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STRUCTURING DESIGN KNOWLEDGE FOR BETTER DESIGN SYNTHESIS

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Abstract

One possible way for better design is innovative combination of existing knowledge. Abduction can play a key role to integrate knowledge for such innovative combination. The paper first discusses knowledge structuring which facilitates knowledge integration by abduction. Then various models of abductive reasoning are introduced. An example of refrigerator design illustrates how structurized knowledge helped to arrive at better design.

Keywords: Knowledge systematization, knowledge structure, knowledge integration, abduction, design methodology

1. Introduction

Design is largely a knowledge-centered activity. A better design is possible, only when various issues and aspects are taken into consideration and brought to a good balance. Concurrent engineering and DfX (Design for X) address exactly this knowledge integration issue. The use of a variety of design knowledge through knowledge integration is also crucial to arrive at creative design. (In this paper, however, we regard creative design as a process to arrive at a new, better combination of known concepts, rather than a new concept.) In addition, giving a new set of requirements often results in a new design forcing designers to look at the use of a different set of knowledge that was not used in previous design cases.

To obtain knowledge that can be easily integrated, knowledge systematization is crucial. Knowledge systematization is a process that contains identification, codification, explicit modeling, representation, and verification of accumulated design knowledge [1]. It lends itself to building knowledge bases for advanced design support systems. Additionally, through knowledge systematization, knowledge should be well structured and organized for further applications. In particular, when there involved more than one system of knowledge (i.e., theory), we need such good structurization and organization.

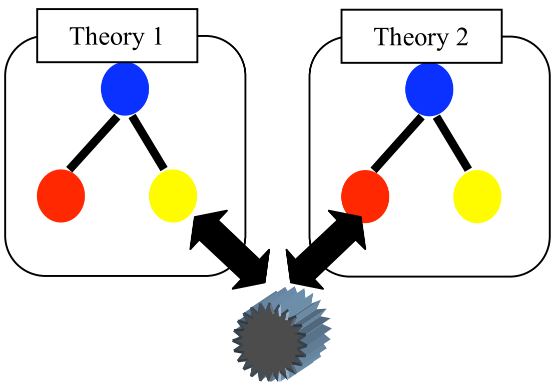
This paper focuses on this structurization of design knowledge that consists of identifying structural elements, integrating various theories, and organizing them. In the past, this was investigated from the viewpoint of knowledge access with multiple aspects. An example is the metamodel concept the author's group has been developing [2]. It manages multiple design object models from different aspects based on a shared ontology in an integrated manner and offers unified access methods to these models. However, the metamodel system itself does not provide a method to integrate these models. It simply assumed that the designer performs this integration manually.

As pointed out by many design researchers (e.g., see [3, 4]), *abduction* proposed by C.S. Peirce [5, 6] is considered to play a key role in creation, i.e., arriving at design solutions. In our previous report [7], we proposed that abduction could also be a guiding principle for the integration of superficially unrelated knowledge systems (theories). In this paper, we further focus on this role of abduction to integrate existing systematized theories to arrive at innovative design and to provide integrated model management, such as metamodel.

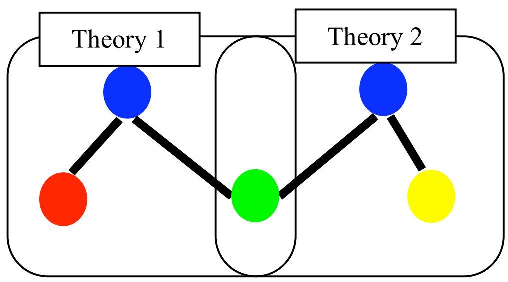
The rest of the paper is organized as follows. First, we discuss knowledge structure. Second, we explain briefly abduction and its role in integrating theories. Third, we illustrate an example of knowledge integration through abduction and how it facilitates "better" design such as innovative design.

