle the first problem I have used a concept called the cogring (see chapter 6). It represents the shared conceptual vocabulary amongst a group of people working towards a common goal. In a team-environment, optimum interaction happens when the concerned people have a good grasp of each others knowledge-humps. In fact, team-building (when stripped to its bare essentials) fundamentally means coming to terms with each others knowledge-humps. In this context, if each team-member possesses an explicit knowledge hierarchy, then the team as a whole is able to transact concepts with minimum loss and high signal/noise ratio. An established and explicit cogring has certain favourable consequences. One of them is the magnification that is evident in work output. The cogring is the vehicle by which integrated division of labor takes place. What the cogring provides is a shared framework for efficient large-scale problem solving. Problem perception, problem abstraction, design synthesis, design analysis, design communication—, these are done at a rapid rate and without misunderstandings and miscommunications. In such a context, problems are rapidly identified and solved. Now this is true in the context of a well-defined organization. But what about the market as a whole? If one could establish a natural and thus generic problem-solving framework in the market as a whole, it would be the first step towards the birth of mass-customized marketing. The “St. Louis-arch” type design-trace framework that we described earlier is a generic problem solving framework that is scalable between various problem solving contexts. It is scalable and generic because it is derived from the human condition, the need to abstract and create concepts in order to overcome our cognitive limitations. It could thus serve as the needed cogring in the context of mass-customized marketing.

In order to tackle the bottleneck problem of customized problem solving we need to defer the discussion until we have visited the concept of cognitive limits and cognitive tools (chapter 6). But here is a preview. As humans we are aware of our physical limitations. In order to overcome these limits we design physical tools (such as the automobile) that efficiently transform and magnify our limited abilities into the desired end. Just as we have physical limits, so also we have cognitive limits that constrain us. We build tools to overcome our physical limitations. So also we need tools (cognitive and otherwise) to overcome our cognitive limits. Research on cognitive tools is in its initial stages. But given our design-trace framework it is easy to see the implications of these tools in the context of mass-customized anything, let alone, mass-customized financial instruments. For in essence, it is the set of well-defined cognitive-tools that will help us overcome the above mentioned bottleneck problem.
To conclude this section on modern finance, this is what we have found regarding the three major trends:

1. **Financial Innovations**: or the deliberate engineering of major innovations. In this context we saw the still-to-be exhausted potential of the various archstands as provided by modern finance theory.

2. **Human/Automated Financial Decision Making**: or the problem of a proper division of labor between the human and the machine. Here we used the inductive versus the deductive thinking to bring about the divide.

3. **Mass Customization of Financial Products**: or the problem of customized decision making and product marketing. In the context of customized decision making, we foresaw the human decision making as a potential bottleneck. We then postulated various cognitive tools to overcome our cognitive limits in the context of mass-customized decision making. In the context of mass-customized marketing, we foresaw the fine-grained nature of client/financial service matching up as a major problem on account of the expected information overload. We proposed our St. Louis arch as a generic human/machine problem solving framework to facilitate and transact the match-making.

### 5.9 Conclusions

In this chapter we have used the archstand framework in order to analyse various business/financial innovations:

1. **James Watt**: Steam Engine.

2. **Gustavus Swift**: Meat Packing/Refrigerated Car for Shipping.

3. **Andrew Carnegie**: Transformation of the Steel Industry from a Railway Systems Perspective.

4. **King Gillette**: Disposabie Safety Razor.

5. **Lee Cole**: Liquid Yield Options Note (LYONS).

We also looked at the major trends in the finance industry and postulated how the design-trace framework might fruitfully be used to tackle these trends. In each of the above cases we have succeeded in showing the critical connection between the archstand and the visionary leadership involved in making radical changes in the industry.
5.10 References


Chapter 6

Summary and Suggestions for Future Work

6.1 Introduction

In this chapter we make our final conclusions along with our summation into what might properly be claimed as original contributions. We also indicate some of the future directions this research might lead into.

6.2 Substative Findings of the Research

These are the major research findings:

1. A Common Conceptual Framework for integrating Design and Innovation: We started off our research by looking for a common basis upon which we could integrate design and innovation. We proposed the knowledge architecture framework as the basis upon which we could integrate. We then validated this framework using the non-Euclidean revolution as an example. We gathered four major insights from our study:

   (a) That human knowledge is hierarchical.
   (b) That it has a pyramidal structure which creates a central bias.
   (c) That perturbations at the central core results in major changes.
   (d) That changes are more probable at the lower echelons as compared to the higher echelons.

   In our literature research, we showed that various related research efforts (in both fields-design and innovation) could be successfully mapped on to our framework.

2. Concept of the Design Trace: In the process of articulating our main problem, we put forth the concept of the design trace. On its own it is a substantial step in providing a cognitive framework for structuring the human process of design.
3. The Archstand Theory of Design for Innovation: Using our design framework to guide us, we abstracted out the fundamental problem of innovation as the need to establish an integrated external perspective (the archstand) from where to architect the innovation process. We then established various ways and means by which we may establish the needed archstand. To check the validity of our claim, we showed various examples in science and business innovations where similar patterns may be discerned.

4. Construction from a Manufacturing Perspective: Finally, in the appendix, we apply the framework in the context of construction automation.

6.3 Suggestions for Future Research

In this section we elaborate on some of the suggestions for future work:

1. Developing the Archstand Theory Further: The Archstand theory needs far more development in order to tease out the finer details. One of the major problems is that of mapping out the knowledge hierarchies in a conceptual sense. One approach the author has found useful is that of graphical abstractions. Graphical abstractions provide means to deal with knowledge in major chunks. This is what we used while mapping the non-Euclidean revolution.

The other venue of research (as indicated in the last chapter) is in finding ways and means to structure history. We need to study history in order to grasp the core structures.

2. Development of Cognitive Tools: We will have more to say on this in the following section. But the essential idea is that both design and innovation is a creative cognitive process. Unfortunately, just as we suffer from physical limits, we also suffer from cognitive limits. We need to design cognitive tools to help us overcome our cognitive limits.

3. Prof. Thagard's overthrow of the Kuhnian Framework: Innovation (especially, of the radical type) no longer may be viewed as a gestalt switch process. By making the connection between Prof. Thagard's work and the possibility of research that it opens up in the context of innovation, we now have the possibility of using maps of conceptual developments to give us solid indications of major innovative trends.

4. Study of the Dominant Design: One intriguing question that has provoked us is the manner in which the market feedback trace adjusts upwards. But what does that say about the location of the dominant design? Clearly the dominant design is a function of the dynamics between these two loops. But what are the underlying factors?

5. Development of the Knowledge-Hump Structure in the Context of Design of Proper Information Systems: What can the pyramidal knowledge structure tell us about
the proper design of complex information systems? If current information systems were to be designed around the knowledge architecture concept, many of the fundamental problems of information processing, retrieval and knowledge dynamics may be more smoothly accomplished.

In the next two sections we explore the design of cognitive tools.

6.4 Human Cognitive Limits

As humans we are aware of our physical limitations. Consider the problem of transportation. There are physical limits to the speeds at which the unaided human body may commute from one point to another. We are severely limited in the physical realm. We manage to extend our range of options by designing clever tools that efficiently transform and magnify our limited abilities into the desired end. If the tool is an automobile, the pushing and twisting of levers and rods within the vehicle is skillfully transformed into the right kinds of motion we desire. We create manipulative tools to help us cope with problems we face every day. Just as we have physical limits, so also we have cognitive limits that constrain us. We build tools to overcome our physical limitations. So also we need tools (cognitive and otherwise) to overcome our cognitive limits.

Given the above framework of design, let us now consider the human cognitive limits. Within the context of design, what are some of our cognitive limits? The following are 5 cognitive limits that we are faced with as designers. There may be more. But these are the ones I am currently working on.

