DESIGN: LOGIC, ILL-STRUCTURE AND CREATIVITY*

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ABSTRACT

Based on the recursive logic, a formal explanation is given to the ill-structureness and the creativeness of design. The ill-structureness is attributed to the undeterminancy of recursive logic and the creativeness is supposed to come from the nonlinearity implied in the recursive logic. The relationship between ill-structureness and creativeness is then discussed.

Keywords: recursive logic, ill structured problem, creativity, chaotic dynamics

The objective of this paper is to investigate the structure of design and the creativity in the act of design. The basis of this research is the recursive logic[1], which has been extended to the logic of nonlinear phenomenon[2]. We first introduce the more complete and perfect form, finished recently, of recursive logic. Then the reason why design is an ill structured

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problem is formally analyzed. The recursive scheme and the ill-structureness naturally relate design to the theory of chaotic dynamics, thereupon, the widely talked intuition to design creativity can be construed theoretically. In the final part of the paper, it is pointed out that the ill-structureness is one of the most important features to make the designing creative. This work provides the formal remedy to empirical studies of design, and may shed some light on the computer simulation of creativity.

IMPROVEMENT OF RECURSIVE LOGIC

In our further research[2,3] on the recursive logic, some concepts in paper[1] have been perfected in terms of the systems theory[4] and the design terminology, as a result, the structure of the logic becomes more explicated.

New Model of General System

Any system, as we all know, can be defined as 'a global set of components or elements related to each other and interacted with environment'[4]. Generally, it is divided into three parts including the input, the structure ('form' in our case. In the paper, these two words may be referred as the same thing) and the output as shown in Fig 1. The structure of a system refers to the form or

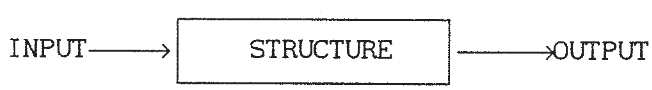


Fig 1. GENERAL SYSTEM

the sequence in temporal and spatial arrangement among the parts or elements. It is that very structure of a system to guarantee its totality and functions. The input and output of a system is due to the interaction between the inner structure of the system and the external environment, whose order and capacity are called the function of system. The definition of 'system' given above, therefore, can be mathematically expressed as

$$\Pi=\langle S, R^{S}\rangle \quad (1)$$

$$\Pi=\langle F, U\rangle \quad (2)$$

$$U=\langle I, O\rangle \quad (3)$$

where Π stands for a general system, **F, U, I, O** denote the structure, the function, the input and the output of system, respectively, **S** is the set of all elements or subsystem included in system with R^{S} being their interaction.

It should be pointed out that several changes occur here to the original definition[1]. First, system function lies in not only its output but its input as well, both of which result from the interaction between structure and environment. Output is just considered to be the system performance. Second, the hierarchical construction of system is taken into consideration besides its operational definition (2) that plays an essential role in the proposal and definition of the recursive logic. It is obvious that the expression (1) is a commonly adopted definition of 'system'. As is based on the concept of 'elements' or 'components' which are themselves systems, this definition is something of recursion. For practical purpose, a decision should be first made on the extent to which 'elements' or 'components' are understood not necessarily through defining them as system, but arguing them in a descriptive way. In this paper, 'elements' or 'components' in this level are called atomic systems. This understanding is similar to the description of hierarchical systems by Simon[5].

Another improvement in system definition is the perfection of the structure or form of a system. Hinted by the system evolution theory[6], we further assumed that the form of a system is generally determined by its quality and quantity. The former refers to the morphology of a system while the latter refers to the measurement of the system states under the given quality. The quality of a system depends directly on the quality of its elements and their temporal and spatial order in the system. That is,

$$Q_s=\phi(Q_{ei},O_{ei}) \qquad i=1,2,\dots,n \qquad (4)$$

where Q_s stands for the quality of system structure, Q_{ei} represents the quality of elements and O_{ei} denotes the elements order making up the system form.

