Design of Constructive Design Processes

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1. Introduction

The purpose of this article is to formalize (design) a design process as a constructive process. We discuss "design" in its widest sense : If we divide design into two categories, grand design and specific design, this article is on the former. Designing a new system/mechanism or a new architecture is within our target, while designing a specific machine or an individual building is not.

In the above sense, a design process is a creative or constructive process. A design process starts from a concept or description of a desired function and tries to find a system that realizes it. Therefore, we will first talk about constructive processes before we define design and formalize the design process.

2. The Sciences of the Artificial

Natural sciences, physics in particular, are the study of the laws governing our world. It starts from natural phenomena and tries to reveal the underlying mechanisms which created the phenomena. In other words, natural sciences start from already existing phenomena or mechanisms and divide them into their parts. They are called analytic in this sense. Descartes [1] is one of the earliest who formalized the method for those sciences : Given a complex phenomenon, we divide it into simpler sub-components and tries to understand the simpler parts and relationships among them ; The process is repeated until each sub-component is simple enough to reveal the law that governs the component.

The study of artificial things is somewhat different. First of all, the direction of construction of artificial thins is almost reciprocal [*1] to analysis of natural phenomenon. We start from simple elements and combine them to form more complex artifacts. The key problems are the selection of the initial components and the way they are combined. Note that neither of them is given in contrast to natural science where all components are given *a pri ori*. Formalization of the constructive processes is the main purpose of this article and we will come back to this issue in section 4.

Harvard Simon named the field as "the science of the artificial" [2] contrasting it to the science of natural phenomenon. He claims (a) that everyone designs who devises courses of action aimed at changing existing situations into preferred ones, and (b) that schools of engineering, as well as schools of architecture, business, education, law, and medicine, are all concerned with the process of design.

There are several synonyms to "construction". "Creation" and "synthesis" are among them. We avoid using "creation" since "creative process" has another connotation related to "creativity" or "innovativeness". "Synthesis" may be a better candidate since it is usually contrasted with "analysis", for example as in "analysis by synthesis". However, when the word is combined with "design", "synthetic design" may have connotation related to synthetic materials or chemistry.

The reason we choose to use "constructive" is existence of "constructive mathematics". According to Stanford encyclopedia of philosophy [3], it is defined as follows :

> *Constructive mathematics is distinguished from its traditional counterpart, classical mathematics, by the strict interpretation of the phrase "there exists" as "we can construct". In order to work constructively, we need to re-interpret not only the existential quantifier but all the logical connectives and quantifiers as instructions on how to construct a proof of the statement involving these logical expressions.*

3. Design

We define design as construction of a new system that has some preferred function or feature. To think about a new function or feature is also (part of) design. "New" is simply defined as something that did not exist before. Under this definition, construction of a new system without intent is also

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[*1] As we describe later, construction and analysis are not precisely reciprocal each other. Our study shows that analysis is a part of constructive process.

called design. Animals are designed through natural selection processes without any intention.

Similarly, intentional unintentionality, decision of no action, is also a design. For example, bonsai, Japanese tree shaping art, is one form of design, but the decision of doing nothing and let the tree grow is another form of design. There is also some intermediate stage where only some of environmental parameters, like lighting or room temperature, are manipulated. They are not direct manipulations of tree shape but an indirect one leaving some room for the nature to take over some part. The hand of nature is an essential part in ceramic or pottery art, and also in calligraphy. There are also many other kinds of spontaneous art where contingency plays important roles.

Furthermore, "verbalizing design is another act of design" [4]. Verbalization is a step toward making the process explicit and shareable. We will focus on this in section 5.

We should also distinguish grand design, design of a type from specific design, design of individual entities. Designing a new type of objects that did not exist or thought about before is a very difficult and creative process. But when a design method of a type is known, then there can be a procedural method to design one instance of the type. The former is an instance of grand design and the latter is an instance of specific design. Designing a rotary engine, for example, is creative while improving its parts is rather routine work of designers.

When we consider grand design, a totally new design may only be found through (random) generate-and-test. But once a new type is found, we can formalize it define a new type. A design of the type is then procedurally (algorithmically) applied for individual designs of many instances. There may be many objections to the view that grand design, or innovation, is achievable only through generate-and-test. Many researchers believe it possible to teach, enhance and systematically support creativity. Before we engage in this discussion (at the end of section 5), let us formalize constructive processes.

4. Constructive Process

We are interested in construction of a new system.

It is generally understood that construction is a reciprocal process to analysis : Analysis is from the whole to the parts and construction is from the parts to the whole. This may sound obvious when we think about plastic model kits. When we buy a kit, the whole set of parts are prepared and we connect them together.