2. Knowledge structure

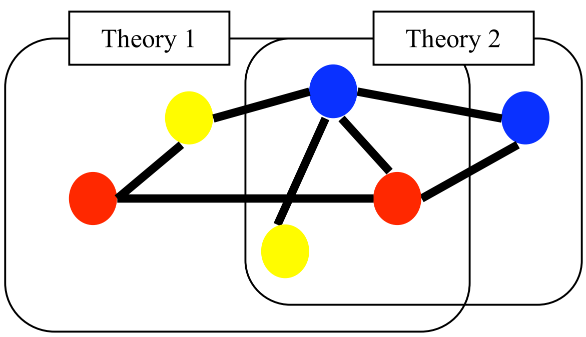
In this paper, we consider that a theory forms a closed domain in which a set of vocabulary is used to describe various concepts. Given a set of axioms **A** (for instance, Hooke's law) and facts **F** (such as Young's modulus of steel), a theory (in this case, strength of materials) can derive theorems **Th** that explain elastic deformation of steel structure, using the reasoning rule $\vdash$ (usually *modus ponens*). Concepts here include such terms as deformation, rigid bar, torsion, etc. This can be logically formulated by formula (1) that includes two important structural elements of a theory; i.e., axioms and concepts, which define the target domain. (Notice the expression $\mathbf{A} \cup \mathbf{F}$. Because both **A** and **F** are sets of logical formula, the operator which signifies logical conjunction is a union operator $\cup$.)



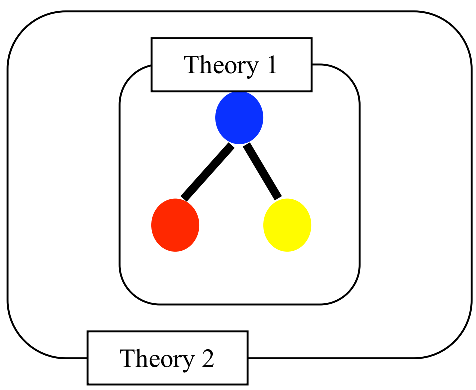
(1) The axioms of the two theories are irrelevant to each other, and the concepts used in the theories are irrelevant as well, but they share the same entity.



(2) The two sets of axioms are irrelevant to each other, but the concepts are shared by the two systems.

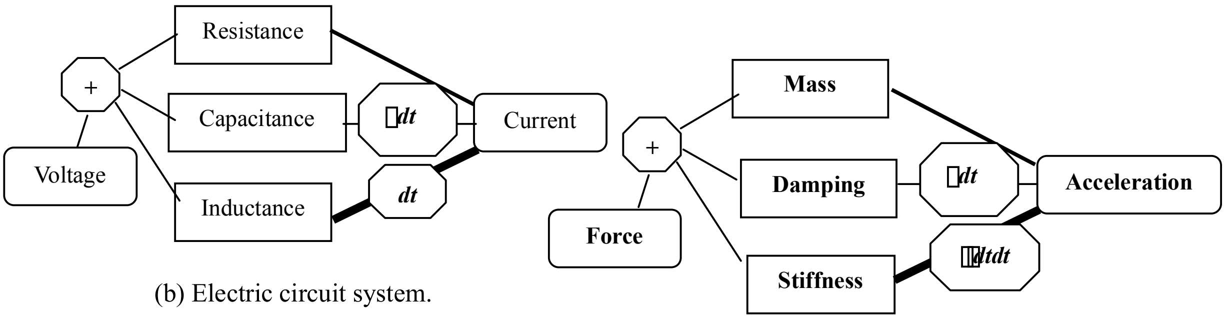


(3) The two sets of axioms are relevant; and one subsumes the other.



(4) The two sets of axioms are relevant; and one subsumes the other.

Figure 1. Relationships among different theories.



(b) Electric circuit system.

(a) Lumped mass system.

Figure 2. Two isomorphic theories.

$$\mathbf{A} \cup \mathbf{F} \vdash \mathbf{Th} \quad (1)$$

Since design requires integration of various issues and aspects, we need to find a method to integrate various theories. A simple case of two theories can be categorized as follows (see Figure 1).