It should be emphasized that the quality of a system is defined relative to particular requirements. One kind of quality may be more abstract than another and can be taken as the genus of the latter[7]. If we put all the quality of a system into an unified schema, we can get an infinite hierarchical structure with the higher layer element more abstract. Take Newton as an example, we may say Newton is a people and so 'people' can be seen as his quality. At the same time, 'scientist' may be also defined as the quality of Newton as something. Keep on listing all kinds of quality of Newton, we have Fig.2. When necessary,

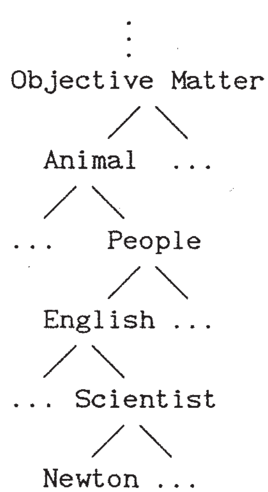


Fig.2 THE QUALITY OF NEWTON

we use Q_s^m to represent the quality dominating Q_s and use

$$Q_s^m \Rightarrow Q_s \qquad (5)$$

to represent that 'Q_s^m deduce Q_s'.

For the term to be used more naturally in design discipline, we replace 'quantity' by 'attribute' in this paper, which doesn't matter critically, accordingly, the form **F** of a general system can be defined as a turple of quality and attribute. Denoting attribute as **T**, we have,

$$F=\langle Q_s, T\rangle \tag{6}$$

Take the structure shown in Fig.3 as an example, the measure(a,b) of the

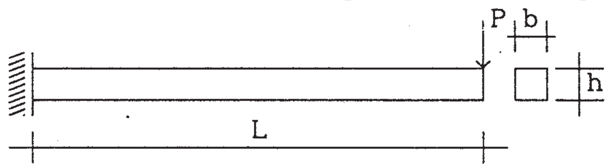


Fig. 3. STRUCTURAL SYSTEM

section, the length(L) of the beam and the external force(P) exerted on the structure fall into attribute category. The abstract concept 'beam' is the form of this system. The detailed explanation of this definition is not our concern here.

Furthermore, as we discussed[1], the environment **E** in which a system works can be said to include the natural laws L_e and the natural actions A_e , that is

$$E=\langle L_e, A_e\rangle \tag{7}$$

and the law L_e is made up of two parts, depending on the the quality of system structure, as shown in (8)

$$L_e:\ \text{if}\ Q_s\ \text{then}\ P_f \tag{8}$$

where P_f is the behavior rule existing in environment, corresponding to all potential qualities (infinite, indeed) of **F**. The behavior rule P_f consists of the external actions A_e and the response of the system R_f, following the form in (9):

$$P_f:\ \text{if}\ A_e\ \text{then}\ R_f \tag{9}$$

Besides, the system structure and environment also have to be taken into account to more precisely specify the function of system. The expression (3) should be altered to include the involved components of system and environment, and the function in this case is called the objective function because of the objective nature of environment **E** and system structure **F**. Denoting objective function as U^o, we have,

$$U^o=\langle F, A_e, R_f\rangle \tag{10}$$

where

$$I=<F,A_e>$$ (11)

$$O=<F,R_f>$$ (12)

In concluding, a general system $\prod$ in environment E can be defined as in (13),

$$\prod=<E,F,U>$$ (13)

When artifacts are involved, however, there will be some change in context. The artifact should be studied also as something to satisfy the human requirements. The main difference, in fact, lies in the definition of function as human beings become one part of its environment so that their value judgments have to be taken into account. Our consideration in this paper is to introduce subjective function as the interaction between the system and human beings. It can be viewed as a profit constraint on the objective function in that it evaluates the objective function from many aspects such as commodities, firmness and delight required in architecture design[8]. As an example, 'the maximum displacement in a structure is confined to be less than D_{max}' is a subjective function that acts on the objective function 'the maximum displacement in the beam is d_{max}'.

The other important feature distinguishing these two functions is their qualities. The quality adhered to subjective function is more abstract than that of the objective one. As in the aforementioned example, the quality of the subjective function is 'the displacement of general structure' while the one of the objective function is 'the displacement of the beam'. Denoting this subjective function as U^s, constraint as P and the quality as Q_s^m, we have

$$U^s=P(U^o,Q_s^m)$$ (14)

and the function becomes

$$U=\{U^o,U^s\}$$ (15)

The system $\prod$ so specified is called an artificial system.