However, in reality, we found it different. First of all, when we design a new system, necessary parts are not known yet. Only after we have enough knowledge on the new system, we can identify necessary components and make it a routine work. To have knowledge, we have to analyze the system. Here comes the second point. Analysis must be a part of construction (Fig.1.) [5]. Thus we can say that analysis is a part of construction.

Let us take an architect as an example. When an architect is given requirements (desired features) of a new type of a

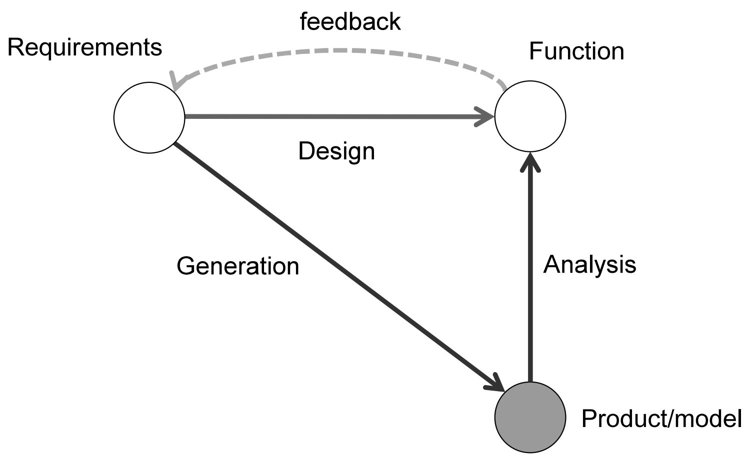

Fig.1. F-diagram of constructive processes

building, he cannot directly design the perfect one on a paper for the first time. Trial and error loop is unavoidable. He first constructs a model [+2] . He then analyzes the properties of the built model. If the result of the analysis satisfies the original specification of requirements and constraints, the design is complete. However, this rarely is the case. There are some differences from the original specification. Then the whole cycle recurs by changing the model to meet the specification. Sometimes, the original specification may be updated reflecting some findings from the model.

Note also that F-diagram applies to the process of theory forming of natural scientists as well. Model generation can be mapped into experiments, and a specification is mapped into a hypothesis that must be proven through experiments.

Actual systems we construct are usually complex. A system is complex when it is build (and therefore should be understood) of multiple layers of sub-systems. For example, a building consists of multiple floors (or stories), which in turn consists of rooms and corridors, which in turn consist of doors, walls and ceilings. A wall consists of some combination of base materials. They may form an arch to support heavy constructions or they may form some other architectural structure.

We are trying to formalize construction of such multi-layered complex systems by extending the F-diagram. To understand the concept of multi-layered system, we found the concepts of noema and noesis [6] useful. Suppose one is playing a piano.

There are two levels involved : one is the conceptual level of music, and the other is physical level of play, including motion of the player and the piano. The player first plans to produce certain music. This plan of the music is in the conceptual level, called a *noema* . Since the concept is not realized yet, we call it a *future noema* . He then begins to realize the music by playing the piano. This activity is called a *noesis* . His activity interacts with the environment, including the room and audience, and actual music is produced. The player then listens to the music he produced. The conceived music is called a *current noema* . The player must readjust his plan (music to be produced) according to the generated music. And this loop continues.

[+2] The “model” here should be understood in a very broad sense. It may be a small scaled model or it may be a real building. Anything but the final version falls into this category of models, and it even covers real buildings with people actually living or working in it.

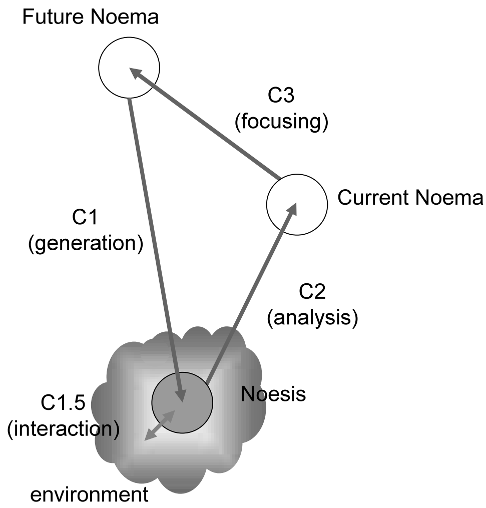

Fig.2. FNS-diagram

The following is a constructive loop in general explained in terms of noema and noesis (Fig.2.) :

(C 1) A noesis is generated from a future noema.