1. The axioms of the two theories are irrelevant to each other, and the concepts used in the theories are irrelevant as well, but they share the same entity.
   Example: The same entity can be a spring in strength of materials as well as a coil in circuit theory.
2. The two sets of axioms are irrelevant to each other, but the concepts are shared by the two systems.
   Example: Strength of materials and vibration theory share the identical concept of spring.
3. The two sets of axioms are relevant and share (at least, a portion of) concepts.
   Example: Thermodynamics and statistical mechanics share a portion of concepts (such as temperature), but they simply provide two different views.
4. The two sets of axioms are relevant; and one subsumes the other.
   Example: The internal combustion engine is a special case of heat engines.

In addition, even if the two sets of theories are irrelevant and do not share any concepts, sometimes there can be analogical (or isomorphic) relationships among concepts. In this case, structural similarity can help analogy, for instance, because the same differential equation governs mechanical vibration and electrical vibration (Figure 2). These relationships among various theories are helpful to structurize design knowledge; we can employ such techniques in systems engineering as Bond Graph [8] and matroid theory [9] to structurize and integrate knowledge through unified operations regardless of the application domains.

3. Knowledge integration

3.1. A model of abductive reasoning

To integrate various theories, providing an integrated viewing mechanism (such as the metamodel mechanism [2]) is one solution. The other solution is to use abduction to integrate multiple theories. Before we explain this role of abduction, let us look at a model of various types of abductive reasoning given by Schurz [10]. Table 1 shows his classification in which indentation means a subcategory of the super. Note that his classification does not imply clarification about all the necessary computational algorithms.

According to him, basically there are three fundamental models of abduction; i.e., factual abduction, law-abduction, and second order existential abduction. Factual abduction is the simplest form of abduction in which both evidences to be explained and abductive conjectures are always singular facts. For example, observable-fact abduction is a reasoning to obtain

$$\mathbf{F} = \{\mathrm{C}(a)\} \tag{2}$$

from

$$\mathbf{A} = \{\mathrm{C}(x) \rightarrow \mathrm{E}(x)\},\ \mathbf{Th} = \{\mathrm{E}(a)\}, \tag{3}$$

which is simply retroduction or backward reasoning. First order existential abduction is a special form of this factual abduction and generates a as a variable to be instantiated.

Law-abduction creates theoretical hypotheses and it is closely related to induction.

Table 1. Classification of abduction (modified from [10]).

Abduction	*Evidence to be explained*	*Abduction produces*	*Abduction is driven by*
Factual abduction	Singular empirical facts	New facts	Known laws or theories
Observable-fact abduction	↑	Factual reasons	Known laws
Unobservable-fact abduction	↑	Unobservable reasons	↑
Historical-fact abduction	↑	Facts in the past	↑
Theoretical-fact abduction	↑	New initial or boundary conditions	Known theories
First order existential abduction	↑	Factual reasons postulating new unknown individuals	Known laws
Law-abduction	Empirical laws	New laws	Known laws
Second order existential abduction	↑	New laws/ theories with new concept	Theoretical background knowledge
Micro-part abduction	↑	Microscopic composition	Extrapolative background knowledge
Analogical abduction	↑	New laws/ theories with analogical concepts	Analogy with background knowledge
Missing-link common-cause abduction	↑	Hidden common causes	Causal background knowledge
Fundamental common-cause abduction	↑	New unobservable properties and laws	Unification of background knowledge
Theoretical property abduction	↑	New theoretical entities	↑
Abduction to reality	↑	External entities	↑

Second order existential abduction contrasts to the two categories of abduction in that it generates “at least partly new general property or natural kind of concept together with an at least partly new theoretical law.” For instance, Schurz [10] points out that analogical abduction generates a statement, “Sound consists of atmospheric waves in analogy to water waves,” from background laws “Laws of propagation and reflection of water waves” and phenomenon to be explained “Propagation and reflection of sound.”

Analogical abduction results from conceptual combination based on isomorphic mapping. An example is shown in Figure 2 depicting an electric circuit system and a lumped mass system. A companion paper [11] applies analogy based abduction to design knowledge integration.