Recursive Logic

According to the definition of system given above, the deductive law dominating the system behavior assumes the following schema:

$$\begin{array}{lll} \textbf{CAUSALITY:} & & \\ \text{If} & IP \le \langle F, A_e \rangle \ (I) & \\ \text{Given} & L_e: \ \text{if } \langle F, A_e \rangle \text{ then } \langle F, R_f \rangle & \\ \text{Then} & OP \le \langle F, R_f \rangle \ (O) & \end{array} \tag{16}$$

We can understand this schema from another viewpoint by combining the behavior rule illustrated in (7) and (8) with the definition of objective function in (9) to (11). As such, the alternative behavior rule of new form becomes

$$L_e: \ \text{if } F \text{ then } U^o \tag{17}$$

which means that the modified causality formulae may be stated as the system will function according to its behavior rule (17) provided that its form is specified, that is,

$$\begin{array}{ll} \textbf{Minor Premise:} & F=\langle Q_s, T \rangle \\ \textbf{Major Premise:} & L_e: \ \text{if } F=\langle Q_s, T \rangle \text{ then } U^o=\langle F, A_e, R_f \rangle \\ \textbf{Conclusion:} & U^s=P(U^o, Q_s^m) \end{array} \tag{18}$$

It is obviously that the causality in (16) is implied in (18), the difference among them lies in that the latter rearranges the terms defining system in argument with the emphasize placed on 'form' and 'function' instead of physical behavior. With this in mind, the recursive logic can be represented as

$$\begin{array}{ll} \textbf{Minor Premise:} & U^s \\ \textbf{Major Premise:} & L_e: \ \text{if } ?F=\langle Q_s, T \rangle \text{ then } U^o=\langle ?F, A_e, R_f \rangle \\ \textbf{Conclusion:} & ?F \end{array} \tag{19}$$

The change in this schema compared with the definition in reference[1] comes from the separation of subjective function from objective function with the nature of logic consistent.

Then the recursive inference can be restated as follows, which is important for later discussion. The form of system can be reducibly resolved as

$$F^{n} = (F^{0},\ F^{n-1}) \tag{20}$$

$$L_{e}^{n} = (L_{e}^{0},\ L_{e}^{n-1}) \tag{21}$$

with the atomic design set F^{0}

$$F^{0} = \{a_{0},\ a_{1},\ a_{2}, \ldots,\ a_{n}\} \tag{22}$$

satisfying the causality in (18). The qualities of all atomic design are deduced from the quality of the subjective function Q_{s}^{m},

Minor Premise: $F^{0} = <Q_{s}^{0}, T^{0}>$ (23)

Major Premise: L_{e}^{0} : if $F^{0}=<Q_{s}^{0}, T^{0}>$ then $U_{0}^{o}=<F^{0}, A_{e}^{0}, R_{f}^{0}>$

Conclusion: $U^{s} = P(U_{0}^{o}, Q_{s}^{m})$

Similarly, the inference process can be constructed as follows:

1) Substitute (20),(21) into (19)

Minor Premise: $U^{s}=P(U_{n}^{o}, Q_{s}^{m})$ (24)

Major Premise: L_{e}^{n}: if $?F^{n}=(F^{0}, F^{n-1})$ then $U_{n}^{o}=<?F^{n}, A_{e}^{n}, R_{f}^{n}>$

Conclusion: $?(F^{0}, F^{n-1})$

2) Substitute (23) into (24)

Minor Premise: $U^{s}=P(U_{0}^{o}, Q_{s}^{m})$ (25)

Major Premise: L_{e}^{n-1}: if $?F^{n-1}$ then $U_{n-1}^{o}=<?F^{n-1}, A_{e}^{n-1}, R_{f}^{n-1}>$

Conclusion: $?F^{n-1}$

3) Repeat 1), 2) until n = 1.

It is verified[2] that the above process satisfies the condition for an inference to be recursive, which was put forward by Smith *et al*[9]. Obviously, although the undeterminancy of the recursive logic embody a great deal of free will in design, the design is constrained ultimately by the quality Q_{s}^{m}.

