INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 03 STOCKHOLM, AUGUST 19-21, 2003

SITUATION THEORETIC ANALYSIS OF FUNCTIONS FOR A FORMAL THEORY OF DESIGN

Makoto Kikuchi Ichiro Nagasaka

Abstract

Function is a key notion for a theory of engineering design. In this paper, we shall give a formal definition of the notion of function by using Situation Theory, a formal theory of natural language semantics. In our formulation, a function is represented by a pair of the situation of the use and the situation of the outer system, and an artifact is also defined by these two situations. This formulation of function changes our naive idea that a function is something intrinsic to a device, and our formulation of an artifact agrees with Simon's view that an artifact is an interface between its inner and outer environment. We can expect that our formulation will induce interactions between design theory and linguistics, philosophy, mathematics, etc.

Keywords: Descriptive models of designing, prescriptive models of designing, design philosophy

1 Introduction

For engineering, design is designing artifacts, and studies for engineering design involve investigations about artifacts. Artificial things come to birth by intentions of human minds. Since our consciousness is hard to deal with, building a theory about design and artifacts is not easy. This is also the reason why design is an attractive theme to study, not only in engineering but also psychology, philosophy, logic, mathematics, etc. Design is related the very feature of the creativity of our minds, and design and artifacts must be crucial topics for understanding the essence of our minds.

It is controversial what are artificial things. This problem is almost equivalent to asking what is design, and it is not easy to define neither artifacts nor design. Simon [11] listed the four features of artificial things: 1) artificial things are synthesized (though not always or usually with full forethought) by human beings, 2) artificial things may imitate appearances in natural things while lacking, in one or many respects, the reality of the latter, 3) artificial things can be characterized in terms of functions, goals, adaptation, and 4) artificial things are often discussed, particularly when they are being designed, in terms of imperative as well as descriptives. In this paper, among these four phenomena, we focus on the third one. An engineer designs an artifact to achieve a function they have in their minds, hence function is one of the key notion for the understanding of artificial things. We need a clear definition of the notion of function for a formal theory of design.

Defining the notion of function in engineering is difficult for two reasons. The first is the inevitable involvement of designers' or users' personal subjectivity and references to the goals and purposes of the artifacts. The second is that the notion has several aspects such as functions relating to maintainability, assembly, manufacturing, and to the environment in which the artifacts are to be used. Although the notion of function is a primary concern in designing of artifacts, the notion has been used without rigorous definition in many existing design theories and methodologies.

The notion of function is also of interest to the philosophy of science. In this domain, it is not easy to explain this notion since it sometimes violates certain widely held assumptions about causation, and also it has connections with teleology that cannot be accepted in natural science. Many definition of function has been proposed in this area, but we have not reached to an agreement. However, it is clear that this area has a close connection to the study of functions of artifacts.

Design is highly conceptual activity of human beings, and our ability of using languages is closely related to design. It is not surprising that there are similar difficulties within defining functions of artifacts and meanings of sentences. Expressions by natural languages are among the oldest artifacts of human beings whose functions are their meanings. In this paper, we give a formal definition of the notion of function to show alternative arguments about functions and to build a formal theory of design. Our formulation is based on Situation Theory [1, 2, 5, 10], a mathematical framework of natural language semantics. By this formulation, we can expect applications of the philosophical and mathematical backgrounds of Situation Theory to a formal theory of design and functions, and we can put the investigations about design and function into a general theory of meaning.

2 Functions in Engineering Design

For the purpose of describing and solving design problems, the notion of function is essential. For example, when designing some artifacts, it typically starts with referring to design tasks or initial specifications that consist of sets of functions. Therefore, most of design methodologies and theories are developed on a basis of the notion of function.

The methodology of Pahl and Beitz called a Systematic Approach [9] is considered as the most comprehensive methodological approach to design. Their approach is to combine various methods in a coherent and practicable way. In their methodology, *functions* are connected to describe three types of flows through a system: energy, material, and signals, and a *function structure* is defined as "a meaningful and compatible combination of sub-functions into an overall function. [9]" The functions comprising the function structure are classified as main or auxiliary functions. Main functions are those sub-functions that serve the overall function directly, and auxiliary functions are those that contribute to it indirectly. In this methodology, the definition of function and relations between functions and design parameters are general, and the final decision of the meaningful and compatible combination of the function solely depends on the designer's personal preference.