1. Problem of Concretes: This is the fundamental constraint on human information processing. The problem of concretes is also the problem of induction. In philosophy, this is called the crow epistemology, or the problem of the crow [Ref. 6.46]. This is what causes information overload: this is what cripples our creative faculties. This is what Prof. George Miller made explicit in his *Magic Number 7 ± 2* [Ref. 6.25]. In our knowledge hump diagram, what it means is that we are deluged with concretes at the lower level. In other words, we lack higher level abstractions to grasp such a multitude. In the context of design, how does it affect the designer? Without the higher level abstractions, the designer is reduced to operating at a low level. He can perceive that there is a problem, but he is unable to abstract out the crux of the problem, he is unable to perform the creative leap. Concepts are our fundamental cognitive tool in dealing with the problems of complexity. The problem of concretes reduces to the problem of concept formation. This is also where one might expect the fundamental division of labor between the human and the computer. While the machine operates primarily in the deductive mode, only humans (so far) have the capacity to induce and abstract out concepts and theories, and (vice-versa) assign meaning to the same. Yet here too (as we mentioned earlier), one could design cognitive tools to aid and abet such an inductive process.
Problem of Concretes

Problem of Memory/Access (Internal Clutter)

Problem of External Clutter

Problem of Focus/Attention

Problem of Design Communication

Figure 6-1: Human Cognitive Limits
2. Problem of Memory/Access (Internal Clutter): Although our subconscious has been claimed to contain the equivalent of 7000 volumes of the Britannica Encyclopedia, we have limited access to it when we need it. Our knowledge is often poorly organized. We have yet to discover the Structural Mechanics of our mental structures. As a consequence, we suffer myriad forms of information failure: difficulty in bringing to bear earlier understandings to the problem at hand, difficulty in organizing the information in front of us, difficulty in reaching the crux of the problem, difficulty in forming the creative leap, confident in what we know. If we somehow could cultivate an organized mind, we could alleviate to a major degree, the problem of information overload, especially in the context of design. Also, an organized mind, rich in content, is a fertile haven for creative thought. What then are some of the tools and techniques towards cultivating an organized mind?

3. Problem of External Clutter: Despite the enormous untapped capacity of the human memory, there are legitimate reasons why one might want to burden this entity to the bare minimum. Of the various reasons, the primary reason is the time and effort it takes to place things in the long-term memory. Clearly one would like to place majority of the items in external records. Historically, two of the most useful cognitive tools in all of human history has been the paper and the pencil. What are some other (contemporary) tools one could put to use in a similar regard? Clearly, the answer to this is coupled with the earlier question on the architecture of the organized mind. What then is the proper division of labor between the internal versus the external records.

4. Problem of Focus/Attention: It is often recounted that some of the great geniuses throughout the ages were capable of intense concentration and focus. Socrates, for example, is said to have sat for hours, thinking in the middle of the marketplace, completely oblivious of the surroundings, as if caught in a trance. Such focal capacity is a rare faculty. Modern life is a beehive of distractions. While we may wish to retreat to a secluded post, far removed from the knock on the door and ring on the telephone, such luxuries are seldom permitted in modern life. Given such a scenario, we would appreciate within ourselves, a Socratic capacity to hold focus. What are some of the tools and techniques towards cultivating such a focal capacity?

5. Problem of Concept Communication: The best social environment for design is where the concerned people have a good grasp of each others knowledge-humps. In fact, team-building is essentially the working out and coming to terms with these knowledge-humps. The only difference being that with an explicit knowledge hierarchy, one has a much more efficient transfer mechanism. What are some of the knowledge explication tools primarily designed for communication between humans?
6.5 Cognitive Tools

We need tools (cognitive and otherwise) to overcome these (and other) cognitive limits. Disciplines that most closely address these issues are Cognitive Science and Engineering. Cognitive Science is an interdisciplinary fusion of disciplines (philosophy, psychology, linguistics, sociology, artificial intelligence, and anthropology) centered around the study of human cognition. Cognitive Engineering is the application of these and other findings (such as ergonomics and human factors) towards the enhancement of human cognition. The current state of knowledge is such that the upcoming field is expected to be practice driven. As Donald Norman puts it [Ref 6.20]:

In fact, for the applications of the science, the cognitive engineering needs so much from cognitive science that it is tempting to say that the science is a subset of the engineering, a statement somewhat at odds with conventional wisdom that suggests it is the other way around. But, actually, this will come as no surprise to any practitioner of a field: the breadth of knowledge required of a practitioner always exceeds that of the science.

I define a cognitive tool as any thing designed to enhance and overcome the cognitive limits of the human mind. In general they could be of three kinds. I denote each kind by the following symbols:

1. R1: the physical construct: for example a pencil, a book, a computer-aided learning program.

2. R2: the social construct: for example a conversation, a debate, or an educational society.

3. R3: the mental construct: for example the memorized multiplication table.

These tools of course do interact to make a whole system of cognitive tools. Of the various tools, the one that is of prime concern here in this thesis is the physical construct R1 (eg., a multi-media computer tool), that helps build and put in place the mental construct R3, that helps overcome human cognitive limits. Such a system of physical/mental constructs (R1/R3) I term the Mentor System.

Literature defines a cognitive tool in various ways. Some are focussed primarily on the physical dimension. Others are more ecumenical in scope. For example, in the proceedings of the NATO Advanced Research Workshop (July 1990), David Jonassen writes [Ref: 6.26]

...cognitive tools [are] both mental and computational devices that support, guide, and extend the thinking processes of their users.

Many cognitive tools, such as cognitive and metacognitive learning strategies... are internal to the learner. However the tools described in this book are external, computer-based devices and environments that extend the thinking processes of learners.... Cognitive tools...are computationally based tools that complement and extend the mind.
With this limited description, one is constrained from bridging the gap and picking up legitimate material from the social world where the maximum amount of work has traditionally been done.

There is one other definition that is more encompassing [Terry Mayes: Ref 6.26]:

The concept of a cognitive tool, as used in the workshop that has produced the current volume, is easy to describe. It is simply a device, or technique, for focusing the learner’s analytical processes.... The cognitive tool concept also carries the implication, as with any tool, that the user will become more skillful with practice, and the tool will therefore be more effective in the hands of an experienced user. This definition is broad enough to encompass a wide range of activities as cognitive tools, ranging from verbal debate to the playing of computer games.

This definition is more encompassing because it includes the social. However, it does not make the R1:physical/R2:social/R3:mental differentiation in any way explicit. Furthermore, it does not make the function or purpose of the tool explicit, namely to overcome definite human cognitive limits.

Having established the scope of the cognitive tool we are here dealing with, let us now suppose that we are attempting design of an artifact within a given discipline (example: structures, software, machine design etc). This design involves a certain process. Call this the primary design circuit (circuit because of the iterative nature of design). The design of a cognitive tool to enhance such a primary circuit is one step removed from it. Call this the secondary circuit of design. While we are here concerned with the secondary circuit, it is important that the product of the secondary circuit couples well with with the primary. This is why we ought to know the primary circuit at least in a loose sense. The major nodes of the primary circuit (as laid out in our earlier discussion on the design framework) is summarized below:

1. Problem Perception
2. Problem Abstraction
3. Creative Leap
4. Design Synthesis
5. Design Analysis
6. Design Communication

Since we are trying to enhance the primary circuit, it is assumed that the domain knowledge to support the primary circuit exists in an explicit sense, at least at the lower levels of the knowledge hump (Fig. 7).

In case the totality of the knowledge is known and explicit (as for example in deductive mathematical systems such as Euclid’s Geometry), it is my hypothesis that one could re-organize it in such a manner to abstract out the core essence of the
system (perhaps composing about 20% of the total). It is this core set of concepts I have termed the innovation axis. Whatever lies outside the innovation axis, I have termed the innovation midwife (See Fig. 1.4).

The following is the general architecture of the various cognitive tools designed to overcome the above discussed human cognitive limits:

1. Tools to Overcome the Problem of External Clutter: Reorganizing existing knowledge is the first step towards the design of cognitive tools to help design and innovate complex systems. Such an organization provides the basis for differentiating between what ought to be internal within the human memory (the innovation-axis), versus external and outside (innovation-midwife) in various records and databases. It further addresses the critical problem of security in information systems by making sure that concepts lying within the innovation-axis are seldom placed in any form of hardcopy or softcopy outside the human memory. Cognitive tools that help (re-)organize existing knowledge structures would help also address the problem of external clutter. Excellent graphical tools exist that help organize such external clutter [Ref. 6.27-29]. When designed deliberately to handshake well with the internal representation of the Innovation Axis, these set of tools could help de-clutter the external records. I call these set of cognitive tools, Exdeclut Tools.

2. Tools to Overcome the Problem of Internal Clutter: Having made such a reorganization, one wishes to consider how best to place the system of concepts within
the innovation-axis in the long-term memory? One might expect two types of cognitive tools in this regard, one that deals with general knowledge structures, the other that is specific to the domain. Cognitive tools that help organize internal knowledge structures would also help address the second kind of cognitive limit, namely the problem of internal clutter. When designed deliberately to handshake well with the external representation of innovation-midwife, these set of tools would help de-clutter the internal records. I call these set of cognitive tools, Indeclut Tools. Design of indeclut tools requires good understanding of how the long-term memory is organized and functions.

What are some of the plausible reasons to assert that

Greater Memory → Richer Creativity?