ILL-STRUCTURE OF DESIGN PROBLEM

Since the first extensive discussion of Ill-Structured-Problem by Reitman[10], some more efforts, such as that of Newell[11] and Simon[12], have been devoted to this problem. More recently, based on Simon's observation, Chan[13] put forward a cognitive model of design, followed by the protocol analysis of a case. All the above work provided the excellent speculation on the empirical features of design, and the current design studies have benefited from them very much. But why are these the case? Is it possible to formally prove these hypothesis and speculation? These questions are very emergent for deeper and further study of design. This is just the tentative task of the present part. We'll try to formally justify them in the light of the recursive logic.

Definition of Design Problem

To understand problem structure, Reitman[10] represented a problem with a turple [A,B,⇒] taken together with its associated requirement in which 'A' and 'B' stand for initial and terminal states, respectively, and '⇒' denotes a process or sequence to convert 'A' into 'B'. Departure from here, he further gave another five kinds of problems, and when talking about design he said

> Being asked to "compose a fugue" or to "design a vehicle which propels itself" would seem to pose formally similar kinds of problems. In all of these cases, as they are stated explicitly, we are asked to begin with nothing in particular and to transform it into (i.e., to create, invent, or discover) a terminal object or state which itself is defined only with respect to certain very general terms or conditions it must satisfy....In this case, since the the object has yet to be invented, the terminal object B is less well specified. As for A, it is left completely up to us.

In defining design problem, Simon[12] gave the similar comments,

> The architect begins with the sole problem of designing a house. The client has presumably told him something of his needs, in terms of family size or number of rooms, and his budget. Additional specification will be obtained from the dialogue between architect and client, but the totality of that dialogue will still leave the design goals quite incompletely specified. The more distinguished the architect, the less expectation that the client should provide the constraints.

These statements precisely delineate the situation designers faced, and may be taken as the fundamental description of design problem. It perfectly corresponds to the recursive logic. The initial design requirements, which comes from human needs and are the mere explicitly described constraints before design begins, are the very subjective functions U^s and, therefore, the minor premise of the recursive logic, as is aforementioned in (19). The remainder of design constraints is deduced from the following design process and can not be explicated in this state of designing. The freedom is left to designers and, obviously, different architect will bring about different new constraints corresponding to objective functions, with the form he(she) will create.

On the other hand, the quality Q_s^m of the subjective function U^s confined the possible candidate forms the designers will create. The intervention must be made of the free will and the design function. In Reitman's case, the result of design will be no other than 'music' or 'vehicle' which are the general quality of the encountered design. The same is true of the act of architect. We can represent "house design" as follows, Minor Premise: U^S=<house-design,house> (26)

Major Premise: L^n_e: if house-form then <house-form,house-design>

Conclusion: ? house-form

Hence, as the design solution and the complete design criterion and constraints are generated simultaneously, design problem is ill structured fundamentally, and naturally obeys the recursive logic.

Recursive Definition of Design Form

The key feature of the recursive inference for design is the recursive definition of design object and constraints. To facilitate the designing, the designer has to first resolve the the design object and constraints according to the resolution of the quality Q^m_s. Simon[12] portrayed house design as

> "house" might transform to "general floor plan plus structure", "structure" to "support plus roofing plus sheathing plus utilities", "utilities" to "plumbing plus heating system plus electrical system", and so on.'and 'The requirements that any of these components should meet can also be evoked at appropriate times in the design process, and need not be specified in advance.

This is precisely the same definition form in (20) to (22). We may redefine "house design" formally as

$$F^0 = \{\textbf{support,roofing,sheathing,plumbing,heating-system,...}\} \qquad (27)$$

$$F^n = \langle \textbf{house} \rangle = \langle a_0, \textbf{house} \rangle,\ a_0 \in F^0 \qquad (28)$$

With every atomic design, there are a set of constraints adhered to it. Take **support** as an example, it is first required to safely resist the loading imposed on by upper structure, then the candidate material will be another consideration, and the related constraints also include the construction process, the environmental condition, etc. As design proceeds, this kind of constraints come into the design problem automatically with the atomic design selected.

