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TOWARDS A SCIENTIFIC MODEL OF FUNCTION-BEHAVIOR TRANSFORMATION

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ABSTRACT
The function-behavior transformation, though widely acknowledged as a significant process of engineering design, is still regarded as a subjective and experienced-based process. To build a science of designing, this paper is devoted to developing a logical and scientific model for this transformation process. Based on the subject-object relationship in philosophy, it clarifies the concepts of function, behavior and structure in designing, with significant features identified for them. Existing understandings about these concepts are also analyzed for comparison. A new concept, *physical action*, is also introduced into design science. A scientific function-behavior transformation model, called the Function-physical Action-Behavior (abbreviated as FAB) model, is then proposed, where the concept of physical action is successfully used to bridge the gap between function and behavior. An illustrative example is provided to demonstrate the proposed FAB model.

Keywords: Design science, function-behavior transformation, design cognition, conceptual design

1 INTRODUCTION
According to Prof. John Gero, the Function-Behavior (abbreviated as *F-B* later) transformation is a critical sub-process of designing, responsible for transforming posited functions to a description of (expected) behaviors [1]. Although the F-B transformation has been widely acknowledged in design society and has been the foundation of much design research work (e.g. in [2-5]), it doesn't provide a scientific theory about how function is transformed into behavior. Instead, Gero argues that human designers produce an experience-based connection between function and behavior [1]. Therefore, the F-B transformation is still regarded as an intuition- or experience-based process.
Since intuition or experience can often be subjective and difficult to be tested and repeated, the above cognition about the F-B transformation implies that engineering design still has to be treated as a kind of art, rather than a kind of science, which doesn't accord with the aim of building a science of designing [6-7]. Therefore, there should be a scientific model that can logically explain the F-B transformation with the scientific knowledge derived from the physical world in an objective way, which is just the primary concern of this paper.
It is self-evident that the concepts of *function* and *behavior* are critical for understanding the F-B transformation. Their concepts should be stable and scientific in order to build a scientific F-B transformation model. However, investigation discloses that there have been many different definitions for these two terms in design society [8]. This paper will clarify these two concepts and some other related concepts at first, prior to elaborating the F-B transformation model.
This paper is organized as follows. Section 2 and 3 clarify two basic concepts, structure and behavior, independently. Section 4 introduces a new concept, *physical action*, into design science. The concept of function is then clarified in section 5, followed by the F-B transformation model introduced in section 6, where physical action is used to bridge the gap between function and behavior. Finally, section 7 concludes this paper.

2 STRUCTURE
Design researchers usually agree that the behavior of a system can be derived from its structure [1, 3-5, 9]. The concept of structure, therefore, is introduced here, prior to the concept of behavior. According to Gero [1], *structure* is a design description that refers to the elements of an artifact and the relations between them. However, this understanding of structure has a limitation.
Consider the nitric-acid cooler [2], a device that has appeared in multiple engineering design papers. Based on the above understanding, its structure is composed of elements such as pipe1, pipe2, pipe3,

pipe4, heat-exchange chamber, water pump, input-ports and output-ports [2]. Here, it is found that the material, *water*, which is indispensable for cooling nitric acid, hasn't been recognized as a part of the structure of the cooling device. An issue then emerges: if water were not considered as a part of the structure of the artifact, then how could the cooler have a desired behavior for achieving the function of cooling nitric acid? Furthermore, if water were separated from the structure of the device, how could the intended behavior for achieving the cooling function be derived from the structure? The above device is not a unique case that has the above issue. Actually, it is a general question about whether an environmental object, which is indispensable for an artifact to work properly, should be regarded as a part of the structure of an artifact or not.

