Model of Design Thinking as Trial-and-Error Process

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Abstract: The author proposes model of design thinking as trial-and-error process of exploring functional relation of goal and means, The key issues are as follows: (1) Design thinking process is a typical human problem solving mode that does through creating artifacts as means for problem solving. (2) As L. S. Vygotsky asserted that human thinking forms indirect relation between <**S**ubject> and <**O**bject> through <**M**edium (means)>. (3) Design thinking is human (**S**) problem solving (**g**) process by making artifacts (**M**) that has functional relation (**f**) with goal. It can be represented as $S \rightleftarrows M = f(g)$. (4) The process of $S \rightleftarrows M$ is composed of bi-directional thinking: representing subject's mental image of means as **M** (**S→M**) and then evaluate it (**M→S**). (5) This process ought to take trial-and-error process. (6) Creative thinking emerges in this process in which goal seeking mind is narrowing search space but same time divergent thinking needs widened search space. (7) This paradoxical process needs strategies to make it free from mental fixation.

Key words: Design thinking, Vygotzky's thinking unit, Functional relation, Trial-and Errors, Creative thinking

1.   Introduction

When we study on design thinking we should recollect the fundamental feature of it. In most generalized concept, design thinking emerges in typical human problem solving mode, which is done not directly but through making means for problem solving. Immediate goal of it is to make a means for solving the problem.

The means are represented as various objective media like verbal descriptions, sketches, models and actual tools, which bridge between subjective world and objective world. These means are got only through trial-and-error processes, because each process needs time differenced bi-directional thinking: firstly search and represent the image of means, and then it can be verified or evaluated. The image of means grows from abstracted media (like verbal ones) to realistic forms (like sketches) of it in such trial-and-error processes.

After the design thinking got suitable means, finally it is actually applied as a tool for solving the problem situation. It changes not only objective world but also subjective world.

The author proposes a model of design thinking based on this thought.

2.   Nature of design thinking as "homo-faber"

2.1   Origin of design thinking

C. S. Peirce [1] pointed out, from the viewpoint of semiology, that specific feature of human understanding and communication are done by using symbol and sign as media in which he/she indicates indirectly some object through another entity. Russian (USSR) psychologist L. S. Vygotsky [2] asserted that the specific feature of human intelligent behavior is using medium object between the subject and the objective circumstance for

understanding it, and this indirect relation makes him/her capable abstract thinking and communicate each other by managing language. Then, basic human intelligent behavior can be represented as triangular relations of <Subject>, <Medium> and <Object>. This triangle forms "basic unit" of human thinking (Fig.1).
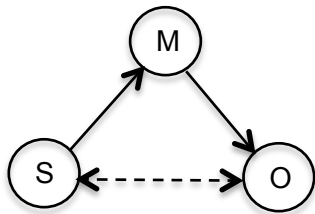

Fig.1: Human thinking unit based on Vygotsky's theory

Based on those precedent researches, the author of this paper asserts that design thinking is essentially included in human goal seeking behavior in which he/she tries to solve a problem emerged between subjective world and objective world by making artifacts as means. It comes from biological base in which physical world is divided into two worlds "external world (circumstance)" and "internal world (inside of cell)". All life form of biological world is in seeking dynamic equilibrium (homeostasis) between external world and internal world (Fig.2).
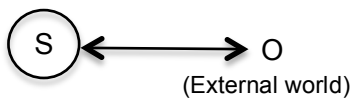