(C 1.5) Generated noesis interacts with the environment and produces some phenomena. This interaction with the environment is both the source of new emergent property [+3] and the obstacle that makes desired result difficult to obtain.

(C 2) Generated phenomenon, larger than noesis, is then analyzed to produce the current noema.

(C 3) Since obtained current noema is different from planned future noema, the future noema must be readjusted. This is the most difficult and creative process. A new future noema is created and the loop recurs.

Existence of (C 1.5) interaction with the environment is a very important phase in the process. If this interaction is small and virtually negligible (as presupposed in experiments of physics), then we can take some deductive approach to run the constructive loop. If all related parameters are known and numerical, then we can take optimization method formalized in operations research. However in reality, this interaction cannot be neglected. To be worse, we do not know related set of parameters beforehand. We cannot circumscribe related elements or limit the affected region. It is only after the analysis phase (C 2) that we know related parameters and

[+3] As we described in section 3, this is where “hand of nature” plays important role in ceramic or pottery art, or in calligraphy.

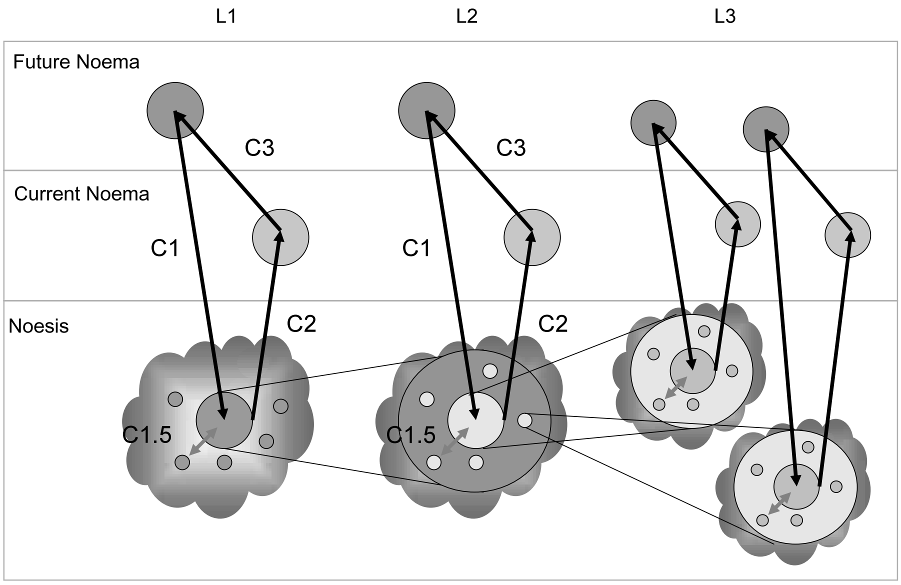

Fig.3. Multi-layered FNS-diagram

consequences. The problem is well known in AI community as the frame problem [7].[+4] This is one of the reasons we claimed (at the end of Section 3) that only generate and test is a feasible strategy for innovative design.

Because of C 1.5 unwanted interactions may occur. In that case, we have to change our plan, the future noema. How? Study of complex systems tells us that any small change in the future noema may cause unbounded amount of change in the noesis. Therefore, adjustment on the future noema may have to be repeated until we get desired current noema. This process may result in complete change of the conception scheme and produce totally different noema. We believe that there is no systematic procedure for C 3. Only a loop of generate (C 1) and test (C 2) is possible. C 3 defines what to generate next from a wide range of alternatives. Thus we call C 3 "focusing".

In the above description, only two levels, music level (noemas) and play level (noeses), are involved. If the system consists of more layers [+5], we will see a hierarchy of nemeses and corresponding noemas. Fig.3. shows multi-layered FNS diagram. Left-hand side shows a higher layer and right-hand side shows a lower layer. A noesis in the higher layer is decomposed into several parts in the lower layer and each of them has its corresponding noemas. In the diagram, we focus only one (in L 2) or two (in L 3) of them. Other parts become part of environment surrounding and interacting with the noesis in focus.

Let us consider the same case of playing the piano as an example. L 1 is the "music" layerl (conceptual music as a noema and actual play as a noesis). Actual play in L 1 is then decomposed into the piano and the player in L 2. From the viewpoint of the player, the piano is a part of the environment here. The player is further decomposed into his brain, the body, arms and fingers in L 3. Noeses in all layers as a whole form a tree structure connected by "part-of" relationship.