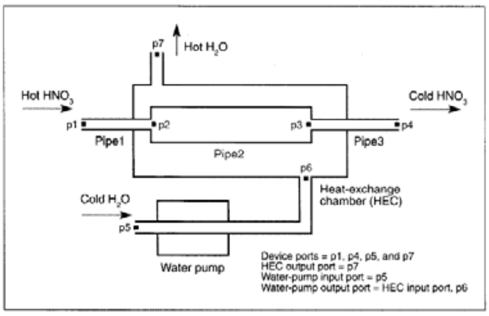

Figure 1. The structure of a nitric acid cooler [2]

To address the above issue, a moderate modification is made to the concept of *structure* here. In our opinion, the goal of designing is not only to create an artifact, but also an environment for the artifact to work properly. The entities in such an environment are called environmental entities, e.g. the water used for cooling nitric acid or the air surrounding a hand-drier. Note that environmental entities here don't involve the functional object(s), i.e. those entities that are regarded as unsatisfactory and will be transformed to desirable states (e.g. nitric acid or hand). Therefore, the aim of designing is to create a design solution, not limited to an artifact. Here, a design solution can often be regarded as a combination of an artifact and the related environmental entities required for the artifact to work. Therefore, the concept of structure here is modified as *the structure of a design solution*, rather than the structure of an artifact alone. Since environmental entities are also regarded as parts of a design solution, the above issue related to the concept of structure then disappears.

3 BEHAVIOR

Although the concept, *behavior*, doesn't appear as a very complex concept, a unified concept about behavior is still absent from design society [10]. Therefore, an explicit and scientific definition of behavior should be proposed here.

3.1 An Explicit Definition for Behavior

To have an explicit and scientific definition of behavior, the simplest approach is to look up it in English Dictionaries. In the Oxford English Dictionary, behavior is defined as: *way of treating others, manners*, or *way of acting or functioning* [13]. This definition is a little bit simple. A more explicit definition is found in the online Oxford English Dictionary, i.e. *behavior refers to the manner or the way in which someone or something behaves or acts (probably in response to external stimuli)* [11]. To understand this definition clearly, some explanations are given as below.

First, any behavior belongs to an entity (i.e., *someone* or *something* in the above definition). For example, when we say that a man is standing there, the man is the entity and standing is his behavior. Similarly, when we say that a paperweight is standing on a pile of paper, the paperweight is the entity while "standing" is its behavior. The above two behaviors are static ones. Of course, an entity may also have dynamic behavior(s), e.g. *a car is moving* or *the Earth is rotating*, where moving and rotating are dynamic behaviors of the car and the Earth, respectively.

Second, behavior describes the *own* manner/way of an entity, where manner can be understood as its physical state or physical state change. For example, the behavior, *standing*, in the previous example, is a kind of state of the man. Similarly, when we say, *the car moves from place A to place B*, the car's behavior, *to move from place A to place B*, describes a change of the place state of the car.

Third, since behavior represents the own manner of an entity, it usually should be orally described with an intransitive verb. For example, the verbs mentioned above, *stand* and *move*, are either an intransitive verb or used as an intransitive verb. The habit of using intransitive verbs to describe behavior coincides well with the usages of the verb, *behave*, e.g. *to behave well* and *to behave oneself*.

Finally, since an entity is often a system composed of multiple parts, the behaviors of its parts can often be regarded as the behaviors of the system. For example, when we say an electrical motor is rotating, we actually mean that its shaft or armature is rotating.

In addition, behavior can also be classified as passive behavior and spontaneous (active) behavior. A passive behavior refers to a state change caused by an external action, e.g. the moving behavior of the desk in the description, *the desk moves as a man pushes it*. A spontaneous behavior often originates from the inner process of an entity, e.g. the moving behavior of a car.

The above features about behavior can guide human designers to describe behavior correctly. It can also serve as a set of criteria for design researchers to judge whether a description refers to the behavior of a design solution or not. Since the behavior of an entity represents its own physical state or physical state change, it is therefore a scientific concept and can be observed objectively.

3.2 A Comparative Analysis

We can now compare our concept of behavior with the existing definitions of behavior in design society and related disciplines to see whether they can reflect the meaning of behavior reasonably. Due to limited space, only some closely-related definitions are provided as below for comparison.

In the qualitative physics research, Bobrow defines behavior as the time course of observable changes of state of the components and the system as a whole [9]. It is self-evident that the behavior of a component is regarded as its own state change. Therefore, it is basically coherent with our definition. A slight difference consists in that his definition merely considers dynamic behavior (i.e. the state change of an entity), with static behavior (e.g. “standing”, “laying”, etc.) neglected.