Fig.2: biological equilibrium of internal world and external world

In case of humankind, they recognize the incompatible situation between their internal world and circumstance as a "problem", and try to solve (get equilibrium) it by using "tool (means)" as an extension of their physical conditions (ex. hands, foot, arm, etc.). The materials of tools can get from external world and they apply the law
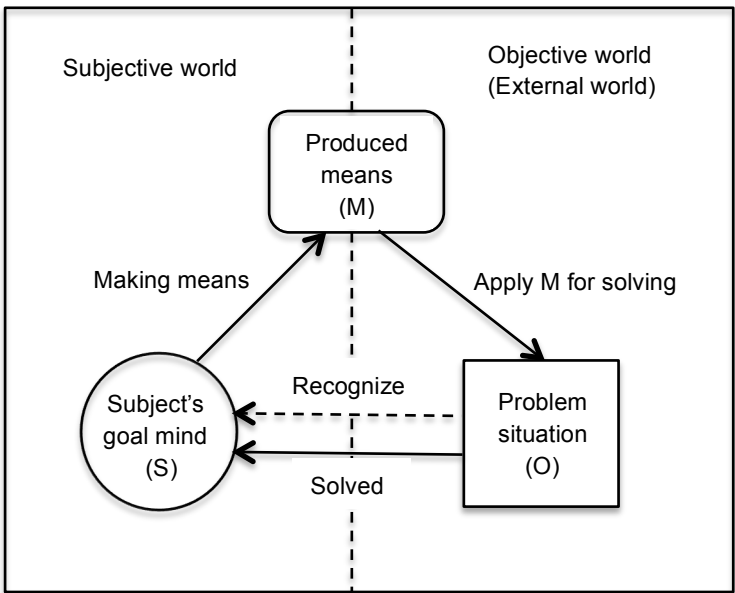

Fig. 3: Basic thinking unit of human problem solving

of nature (physics) to accomplish their goal. They represent their intention as problem requisition to be solved, and search a means (including methods) for solving it. Then, human problem solving can be depicted as triangular "means-goal relation" as shown in Fig. 3. The design thinking is on this base frame. On the basis of this framework, the author makes discussion on the meaning of "function".

2.2 Precedent researches on the meaning of "function"

In the problem solving, the subject searches means that has function to be able to solve the problem. The function, in this discussion, is not only narrow meaning such as physics of hardware (ex. mechanism) but also includes wide meaning such as concerning user's physiological require (usability, easiness of recognition) and psychological require (giving satisfaction). Psychological level function must be included in physiological level function, and physiological level function must be included in physical level function.

The subject is pushed to create a means if he/she cannot get it from existing state, and must think function of the creating means. This is start point of the design thinking. In design process, created means is represented as a design object, and it can be evaluated only in the light of functional relation between means and goal.

J. S. Gero [3] pointed out in his proposal of Function-Behavior-Structure framework (Fig. 4) on design process, that evolution in thinking expected structures of design object motivated by the situated sequence in the state space in time flow (Fig. 5).

formulation: $F \rightarrow B_e$
synthesis: $B_e \rightarrow S$ via B_s
analysis: $S \rightarrow B_s$
evaluation:$B_s \leftrightarrow B_e$
documentation: $S \rightarrow D$
reformulation - 1: $S \rightarrow S'$
reformulation - 2: $S \rightarrow B_e'$
reformulation - 3: $S \rightarrow F'$ via B_e
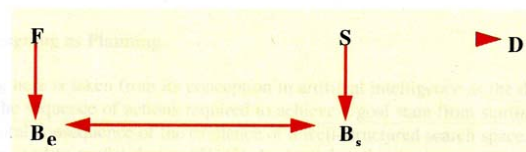
The *Function–Behaviour–Structure* framework as a basis for models of designing, where B_e = expected behaviour; B_s = behaviour derived from structure; D = design description; F = function; $\rightarrow$ = transformation; and $\leftrightarrow$ = comparison (after [1])

Fig.4: "Function-Behavior-Structure" proposed by J. Gero.
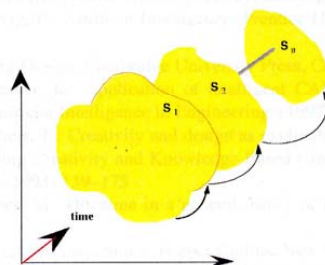
The notion of conceptual designing as a sequence of situated acts modelled as a sequence of state spaces, which are interpreted as the situation; these state spaces change over time as the designer acts

Fig.5: Situated sequence in state space proposed by J. Gero.

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It seems reasonable proposal, however, Gero treated "function" not from designer's internal (subjective) side but only from externalized (design object) side.

The author of this paper proposes that function should be treated from both sides: designer's internal side in which the situated intention is generated, and design object side in which designer's goal-mind is represented as an externalized thing.

It seems need to make definition of the function of designed entity from the viewpoint of the relation between subjective thinking and objective outcome.

2.3 Functional relation between goal and means

The process of design thinking can be said as finding process of means that has suitable functional relation with goal, through trial and error processes. Simon [4] often referred to "means-end relation" in his papers, but in his logic the word 'end' is meaning the result of goal-minded thinking. The author of this paper uses the word "goal-means relation", which represents relation of expected goal in the mind of subject and represented means.