Here are some of the plausible reasons why:

(a) Ideas are not solitons: they in fact interact within ones mind. As the number of ideas goes up, the number of interactions may be expected to go up combinatorically. This does not necessarily mean that the full scope of combinations are actually being brought about, or that such interactions inevitably lead to creativity (some of them might be valueless). What it means though is that the mental infrastructure for human creativity has been enhanced. The mind now is not an impoverished desert island of random thoughts. It in fact is a resilient springboard for innovative thought. But of course, finally it is up to the volitional faculty to put this enhanced infrastructure to good use. Here too, one could device useful methods for innovative construction.

(b) With an organized mind, the very process of thought is a deliberate purposeful activity. One would not say that about a disorganized mind. The thought process within a disorganized mind is akin to the random walk.

(c) A rich, organized mind can nurture, nourish and provide the playground for a host of creative habits: in the case of a disorganized mind, creative habits of thought seldom take root.

(d) Wealth creates new wealth. So also it could be supposed that creative skills beget further creative skills.

(e) A rich, organized mind is in a better capacity to deliberately put to use the vast subconscious machinery that is at hand. In contrast, the disorganized mind is more at the mercy of the subconscious.

These two sets of tools, namely indeclut tools and exdeclut tools are probably the first kind of cognitive tools that need to be designed.

3. Tools to Overcome the Problem of Concretes: To address the fundamental problem of concretes (or the problem of induction) requires proper explication of the existing knowledge. This is what the de-clutter tools help establish. They
help establish an organized mind and an organized workspace. This is the pre-requisite for efficient induction. But beyond that how might one help the process of induction? It is my hunch that the process of induction might be enhanced if we knew more about how our subconscious mental processes are organized and interact. In the following paragraphs I lay down a preliminary theory that addresses some of these issues. But whatever be the nature of these tools, I call these the Coginduct Tools. They ought to prove of significant value during the creative leap in design.

4. Tools that address the Problem of Focus/Attention: In order to address the problem of focus/attention, one needs to study the interaction between the conscious (C) and the subconscious (SC) units of the human mind; and the process of habit formation.

Of the two, the C (or the working memory WM) & SC (or the long-term memory LTM), the C is of course the active protagonist. SC is the reactive component, but it has its own unique nature (Fig. 6.3).

These two units could also have one-point sub-feedbacks that refer back to itself. For example, the WM could feed on its own contents. So also, the LTM could fuse and integrate with itself. The first I call, the alpha process, the second, the beta process (Fig. 6.4).
Figure 6-4: Alpha/Beta Processes and Habit Formation

If these point feedback processes do exist, they probably have relevance in the context of habit formation. Habits are automatic daemons sitting in the background, waiting for their cue somewhere from the three main systems namely, the conscious (C), the sub-conscious (SC), and the external world. Habits are formed mainly in the context of single-point feedback loops. However, they may migrate ultimately to the SC. Design of cognitive tools to help enhance the alpha/beta processes could help nurture habits of intense focus and attention. Tools that put in place specific alpha/beta processes I term the $\alpha/\beta$-tools. Also, some of the coginduct tools might perhaps be a subset of the $\alpha/\beta$-tools.

5. Tools to Overcome the Problem of Concept Communication: Concept communication tools are cognitive tools in a social context and hence mostly of the R2-variety. For they span two or more cognitive entities. They help identify the communication context, the target level, the target style, the concept pathway, the communication medium, etc. I call these set of tools the concept-communication, or Concom Tools.

As we mentioned earlier, the best social environment for design is where the concerned people have a good grasp of each others knowledge-humps. In fact, team-building (when stripped to its bare essentials) fundamentally means coming to terms with each others knowledge-humps. In this context, if each team member possesses an explicit knowledge hierarchy, then the team as a whole is able to transact concepts with minimum loss and high signal/noise ratio. In
Figure 6-5: The Cogring

In this context I came up with a concept I call the cogring. It represents the shared conceptual vocabulary amongst a group of people working towards a common goal [Fig. 6.5]. An established and explicit cogring has certain favourable consequences. One of them is the magnification that is evident in work output. For the cogring is the vehicle by which integrated division of labor takes place. What the cogring provides is a shared framework for efficient large-scale problem solving. Problem perception, problem abstraction, design synthesis, design analysis, design communication— these are done at a rapid rate and without misunderstandings and miscommunications. This then is the underlying cause of the cogmag(nification). In such a context, problems are rapidly identified and solved.

As do all conceptual structures, an established cogring has a certain hierarchic structure. In other words there are certain core beliefs that provides the organizing philosophy of the organic and evolving cogring. Define this as the innovation-axis of the cogring. It is the innovation-axis because any change in this core set of beliefs fundamentally changes the very architecture of the interacting team.

Whether explicit or implicit, the establishment of a given cogring is problem driven. It is the nature of the problem at hand that dictates the nature of the cogring to be established.
With or without the cogring, concept communication is essentially an inductive process (although other forms of communication may also be present: ostensive, deductive, emotive, etc). Thus coginduct tools might play a major role in all concom tools. In general concom tools are probably based on the earlier set of cognitive tools and are therefore more advanced.

6.6 Conclusion

In this final chapter we have summarized the main research findings. The bottom line here is the following:


3. Three Methods to find the Archstand: The Inductive, the Abductive and the Integrative.

We then sketched the areas of research that remains to be done. In this context we focused primarily on the conceptual design of cogtools. We discussed the following five cogtools:

1. Exeduct Tools $\rightarrow$ Problem of External Clutter

2. Indeduct Tools $\rightarrow$ Problem of Internal Clutter

3. Coginduct Tools $\rightarrow$ Problem of Concretes

4. $\alpha/\beta$ Tools $\rightarrow$ Problem of Focus/Attention

5. Concom Tools $\rightarrow$ Problem of Concept Communication

In the appendix that follows we put forth a vision for automated construction based on the archstand approach.

6.7 References


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Appendix A

Self Articulating Formwork For Construction Automation

A.1 Introduction

Construction Automation has been a major challenge for more than two decades. Economically, the biggest problem in justifying automation is the lack of scale in the number of similar projects to be executed. Unlike manufacturing, construction projects are typically “one-of-a-kind”. It is therefore difficult to justify the equivalent of setting up on-site of a whole automation factory just to build one project. The fundamental problem is how to adapt the tool, namely the automation system for various sizes and shapes. In the context of concrete construction, the fundamental shape-forming tool is the formwork. “Forms are the tools and dies of concrete construction. They mould the concrete to the desired size and shape and control its position and alignment [Ref. A.1].” In modern concrete construction, the cost of formwork can typically range between 30-60% of the structural cost (80% of which is labor, 20% is material). The question is how to design a formwork system that can articulate and take shape with minimum human labour and maximum variation.

If it is feasible, it might provide the “mass-customizing” answer to the monotony of the cookie-cutter problem in industrialized buildings and facilities, while at the same time affording economies of scale (thus helping overcome the above mentioned “one-of-a-kind”, scale problem) The answer might be found in “self-articulating formwork.” It is basically an assembly of reticulated cells that self-connects and organizes itself as per given shape requirements. Normally architects shy away from the monotony of industrialized facilities. The above system would bring architects on to the side of automation in embracing construction robotics because of the vastly superior variations that such formwork assemblages provide. In the long-run, architects could turn out to be one of the key decision players in demanding construction automation. For at stake is the economic issue of providing “customized” facilities at “mass” prices. Proposed in this appendix is a Self-Articulating Formwork (SAFO) Cell system which could help mitigate construction costs while at the same time offering greater design flexibilities. The archstand under which the SAFO-Cell system has been developed
is: to re-engineer construction from a manufacturing perspective. Construction industry could thus reach the same target that manufacturing is today reaching towards, namely mass-customization of products and facilities (Fig. A.1(a)).

In this appendix, we first look at the automation revolution as replacing manual/deductive labor. Here we use comparative trends between manufacturing and construction in order to induce out the future trends in these industries. With this in hand, we are able to explicate the necessary archstand: to re-engineer construction from a manufacturing perspective. We then look at the logical denouement of construction automation; of the temporal sequence of events we might expect in the near future. Given this context, we then propose the Self-Articulating Formwork technology and design the overall task-planning that is involved in the execution of such a system. We then focus on just one of these tasks namely, the task of cell coupling in order to illustrate in a laboratory environment (using peg-insertion as the generic task), the problems and challenges involved in multi-robot systems that will be involved in the implementation of the SAFO cell system.