Recursive Resolution of Design Problem

As is described, the ill structureness of design problem just qualifies itself with the recursive logic. So the recursive inference can be naturally turned to do design. In this schema, the "house design" problem can be solved as follows,

Atomic Design:

Minor Premise: $F^0 = \langle Q^0_s, T^0 \rangle$ (29)

Major Premise: L^0_e : if $F^0 = \langle Q^0_s, T^0 \rangle$ then $U^o_0 = \langle F^0, A^0_e, R^0_f \rangle$

Conclusion: $U^s = P(U^o_0, Q^m_s)$

Inference Process:

1) Substitute (27),(28),(29) into (26)

Minor Premise: U^s=<house-design,house> (30)

Major Premise: L^{n-1}_e: if house-form then <house-form,house-design>

Conclusion: ? house-form

2) Repeat 1), until n = 1.

In this manner, the design problem is transformed into a set of well structured problems expressed in (29), just as Simon[12] argued,

> The whole design, then, begins to acquire structure by being decomposed into various problems of component design, and by evoking, as the design progress, all kinds of requirements to be applied in testing the design of its components. During any given short period of time, the architect will find himself working on a problem which, perhaps beginning in an ill structured state, soon converts itself through evocation from memory into a well structured problem. We can make here the same comment we made about

playing a chess game: the problem is well structured in the small, but ill structured in the large.

The difference between Simon's proposal and our scheme lies in problem resolution. In Simon's case, design was taken as 'Whether organized as a system of productions or as a system of subroutine calls, the evocation of relevant information and subgoals from long-term memory can be *sequential*." As a result, 'Interrelations among the various well structured subproblems are likely to be neglected or underemphasized. Solutions to particular subproblems are apt to be disturbed or undone at a later stage when new aspects are attended to, and the considerations leading to the original solutions forgotten or not noticed.' But, as the conception of recursion implied, we assumed the existence of a stack in human mind to manipulate the complex objects and their interrelations, which render the design process nonlinear and parallel. The two potential threatening to design are not the nature of design but the fragileness of human memory relative to the recursion depth.

On the other hand, it is the different strategy of recursive resolution that constitutes an essential factor which makes different designers get different design proposals. The resolution strategy can be looked as the style in design suggested by Simon[14], which expresses itself in the inclined choice of atomic design. We can see it clearly from Simon[14]

The richness of the combinatorial space in which the problem solver moves, then, rather than the number of elementary components he has at his disposal, is the hallmark of design activity. By virtue of this richness the designer must search selectively; for among the immense--and possibly available to him, he can examine only a tiny number. The designer exercises choice, hence introducers style into style into his design.

After all, both in problem representation and solution strategy, the recursive logic can formally represent the design problem, and it matches the empirical studies of design well.

CREATIVITY IN DESIGN

A great deal of research works have been done on human creativity, which covers philosophy, psychology, computer science and so forth, ranging from the phenomenon[16,17], the nature[18], the cognitive model[16,19] and the mechanization[15] of creativity. But by now it still remains in empirical level. Recently, as the artificial intelligence has found some successful applications, peoples are not satisfied by the computer simulation of human routine behavior any more. The formal studies of creativity becomes urgent. In the present part, we shall investigate the formal structure of design creativity, based on the research of recursive logic as the underlying logic of nonlinear mechanism[2]. The creativity appears when the chaotic motion occurs to the structure.

Empirical Observation of Creativity

To understand design creativity, one should first answer the question: what are the basic features and characteristics of creativity? Or in other words, what are the differences between the creative act and the noncreative one? However, in here we do not intend to look into this problem but review others' work as our departure.

Indeed, it is difficult to define creativity precisely. Even it seems undefinable for if it can be unvaguely understood it will fall into the category of the logic schema (by logic here we mean the traditional causality) and therefore is no different from the noncreativity. This just gives rise a dilemma. As a result, peoples usually can only describe it in this or that manner, just as S. Amarel[15] said,

> There is no general agreement on the nature of creativity or the characteristics of a creative act. Such an act is often surprising, has elements of a new approach, and is not stereotypic. Beyond these phenomenological properties, one finds that a creative act has a strong element of synthesis. It is usually associated with ill-defined goals or it involves reformulation of externally imposed goals. Some students of the human mind feel that formation of powerful imagery, abstraction to appropriate spaces, flexible associations, and rich generation of analogies are key elements of creative processes.Others feel that,in addition to these elements, some mysterious, unexplainable processes control the genesis of ideas and insights in man's creative process.

