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ABDUCTION FOR CREATIVE DESIGN

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ABSTRACT

While abduction is considered crucial for design in general, this paper focuses on the role of abduction to integrate knowledge assuming that creative design can come from innovative combination of existing knowledge. Based on Schurz's classification of abductive reasoning, the paper identifies that abduction for integrating theories can be performed by a special type of abduction called second order existential abduction. The paper then analyzes refrigerator design cases to understand how knowledge is used and shows that abduction is indeed central to design. It also discusses that knowledge structure is a key concept in abduction for integration.

Keywords: design knowledge, design reasoning, abduction, knowledge integration, knowledge structure.

INTRODUCTION

This paper is a preliminary report on an attempt to understand the mechanism of design, and to formalize it with a special focus on design knowledge. While we acknowledge the importance of generating new knowledge (such as discovery and invention) to arrive at innovative, creative design, we also believe that considerable cases of creative design come from innovative, new combination of existing well-known knowledge. In addition, giving a new set of requirements often results in a new, creative design forcing designers to look at the use of a different set of knowledge that was not used for previous design cases.

In this paper, we focus on the use of innovative, new combination of existing, well-known knowledge. However, this means that the paper do not explain all the creative designs. It may explain only a small portion of cases in terms of creativity, but perhaps can do so in terms of the number of cases.

Abduction, proposed by C.S. Peirce [1, 2] is considered to play a key role in design (e.g., see [3, 4]). Roozenburg and Eekels [5] further proposed *innoduction* as a reasoning mode more appropriate than abduction. Under an assumption that design is largely a knowledge-centered activity, our previous report [6] proposed models of analysis and synthesis (as a part of design) that both include deduction and abduction. In particular, we pointed out that abduction could be a guiding principle for not only creation (such as design) but also integration of superficially unrelated knowledge systems (theories). The latter role is crucial to combine existing theories to arrive at creative design.

Despite its importance to design, the design research community seems to fail building full understanding of abduction and its role in creative design. Although within both the research communities of philosophy and AI [7], until recently there was no comprehensive model of abduction, Schurz [8] has seemingly succeeded in compiling such models of abductive reasoning. Based on his classification, this paper tries to identify abduction that can be useful for creative design.

The rest of the paper is organized as follows. First, we will define the scope, method, and approaches of the paper. Next, we make a brief overview of abduction and introduce Schurz's classification of abductive reasoning [8]. We then discuss roles of abduction in design. (In a separate report [9], we discuss a computational method and its implementation of abduction for knowledge integration based on so-called analogical abduction.) Then, as an example, we look at design cases of refrigerators. These cases will be further analyzed from the viewpoints of knowledge used. We will discuss that the combination of theories was actually crucial in arriving at interesting refrigerator designs. Finally, we will argue that to easily integrate knowledge, knowledge should be well-structured and organized, by presenting some models of knowledge structure.

CREATIVE DESIGN

While the purpose of the paper is not to clearly define creative design, we discuss here the scope of the paper, i.e., *creative design*. It seems difficult, if not impossible, to define creative design, although a reasonable way to do so is to define it according to the characters that the design has. Creative design exhibits functions, show performance, or have features that existing artifacts in the category do not have and may surprise people. However, because this definition could be relative and subjective, it may cover something that can be called invention to other things that are merely minor improvement of existing designs. In addition, creativeness is related to customer's value or perception to a large extent. Technological innovations do not necessarily lead to a big commercial value.

In this paper, we regard creative design as new design and design itself is largely a knowledge-centered activity [6, 10]. Figure 1 depicts this situation in which design is a process that converts requirements into a design solution under some constraints. This conversion requires design knowledge. This formalization primarily has two possibilities to generate new designs.

One possibility to obtain a new design happens when new requirements and/or constraints are given even with the same design knowledge. The other possibility happens when new design knowledge is given. This case can be further broken down into two cases. The first one is the case in which purely new design knowledge is created; this may correspond to an invention based on a new discovery. The second one is the case in which the designers' knowledge itself does not change, but the way he/she uses it changes. Obviously they do not (or cannot) use all the knowledge they have. The designers may use a portion of knowledge that they intuitively judge relevant for unaccountable reasons or based on past experiences. Or, it happens that they may create mental blocks that prevent them from explicitly using some knowledge, although they surely know it if they are asked.

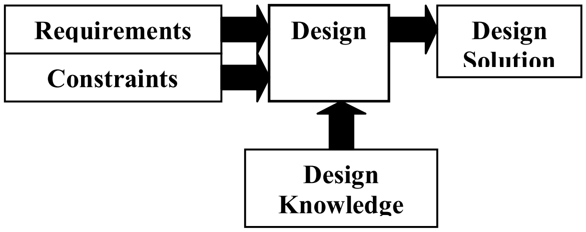

Fig. 1. Knowledge-Centered View of Design

This paper focuses on this second case in which design knowledge itself is known very well, but its new usage brings in new design solutions. In other words, we deal with creative design that comes from innovative, new combination of existing well-known knowledge. As discussed below, the paper will particularly discuss how to combine knowledge, but it will not deal with the problem of how to find such a relevant set of knowledge.