According to this thought, goal-means relation can be represented as following [4].

$$\mathbf{m} = \mathbf{f}\,(\mathbf{g})$$

where:

$\mathbf{m}$: means to be met problem requisition

$\mathbf{f}$: functional relation between goal and means and also represents as mathematical function

$\mathbf{g}$: subject's goal seeking mind

At first, subject searches a means to meet the problem requisition in existing instances. If it cannot be obtained from existing instances, then he/she must create it. Now, the subject can be called "designer" as most generalized meaning. The search is composed of bi-directional process. At first, the designer tries to generate an image of $\mathbf{m}$ in his/her mind, and then he/she represents it to be recognizable. After that it can be represented as $\mathbf{M}$. This process can be represented as:

$$\mathbf{S_g} \rightleftarrows \mathbf{M} = \mathbf{f(g)}$$

Where:

$\mathbf{S_g}$: designer's goal mind.

$\rightarrow$: representing image of means as externalized form

$\leftarrow$: recognizing it as represented $\mathbf{M}$

Then after the designer recognized the represented $\mathbf{M}$ as a candidate solution, he/she can tentatively apply functional relation $\mathbf{M} = \mathbf{f(g)}$ to the problem situation and verifying if $\mathbf{M}$ could meet the problem requisition (including constraints) or not. If it could not accept as a solution, then he/she must go again searching process.

From the viewpoint of ontology, represented $\mathbf{M}$ shows a new "meaning" of substantial object, which has generated from designer's intention. In other words, the functional relation represents "meaning" of the means.

2.4 Basic structure of design thinking as exploring and representing functional relations

From the viewpoint of above mentioned, basic structure of design thinking can be depicted as shown in Fig. 6. Design thinking is "pre-doing" part of human problem solving behavior as shown Fig. 3. After the designer recognized an incompatible situation, he/she represents it as "problem". Then, a goal-seeking mind ($\mathbf{g}$) is brewed

in designer's brain and he/she begins to search **m** (means) for solving it. If the designer can generate image of **m** in his/her mind, at first, he/she tries to fix it by externalizing form **M**. Designer can recognize his/her inner image only after externalized it. This nature of "expressing first recognizing after" is the reason why design thinking inevitably takes trial-and-error processes.

Then he/she can recognize if it can have functional relation "**M = f(g)**" or not by tentatively applying to the problem situation. If the **M** is recognized as not capable solution, another thinking cycle must be started.
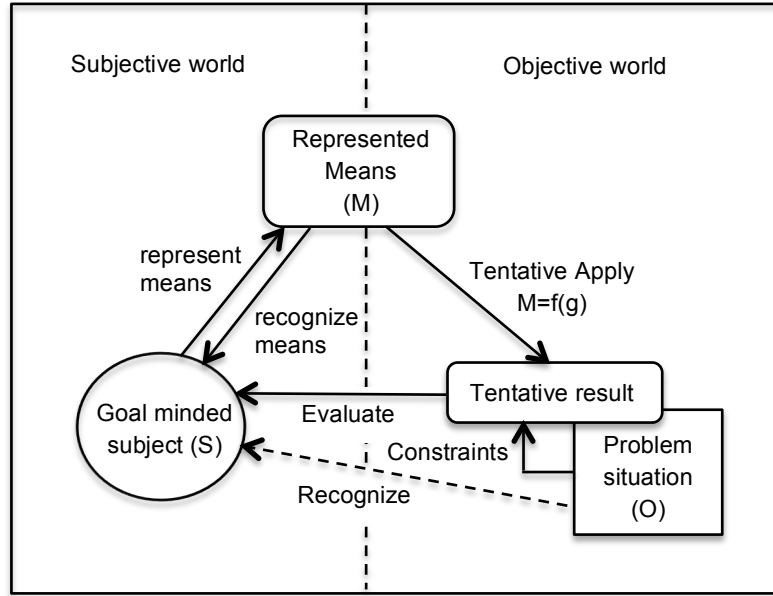

Fig. 6: Basic unit of design thinking

2.5 Trial-and-error process of searching functional relations

Simon [5] pointed out, in quoting with Alexander's theory [6], that "ill-structured problem" like design problem should be treated in two ways: the first is decomposing a problem into sub-problems in which method for "well-structured problem" can solve each of them. The second is "retrieval system", which continually modifies the problem space by evoking from long-term memory of new constraints, new sub-goals, and new generators for design alternatives. But how such retrieval process can get a solution, and when emerge creative thinking? Simon did not answer these questions. The author of this paper tries to answer them on the basis of the proposed model.