Gero and his collaborators define behavior as what something does [12]. For example, what a window does can be *ventilation-restriction*. However, as pointed out by Dorst and Vermaas [10], Gero and his collaborators’ concept of behavior can lead to a philosophical contradiction, i.e. *the behavior of an entity unreasonably depends on properties that do not count as properties of the entity*. For example, since air flow doesn’t belong to a window, it is unreasonable to treat ventilation as a property of the window, i.e. ventilation-restriction cannot be regarded as a behavior of window. Compared with their definition, our definition of behavior will not incur the above philosophical contradiction. According to our definition, a window has behaviors such as *standing in the wall* (a static behavior), *shrinking in a cold weather* (a dynamic behavior), etc, but not including *restricting ventilation*.

Goel and Stroulia [4] argue that the (internal) behaviors are the causal processes that result in the output behaviors, and that behavior can be represented with a set of behavioral state transitions. After a careful study, it is found that Goel and Stroulia’s understanding about behavior also possesses the similar philosophical contradiction mentioned above. For example, they describe the behavior of a nitric-acid cooler as a causal model composed of the *CoolNitricAcid* behavior and the *HeatWater* behavior; however, since both nitric-acid and water are the flows through the cooling device and don’t belong to the device, they shouldn’t be used to represent the behavior of the device.

Umeda *et al* define behavior as sequential state transitions along time [5]. It seems that they agree with Boborow’s definition. However, their definition of behavior actually doesn’t accord well with the examples they list as behaviors. For example, they list “hitting a bell” and “oscillating a string” as examples of behaviors, which, however, violate a behavioral description feature we have listed, i.e. behavior should be described with intransitive verbs to denote its own state or state changes. Furthermore, the owners (i.e. the entities) of these behaviors are also lost in these descriptions.

From the above analysis, it is found that our understanding of behavior is basically coherent with that proposed by Bobrow. Compared with other understandings about behavior, our concept of behavior is more explicit and more reasonable.

4 PHYSICAL ACTION

As shown later, the concept of physical action is the foundation of the concept of function. Furthermore, it also plays a critical role in bridging the gap between function and behavior. Therefore, it is introduced here, prior to the concept of function.

4.1 The Concept of Physical Action

Physical action is a kind of action that exists in the physical world. According to the Oxford English Dictionary, *action* represents the effect that one substance has on another [13]. Therefore, a physical action can be regarded as that one physical entity exerts on another in the physical world in order to change its physical state(s). Some detailed explanations about this concept are given as below.

First, a physical action has a subject, *i.e. the entity that exerts the action*, and an object, *i.e. the entity that is acted on*. Here, subject is a philosophical term, which refers to an entity (observer or actor) that can form knowledge about another entity (i.e. the object) or can act on it. For examples, when we say, *a man is hitting a bell*, the man is the subject and the bell is the object; when we say, *a device is cooling nitric-acid*, the device is the subject and nitric-acid is the object.

Second, what a physical action primarily concerns is often the result of the action on the object, i.e. the final physical state or physical state change of the object. For example, when a device is said to have an action of cooling nitric-acid, what is concerned with is that the object, *i.e. nitric acid*, gets cool.

Thirdly, a physical action usually should be orally described with a transitive verb, to show the effect of the subject upon the object. For example, the verbs in the above action phrases, i.e. *hit* and *cool*, are either a transitive verb or used as a transitive verb.

Fourthly, a physical action directly corresponds to a physical law, where the action manner between the subject and the object is definite. The action manner of a physical action prescribes and illustrates how its object achieves the final physical state. This is completely different from a behavior, which is merely concerned with the state or state change of an entity, other than how the state or the state change is achieved. For example, a behavior can be described as: *the air's temperature goes up*, while a physical action should be described as: *a heater heats the air's temperature via heat-exchange*, where *heat-exchange* is the action manner.

Fifthly, a physical action requires that its subject often should be in observable and direct contact with its object, where an exception can be the magnetic field based action. Here, the observable and direct contact guarantees that each physical action can be explained with a physical law. For example, if a small bookshelf with books in it is standing on a desk, two physical actions can be found, i.e. *a desk is supporting the bookshelf* and *the bookshelf is supporting the books*; however, the description, *a desk is supporting the books*, cannot be regarded as a physical action.