Suh's formal design theory called Axiomatic Design (AD) [12] provides basic framework to design and a set of axioms to evaluate relations between intended functions and means by which they are achieved. In the axiomatic design approach, the product development process is divided into four different domains, i.e., customer requirements, functional requirements, design parameters and process parameters. The goal of AD is manifold: to make human designers more creative, to reduce the random search process, to minimize the iterative trial and error process, and to determine the best design among those proposed. In AD, *functional requirements* are defined as “the minimum set of independent requirements that completely characterize the design objective for a specific need. [12]” Here, the functional requirements correspond to the functions in function structure of Pahl and Beitz, while there is no distinction between main and auxiliary functions in AD. The definition of function in AD is also largely subjective.

General Design Theory (GDT) proposed by Yoshikawa [15] is another formal theory of design. GDT aims at clarifying the human ability to design in a scientific way and producing practically useful knowledge about the design methodology. It is noted in GDT that, “When an entity is exposed to a circumstance, a peculiar behavior manifests correspondent to the circumstance. This behavior is called as *visible function*. Different behaviors are observed for different circumstances. The total of these behaviors is called as *latent function*. Both are called *function* inclusively. [15]” Here, the set of functions is a sub-class of the abstract concepts derived by the classification of concepts of entity according to the meaning or the value of the entities. When attention is given to the functional value, the concept of the function is obtained.

In these design methodologies and theories, the arguments on functions are not intended to give a clear definition of function itself, but to show how desired overall functions are decomposed into identifiable sub-functions until they correspond to certain entities or design objects. Entities are composed according to the principles derived from the structure of functions to satisfy the overall function. In this way, these theories show designers’ concrete courses of actions for the design of technical systems to achieve general and specific goals.

However, in these arguments, it is not clear how and why the lowest sub-functions correspond to entities. In the methodology of Pahl and Beitz, a function is fulfilled by the physical effect. In GDT, a function is a particular behavior which corresponds to a certain circumstance. But physical effect or behavior alone fails to offer clear correspondence needed to know which of the many possible entities will fulfill the sub-function and behave as desired. Furthermore, understanding of how a composition of the entities contributes to overall function is not made explicit by its behavioral constraints. In other words, the correspondence between the sub-function and the entity are assumed and the agreement is taken for granted on a basis of the meaning or the value of entity.

3 Functions in Philosophy of Science

Function is an important notion in biology also. In biology, organs in a organism are explained by its function such as “the function of a heart is pumping blood.” However, this notion has been embarrassed philosophers for a long time. Clearly we distinguish functions of organs from other accidental behavior, but we cannot define the difference clearly without referring transcendental concepts like the intention of the creator.

Two arguments about functions by Wright and Cummins in 70’s are especially important in philosophy of biology. Wright [14] proposed a criterion for a sufficient definition of functions which consists of two conditions: firstly, the definition must distinguish functions from accidental behavior, and secondly, artifact function and natural function must be treated in the same way. Then Wright defined function as follows: "the function of X is Z means that (a) X is there because it does Z, and (b) Z is a consequence (or result) of X's being there. [14]" Cummins discussed relations between a device and its outer system, and proposed the following definition: "x functions as a Φ in s (or: the function of x in s is to Φ) relative to an an analytical account A of s's capacity to Ψ just in case x is capable of Φ-ing in s and A appropriately and adequately accounts for s's capacity to Ψ by, in part, appealing to the capacity of x to Φ in s. [4]"

There are many discussions about these two arguments in philosophy of biology [3]. Kitcher [7] tried to unify these two arguments and proposed his own definition: "the function of an entity S is what S is designed to do. [7]" Needless to say, Kitchter's definition makes sense only when we know what design is, so it is useless for our purpose. These arguments reduce problems about function to the notion *because*, *capacity*, and *design*, and they are not sufficient for our purpose since such notions are also inscrutable.