The way from finding problem to actual solution it can be represented as basically three-layered spirally triangle process as shown in Fig. 7.

At Stage I (problem grasping), the subject meets with problem situation, and he/she tries to represent it as "problem" to be solved (M_p). Represented problem makes possible to grasp explicitly problem requisition in subject's goal mind (S_g). After that, verification can be taken if it adequately represents the problem situation (O_p) or not. If not, problem grasp must be repeated.

Stage II (design thinking) is transforming process from problem requisition (M_p) to create candidate means (M_m). This process is composed of searching **m** and representing it as M_m motivated by subject's goal seeking mind S_m, and evaluating if it can be tentative solution (O_{ps}) or not in the light of M_p.

Usually, the representing process of **m** takes divergent thinking in which search space make widened because the subject needs divergent thinking to generate as many possible **m** as he/she can image. This representing process is, however, taken in the goal-oriented process as inevitably narrowing and focusing search space into the goal. Because of this paradoxical situation, the subject needs some strategies as mention afterward.

Then, after **m** was represented as $\mathbf{M_m}$, evaluation is started as convergent thinking process. If $\mathbf{M_m}$ could not meet the M_p (problem requisitions), next cycle must be started with the knowledge and experience gotten from precedent cycle. The subject's goal seeking mind ($\mathbf{S_m}$) is now more clarified than before, and he/she has now much better chance to get more realistic solutions in searching **m**. This trial-and-error process will be finished at the time when the goal minded subject has reached at acceptable state.

After suitable solution was got, the subject proceeds to Stage III (producing) and he/she actually makes it as a tool ($\mathbf{M_a}$), and applies it to actual problem situation. If it can modify the problem situation to acceptable state ($\mathbf{O_s}$), the subject will get fulfillment and new equilibrium state between the subject and objective circumstance will be established. If not, process must be taken backtracking.

These are not simple processes but take complex spiral structure through three vertexes of **S**, **M** and **O**, which have vertical depth that indicates degree of problem grasp and degree of realizing solution.
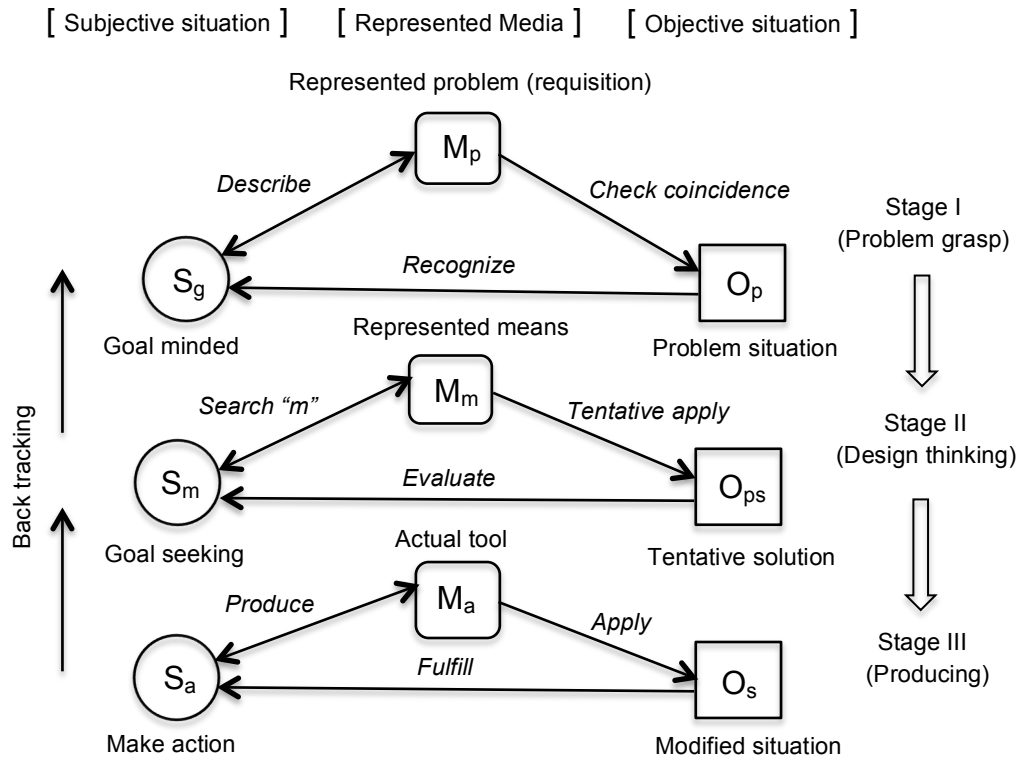