Finally, if an object is composed of multiple parts, the physical action of a subject on a part of the object can often be regarded as the action on its object whole. For example, assume a bell part is connected with a string, i.e. *the string is regarded as a part of the bell*, and a man is oscillating the string to make the bell part ring, we can say that a man has a physical action on the bell, i.e. *he oscillates/hits the bell*, where the bell is an assembly of the bell part and the string.

4.2 Physical Action vs. Mental Action

Mental actions are those actions that exist in the mental world, i.e. in the minds of human beings. Mental actions have many features similar to those of physical actions. For examples, a mental action also has a subject and an object; it should also be represented with a transitive verb; etc. However, different from physical actions that are objective and tangible in nature, mental actions depend on human being's knowledge and conceptualization about the physical world. Therefore, many mental actions are subjective and cannot be explained with physical laws. A typical example is that ancient people believe that the dance of a sorcerer can drive disease away from a patient. However, it should be admitted that there are also some mental actions that are objective. These mental actions are based on the correct conceptualization (knowledge) about the physical world.

In our daily life and engineering design practices, many mental actions are often unconsciously misunderstood as physical actions. For example, people may think that a hair-dryer has a <u>physical action</u> on wet hair, making it to get dry. However, this action is actually a <u>mental action</u>. A primary proof is that a hair-dryer doesn't act on hair directly. Instead, the hair-dryer only heats the air flowing into it. When the hair-drying action is mentioned, it is subjectively regarded that hair has two states (i.e. the *dry* state and the *wet* state), and the hair-dryer transforms hair from a dry state to a wet state. However, *dry* and *wet* are two mental states that don't belong to hair in the physical world. According to physical science, what the heated air from a hair-dryer actually acts on is not the wet hair, but the water on the hair. Therefore, the real physical action here is that water is evaporated, other than that hair is dried.

4.3 Physical Action, Behavior and Phenomenon

According to the previous explanations, it is not difficult to find the major differences between physical action and behavior. Here, we are primarily concerned with the philosophical differences between them.

When elaborating the concept of physical action, the most important thing is that the subject-object relation is imported. As a result, the (two) entities involved in a physical action are classified as a subject and an object, where the subject plays an active role in changing the state of the object. Based on the subject-object relationship, a fundamental difference between function and behavior can then be identified. Since a behavior belongs to an entity, the entity can also be regarded as its subject. Therefore, what a behavior cares is the state or state change of the subject, which is fundamentally different from a physical action, which cares the state or state change of the object.

In the *physical sciences*, there is also a concept similar to physical action, i.e. *physical phenomenon*. Based on the subject-object relationship, the difference between physical action and physical phenomenon can also be identified. In a physical phenomenon, all related entities are said to participate in the phenomenon equally, and no entity takes the active or passive role, i.e. *neither subject nor object exists*. In this sense, phenomenon, therefore, is similar to the concept of behavior. However, there is also a major difference between phenomenon and behavior: a behavior merely belongs to one entity, while a phenomenon maybe involves multiple entities as participants. For example, the behavior, *a car moves too fast*, can also be regarded as a phenomenon, while the phenomenon, *two cars collides together,* can't be regarded as a behavioral description.

5 FUNCTION

Function has been widely accepted as a critical concept of design science. However, it has also been attributed to diverse definitions by different researchers. Even in the engineering design practice, the understandings about function are diversified. To develop a science of designing, it is necessary to have a unanimous and reasonable understanding about function.

5.1 The Concept of Function

A possible way to develop a suitable concept of function is to return to its root in English. According to the Oxford English Dictionary [13], function has multiple meanings. Among them, the meaning most relevant to design science is that function represents the purpose of a person or a thing, i.e. function is equivalent to purpose. However, as a purely subjective concept, purpose often can't be explained with objective concepts in the physical world. For example, if the function of an Apple iPod is regarded as to amuse a human being, how can the concept *amusement* be described with a physical term? Therefore, treating function as purpose would make engineering design science founded on a subjective concept that often couldn't be modeled with physical science-based concepts.