While peg-insertion is a generic problem, it provides a convenient template for illustrating the various issues at hand [Ref. A.25]. For example, part assembly using position control is difficult because of the forces generated thru 1): unwanted contact of workpieces that have profile variations, and 2): unwanted contact of workpieces on account of positioning errors. One option is to use some form of hybrid control that senses transmitted forces as well as position in order to control and execute the task. But in this case one could run into problems of system stability on account of non-collocation of sensors and actuators. If however the task permits the two part-mating systems to directly signal to each other, use of a dither motion in one (or both) of the end-effectors (along with appropriate chamfers) could help guide the mating pieces in smoothly. Adopted here is the “bar-coding” approach of a two-robot motion coordination using magnetic sensors and dither. By shaking the end-efforts with a low-amplitude, high-frequency sinusoidal signal, one could overcome simple cases of friction and jamming. The assumption here is that engineering widgets (such as beams and angles in construction) have regular profiles. Cheap “bar-coding” technology exists today to “bar” the widget vertices with magnetic (or other convenient format) information that may be sensed by the coupling widget to help keep track of the relative positions. Thus, instead of costly force-feedback (which is akin to a blindman's use of a walking stick), we can use normal-vision position-control for interfacing the coupling robots. The analogy is that of giving vision to the blind-man, thus helping him off the crutches.

A.2 Automation Revolution as Replacing Manual/ Deductive Labor

Viewed in essentials, teaching a mule to follow a proper sequence of actions while moving earth from one site to another is not fundamentally different from teaching a slave-robot to follow a given trajectory repeatedly (say, while placing stirrups on a
**A1(a): Mass-Customization Trends in Construction and Manufacturing**

**A1(b): Traditional Construction (Projects "One-of-a-Kind")**

**A1(c): Industrialized Facilities**

**A1(d): Design for Maximum Variance using Automated Construction**

Figure A-1: Mass-Customized Systems
reinforcement cage). Thus, in one sense (i.e., the task-planning involved in robotics), the idea of construction automation is as old as the use of draught-animals in construction. But such a comparison is only partial in scope; for the modern ability to specifically design diverse robotic systems (for the specific construction task at hand) simply has no parallel in animal husbandry. The scope and potential of automation in construction is thus total and comprehensive. To appreciate the on-going trends, let us step back and consider the changes over the past 150 years.

Before the American civil-war, before the introduction of the interchangeable-parts manufacture (in the context of the armaments industry), both construction and manufacturing were highly manual, customized and “one-of-a-kind-product” industries. Rifles, for example, were tailor-made to fit the individual characteristics of each soldier. This status of high-customization is as depicted in Fig. A.1(a), in the bottom right. Here the x-axis depicts the degrees and techniques of customization available. The y-axis depicts the degrees and techniques of mass-production. The concentric circles at various corners denotes the contours of the knowledge-architecture that is involved at the various stages; higher the levels of abstraction, greater is the degree of shading.

Under the impetus of the civil-war, the attempt was made by (Eli-Whitney and others) to produce truely interchangeable parts manufacture in the armaments industry. Thus parts that were run-down could be easily replaced without having to discard the weapon in the battlefield. This gave birth to the manufacturing industry as we know it today. The manufacturing practice shifted to the upper-left corner, ready to exploit the economies of scale provided by mass-manufacture afforded by the standardization that resulted from the interchangeable-parts ideology. The paradigm example of this trend was in Henry Ford’s classic “any color, so long as it is black” comment regarding the color-combinations for the Model-T he intended for the mass-market.

Consider now the status of the construction industry. From a historic perspective, the industrial revolution definitely has boosted the scope and productivity of the construction industry in significant ways. For example, the cheap production of cast-iron enabled the efficient spanning of bridges using this material. Steam power enabled the operation of various lock-mechanisms along irrigation and navigational canals. Cheap production of steel enabled the birth of the “lofty” sky-scraper as well as the elegant suspension bridge. Various mechanical power-tools have significantly enhanced construction work productivity. All these are relevant examples of how the industrial revolution affected the construction industry. Yet in a fundamental sense, the intensity and totality with which the economies-of-scale obtained under mass-manufacturing techniques, revolutionized and transformed the manufacturing sector has yet to visit the construction industry. If we look at the recent past, we have had various attempts at industrialized buildings. We have thus had experiments such as the Operation Breakthrough (1960s) in U.S, where prefabrication and industrialization was attempted on a massive scale in the context of residential housing. Although it costs more than $60-million to the Federal budget, it simply did not succeed. And one of the reasons cited has been the monotony of the designs. Ever since that experiment, architects and clients have shied away from the monotony of industrialized
facilities. The statistical sampling of the two styles, traditional versus industrialized, is as captured in Fig. A.1(b&c). Industrialized facilities restrict the flexibilities the system has to offer.

In a fundamental sense, construction has thus remained at the same spot (the lower-right corner) in our Fig. A.1(a). For until the birth of the current robotics era, the flexibility that is needed in the “one-of-a-kind” construction projects has not been addressable except by the dexterity of human hands. But now with the ongoing robotics revolution, we have the historic opportunity to bring about a total revolution in construction. Robotic systems could bring architects on to the side of automation because of the vastly superior variations that such systems provide. In the long-run, architects could turn out to be one of the key decision players in demanding construction automation. For at stake is the economic issue of providing “customized” facilities at “mass” prices. Construction industry could reach the same target that manufacturing is today reaching towards, namely mass-customization of products and facilities.

Both construction and manufacturing are now moving towards the common goal of mass-customization as depicted in the top-right corner of Fig. A.1(a). In this context, both these disciplines could gain from studying methods and techniques from each other. Thus, while manufacturing could gain by studying individuating and customizing methodologies such as the art of programming as used by architects in inducing out the specific requirements of each individual customer, construction could gain enormously by studying the flexible manufacturing techniques. It is in this spirit that we have proposed the SAFO cell architecture. The statistical sampling of the automated mass-customized construction is as depicted in A.1.(d). The flexibilities a system such as this could offer might surpass that of the traditional construction. Before we turn to the SAFO cell technology, let us consider the above changes from a more fundamental point, namely the proper division of labor between the human and the machine.

In hindsight, change often seems sporadic and spontaneous. Yet if one observes closely, one may see that these transistions are not without their logical underpinnings. Each system has only a certain capacity for change. Changes that are targeted at levels more fundamental than existing systems may only be attempted outside the jurisdiction and context of the existing system. Construction automation is not targeted at a level more fundamental than the construction industry as a whole. This change is thus occurring within the context of the construction industry. It is thus not replacing the industry as such, but transforming it. Fundamentally, this shift is replacing human labor at various levels of the construction process. Given the state-of-art of the robotics technology today, certain of the tasks are more easily replaced than others. Tasks that are well-defined, repeatable, monotonous and manual are the first targets for automation. Thus fire-proofing, floor-finishing, wall-painting, etc., are the first-targets in automated-construction. At a different level are analytic tasks (such as FEM analysis, project cost-analysis, geotechnical data analysis, etc.) that are strongly deductive in nature. And once the deductive logic is systematized, it is easily automated.

In contrast, tasks that require human ingenuity and inductive thinking, in prin-
ciple, can never be automated. For the machine operates within the conceptual corpus established by the human. To step outside it, one requires human inductive thinking, not capable within the deductive framework of the machine. Thus architectural tasks such as problem abstraction and creative design (that are strongly inductive in nature) would be outside the reach of automation per se. Both economically as well as logically, induction versus deduction is the proper basis for the division of labor between the human and the machine. Construction robotics in contrast, is targetted at replacing manual human labor.

This then is the overall scope of construction automation. The transition may thus be summarized as follows:

1. Physical Labor:
   - **Traditional Construction**: Human Control with Mechanized, Labor Saving Equipment.
   - **Modern Construction**: Multi-Robot Systems with System Level Human Coordination and Control.

2. Mental Labor:
   (a) **Analytic Tasks**:
      - **Traditional Practice**: Human agents versed in the techniques of analysis and the use of various tools of analysis such as the Finite Element Method (FEM).
      - **Modern Practice**: Integrated Analytic Systems with System Level Human Coordination and Interpretation (such as knowledge-based integrative shells).
   (b) **Synthetic Tasks**:
      - **Modern Practice**: Ad-hoc approaches to human creativity and thus methods of design synthesis.
      - **Future Need**: Approach that views human creativity as a collection of “designerly” habits of thought (such as memory, focus, etc.) that could be taught and learned.