Fig. 7: Design thinking in three-layered problem solving process

3. Features of the creative thinking

On the basis of thought above mentioned, now we move to discussion on the creative thinking.

Usually, in design thinking process, designer illuminates suddenly creative idea that evokes entirely new

viewpoint as a whole, not in logically step-by-step decompose of sub-problems. We should see precedent researches on the features of creative thinking before move to discussion..

3.1 "Function follows form" approach

Finke, Ward and Smith [7] proposed that creative thinking process is composed of two different phases: "generation of pre-inventive structures" and "pre-inventive exploration/interpretation". They represented it in their "Geneplore model" (Fig. 8).
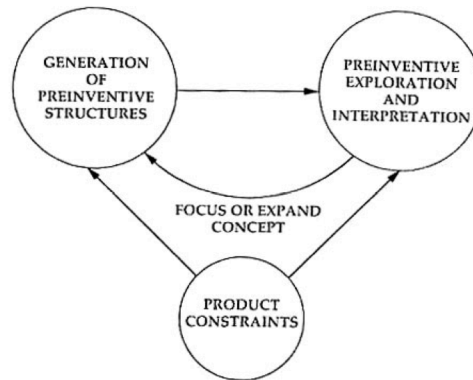

Fig. 8: "Geneplore model" proposed by Finke, Ward and Smith

They said that the "pre-inventive structures" have various emergent properties that are exploited for creative purposes in the exploratory phase, and the resulted creative cognition can be focused or expanded according to task requirements or individual needs by modifying the "pre-inventive structures" and repeating the cycle. They said that progress on a problem solving could be blocked by fixation on ideas that are not getting one closer to a solution and an inability to free oneself from that fixation.

On the basis of this framework, they had mental synthesis experiments using students as subjects. Simple line drawn shapes were shown to the subjects. The subjects were assigned to synthesize some useful objects in the brain using three parts of shown shapes and put name indicating what is the generated objects. As the results, many creative solutions were got.

They asserted, based on the results of these experiments, that the "function follows form" approach (reverse flow of famous functionalist's these "form follows function") considered in their experiments could be useful in complementing current approach to invention and design. They suggest that it may be helpful to consider an alternative approach to exploring new problems and functions that are suggested by particular forms and structures.

3.2 "Unexpected discovery" in design thinking

When one stays in no goal-oriented mind, sometimes, he/she suddenly illuminates new idea. It makes new interpretation of the "M = f(g)" that gives break-through to the existing relations of it. In such case, one is free from fixations and unconsciously widened one's searching space in latent process. This is called "Incubation" [8]. It makes him/her sensitive to find out new goal-means relation in things or events those have been thought to be

not concern with present design problem. This happens sometimes in relaxed reviewing one's idea sketches.

Designer often finds an unexpected clue of discovery in his/her own sketches. Suwa, Gero and Purcell [9] observed an architect's design process, and analyzed it by using protocol analysis method. As the result, they found the architect illuminated new design idea by reviewing his own sketches.

Oxman [10] pointed out in her research into the visual re-cognition in design emergence, visual prototype may act as guide for finding new meanings in drawn sketches. Goldschmidt [11] also referred to similar phenomena observed in design thinking.

From those precedent researches, they can have question "Why creative solution can often get not from goal seeking mind but from unexpected situations?" and/or "Is design thinking essentially goal-oriented process?" The author of this paper tried to answer this question from the viewpoint of mentioned above.