To develop a reasonable concept of function for engineering design, it is useful to retrospect why human being designs. Design activities exist because the physical worlds around human beings or designers do not suit them, and their goals are therefore to change the worlds with the design solutions they are to design. Therefore, it is reasonable to treat *the function of an existing/desired design solution as a desired action on the physical world of interest, aiming at transforming it from a problematic physical state to a satisfactory one*. More details about this definition are given as below.

First, function is a kind of mental action, which can be regarded as a subjective conceptualization of the role that the subject plays in changing the problematic physical world of interest. A function, therefore, also has a subject and an object and should be described with transitive verbs. The subject of a function is an existing or desired design solution, while the object is the physical world of interest.

Second, a function is related to the physical state transformation of a physical world, i.e. the transformation(s) of the related object(s) should be represented in terms of physical states. This feature is critical for differentiating the concept of function from other kinds of mental actions. For example, since *dry* and *wet* are two mental states, it is not reasonable to say that the function of a hair-dryer is to dry hair (i.e. change the state of hair from wet to dry). Instead, it is more reasonable to describe its function as to separate water from hair, i.e. to change the location relation between hair and water. Relating function closely with physical states leads to a major advantage, i.e. the related transformation can be represented with physical states. For example, the above transformation can be represented as: $(\text{WATER}.\mathit{location} = \text{HAIR}.\mathit{location}) \rightarrow (\text{WATER}.\mathit{location} \neq \text{HAIR}.\mathit{location})$.

Thirdly, function usually represents an abstraction or a generalized (summarized) description of all primary physical actions used in an existing/desired design solution. This means that it is often impossible to achieve a functional action with a simple physical action. For example, to achieve the function, *to separate gravels from salt (i.e. to refine raw salt)*, man often needs three primary physical actions, i.e. to dissolve the raw salt into water, to transport saline water into an evaporator, and to evaporate water. This feature guarantees that function can still be explained with physical actions. In addition, it also implies that there should be physical actions between the design solution of a function and its object.
Fourthly, since the object of a function is a physical world that often comprises multiple objects, what a function aims to change can not only be the objects, but also the relations between them. For example, the function, *to separate gravels from salt*, deals with not the specific state change of either gravels or salt, but the change of their location relationship, i.e. they shouldn't be put in the same location. The above feature means that function is significantly different from a physical action, which can merely act on an object to change its physical state.
Finally, function should often be described in a solution-neutral (i.e. physical action-neutral) manner. This feature accords well with the systematic design methodology [14], which suggests that function should be represented in a solution-neutral way to allow more novel physical actions found for it.
We believe that our concept of function can provide a solid and reasonable conceptual foundation for design research. The concept of function bears two-fold properties, which enable it to bridge the gap between technical/objective and social/subjective worlds. On one hand, it bears the technical/physical property since it can merely be represented with the physical state terms. On the other hand, it bears the social/subjective property since the transformation represented by it is a subjective abstraction of multiple physical processes, which often can't be directly achieved with a single physical action.

5.2 A General Category of Actions

Based on the above research, it is now possible to produce a category of actions, as shown in Figure 2. Some notes about the categories are given as below.

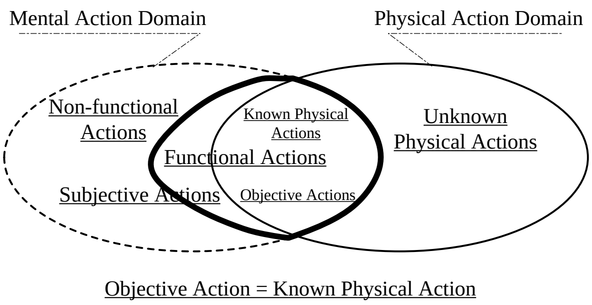

Figure 2. A General Category of Actions

First, actions can be basically classified as physical actions and mental actions. Second, physical actions can be further classified as known physical actions and unknown physical actions. Known physical actions have been recognized by human beings, which constitute a major part of human knowledge, while unknown physical actions still haven't been discovered by natural scientists. Thirdly, mental actions can be further classified as subjective actions and objective actions. Objective actions are the objective conceptualization of known physical actions. Therefore, each objective action can correspond to a known physical action. Subjective actions are imaginative actions that don't exist in the physical world. Some subjective actions are completely wrong, while others may have scientific foundations, i.e. can be indirectly explained with some physical actions. Finally, mental actions can also be classified as functional actions and non-functional actions. Functional actions are composed of objective actions and some subjective actions. A subjective action is a functional action as long as it can be described with physical terms in the physical world. The non-functional actions are those mental actions that can't be described with physical terms.
Still using a hand-dryer as an example, the above differences between such actions can also be elaborated as below. The phrase, *to dry hands*, is a subjective action (purpose) of the device since the action verb, *dry*, is a subjective action. The phrase, *to separate water from hands*, represents a