Note that they are systematically connected only in the noeses level. Noemas for each layer have looser connection. They may or may not be independent each other. In other words, each layer corresponds to different cognitive levels and they follow different rules. Description of music and description of body movement are in different description layers and there are no logical or causal relations between them : The behavior of the upper layer cannot be reduced into the behavior of the lower layer. Yet, there is some relationship between them. We call it "vertical causality" [8]. It is called vertical because the

[+4] It is worthwhile to point out that this problem is found when they tried to design intelligence machines. The problem could not be found in the long tradition of either analytic science or philosophy.

[+5] We use "level" to differentiate noema and noesis. We use "layers" to distinguish different conceptual layers of the objective systems.

relationship connects different layers. We do not precisely know the relationship or we do not have any descriptive language to define the relationship.

Vertical relationship nevertheless is one of important one in design. When a designer wants to realize some function, and when that function cannot be straightforwardly implemented by a noesis within the same layer, then the designer must go to a lower layer. A simple example is driving a car. If you want to run fast through a curved mountain road, you cannot stay within "driving" layer. You have to go down to the lower layer to plan (a) turning wheels, (b) select gear position, (c) applying proper amount of gas, or (d) stepping on the brake pedal. The relationship between the fastest path through the mountain road and your driving activities (a) to (d) is not clear. This relationship is what I call a vertical causality because it can be talked in the same vocabulary of usual causality − the car skidded "because" you applied too much acceleration, or "to" run the car smoothly you should be delicate on the acceleration pedal, etc. You may have to practice or try some new technique because vertical causality is hard to understand or realize.

5. The Design

What is the essence of the activity called design (let us call the essence "the Design")? This is a meta-level question on design − design of design. The theme of this special issue is one further up in the *meta* hierarchy − What is "design of design"? What do we have to do to understand design of design? Let us consider some characteristics of the Design.

First of all, the Design and the technology to support its realization are complementary each other. They cannot be separated. A design is meaningless if it cannot be implemented using existing technology. Research and development of technology should also be guided by good design. Of course there are bottom-up characteristics in basic research and they should not be neglected. Nevertheless top-down guidance is equally important.

The author's research background, for example, is information technology (IT). The research of the author focused on new design of social systems that are only achievable with full use of IT. It is different from computerizing existing system. A new system must be designed with regard to the full capacity of IT.

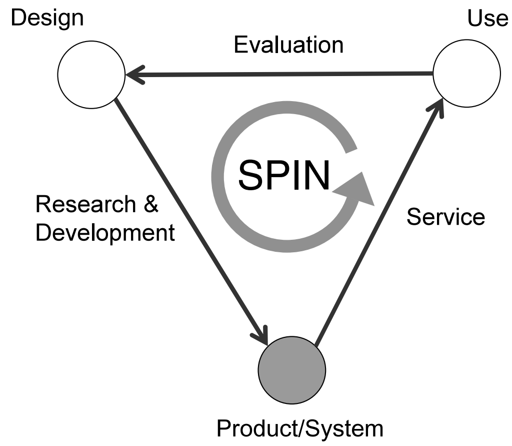

Fig.4. The service loop

Secondly, the Design should be a part of a service loop [+6] of the designed product (Fig.4.). It forms a develop-service-evaluate loop. Or in case it requires further research, construct part is further decomposed into research-construct-evaluate loop. Therefore, design process can be understood as one of constructive processes formalized as our FNS-diagram. Let us use an example of airplane. Boeing or Airbus (designer) designs and then develops a new airplane. An airplane (product) is owned and operated (service) by airlines like JAL and ANA. Their service is evaluated by users. This evaluation unfortunately includes occasional accidents. Experiences from service are fed back to design of safer and better airplane.

Let us review the loop from a larger perspective. Technology produces alternatives, humanity selects and puts it into service, and science evaluates the result.

The third point is on the methodology for the Design, in particular innovative designs [9]. As we formalized in section 4, the Design is a constructive process. Transition C 3 of Fig.2. is where creativity is called for. If there is a systematical method, like optimization method for specific designs, then it can be achieved somewhat mechanically. This kind of optimization method is also teachable. However, on the other hand, if a new jump is required, we have only two ways : (1) rely on random generation, and (2) rely on human intuition, which we know nothing about. Either solution cannot be taught systematically. True innovation is just an outcome of a random jump.

[+6] "Service" here means to actually put the product into use.

6. Summary

We claimed that the Design is a constructive process and formalized the process. The Design and the technology to realize it are complementary each other. There is no royal road to the Design, but a loop of generate and test, which we formalized as FNS-diagram. Finally we claimed that design should be a part of a service loop.

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