It is in the synthesis of artifacts (whether physical, social or mental) that humans will find their fundamental economic niche as compared with manual tasks or analytic thinking (where the machine has the advantage). Now this does not mean that training and education should focus solely on the synthetic skills. For the ability to synthesize requires a broad range of skills and experience, including things manual as well as analytic. What it though means is that the later two would not provide an economic advantage stand-alone. Thus, of the three, the synthetic skills are primary. Educational institutions thus ought to be cognizant of the kinds of human skills we will be requiring in the not-too-distant future; and thus act to attain it. If the educational institutions pro-actively work towards instilling the various “designerly” habits along with the traditional emphasis on manual skills and analytics, we will not be faced
with the problem of massive unemployment that would result from the introduction of automation in various industries. However, if the current educational bias continues, it is only too certain that the problem of unemployment and labor unrest will raise its political head to thwart attempts towards automation. The fundamental problem in this regard would lie within the educational institution; not within the various industries. It should thus be solved within this sphere, rather than spilling over into the industrial realm. But considering the fact that our current educational systems are notoriously out of phase with the needs of the industry, it is most likely that the problem will be addressed and solved via the various training programs within the industry. In any case, we have now established the overall social perspective in the context of automation. Let us now focus on the logical denouement of construction automation.

A.3 Logical Denouement of Construction Automation

Presuming that there are no major conflicts of interest (such as the fundamental fear that the introduction of robotics will result in wide-spread unemployment), let us now consider the problem of the logical denouement of the introduction of automation in construction. Here we may follow two basic concerns:

1. the comparative economic or market viability (or market pull) of a given transition.

2. the comparative technological viability (or technology push) of the given transition.

The comparative economic analysis of the various tasks to be automated does provide a logic as to which aspects to automate first. The comparative technological analysis of the various tasks provides us a rationale as to which tasks are technologically feasible with respect to off-the-shelf technology as compared to tasks that need major R&D effort in order to successfully automate. Of course, these two are not independent: they do interact. Thus a recognition of the technological viability does enhance the market viability; and vice-versa, a recognition of the market potential does create enough momentum to lower the technological barrier. Thus there is constant feedback between these two perspectives.

These two modes of analysis may be plotted as shown in Fig.A.2. On the x-axis is the dollar estimate of the cost input: the amount of technical research & development effort required to overcome the technical problem of automation, the capital investment in the technology, etc. On the y-axis is the cost output: the cost-savings at the market front from introducing the specific item of automation. These cost-savings could result from a combination of financial interest savings due to quicker completion of the project, cost-of-labor savings due to replacement of expensive manual labor, insurance and legal savings due to enhanced safety on the site, long-term maintenance savings due to higher reliability of systems and components assembled via automation, etc. Supposing that the state-of-art in robotics technology has been mapped
Figure A-2: Logical Denouement of Construction Automation
close to the origin along the x-axis, one would then expect a profit-maximizing contractor to opt for region-1 in the map. For it has the maximum gain: maximum output for minimum input. One would thus expect the construction industry to scope out region-1 before scoping out any other adjacent regions. Having scoped out region-1, each contractor, depending upon his assets and capabilities, might choose various local trajectories. Thus bigger firms might pro-actively opt for a long-term plan of moving both horizontally as well as vertically on various fronts. Smaller firms would be averse to moving too far horizontally; thus they would be constrained to traverse the vertical dimension. Specific strategies depend upon the micro-analysis at the firm level. At the industry level one could nevertheless say that in the initial stages, the top-left is more attractive for the industry as a whole as compared to the bottom-right.

In addition to the above two modes, we may also recognize a third modality, namely:

- the fundamentality, or the over-arching nature of the problem under consideration.

More fundamental the problem, greater is the (potential but uncharted) scope of the applicability of a solution to it. Also more fundamental the problem, greater is the risk of market mis-match. Thus if the option is to attempt problems that have equal gain (equal dollar input to dollar output) but differ in their fundamentality (i.e., one is more fundamental than the other), chances are that one would opt for the more fundamental provided one is convinced that indeed the problem that has been identified is truly representative of the market at hand. Validating the problem statement here requires application of analytic methods such as methods of inductive proof (for problem abstraction is fundamentally inductive in nature). Note that in the above context, the dollar estimates are being made within a specific problem context. For if we were to delimit the problem context, the fundamentality issue would collapse to that of greater paybacks from the greater scope (a scope that is often potential, and therefore not well known) of the solution (if it were found). We may plot the fundamentality issue along a third axis as shown in Fig. A.3. The preferred region would thus be the shaded cube as shown in the diagram.

Unfortunately, the three-dimensional graph does not provide any real insights into the problem of how to judge the issue of fundamentality. In order to bring out the basis of the fundamentality criteria, one has to somehow grasp the fundamental versus the non-fundamental. For example, how is it possible to indicate that solving problems at the systemic level (for example, the coordination and control of a system of multiple robots) is more fundamental than solving a given robotic task (say, that of fire-proofing).

It is possible to plot all three modalities using a one-dimensional conceptual network via the framework of the design trace. This is as shown in Fig. A.4. The design trace is essentially the plot of the problem solving process along the abstraction hierarchy. The abstraction hierarchy is outlined as the pyramidal hump indicating the fact that within a given knowledge domain, concepts are organized in a hierarchical fashion, with a given higher level concept subsuming more than one lower level
Figure A-3: Addition of the Fundamentality Dimension
Figure A-4: Use of the Design Trace in Mapping Fundamentality
Figure A-5: The Design Trace

concept/concrete (hence the pyramidal nature). The assumption here is that human knowledge is hierarchical. A simple example of the abstraction hierarchy might be (living-organism(plants(conifers...), animals(mammals, reptiles, insects,...))). The vertical dimension indicates the abstraction "hierarchy." Thus the concept "animal" is more abstract and fundamental than the concept mammal.

As we mentioned in chapter 1, the horizontal "axis" in figures like Fig. A.4, is not really an axis that measures any given metric; it is instead an identity "axis" used to indicate that things along this axis have different identities. Thus depending on the context, it could be made to represent various metrics (for example, project cost incurred by design decisions at a certain abstraction level).

Let us recall the various aspects of the design trace architecture from our introductory chapter (chapter 1). The process of design (and in general, the process of problem solving) definitely occurs within the context of the knowledge hierarchy; but this does not preclude the need sometimes to induce out new concepts. The design trace captures the fact that every problem of design undergoes the following steps (and not necessarily in the same order):

1. Problem Perception

2. Problem Abstraction
Figure A-6: Multi-Robot System Architectures

(a) Problem Abstraction Synthesis
(b) Problem Abstraction Analysis

3. Design Proper

(a) Creative Leap
(b) Design Synthesis
(c) Design Analysis
   i. Validity Analysis
   ii. Decompositional Analysis

4. Design Communication

5. Market Feedback

This is as captured in Fig. A.5. In essence one recognizes that solving problems in design requires perceiving that the problem exists, abstracting it out to a general enough level by teasing out the causal connections (thus capturing the full context of the problem), the conceptual design (i.e., the creative leap), the detailed design, the communication of the design, the implementation and market feedback. For a more exhaustive exposition on the above framework, please refer back to chapter 1.

Now coming back to Fig. A.4, we have here two design-trace illustrative examples that have been plotted in order to indicate just how the design-trace analysis might be
used to compare different technical and market options along with the fundamentality issue. One of the problem is the one about multi-robot system integration; the other is about robotic fire-proofing of steel-frameworks. The first is generic and therefore fundamental in nature; the second is specific and thus less fundamental in nature. The left-arch of the design trace captures the market-viability of a solution to the problem; thus the basal cross-section of the trace could indicate whether the problem does/does not scan a substantial market need. It thus is made to match the metric along the y-axis (i.e., the cost savings from solving the problem) of Fig. 1. Thus for example, in the case of multi-robot system integration problem, a solution to this problem could in principle be applied within diverse contexts (for example, multi-robot materials handling in a warehouse, multi-robot shell system articulation, multi-robot space-station assembly etc). A firm that is specializing in this arena could potentially apply its technology in all these diverse contexts. In contrast, the problem of fire-proofing is specific in its scope; it probably therefore has limited market viability. But note that this hypothetical analysis is merely a sketch of how one might go about using the design-trace analysis. It could very-well be that the actual dollar figures to be reaped from fire-proofing far exceeds that to be made in the context of multi-robot systems integration. A true picture would arise only when we have the actual estimates of (industrial) dollar figures on the potential market scope. This however, is beyond the scope of the current study.

In a similar manner, the basal cross-section of the right-arch could be made to indicate the technological effort needed to solve the problem that was posed along the left-arch. Thus for example, the figure indicates that the solution to the multi-robot integration requires far more technical effort as compared with the fire-proofing problem. This may be because the technology that is presumed in the case of multi-robot system integration is rather intricate and involved (for example, the sheer amount of computations involved in collision-avoidance and path-finding may be combinatoric and thus time-wise exorbitant), or it might be that the state-of-art of the technology is such that there are major technical road-blocks that first need to be overcome before one may conceive of a total system solution. In comparison, the technological problem of fire-proofing is rather straight-forward and fairly repetitive.