functional action (i.e. function) of the whole design solution. The phrase, *to heat air via heat-exchange*, represents an objective action (physical action) of the device on the air surrounding it.

5.3 A Comparative Analysis

To clarify the concept of function, it is helpful to compare our functional concept with those given by other researchers. Due to limited space, only typical functional definitions are analyzed here.

Rodenacker defines function as a relationship between the input and output of energy, material and information [15]. Since the relationship between the input and output can be regarded as the behavioral state change (i.e. behavior) of the objects flowing through a system, this definition seems to mean that function is equivalent to behavior. Compared with our definition of function, it is not a complete understanding of function since it neglects the subject of a function and the action of subject on object. In addition, it doesn't distinguish the desired behaviors of objects from those unexpected behaviors, which are probably undesired or can even do harm to the working mechanism of the system. This later issue has been removed by Pahl and Beitz, who define function as "the general relationship between the input and output of a system, aiming at performing a design task" [14]. However, their definition still has the former issue.

Bobrow defines function as "the relation between the goal of a human user and the behavior of a system" [9]. This definition means that the function of a system depends how it is used to achieve human user's goal, i.e. function can be regarded as goal. Similarly, Gero argues that function embodies the expectations of the purpose of the resulting artifact [1]. However, treating function as goal or purpose can make it difficult to represent a function with physical terms since purpose is often a subjective and mental concept. As a result, function then cannot be regarded as a scientific concept, and is therefore not suitable for serving as a basic concept of design science.

Goel and Stroulia define function as intended output behaviors of a device [4]. Similar definition can also be found in the work of Chandrasekaran and Joseph [16], where the function(s) of a device is (are) regarded as the desired behavioral constraint(s) that could be achieved in a specified environment (i.e. a mode of deployment). A major issue of these two definitions consists in that they are not based on an explicit and stable definition of behavior. For example, Chandrasekaran and Joseph have defined five kinds of behaviors [16], which include not only the behavioral state of an entity (e.g. a car is moving), but also the mental action of the subject on the object (e.g. a window has a function of transmitting light). Note that according to physical science, light transmission can't be regarded as a behavior of a window; in fact, light flows through a window automatically.

Recently, Vermaas and Dorst define the function of an artifact as a physical disposition of the artifact that contributes to the purposes for which the artifact is designed [17]. Here, physical disposition refers to the way in which artifacts physically react to given physical circumstances [17], which is very similar to our concept of behavior. Therefore, they actually define function as intended behavior. Compared with our concept, their concept of function is, therefore, also incomplete.

In summary, existing understandings about function possess various issues, which make them unsuitable for serving as a basic concept of design science. Compared with these understandings, our concept of function is more reasonable to serve as a foundation for design science.

6 FUNCTION-BEHAVIOR TRANSFORMATION

Based on the above research on related concepts, it is now possible to study the function-behavior (F-B) transformation process. As mentioned before, function is more concerned with the action results of the subject on the object, i.e. how the object changes its state in response to the action of the subject, which can also be regarded as the behavior of the object. On the other hand, when the F-B transformation is achieved, the result is the behavior(s) of a desired solution, i.e. the behavior(s) of the subject, for achieving the function. *A gap then emerges: how can the behavior of the object (in the functional representation) be transformed into the behavior of the subject?* We argue that physical action plays a critical role in bridging the above gap. A new function-behavior transformation model, called the FAB (abbreviation of Function-Physical Action-Behavior) model, is proposed as below.