In Schurz’s classification [10], another interesting model of abduction is fundamental common cause abduction that generates “a new unobservable property together with laws connecting it with observable properties.” It could be formalized as abduction from observed effects:

$$\mathrm{F}(x) \ \square \ \ \mathrm{G}(x) \text{ (where F, G are observable properties)} \tag{4}$$

to generate

$$\mathrm{F}(x) \ \square \ \ x \text{ has causal power } \mathrm{P}_{\mathrm{F/G}(x)}\text{, which produces } \mathrm{G}(x). \tag{5}$$

A special kind of fundamental common cause abduction is theoretical property abduction. In this case, from a number of correlated observations, one observation seems to explain all of them. An example given by Schurz [10] is that “Whenever an object exhibits conductivity of heat, it also exhibits conductivity of electricity, characteristic flexibility and elasticity, hardness, characteristic glossing.” Then, we might suppose that “there is a really existing material characteristics which is the common cause of all these empirical” propositions, which is metallic character. From this, we actually create metallic character that unifies those theories about behaviors such as heat conductivity, electricity conductivity, elasticity, etc.

3.2. Abduction for creation

Within the design research community, it is often pointed out that synthesis is largely performed by abduction in the sense of factual abduction [3, 4]. Roozenburg and Eekels further proposed innoduction as a conceptual model of design reasoning but did not provide with a computational mechanisms [12]. Indeed, first order existential abduction generates an entity that performs the given requirements. While philosophically this analogy seems valid, computationally, we can see that factual abduction does not really lead to creative and innovative design. First, it generates facts from a known set of axioms and theorem (i.e., requirements) in a domain that is more or less covered by the axioms. In this sense, such a mode of abduction cannot go beyond what the axioms cover nor result in creative design. This can be seen in the formalization denoted by formulae (2) and (3). To computationally perform this type of abduction, we must be given a knowledge base that contains *a* and *a* should satisfy C(*a*) in formula (2), before even we design. This means that we should know the solution before we design and that design boils down to search problems.

3.3. Abduction for integration

While abduction is a crucial concept as discussed in the previous section, abduction also plays another important role in integrating multiple theories [7]. Given a problem and a set of theories, if judged impossible to find a solution within the domain, abduction can introduce an appropriate set of relevant theories to form a new set of theories, so that solutions can be

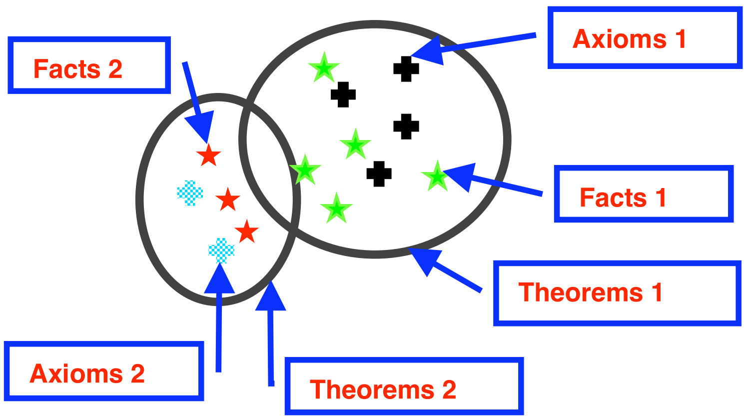


Figure 3. Abduction for integrating theories.

found with the new set of theories. For instance, as long as our knowledge is limited to the structural strength of materials of given shape, we will never reach such an innovative design as "drilling holes" for lighter structure while maintaining the strength. This is only possible when we have a piece of knowledge that removing material that does not contribute to strength does not make any harm but only makes the whole object lighter.

Figure 3 depicts abduction for integrating theories. First, we are given axioms 1 as background knowledge and the combined domain of theorems 1and 2 as requirements. However, we may notice that there is no way to arrive at design solutions that can cover the domain designated by theorems 2 with only axioms 1 (hence theorems 1). This may request us to incorporate a new theory, i.e., axioms 2 that may be able to cover this domain. After factual abduction using both of axioms 1 and 2, we may arrive at facts 1 and 2 that describe a design solution for these requirements. However, notice that as a consequence of taking into consideration additional axioms 2 besides axioms 1, we effectively integrated axioms 1 and 2. This is an example of innovative design coming from innovative combination of knowledge. In Schurz's classification, this abduction for integrating theories seems to be carried out by combination of modes of second order existential abduction [10].