What we have done in the above analysis is to connect the epistemological process of problem solving with the costs that are involved (both input as well as market payback). While the cross-sectional metric that we use has to be normalized with the actual costs, we are (via the above analysis) able to pin-down and plot the dollar-costs (of the project, from design decisions) along one side of the trace-hierarchy, while along the other side we capture the market payback information. In general one wants to minimize the cross-section along the right-arch, maximize the cross-section along the right arch, and try to attempt the most general problems in order to capture the maximum solution potential. While traditional optimization schemes work within a given problem context; here we also ask ourselves whether we are working on the right problem. Of course, as the market evolves, the top priority problems get solved first (assuming that the risk of market mis-match has been factored in); that which remains are the low-priority problems that provide marginally lower returns on investment. But under increased competition, there will be firms that will take the risk and try to
get paybacks from even these marginal options. In any case, construction automation is nowhere near such a state; it in fact is in the preliminary stage of establishing and solving the first batch of problems. With the above context, we shall now look into the fundamental problem of coordinating multi-robot systems in construction. The question as always is to find a problem that maximizes the left arch (and is also true and fundamental enough), and a solution to this that minimizes the right arch. We think that given the state-of-art of the robotics technology, that the coordination of multi-robot systems in general is one such problem. Let us now look at the problem of coordinating multi-robot Systems.

A.4 Coordinating Multi-Robot Systems in Construction

A given construction project consists of multiple tasks (for example, excavation & ground work, foundations, super-structure, electrical/mechnical, interiors, etc). Each of these may in turn be decomposed into sub-tasks that are fairly repeatable between projects. In general, the principle involved in successfully robotizing a complex and "one-of-a-kind" construction project is to decompose the primary task to a level that is fine enough to reach a granularity that is repeatable between successive projects. Having decomposed it to the required level, the problem then arises as to how to coordinate and control these various robotic sub-systems into an overall integrated system.

There are various approaches to tackle the problem of multi-robot system integration. In principle they may be classified into the following three categories:

1. Centralized Coordination: Here, a centralized control-system does the data-aquisition and coordination of the various robotic agents in the given construction environment (Fig. A.6(a)).

2. Distributed Coordination: Here each of the robotic agent is individually responsible for all of its decisions and has the knowledge and capability to interact with its local environment (Fig. A.6(b)).

3. Hybrid System: Here the robotic motion is divided into "gross" and "fine" motion. The gross motion is coordinated in a centralized fashion (Fig. A.6 (c-i)); while the fine motion is the responsibility of the individual agents that have the knowledge and capability to interact with the local environment (Fig. A.6 (c-ii)).

Of the three, the hybrid federal system (Fig. A.6 (c)) provides the advantage of overall systemic coordination at the gross level, coupled judiciously with local decision making at the fine level. Thus the sensory mechanisms that the individual robots have to be equipped with need only be designed for tolerances in the fine motion context. Centralized coordination at both the gross as well as the fine level motion demands centralized precision technology at all levels regardless of the actual need. Decentralized coordination, on the other hand, is burdened with computing and executing path-trajectories at every level of the robotic path. Such a strategy would
demand precision equipment capable of ranging over the totality of the environment to coordinate and execute its motion without conflict with others. In contrast, the hybrid system would require that components need to be equipped with sensible identification “beacons” at strategic locations (such as the corner nodes) that help figure out the relative positions of mating pairs when they are proximous. Such identification beacons could be as simple as the magnetic doping of the component corners which can then be detected by magnetic reed sensors or Hall-effect sensors to calculate the relative positions without coming into actual contact. Moreover, this technology is fairly cheap (less than 25-cents per sensor and fairly off-the-shelf technology), and thus satisfies our cost-criteria along the right arch, namely minimum cost. All said and done, the hybrid system seems to be the best approach to coordinate large numbers of robotic systems as envisaged on the construction site. Our prediction is thus that in a complex “one-of-a-kind” project such as a construction project, industry will adopt a hybrid system for coordination and control.

At the logistics level, we have the problem of materials handling on the construction site. Components that have already been magnetically (or otherwise) “bar-coded” have the necessary “identity” that they can now be kept track of as it moves through the site and warehouses. In other words the bar-coding technology can be extended not merely for just tracking the material through the total system, but also for its final robotic positioning. Since these two operations are closely related, it pays to integrate the two. Such components may be called “smart components” on account of the fact that it contains “intelligent” parts embedded within it.

At a different level of the logistics equation is the tracking of construction materials that need to be brought together from various parts of the globe. Steel, copper, cement, granite, marble, tiles..., these are manufactured on an international stage, and have to be assembled onto a single site in a timely, coordinated fashion. If the materials are packaged in an “intelligent packaging unit,” the most-current status of the package could be encoded onto it by the shipping agent and read-off by a tracking system patented along the Global Positioning System (GPS). The idea is to close the gap between the material and the basic information file pertaining to it.

At the maintenance level, our “smart components” can be embedded with cheap but reliable status-broadcasting electronic hardware (such as stress-sensors at strategic locations) which later may be read by monitoring robotic agents. These are some of the ways in which one might envisage how the automation revolution is going to transform the construction industry. Let us now consider the proposed Self-Articulating Formwork (SAFO) cell system in detail.

### A.5 SAFO Technology

In its bare-bones format, the self-articulating formwork technology consists of a set of rigid plates (called SAFO-cells; SAFO for “Self Articulating Formwork” cells) that can:

1. Move under central command, and position itself against other similar pieces.
2. Interlock with adjacent pieces and create revolute joints at the interstices.

3. Having interlocked, achieve a target overall shape.

4. Maintain that target shape with least expense of energy.

Suppose the target shape was a shell structure (Fig. A.7), similar to the Kresge Auditorium or the Sydney Opera House. Initially the SAFO-cells are packed away in some convenient pile for easy storage. Under central radio-control, they start moving onto a highly structured work-space where they will then come together and interlock and start actuating against each other and against the supports in order to slowly take the final shape. Having reached the target formation, they are then transported from the dedicated and structured workspace onto the final construction site. After this, the inside of the unit is sprayed for providing a thin non-bonding chemical layer for ease of later separation between concrete and formwork. Reinforcements are then placed as usual; and concreting is done. After the concrete has set (the formwork could also be designed for ease of curing using water circuits embedded within the SAFO cells), the formwork units are decoupled from the monolithic structure and returned to the dedicated forming workspace. Here, again under central command, the SAFO-cells decouple systematically step-by-step, and pack themselves in an organized fashion for re-use.

To prove the concept we need to show that two such units can indeed come together and interlock. If two can do it, then so can many. The pre-assembly motion that is required by the SAFO-cells may be assumed to be simple reticular/cartesian. Thus during pre-assembly, the SAFO-cells require ability to commute over short and highly-structured distances (gross motion). However once they are nearly in contact, the SAFO-cells need to position themselves (fine motion) and inter-lock in such a way as to create the revolute-joint that can be actuated from one of the coupling cells. It is this part of the overall assembly task that we shall attempt to imitate in the laboratory.

After assembly, the system should act as an integral whole, transferring forces and moments mainly through membrane and support action rather than through the actuators. The actuators are designed to automatically position the relative position of the inter-locking cells. Having achieved the proper configuration, passive inter-locking support elements should engage in order to transfer inter-cell reactions without further expense of energy.

A.6 Task Planning

In the above sections we laid out the motivation as well as the overall system design. Herein we look at some of the details. The technical proving of the overall project concept may be divided into three phases:

1. Basic Technology: In order to prove the feasibility of the concept, we first need to demonstrate the underlying robotic technology. The basic SAFO-cell structure is envisioned as consisting of the following subsystems:
Figure A-7: Self-Articulating Formwork System
Figure A-8: Task Planning
Figure A-9: Basic Coupling Design
Figure A-10: Project: Lab Mimicry of SAFO-Cell Coupling
Figure A-11: Modeling, Analysis and Control
(a) *The Traction System (TS):* for gross and fine motion that bring the mating cells adjacent to each other.

(b) *The Self-Actuating Coupling System (SACS):* that part of the SAFO-cell responsible for the relative organization between the SAFO-cells. Two cells having positioned themselves for interlocking, the SACS then takes over from the traction-system and creates the inter-cell joint that is capable of achieving the proper relative cell organization.

(c) *The Support System (SS):* Having achieved the requisite relative cell organization, the support-system should take over and provide for efficient means of transferring the intra- and inter-cell forces and moments.

2. **Multi-Robot Systems:** Having demonstrated the basic technology, we then need to show what is involved in commanding and controlling a multitude of such SAFO-cells in systematically coming together and organizing into an overall target shape-system. Such a problem is in the aegis of large-scale systems: command and control [Ref. A.10-22]. The problem at hand is the fundamental architecture of a multi-robot system which could easily comprise of more than a thousand SAFO-cells.