There is two reasons why defining function in philosophy is not easy. Firstly, philosophy does not have the definitions of devices. When we argue what is the function of a device, it is usually assumed that what the device is. We believe that we know what a heart is, what a kettle is, etc. but it is not always clear and our intuition about a device is referred in arguments about its function. Secondly, we do not have a clear extension of the notion of function. Defining function is giving the intension of the notion, and it makes sense only when the corresponding extension is clear. We can find the definition of a set $\{2, 4, 6, ...\}$ since (we believe that) it has a determinate extension. The extension of functions is not clear, and we have to use our intuition again. It is hard to build rigorous arguments based on our intuition.

4 Situation Semantics

It is notorious that meanings of expressions in natural languages are hard to deal with formally. Naively speaking, the meaning of an expression is the intention of the speaker or the writer of the expression. Such an intention must be treated in a formal theory of natural language semantics, and this is not an easy task.

Frege's argument [6] on meaning is classical. He distinguished the meaning and the sense of an expression. The *meaning* of an expression is the thing which is indicated by the expression, and the *sense* of the expression is the way how the meaning is indicated by the expression. That is, the meaning of the word *the evening star* is the planet "Venus" and the meaning of a proposition $1 + 1 = 2$ is its truth value "true". The senses of *the evening star* and *the morning star* (or the sense of propositions $1 + 1 = 2$ and *Fermat's Last Theorem*) are different, while their meanings (or their truth values) are the same. This idea of meaning is applied to the construction of formal semantics of first-order predicate logic by Tarski [13]. This formal semantics has grown up into a fruitful branch of mathematical logic, but it does not fit for natural languages since the sense cannot be treated. What is important for natural language semantics is the sense.

An acceptable formal semantics of a natural language was firstly obtained by Montague [8] around 1970. He build a mathematical theory of natural language semantics by using a type theory and a possible world semantics of modal logic. Inspired by this formal semantics, many formal semantics has been proposed. Situation Semantics by Barwise and Perry [1] is one of the most successful formal theories of natural language semantics. Situation Theory is the background mathematical theory for Situation Semantics.

The meaning of an expression is formulated by the notion of situation in Situation Semantics. A *real situation* is "a part of reality that can be comprehended as a whole in its own right—one that interacts with other things. [2]" It is not easy to explain what a real situation is. "Real situations are not set, but parts of reality. They comprise what might be called the causal order. We view *real* situations as metaphysically and epistemologically prior to relations, individuals, and locations. [1]" We remark that an object itself is not a situation although it occupies a portion of the real world and every part of the real world can be a situation. The concept of the object is something ideal, not real. Roughly speaking, the situation which corresponds to an object is the object with its behavior. A situation is not a collection of objects but a collection of events.

An *infon* (or a *state of affairs*) is a sort of proposition which is satisfied or not satisfied by real situations. An *abstract situation* is a mathematical structure which represents a real situation, and it is represented by a set of infons [5]. An abstract situation stands for partial information about the real world. We can consider situations in a formal way by means of abstract situations. When we use a language of first-order predicate logic to formulate infons and abstract situations, an object and an abstract situation correspond to a term and a set of sentences respectively. A structure (or a model) of the language is characterized by a set of sentence, so an abstract situation is similar to a structure except that incompleteness of information about the satisfiability of atomic formulas is allowed for an abstract situation.

In Situation Theory, the meaning $[D]$ of a sentence D is a relation between the utterance situation u and the described situation s. When we fix or ignore the utterance situation, the difference of the meaning of an expression in Frege's argument and Situation Theory is the target. That is, objects and truth values in Frege's argument are replaced by situations in Situation Theory.

5 Functions and Situations

In most of design theory, functions have been studied by focusing on either of two essential aspects: designers' or users' intentions (i.e., what a device is for), and certain kinds of attributes or behaviors of artifacts (i.e., what a device is and what a device does). This duality of functions makes their analysis difficult. For example, although the function of a kettle is originally to boil water, it could be to generate steam when we use it as a humidifier in a dry room. Very different events, such as boiling water and generating steam, can be resulted from the very same behavior of the kettle. The notion of function has this kind of ambiguity that causes endless arguments of "What is its function indeed?"