In a recent paper by Akin[16], based on the empirical observations on creativity, he gives several common points of creativity:

o creativity arises under special conditions
o creativity is manifested through a product or act
o creativity spans a considerable range of activities and products from the arts and everyday occurrences
o the product of a creative act is novel and unusual in some sense
o it is possible to discern some gradation of creativity among these acts and

products at least in terms of their social or lasting values

As the title of the paper implied, our main concern among all the above aspects of creativity will be focused on the first one as most researchers do.

Tentative Interpretation for Creativity

Instead of attributing creativity to intangible reasons or divine inspiration, which can be found in many situations, we shall try to explicate the creative design process. Considering the dilemma one confronted with in defining the creativity, one can see that the difficulty stems from the endeavor to construe it in the logic scheme of deduction. Our research disclosed that the recursive logic just underlies the creative act for it is implied in chaotic dynamics which naturally brings about the surprising and abrupt occurrence of creativity.

Chaotic dynamics and recursive logic

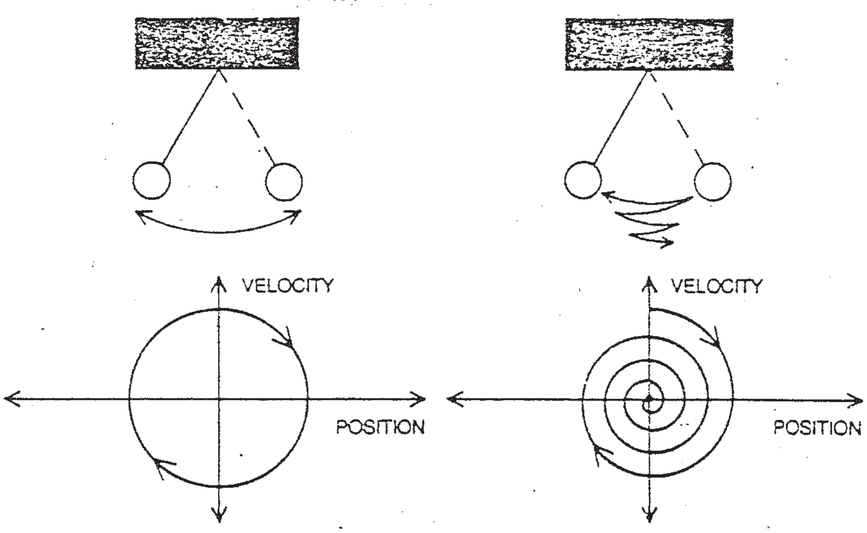
Classical sciences were built up on the basis of deterministic law, from which the Laplace's statement was deduced that

> The present state of the system of nature is evidently a consequence of what it was in the preceding moment, and if we conceive of an intelligence which at a given instant comprehends all the relations of the entities of this universe, it could state the respective positions, motions, and general affects of all these entities at any time in the past or future.[20]

But it was challenged at the turn of the century by the French mathematician

Poincaré in that certain mechanical systems whose time evolution is governed by Hamilton's equations were found to display chaotic motion.[21] Seventy years later, the meteorologist E.N.Lorenz[22] found that even a simple set of three coupled, first order, nonlinear differential equations can lead to completely chaotic trajectories. By now, it is widely recognized that this phenomenon is abundant in nature and has far-reaching consequences in many branches of science.