3. **SAFO-Cell Family:** Having demonstrated the basic technology, as well as the means by which to control their large-scale system articulation, we now turn to the issue of SAFO-cell shape-grammers. What are the basic cell-structures which when brought together, could achieve a variety of target shapes? What freedom of expression does SAFO-cell technology provide the architect? While the underlying basic SAFO-cell technology remains invariant, the liner that is carried by the cell can be re-fitted to produce a variety of shape-architectures. For example, properly designed fiberglass reinforced polyester panels could economically be molded into a variety of reusable shapes [Ref. A.4]

Figure A.8. provides the generic set of tasks that need to be planned for in the self-articulating formwork construction. The overall command and control is via radio control. In all there are twelve tasks that the SAFE-cells need to execute:

1. **Stack to Workplace Motion (Gross Motion):** Here the SAFO-cells move down from their respective stacks, fit themselves with their respective liners, and move over to the dedicated workspace in an organized, army-like, orderly fashion. In other words they maintain proper distances between them during this gross-motion.

2. **Cell Pairing (Fine Motion):** During this action, the various SAFO cells take up their respective positions ready for cell coupling.

3. **Cell Coupling (Fine Motion)**: During this phase, the cells come together one at a time and couple to form the SAFO-mesh.

---

1It is this task we shall demonstrate using two-robot motion coordination. For details please refer section A.7
4. **Insertion and creation of telescopic/revolute joint:** After the cell coupling is complete, the female-cell inserts the telescopic joint thru the recently aligned hinge-elements in order to form the revolute joint. Future articulation will take place around this revolute joint. Thus this telescopic joint needs to be designed strong enough to transfer the torque (that will be later involved) as well as light enough for the telescopic insert. Furthermore there needs to be a locking/unlocking mechanism at the free end.

5. **Cell Articulation:** This is the major task whereby the unformed mesh as a total system starts to articulate and take shape. Depending upon the target shape, there would be a logical sequence of individual cell articulation and support action.

6. **Support:** Having articulated, the respective actuators could disengage provided there is some mechanism to transfer the various forces within and between cells. Formworks typically have to hold their respective shapes for considerable lengths of time until the concrete has set. Also the forces involved (during and after concreting) is considerable enough that it might be best to make use of (auxiliary) support skeletal work to collect and transfer the involved forces.

7. **De-Support:** Here the context is that the concrete has set and is strong enough to support itself. We are now in the formwork stripping phase. Forms could either against the mature concrete in order to loosen itself from the monolith. Joint actuators could power up and get ready to transfer intra-cell forces. Certain of the support mechanisms could withdraw to free-up the assemblage.

8. **De-Articulation:** The mesh as a whole could then start collapsing and de-articulating. Although de-articulation might follow its own logic, it most probably would have a reverse logic compared to the articulation phase.

9. **De-Insertion of Telescopic/Revolute Joint:** Having collapsed, the revolute joints between cells could withdraw to start the disengage and tearing process.

10. **De-Coupling (F.ire Motion):** Here the moving-cell moves away normal to the cell edge. The dis-engaging cells could also use dither to help dislodge each other.

11. **Parade Assembly (Fine Motion):** This is the army-like “falling-in-line” task that the cells organize into, in order to start the “return-to-stack” motion in an orderly fashion.

12. **Return to Stack (Gross Motion):** This is the equivalent of the “dismiss” task in an army context, whereby the cells return to their respective stacks for maintenance, storage and repair.
A.7 Two Robot Motion Coordination Using Magnetic Sensor and Dither

The cell-coupling task (Task 3 above) is very much similar to the peg-insertion problem in modern assembly. The laboratory robotic project is designed to mimic this task specifically. In the actual task, the cells have to align themselves within a given tolerance before proceeding to begin the insertion task. Figure A.9 shows the respective positions and natures of the two-cell assembly. By using dither in one of the mating cells, problems like friction and jamming could be overcome more easily. Accordingly, there are four types of cell-inserts (see the notation in Fig. A.9):

- Female sans dither
- Female with dither
- Male sans dither
- Male with dither

In the laboratory experiment, it is the “female with dither” case that has been implemented. However, there is a research question in this regard namely, is it better for the male cell or the female cell to undergo dither? Or is it best that both dither together? My hypothesis is that it would depend on the insert shape grammers.

Figure A.10 shows the task as it is mimicked in the laboratory project. Here the two, two-linked lab robots have been aligned to more or less begin the task insert. Robot B represents the “female with dither,” while Robot A represents the “male sans dither”. We will use a magnetic reed contact switch to detect the moment when the insertion pins have aligned for task insert. When the two elements have been aligned, the attached A/D convertor should read zero. The magnetic reed switch is a very cheap (costing only $6.00/-)\(^2\)yet sufficiently reliable and robust sensing device that is not hampered by dust and other obscuring facets of the work environment. But care must be taken in interpreting the sense data (as discussed in section A.9). The magnetic switch is attached to the end-effector of Robot B. It sits ensconced in the hollow cylindrical end-piece into which the rod attached to Robot A is to be inserted. At the tip of the rod is the cylindrical magnet. When the rod (i.e., the peg) and the cylinder attached to B are centerlined, the reed switch reads zero.

The task to be mimicked is then is as follows:

1. **Step One:** Robot B positions itself in its insert position (i.e., the gross motion control).

2. **Step Two:** Robot A positions itself off-center to B in order to begin the data-sensing task. Call this A's initial position.

\(^2\)An even more cheaper and reliable technology is the Hall-effect sensor that costs less than 25 cents.
3. Step Three:

(a) Phase I Sweep: Robot A then sweeps transverse to Robot B’s arm axis while collecting reed-switch data. This step may be repeated a number of times in order to average the data to reduce noise. In retrospect, because the data obtained was so reliable, a single sweep would have been more than sufficient. In the implementation we have the arm averaging over five data-sets.

(b) Phase II Sweep: Having collected the reed-data, Robot A continues the sweep action until it reaches a set point on the other side of the Robot B arm. Call this the final position for Robot A. This is done in order to overcome positioning error during the data-collection stage. Otherwise positioning error might lead to insufficient clearance during the return sweep to initial position.

(c) Phase III Sweep: Robot A then returns to the initial position.

(d) Phase IV Insert: Robot A then interprets the data to locate the precise position at which to insert. Robot A then begins the insert motion while B goes into a dither mode of low-aptitude, high-frequency sine-motion.

Note that only the controller for Robot A is reading the reed-switch. When it has gathered sufficient data and positioned itself for the task insert, it then signals Robot B’s controller to execute the dither mode. This is done by sending a digital signal (Binary 0001) to B’s DAS-1601 A/D port. The A/D port is being used because the two D/A convertor slots are been used for controlling the two-link actuator motors. However it should not be a problem receiving a digital signal at an A/D port because all that we are interested in signalling is the exact time when A intends to begin the insert task and thus requires B to start dithering. This is the basic method by which both computers are synchronizing. In real-life, the communication between the SAFO-cells could be via a local hierarchical coordinator [Ref. A.10].

A.8 Modeling, Analysis and Control

The basic control algorithm uses the inverse dynamic model of the lab robot along with its attachments. It includes damping and friction compensation as well as compensation for inertial coupling torques as well as centrifugal torques. The program uses iterative control to achieve a desired accuracy as specified by the maximum Euclidean Norm between the target and the actual positioning. The algorithm iteratively generates and implements new trajectories based on the current and the target position until the norm has been satisfied to a desired accuracy. This approach can quickly reduce positioning errors to the Euclidean Norm set at 1-2mm deviances. This is the basic approach to guarantee fine-motion control. The control system is as shown in Fig. A.11.