We use Situation Theory to analyze the notion of function. In Situation Theory, the meaning $[D]$ of a sentence D is represented by a pair of the utterance situation u and the described situation s. In the case of a function of an artifact (or a device) D, we consider also two kinds of situations. One is the situation u that a person is using (or designing, observing, etc.) D, and the other is the situation s of its outer system. In the previous example of the kettle, u is the situation that a person is putting the kettle with water on a stove, and s is the situation that the water is boiling and the kettle is steaming. Our main claim is that the function $[D]$ of D is a pair of such u and s. The intention of the person is embedded in u, and the attributes or behaviors of D are accounted in s. We remark that u and s are not unique even when we are considering the same event. Essentially, situations are due to our subjective choice, and the variety of the situations we can choose causes the difficulty of defining the function. In this formulation of functions, designing is an activity that connects u and s. That is, designing is designing functions.

In the both domains of engineering design and philosophy of science, the notion of function is referred in expressions of the form "a function of a device D is F". Therefore, investigations about functions are apt to be analysis of these expressions, and a typical form of questions about functions is "What is D's function?" Our formulation of functions shifts the question about functions from "What is its function?" to "How does it function?" As a result, we can be free from the idea that the function is something intrinsic to a device. A pair of situations does not belong to any particular device. It represents what is the effect of the function.

The purpose of an argument about function in design theories is not to serve a plain and easy explanation about function, but to give a formal framework to represents (effects of) functions of a device. In our formulation, functions are not reduced to primitive functions about which we have sufficient information. Any pair of situations can be called function in our framework, hence we can discuss imaginary functions.

Barwise listed the three basic ideas of Situation Semantics in the new edition of the textbook of the theory [1]: *Partiality*, *The relational theory of meaning*, and *Realism*. We have already explained the former two ideas. Realism means that "properties, relations, and situations are taken to be real objects, not bits of language, sets of n-tuples or function. [1]" However, we have to formulate these notions when we seek a formal theory. Real situations are represented formally by abstract situations which are sets of infons in Devlin's formulation [5], and it is a problem how to formulate infons. Some mathematical structures for formulating situations have been proposed in Situation Theory and we can use them, but it seems that we need our own formulation of abstract situations and infons for the construction of a formal theory of design. An argument about design and functions will be a new aspect of Situation Theory as a general theory of meaning.

6 Artifacts as Situations

In our view that a function is a pair of the using situation u and the outer system situation s, we can argue a function itself without mentioning a device which have the functions. This is a good feature of our formulation when we want to apply them to a design theory, since we do not have any artifact at the beginning of design activity: if we have artifacts in advance, the problem of design is just the efficiency of a search problem. However, we have to return to an artifact in a design theory at some point since artifacts are original concerns.

Defining an artifact is not straight forward in our formulation. We start from situations, not from objects. Artifacts are objects, but there is no standard way to obtain objects from situations in Situation Theory. This is a natural phenomenon because it is not easy to create an artifact having a desired functions. One approach to this problem is defining an artifact by a set of functions.

We have defined u as a situation of the use of a device D. Hence, it is clear that D must be included in u in a certain way. When D is an object, D must be an ingredient of some infons which belongs to u. In this case, we have to assume the existence of the object D in advance. When D is a situation, we can consider it as a part of u. Arguments about the situation s of the outer system is similar. That is, there is a part-whole relation $<$ such that D is the largest situation such that $D < u$ and $D < s$, and D. This definition of artifacts and relations between artifacts and functions is based on the part-whole relation $<$. We remark that $<$ does not mean the inclusion of the physical extents of situations. It is a rather abstract relation. We note also it is possible that such a device must be empty. In this case, the function is completely imaginary thing which cannot be realized in the real world. Then, design is an activity of changing the two situation u and s so that it has a appropriate common sub-situation.

In this formulation, an artifact is defined by a function. This is a natural choice. Any biological organ in a organism is considered as a device since it has a function or it is assumed to have a function. That is, a device is defined by its function. This is true also in engineering design. We ask the function of an artifact only when it is assumed to have a function. A mass is considered as an individual since it has a function.