4.   Position of creative thinking in proposed model

4.1   Two directions of thinking

In the Geneplore model (Fig.8) "interpretation" is not separated in the "pre-inventive exploration and interpretation" phase. The author of this paper, however, proposes that representing process should be separated from interpreting process [12]. As mentioned above, recognition always comes after representation, and "interpretation" is a typical recognizing process. In representing $\mathbf{m}$, the subject makes effort expressing an image of $\mathbf{m}$ in his/her brain to an externalized form $\mathbf{M}$. After that, he/she can interpret M as has some understandable meaning in the functional relation "$\mathbf{M} = \mathbf{f(g)}$". It is most important character of the design thinking as typical feature of "time-preoccupied thinking", because we have not any recognizable entity yet before it is represented as objective (externalized) form.

In Fig.7, representation appears in the process of $\mathbf{S} \rightarrow \mathbf{M}$, and recognition appears in the process of $\mathbf{M} \rightarrow \mathbf{S}$ and $\mathbf{O} \rightarrow \mathbf{S}$. In $\mathbf{M} \rightarrow \mathbf{S}$, recognition appears as intuitive feedback process, and in $\mathbf{O} \rightarrow \mathbf{S}$, it appears as rational understanding or interpreting process.

As the design thinking is essentially goal oriented, searching space inevitably narrowed to be able to get possible $\mathbf{m}$. However, on the other hand, the searching process needs divergent thinking to get as many candidates as possible. It is paradoxical thinking phase. So that, experienced designer frequently uses strategy of the "incubation" and/or "forced inference" in abnormal condition to escape from fixated goal mind.

In case of design experiments by Finke, Ward and Smith, the subjects were started by given shapes as external stimuli and imposed to accomplish design task in short time. The subjects were in no goal-oriented situation but compelled to generate "something" in restricted time. Then they synthesize some curious tools from combinations of the given stimuli. This is not normal design thinking but is rather puzzle solving in open-ended situation. This type of "function follows form" thinking may useful in design thinking but the author of this paper asserts that it is only useful when it basically included in goal-minded thinking such as "form follows function".

4.2   "Awareness" from represented object

Every person has his/her mental world as an individual set of long-term memories those have been made by enormous amounts of records and knowledge accumulated through lifetime experiences from his/her birth to now.

Depending on the difference of each person's experience and biologically inherited gene, one has unique mental

subjective world, which stored in long-term memories. This means, however, that a human mental (inner) space is always included in the objective (external) world as a whole and smaller than it ($S \subset O$).

The author of this paper proposes that the represented **M** is a symbol, which indicates interacted states of both subjective goal mind (**S**) and objective condition (**O**). As soon as **m** is represented as **M**, it becomes to a part of external world even if it has whole of the designer's inner world. Then, **M** can give "awareness" as an external stimulus to the designer in reviewing phase.

The reviewing process appears as in relaxed atmosphere in the process of design thinking. In that situation, designer is put in not strictly goal-oriented state and it makes possible "unexpected discovery" in unconsciously widened searching space.

The "awareness" sometimes evokes backtracking from lowest stage to top stage and inspires perfect re-grasp of problem situation. This backtracking process often generates innovative solution.

5. Conclusion

As Simon pointed out, design thinking is typical "retrieval system". The author proposed that, on the basis of Vygotsky's theory, it can be represented as multi layered spiral formed model in which each layer is composed of triangular relation of "Subject", "Object" and "Medium". In each layer, designer is motivated by his/her goal-oriented mind, and searches for adequate means (as medium) to be able to solve the problem situation.

In the search process, the designer generates image of means (**m**) in his/her mind then represents it to be recognizable (**M**). The author pointed out that the goal-oriented design thinking is essentially trial-and-error search process of functional relation of goal and means: $S \rightleftarrows M = f(g)$.

Based on this model, the author can put position of creative thinking. The process of $S \rightarrow M$ goes paradoxical way that in one hand it is goal-oriented process in which searching space should make narrowed but the other hand it needs wider searching space for divergent thinking. In that paradoxical situation, some outside stimuli (including his/her idea sketch) can make widen the searching space, because always the outside world is larger than designer's inner world ($S \subset O$).

From this viewpoint, the Finke, Ward and Smith's proposal "function follows form" can be said as awareness phase in the "form follows function" in the wide meaning of functional relation.

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