For instance, we can think about the following two-step algorithm to integrate multiple theories from different domains (that are superficially irrelevant to each other); first to identify the applicability and the domain of the theories to be introduced, and second to integrate the new set of theories. The first step identifies the relevance of the structural elements of theories, i.e., axioms and concepts, and very much the same as analogical abduction. The second step actually does the integration based on, for instance, theoretical-property abduction.

To effective carry out such an algorithm, knowledge (or theories) must have clear structures. First, relationships among domain theories should be identified as depicted in Figure 1. Second, the concepts belonging to those domain theories must also have relationships with each other (including relationships such as part-of, super-sub, and is-an-instance-of) and this is what ontology clarifies. Having done these, for example, we are able to judge the relevance of different domain theories to be integrated.

4. An example: Refrigerator design

One of the goals of design studies is to eventually lay a foundation for various design methodologies on a theoretical basis of design theories. This lends itself to a better design, by systematically organizing and applying design knowledge. This situation can be visually illustrated in the following example. Axiomatic design of Nam Suh [13] has two axioms to facilitate better design.

Axiom 1: The Independence Axiom. *Maintain the independence of function requirements*.

Axiom 2: The Information Axiom. *Minimize the information contents of the design.*

Functional requirements (FRs) are defined as the minimum set of independent requirements that characterize the design goals. A formalized tool to support the independence axiom is the design matrix that represents the relation between FRs and DPs (design parameters, representing the embodiment in the physical world). Axiom 1 requests that the design matrix is diagonal in case of an uncoupled design, or at least, lower or upper triangular in case of a decoupled design. Any other case is called a coupled design.

While these two axioms seem intuitively correct, unfortunately so far, no theoretical foundation is given; in particular, there is no explanation, for instance, why Axiom 1 (Independence Axiom) is valid and indispensable to arrive at a good design. However, the theory to structurize design knowledge illustrated in the previous section can present a clue.

Let us consider a conceptual design of refrigerators [14, 15] (this example was inspired by [13]). While refrigerators are originally simple devices, today we can find a variety of sophisticated designs including traditional design with a large compartment for normal temperature and a freezer, advanced design with multiple compartments including drawer-type storage and even a door in a door, and special design for supermarkets (i.e., a box with a vertical opening but without lid or a showcase with circulating cool air without loosing it).

Now let us analyze the most fundamental refrigerator design with only one cooled space, based on Suh's axiomatic design. The main function requirements are:

FR1: to store food and to provide access to it, and

FR2: to keep the food cool.

Having defined FRs in this way, we obtain a little bit of embodiment. We need a storage space that should be accessible (either from the front or from the top) and efficient enough to keep the food cool, as well as a cooling device. Thus, we obtain two DPs, *viz*., a storage space (S) and a cooling device (C) resulting in the following expression. (By the way, according to [13], this is a decoupled design that is not necessarily a good design.)

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} x & 0 \\ x & x \end{bmatrix} \begin{Bmatrix} S \\ C \end{Bmatrix} \tag{6}$$

Now, FR1 can be decomposed into:

FR11: to store the food in storage, and

FR12: to access the food in the storage.

The decomposition of FR2 depends on the embodiment, and for instance, it can be decomposed into

FR21: to generate cool air, and

FR22: to maintain cool temperature in the storage with cool air.

The next step is embodiment. For FR11, we may need an enclosed space (E), and for FR12 an access method to it (A). For FR21, as working principles we may use cooling with cool air generated by a cooling device physically realized by an evaporator of a cooling cycle (Cd). FR22 requires thermal conduction and insulation for the space (Tc). We may employ other principle such as ice or radiation, but of course this will result in another design. Consequently, we obtain the following representation, which again is a decoupled design.

$$\begin{bmatrix} FR11 \\ FR12 \\ FR21 \\ FR22 \end{bmatrix} = \begin{bmatrix} x & 0 & 0 & 0 \\ x & x & 0 & 0 \\ 0 & 0 & x & 0 \\ x & 0 & x & x \end{bmatrix} \begin{bmatrix} E \\ A \\ Cd \\ Tc \end{bmatrix} \tag{7}$$

This decomposition can be continued until we identify sufficient information regarding FRs and DPs with which we may proceed to basic design stage. For instance, regarding the identified enclosed, cooled storage, we need to consider accessibility. This requires a piece of knowledge about accessibility of human hands to an enclosed space. Our functional knowledge about mechanisms tells that for horizontal access a door and a sliding door are options, and for vertical access a lid or a sliding door. We may identify a trade-off here; having a door for horizontal access may release cooled door, whereas doors for vertical access may not be good for food access.