This formulation of artifacts agrees with Simon's view [11] of considering an artifact as an interface between its inner and outer environments. The inner and outer environments of an artifact D correspond to u and s in our definition, while we have to understand the words *inner* and *outer* in an abstract way. That is, D is a part of the situation of u and s, but, at the same time, we can say u and s are also constituents of D. When we drive a car, the car is a part of the situation that we are driving the car. At the same time, from the viewpoint of the car, the deriver of the car is a part of the system which controls the car. There are two kinds of part-whole relations. The part-whole relation is not a trivial matter in Situation Theory. Seligman and Moss remarked that "How smaller situations relate to larger situations is perhaps the most controversial issue in Situation Theory. [10]" They proposed a definition of part-whole relation, which is equivalent to set-theoretic inclusions of abstract situations as a set of infons. That is, a is a part of b if avery infon contained in a is also in b. This relation does not equivalent to the inclusion of physical extents of situations. We have to elucidate the duality of the above part-whole relations for the construction of a formal theory of design.

7 Conclusions

By using Situation Theory, we have formulated the notion of function as a relation between the situation of the use and the situation of the outer system, and defined artifacts as a common sub-situation. Functions are not something intrinsic to devices in this formulation, and the definition of artifacts agrees with Simon's view. We can expect our formulation induces interactions between design theory and the study of linguistics, philosophy, mathematics, etc. However, these definitions are incomplete at moment, and we have to formalize situations, infons, part-whole relations for a formal theory of design based on this formulation of function. Thought these consideration, we hope design theory will be a new aspect of Situation Theory as a general theory of meaning.

Acknowledgments

This research is partly supported by Grant-in-Aid for Scientific Research 14350210, 15700132 of Japan Society for the Promotion of Science.

References

[1] Barwise J. and Perry J., "Situation and Attitude", CSLI Publications, Stanford, 1999. (Originally published by MIT Press, Cambridge, 1983.)

[2] Barwise J., "Situation in Logic", CSLI Publications, Stanford, 1988.

[3] Buller D.J. (ed.), "Function, Selection, and Design", SUNY Press, New York, 1999.

[4] Cummins, R., "Functional Analysis", The Journal of Philosophy, Vol. 72, 1975, pp.741–765. (Reprinted in [3], pp.57–83.)

[5] Devlin K., "Logic and Information", Cambridge University Press, Cambridge, 1991.

[6] Frege G., "Über Sinn und Bedeutung", Z. Philos. Philosoph. Kritik, Vol. 100, 1892, pp.25–50. (English translation: "On sense and reference", Translations from the Philosophical Writings of Gottlob Frege, Greach P. and Black M. (eds.), Blackwell, Oxford, 1960.)

[7] Kitcher P., "Function and Design", Midwest Studies in Philosophy, Vol. 18, 1993, pp.379–397. (Reprinted in [3], pp.159–183.)

[8] Montague R, "Formal Philosophy (Selected Papers of Richard Montague, edited and with an introduction by Richard Thomason)", Yale University Press, New Haven, 1974.

[9] Pahl G. and Beitz W., "Engineering Design - A Systematic Approach (2nd ed.)", Springer-Verlag, London, 1996.

[10] Seligman J. and Moss L.M., "Situation Theory", Handbook of Logic and Language, van Benthem J. and ter Meulen A. (eds.), North-Holland, Amsterdam, 1997, pp.239–309.

[11] Simon H.A., "The Sciences of Artificial (3rd ed.)", MIT Press, Cambridge, 1996.

[12] Suh N.P., "The Principles of Design", Oxford University Press, New York, 1990.

[13] Tarski A., "Der Wahrheitsbegriff in den Formalisierten Sprachen", Studia Philosophica, Vol. 1, 1935, pp.261–405. (English translation: "The Concept of Truth in Formalized Languages", Logic, Semantics, Metamathematics (2nd ed.): Papers from 1923 to 1938 by Alfred Tarski, Hackett Publishing, 1983, pp.152–278.)

[14] Wright L., "Functions", Philosophical Review, Vol. 82, 1973, pp.139–168. (Reprinted in [3], pp.29–55.)

[15] Yoshikawa H., "General Design Theory and a CAD system", Man-Machine Communication in CAD/CAM, Sata T. and Warman E. (eds.), North-Holland, Amsterdam, 1981, pp.35–58.

Makoto Kikuchi
Department of Computer and Systems Engineering
Kobe University, Kobe 657-8501, Japan
E-mail: mkikuchi@kobe-u.ac.jp
URL: http://kurt.scitec.kobe-u.ac.jp/~kikuchi/