One can understand chaos from the theory of dynamical systems (For detailed introduction of the chaos, we refer readers to an excellent paper by Crutchfield *et al*[23]). A dynamical system consists of two parts: a state and a dynamic. One can visualize the evolution of a system obeying the dynamic in its state space. In the state space, the behavior of the system can be represented in geometric form. Any system that come into stable motion with the passage of time can be characterized by an attractor in state space, in which rest is an extreme case. There are many forms of attractor with the fixed point, limit cycle and torus as the known basic three. Take the simple pendulum shown in fig.4 as an example, when the pendulum moves under a



a) FORCED PENDULUM b) FREE PENDULUM

Fig. 4. ATTRACTOR FOR PUNDULUM WITH FRICTION

periodically acted force, then it is attracted to a limit cycle, otherwise the fixed point.

The most fundamental characteristic of chaos is its sensitive dependence on the initial conditions. A small fluctuations can be amplified in its time evolution, in which the qualitative change occurs to the considered system. The fact can be clearly explained by considering the map

$$x_{n+1}=f(x_n) \tag{31}$$

which leads to chaotic motion. The initial difference ε between states is amplified to the separation $\varepsilon e^{N\lambda(x_0)}$, as shown in Fig.5. As a result, because

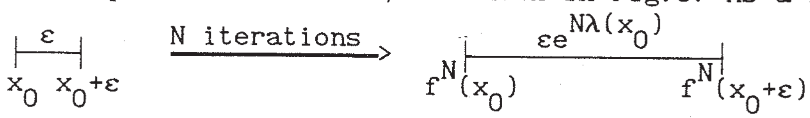


Fig. 5. CHAOTIC MOTION

a system may have several attractors, the system may evolve to different attractors under different initial conditions.

However, not all nonlinear dynamical equations will bring about the chaotic motion. An important element in chaotic dynamics is the existence of a simple stretching and folding operation in the state space. 'Exponential divergence is a local feature: because attractors have finite size, two orbits on a chaotic attractor cannot diverge exponentially forever. Consequently the attractor must fold over onto itself. Although orbits diverge and follow increasingly different paths, they eventually must pass close to one another again. The orbits on a chaotic attractor are shuffled by this process, much as a deck of cards is shuffled by a dealer. The randomness of the chaotic orbits is the result of the shuffling process.'[23] Indeed, the stretching operation can be seen as the nonlinear term in evolution equations, which make the orbits diverge exponentially, while the folding operation just corresponds to the bounded domain of the orbits and can be taken as the scattering term in evolution equation, which keep the orbits from infinitely divergence.

In H.G.Schuster's book[24], it is pointed out that a common feature of the dynamical systems is that they can be characterized by low-dimensional first-order differential equations

$$\dot{\mathbf{x}}=\mathbf{F}(\mathbf{x},\lambda);\quad \mathbf{x}=(x_1...x_d) \tag{32}$$

that are autonomous and nonlinear.

These equations lead to chaotic motion if an external control parameter λ is varied. Furthermore, the equations (32) are often conveniently studied via the corresponding (d-1)-dimensional Poincaré map

$$\mathbf{x}(n+1)=\mathbf{G}[\mathbf{x}(n),\lambda];\quad \mathbf{x}(n)=[x_1(n)...x_{d-1}(n)] \tag{33}$$

which are obviously recursive formulas.

Up to this point, we can rewrite the formulation for recursive logic and recursive inference in (19)-(25) as

$$F(n+1)=\mathbf{G}[\mathbf{F}(n),\mathbf{U}^{\mathbf{S}},\lambda] \tag{34}$$

where **G** represents the redesign rule while λ controls the redesign process.

This fundamentally matches (33), thereby the recursive logic may imply the nonlinear mechanism. This will be further studied and discussed in Zeng[2].

Construing creativity

Based on the discussion in the above section, we may conclude that the following mechanism underlies the generation of design proposals. The recursive schema provides the dynamical structure of designing, the potential operation on forms may give the nonlinear term, and the quality Q_s^m of the subjective function acts like the scattering term. Hence, the chaotic motion may happen to desiger's thinking process. The different attractors correspond to different design proposals, among which some are usual solutions while others are unusual and innovative, which is wholly dependent upon the 'special conditions'.

Therefore, as is given by (34), we can assume that lied in any designer's mind is an nonlinear design knowledge structure. Under changing design requirements, varied initial atomic forms and different redesign strategies (corresponding to the selection of G and λ), the design process may result in distinguished design proposals due to the occurrence of potential chaotic motions dependent on the initial conditions sensitively.