After a function has been clarified, a design agent is responsible for finding a design solution for it. Due to the gap mentioned above, he can't transform function into behavior directly. Instead, he should first transform function into physical action, and then transform physical action into behavior. The whole FAB transformation process is shown in Figure 3. It is primarily composed of four major sub-processes, i.e. *search & select, check & decide*, *predict & analyze,* and *verify & propose*. These sub-processes are elaborated as below in details.

The first sub-process of the FAB model is "*search & select*". Since function is a special kind of mental action, it is then natural for a designing agent to search for some similar physical actions or their combinations for achieving the desired mental action. As a result, function can then be mapped into similar physical action(s). During this sub-process, the primary criterion for selecting similar physical action(s) is that the state transition of the object of a desired function should be similar to that of the object of the physical action(s). For example, since the function of cooling nitric acid has a state transition similar to that of the physical action, *to decrease the temperature of something via heat exchange*, this physical action can then be chosen to achieve the desired function. Note that when multiple similar physical actions are found, the designing agent should select one or multiple promising ones from them for further exploration.

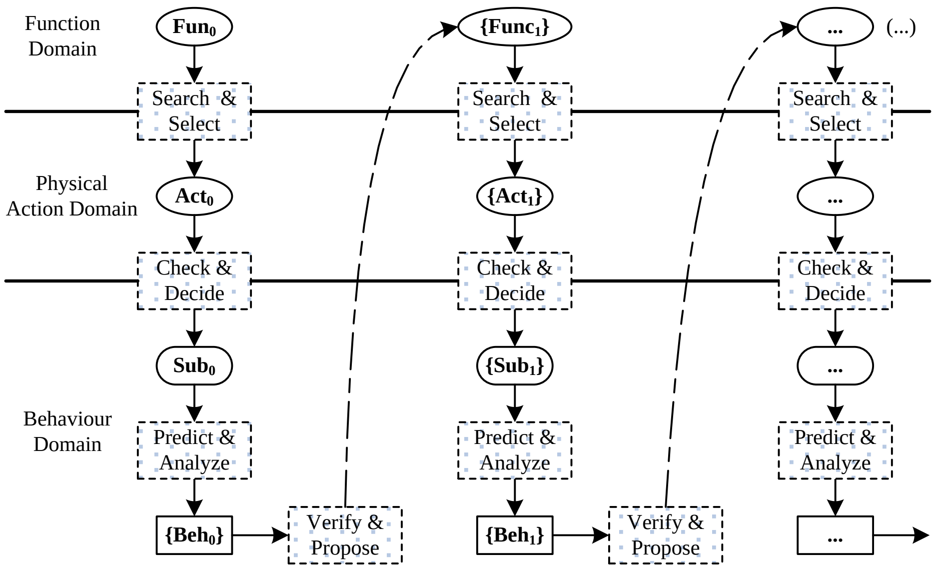

Figure 3 The FAB transformation process

The second sub-process is "*check and decide*". During this sub-process, the designing agent is responsible for checking whether the selected physical action is eligible for achieving the desired object transformation and for deciding a subject for executing the physical action. During the checking step, he should judge whether the object of the function can satisfy the requirements of the physical action on its object. For example, since the physical action, *to heat something via micro-wave*, requires that its object should be non-mental, it is then impossible to use it to achieve the function, *to heat an iron workpiece*. During the deciding step, the designing agent should investigate the requirements of the selected physical action on its subject and decide what entity should be used as the subject to execute the selected physical action. *As a result, the concern of the design agent can then be shifted from the object to the subject*. For example, when physical action, *to decrease the temperature of nitric acid via heat-exchange*, is selected for further exploration, the designing agent then knows that there should be a subject that should have lower temperature according to the related requirement, i.e. $Obj.temp_{in} > Sub.temp_{in}$. If multiple factors are considered (e.g. nitric acid should be cooled continuously and efficiently), he will then select water as the most suitable subject.