Traditional refrigerator design is to have big frontal doors for horizontal access, which may sacrifice efficiency by loosing cool air. Better designs include having smaller doors instead of a single big door, drawer-like design with cooled compartments for separate vertical access, or even more innovatively having a smaller door in the big door. If we neglect efficiency and emphasize access, an extreme design is a box with a top opening without a lid.

In these design examples, we notice that the knowledge describing accessibility was combined with the knowledge about the behavior of cooled air for "better" designs. This combination process is exactly the result of abduction to integrate these two pieces of knowledge and illustrates the power of "abduction for integration" to arrive at better design.

The relationships among different theories can be more precisely analyzed by clarifying which theory was employed in obtaining design matrix representation such as formulas (6) and (7). For example, a theory about evaporator:

TH1: An evaporator of a cooling cycle cools objects in the space.

was used to derive the relationship between FR21 and Cd.

Similarly, we can discuss knowledge about space and accessibility.

SK1: Two objects cannot simultaneously occupy the same space.

This spatial axiom can lead to a couple of other knowledge.

SK2: To move an object, a path is needed.

SK3: If a path is blocked, it can be cleared by removing the blocking objects to make an opening.

We also need some knowledge about "mechanisms," such as enclosed space, door, and drawer, organized in the form of "entity property or function" [16].

SK4: An enclosed space is a space surrounded by walls in every direction.

SK5: A drawer is an enclosed space with an opening for vertical access, when it is open.

SK6: A horizontal door attached to an enclosed space allows horizontal access to the space when it is open.

SK7: A vertical door attached to an enclosed space allows vertical access to the space when it is open.

From these theories, based on forward chaining, we see that

SK8: If an enclosed space has a door in front, then an object can be horizontally taken out from the enclosed space.

SK9: If an opening on top of an enclosed space is no option (top surface is blocked by object), then a drawer is used and the object can be accessed vertically.

through

SK3 □ SK 6 □ “direction is horizontal” |– **Th** SK8,

SK3 □ SK5 □ “direction is vertical” □ “vertical direction should be open” |– **Th** SK9,

where is set-theoretical inclusion but not logical implication. This shows that combining such rather trivial theories can lead to interesting design solutions. The core issue here was to organize these theories ready for combination, performed by abduction for integration. We see that theories SK1 to SK9 share certain concepts to form an ontology about space and accessibility, and that they build a certain structure among them (for instance, SK1 is a super theory subsuming SK2 and SK3).

Suh’s Axiom 1 lends itself to identifying the dependencies among different theories (each of which valid for one design domain, representing a “function”) and design parameters to control the function within that domain. This suggests that perhaps, the excellence of axiomatic design relies on how well functional domain theories are organized, so that Axiom 1 can hold. In other words, to arrive at a better design, it is more critical to find independent functional knowledge structure that can be controlled by uncoupled design parameters than to find design parameters that guarantee functional independence.

6. Conclusions

Knowledge systematization is necessary not only for building and implementing advanced knowledge-based design support systems but also for structurizing design knowledge. This paper described a method for structurizing design knowledge by identifying knowledge structures, integrating various theories, and organizing them. To do so, metal-level knowledge relationships among various theories becomes critical. Abduction can be a tool for integrating theories. This paper identified some models of abductive reasoning useful to do so.

Future work includes, among other things, clarifying algorithms of abduction for integration and of identification mechanisms of relevant theories in a particular context. (An example of research in this direction is [11]). This may further involve ontological research of engineering design knowledge to structurize actual knowledge.

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