The above conclusion coincides with the speculations of many other authors'. Crutchfield *et al*[23] put creativity in the way that

> Innate creativity may have an underlying chaotic process that selectively amplifies small fluctuations and models them into macroscopic coherent mental states that are experienced as thoughts. In some cases the thoughts may be decisions, or what are perceived to be the exercise of will. In this light, chaos provides a mechanism that allows for free will within a world governed by deterministic laws.

Bradburne[25] went further to work on the possibility of the application of dynamical system theory to artistic action which bears resemblance to general design. He stated

> Gaston Bachelard states that "by its novelty, a poetic image sets in motion the entire linguistic mechanism. The poetic image places us at the origin of the speaking being." He notes as well the curiously unremarked upon fact that unlike normal reading, the reading of poetry demands that we stop reading at each verse to allow the memories, resonances, and semantics to cycle, reverberate, and thereby enrich the poem, to infuse and impregnate it with our own history. He said, " When I relive dynamically the road that 'climbed' the hill, I am quite sure that the road itself had muscles. ...As I write this page, I feel freed of my duty to take a walk; I feel sure of having gone out of the house."

Because of this peculiar cyclic, repetitive, and semantically heterogeneous experience of poetry, it might permit modeling in terms of a dynamic system.

In another paper, Lansdown[26] models the creative act by the catastrophe theory, combining the routine design and creative design into an united schema. Besides, it provides a possible way to represent the nonlinear operation of forms which underlies the design creativity.

Ill-structure vs Creativity

Although recursive logic implies chaotic motion in some cases, not all design are so creative. On the other hand, designers never tell themselves when to design creatively and when routinely. These considerations urge us to look for the condition under which the recursive logic will give out creative design or routine design. The other equivalent statement for this problem is finding the condition for the recursive logic to underlie the chaotic motion. The study on this condition is our goal in this section.

In fact, Amarel[15] has implicitly pointed out the condition of the creative act as 'it is usually associated with ill-defined goals or it involves reformulation of externally imposed goals.' In the following, we shall discuss the relationship between the ill-structure and creativity.

By routine design we mean to design deductively. Considering the design problem definition in (19)-(25), it is only possible to have an atomic design with mere one ply of recursion to finish the design. This is rarely feasible unless the designer is very experienced to the problem at hand or the problem is so simple that everyone is expert relative to it. The atomic design in this case is the so-called prototype or pattern. The quality of the pattern existing in designer's mind will not suffered from any alternation but the attribute or quantity bears some change. If it can happen then we could say that it is not ill-structured for the pattern implies the premise relating the subjective functions to form.

On the other hand, even if one ply pattern does not exist, if the final form just comes from the proportional widening or lessening and the simple addition or subtraction of atonic designs, the designing will not be called creative. In this situation, the style plays little role in designing, and the whole design could be deductively finished at all.

Therefore, from the recursive logic point of view, the creative design stems from several sources. First, the problem should be ill-structured so that the dynamical structure exist for the solution. Second, operators should be available to manipulate the atomic design nonlinearly. Third, of course, the proper context for designing to make the design to be attracted to creative attractors.

CONCLUDING REMARKS

In this paper, we improve the recursive logic in the following aspects:

- the artifact is defined in terms of quantity and quality, so that it can be more clearly displayed that the recursive logic mainly deals with the quality of the artifact
- the function of an artifact include both the input and the output when it is seen as a system in environment
- two different kinds of functions are given, that are the subjective function and the objective function, according to its relation to nature or human

o the quality is also attributed to the subjective function, which leads the direction of the design and bound the domain of the design proposals

Besides, based on the recursive logic, we investigated the structure of the design problem. Formal explanations are given to the speculation of Simon *et al* that design is an ill structured problem.

Finally, design is related to chaotic dynamics through the recursive logic. As a result, the creativity of design is supposed to come from the sensitive dependence of human thinking structure upon the initial condition. Also, the ill-structureness is taken as the main condition to bring about creativity, and several other conditions are proposed.

The future work of the recursive logic's application to design are expected in the studies of the atomic design, the operator on atomic design and the formalization of the recursive logic.

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