The third sub-process is "*predict & analyze*". This sub-process is responsible for deriving possible behaviors of the subject and the object for further exploration. During the predicting step, the designing agent should predict the interaction between the subject and the object using the physical knowledge related to the selected physical action. As a result, he can then know how the subject and the object will behave due to this physical action, i.e. the behaviors of both subject and object. This also illustrates how the behavior of a subject can be scientifically derived from a desired function through the related physical action. During the analyzing step, the designing agent should analyze possible unexpected physical actions that can take place unexpectedly between the subject and the object. This is because the subject and the object often have some unexpected characteristics that may cause some unexpected physical actions. For example, when the physical action, *to decrease the* *temperature of something via heat exchange*, is selected to cool the nitric-acid through water, there would be another physical action, *to dilute solution*, if water and nitric-acid were not separated from each other. It should be pointed out that much attention should be paid to the behaviors from unexpected physical actions during the designing process since they can lead to many design failures.

The final step is "*verify and propose*". Due to the occurrence of the selected physical action and the unexpected physical action(s), the related subject and object will often exhibit multiple unexpected behaviors, besides the expected behavior(s) required by a desired function. Note that unexpected behaviors can also come from expected physical actions, besides unexpected physical actions. The designing agent should verify such unexpected behaviors to see whether they are acceptable or not. If not acceptable, then either the already-selected physical action should be rejected, or he should propose a new function to change the behavioral states of the related subject and object, which will then lead to a new functional design cycle. For example, since the temperature of water will go up after it cools the nitric-acid, which is unacceptable for the cooling device, a new functional requirement is then proposed, *to transport the heated water away*. In addition, the designing agent often should verify whether the states of the available subject can satisfy the requirements of the physical action on it. If can't, he usually should propose a new function for further design exploration.

The above four major sub-processes elaborate the primary processes of the FAB model. It can be seen that physical action indeed can bridge the gap between function and behavior. Note that the above process is only one cycle of the model. As new functional requirements are proposed, the design process will continue until all functional requirements have been solved and all related subjects and objects can reach acceptable behavioral states. In addition, it should be pointed out that iterations can often occur in the above process, which, though, hasn't been shown in the figure.

7 CONCLUSIONS

As a critical process of designing, the Function-Behavior (F-B) transformation is still regarded as a subjective and experienced-based process. To develop a science of engineering design, a logical and scientific F-B transformation model should be developed, which is just the primary concern of this paper. The primary contributions are as follows.

First, it clarifies the concept of behavior as the manner *in which the way an entity behaves or acts (probably in response to external stimuli)*. The primary features of the concept of behavior are also identified. A comparative analysis discloses that our concept of behavior is largely similar to behavior as physical state change, but different from other understandings of behavior in design society, such as *behavior as action (i.e. what something does)*, *behavior as causal process*, etc.

Second, it formally imports a new concept, *physical action*, into design science. Based on the subject-object relation, physical action is explicitly illustrated as a kind of action that one physical entity (i.e. subject) exerts on another (i.e. object) in the physical world in order to change its physical state(s). The primary features of physical action are also listed, and the differences between physical action and other kinds of actions (e.g. mental action, subjective action, etc.) are also studied.

Thirdly, a reasonable concept of function is proposed. The function of an existing/desired design solution is regarded as a desired (mental) action on the physical world of interest, aiming at transforming it from a problematic physical state to a satisfactory one. This concept of function is different from all existing understandings of function, such as *function as (intended) behavior*, *function as purpose*, etc. The proposed function concept bears two-fold properties. On one hand, it bears a physical property since a function should be represented with explicit physical state or its changes. On the other hand, it also has a social/mental property since function is a kind of mental action and often can't correspond to known physical actions directly. Therefore, it is eligible for standing between the social/mental world and the technical/physical world.

Finally, a logical F-B transformation model, called the FAB model, is proposed, where physical action plays a critical role in bridging the gap between function and behavior. The FAB model discloses that the F-B transformation can be explained with the knowledge derived from the physical world. Therefore, it also demonstrates that the F-B transformation can be undertaken in a logical and scientific manner, which means that it can serve as a solid foundation for research in design science.

The research introduced in this paper is not only beneficial for design cognition, but also for design computing. It can provide a scientific and solid concept foundation for next-generation computer-aided design system since these systems will inevitably be based on the concepts such as function, behavior, physical action and structure. Especially, since the FAB model can bridge the gap between function and behavior, it is then possible to develop a computer-aided conceptual design tool for helping human designers to achieve F-B transformations automatically.

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