Friction is modelled as Coulomb Friction and is given by \( \tau_{frict} \text{sign}(\dot{\theta}) \) where \( \tau_{frict} \) is the magnitude of Coulomb friction (as given in Fig. A.11.). To compensate for
inertial and centrifugal torques we use the inertial parameters of the robot plus the
attachments. Once again they are as listed in Fig. 6. The generalized forces in the
relative coordinate system is [Ref. A.25]:

\[
Q_1 = H_{11} \ddot{\theta}_1 + H_{12} \ddot{\theta}_2 + h \dot{\theta}_2^2 + 2h \dot{\theta}_1 \dot{\theta}_2 \quad (A.1)
\]

\[
Q_2 = H_{21} \ddot{\theta}_1 + H_{22} \ddot{\theta}_2 - h \dot{\theta}_1^2 \quad (A.2)
\]

where

\[
H_{11} = M_1 L_{c1}^2 + I_1 + M_2 (I_1^2 + L_{c2}^2 + 2L_1 L_{c2} \cos \theta_2) + I_2 \quad (A.3)
\]

\[
H_{12} = M_2 L_1 L_{c2} \cos \theta_2 + M_2 L_{c2}^2 + I_2 \quad (A.4)
\]

\[
H_{21} = H_{21} \quad (A.5)
\]

\[
H_{22} = M_2 L_{c2}^2 + I_2 \quad (A.6)
\]

\[
h = -M_2 L_1 L_{c2} \sin \theta_2 \quad (A.7)
\]

Here \(M\)'s are the link masses; \(L\)'s the link lengths; \(L_{c1}\)'s etc., the lengths to the center
of mass; \(I\)'s the moment of inertia. For details of the derivation, please refer to [Ref. A.25]. On account of the design of the robot arms, there is no gravity term in the
above equations. The actuator motion \((\theta_{1m}, \theta_{2m})\) relate to the relative angles \((\theta_1, \theta_2)\) as follows:

\[
\theta_1 = \theta_{1m} \quad (A.8)
\]

\[
\theta_2 = \frac{28}{34} (\theta_{2m} - \theta_{1m}) \quad (A.9)
\]

Robot A is designed to track straight-line trajectories. Thus given the initial
and final positions, the trajectory generator can calculate the desired straight-line
trajectory for appropriate velocities. Robot B is designed to track both straight-
line as well as dither trajectories. Straight-line tracking involves iterative control.
while dither trajectories involve single-loop control. Considering the minuteness of
the vibratory dither amplitude, it is already close to the desired Euclidean norm.

A.9 Sense Data Interpretation

The data that is sensed by the reed-switch for a typical pass is as given in Fig. A.11. It
starts off at a zero value very close to the initial position for Robot A. It then follows a
parabolic path and reaches a maximum value of 200 millivolts just before the switch
finds itself aligned with its counterpart. The switch then rapidly drops to a zero-
output and holds that level until it is outside the direct vicinity of the counterpart.
It then ramps up again to the +200 level. Care must be used in interpreting the data
because of the fact that it starts off very close to the required zero-value. Apparently
there exists sufficiently powerful magnetic fields in the vicinity of Robot B initial
position, created by the direct-drive motors that induce the reed-switch attached to
Figure A-12: Sense Data Interpretation

Robot B to read zero when A is at its initial position. But as Robot A begins its sweep action, this extraneous influence is rapidly overcome. Henceforth the switch data behaves as expected. Thus in interpreting the data, it is important to ignore the initial zero-value which happens around time-index of 5. The various segments on the reed-data is as follows:

1. OA: Segment where reed-data drops to zero-value (Index 0-5).
2. AB: Segment where reed-data parabolically rises to 200+ value (Index 5-135).
3. BC: Segment where reed-data sharply drops to near-zero value (Index 135-140).
4. CD: Segment where reed-data maintains its zero value for the length of the sweep where the mating items are closely aligned. Midpoint of this segment is where we wish to begin the insert operation (Index 140-240).
5. DE: Segment where the reed-data rises sharply once again to its 200+ value (Index 240+).

Our task is to detect the begin and end of segment CD. We do this by first identifying point B, the highest value attained before the elements are aligned. The next zero reading is our point C. Once we are in segment CD we wait until the signal starts rising sharply again, thus indicating the end of segment CD.

Properly interpreting the sense data is crucial. In retrospect, it was this task that took most effort during the coding and debugging stage of the project. Until the
actual magnetic profile was plotted, it was not clear why robot A kept performing
the insert action at point A rather than at midpoint of CD. It was as if the robot
senses were cross-eyed.

A.10 Implementation/Results/Discussion

As such the parts to be inserted have sufficient tolerance between them (3.3 mm)
to easily perform the task insert (see Fig. A.10). However by winding tape around
the inserting rid, the tolerance can be reduced to the 2mm range. With such a
tolerance the task insert often fails. It is perhaps in this stage that dithering is of
value. Accordingly four experiments were performed to see the value of dither in
task-insertion:

1. Expt I: High Tolerance Insertion (3.3 mm) without dither.

2. Expt II: High Tolerance Insertion (3.3 mm) with dither.

3. Expt III: Low Tolerance Insertion (2.0 mm) without dither.

4. Expt IV: Low Tolerance Insertion (2.0 mm) with dither.

Experiments I & II were fairly easy for the robotic setup. Given the high tolerance, it
achieved task insert consistently regardless of the presence of dither. Fig A.13. shows
the plot of the insert task for Expt II³. The diagonal sweep starts at the bottom right
in the plot. By the time it has finished the data-collection action of Phase i, there is
significant positioning error which needs to be corrected (Phase II) before the return
to the initial position (Phase III). Also plotted is the final segment of the Phase IV
insert task. If this insert were blocked due to jamming or friction, the bold segment
that is tracking the dotted line would be seen as a dot. In our experiment, such is
not the case, thus confirming task-insert success.

Contrast this with Fig. A.14. wherein is plotted the results from Expt III which
is low-tolerance insertion without dither. Firstly the dotted line of Phase IV insert is
badly off from the ideal normal, indicating that the insertion task has badly jammed
and deflected the work-pieces towards the top-left. Secondly, note the mere speck
indicating that there is virtually no motion possible. Low tolerance insertion (Expt.
III) did not succeed.

In Fig. A.15. we plot just the Phase IV final insert trajectories for Expt IV
(Low Tolerance with dither). Here the scale is magnified, thus positioning errors may
seem too large. But the graph shows that the motion is not blocked, thus confirming
the value of dither. Futhermore the skewness could be because the fairly compliant
insert rod is following the target profile of the inside of the cylinder rather than the
theoretical target trajectory.

Figures A.16 & A.17 show the world-view as seen by Robot B for dither Experi-
ments II & IV respectively. The problem of jamming creates fluctuations in actual

³Notation: The dotted line is the desired trajectory; the bold line is the actual trajectory
position only in the very early stages of the task insert. Once the mating pieces are
more-or-less inside one another, there is less occasion for jamming. Also Expt IV re-
sults show greater fluctuations as compared to Expt II, indicating the greater difficulty
of task insert with low tolerances.

Our results show that our strategy of using the "bar-coding" technology of mag-
netic reed switches along with dithering can actually mitigate the basic problem of
fine-motion control. Specifically,

- that the task insert is more difficult with low tolerances.
- that the insert task is most difficult during the very early stages as compared
to the later stages.
- that properly interpreting the sense-data is crucial. That one needs to extraneous
magnetic fields that might skew the results.
- and finally that providing dither may help overcome problems of friction and
jamming.

These preliminary experiments where by way of proving the "off-the-shelf" technology
that exists today. Further work needs to be done in making an economic case for the
SAFO-cell technology. Specifically, how much would a full-blown system cost; and
how does it compare with the current manual system? These questions could perhaps
be answered more accurately in an industrial setting.

A.11 Conclusions

In this appendix we projected the on-going trends between construction and manufac-
turing in order to abstract out our archstand: re-engineering construction from a
manufacturing perspective in order to deliver mass-customized systems. We then spe-
cialized this archstand in the context of concrete construction by proposing the Self-
Articulating Formwork (SAFO) cell system. We analysed the SAFO-cell approach
and put together the overall task-planning. We then focused on a single task and
mimicked it successfully in the laboratory setting. Our strategy consisted of using
the "bar-coding" technology of magnetic reed switches along with dithering in order
to perform the task of peg-insertion (designed to mimic the cell coupling task).

One of the techniques that was suggested, but couldn't be implemented for lack
of time was to study the effects of chamfering on the tolerance hurdle that could
successfully be overcome. This shall be taken up in a later study.

All said and done, the basic technique of motion coordination using a magnetic
sensor like the reed-switch is similar to the bar-coding technology. Given the fact that
most engineering profiles are regular geometries, it is fairly easy to dope the shape
vertices with some digitized and easily detectable information. Using this information
as orienting beacons, one ought to be able to achieve task assembly fairly easily.

Placing this project in the overall context of automated construction, one sees it is
merely the first step towards the SAFO-cell technology. If the SAFO-project succeeds,
Figure A-13: Expt II: High Tolerance with Dither

Figure A-14: Expt III: Low Tolerance without Dither
Figure A-15: Expt IV: Low Tolerance with Dither

Figure A-16: Expt II: High Tolerance with Dither (Robot B Data)
Figure A-17: Expt IV: Low Tolerance with Dither (Robot B Data)

It could substantially help the construction industry in bringing down material and labor costs via re-use and automation. The economic incentive is there; the aesthetic incentive is there. What is required is the technology to put together the formwork construction tool.
A.12 References