Shah [11] points out two approaches to achieve creative designs, *viz.*, intuitive and systematic. Intuitive approaches, such as brainstorming, increase the flow of ideas, remove mental blocks, and increase the chances of conditions perceived to be promoters of creativity. Systematic approaches, such as morphological analysis in German design methodology [12] and TRIZ [13], define methodologies to apply design knowledge and to arrive at creative designs more rationally and systematically.

ABDUCTION

Deduction, Induction, and Abduction

In a traditional, simple set up, a theory consists of such elements as axioms, facts, reasoning rules, and theorems. A theory forms a closed domain in which a set of vocabulary is used to describe various concepts. This can be logically formulated as follows. A theory consists of:

$$\mathbf{A}\ \square\ \mathbf{F} \vdash_{\square} \mathbf{Th} \qquad (1)$$

where **A** is a set of axioms (or rules), □ is the reasoning rule (usually *modus ponens*), **F** is a set of facts, and **Th** is a set of theorems. (Notice the expression **A** □ **F**. Because both **A** and **F** are sets of logical formula, the operator which signifies logical conjunction is a union operator □.)

Given a set of axioms (for instance, Hooke's law) and facts (such as Young's modulus of steel and geometric configuration of structure), a theory (in this case, strength of materials) can derive theorems that explain elastic deformation of various types of structure. Concepts in this example include such terms as deformation, rigid bar, torsion, etc. This reasoning mode is *deduction* to obtain **Th** from **A** and **F**, while *abduction* obtains **F** from **A** and **Th**, and *induction* **A** from **F** and **Th**[1]. In this formalization, there are two important structural elements of a theory; i.e., axioms and concepts, which define the target domain. In the final section of the paper about knowledge structure, the elements of a theory and their relationships among different theories will be further discussed

It is helpful for the reader to understand that in design context, axioms **A** represent design knowledge, design procedures, physical laws, etc.; facts **F** represent descriptions about design solutions; and theorems **Th** include properties of design solutions, respectively. At the beginning of design, design requirements can be set as partial descriptions of properties in **Th** [14].

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[1] Note that Peirce had two definitions of *abduction* and *induction*. The explanation here is based on his early version [1, 2]. In his later version, Peirce regards abduction as a reasoning operation more essential than induction.

Models of Abductive Reasoning

Schurz [8] has compiled a (seemingly) complete model of abduction that classifies various types of abductive reasoning. 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: there are still many tasks to be accomplished, although some of them can easily be implemented computationally.

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

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

from

$$\mathbf{A} = \{C(x) \square\ E(x)\} \tag{3}$$

and

$$\mathbf{Th} = \{E(a)\}, \tag{4}$$

which is simply retroduction or backward reasoning (C and E are any predicate). *First order existential abduction* is a special form of this factual abduction and generates *a* as a variable to be instantiated. These modes of abduction perform creation of design solutions from the given design knowledge.

Law-abduction creates theoretical hypotheses and it is closely related to induction. Schurz [8] explains as follows: given a background law,

$$\square x(C(x) \square\ E(x)): \quad \text{Whatever contains sugar tastes sweet,} \tag{5}$$

and an empirical law to be explained,

$$\square x(F(x) \square\ E(x)): \quad \text{All pineapples taste sweet,} \tag{6}$$

we may obtain

$$\square x(F(x) \square\ C(x)): \quad \text{All pineapples contain sugar.} \tag{7}$$

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 [8] 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 Fig. 2 depicting an electric circuit system and a lumped mass system. For the both systems, an identical differential equation holds, because there exist isomorphic mappings of system parameters between these two systems (naturally, we need an additional piece of mathematical knowledge about linear ordinary differential equations).

In Schurz's classification [8], 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:

$$F(x) \square\ G(x) \text{ (where F, G are observable properties)} \tag{8}$$

to generate

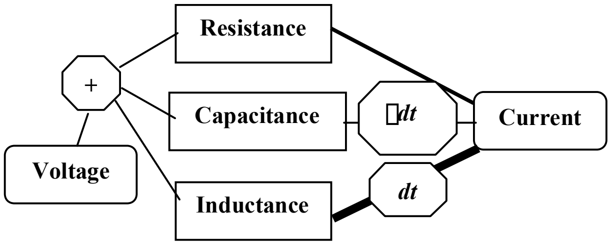
$$F(x) \square\ x \text{ has causal power } P_{F/G}(x)\text{, which produces } G(x). \tag{9}$$

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. Assume we have a set of propositions for some but not all objects *x*:

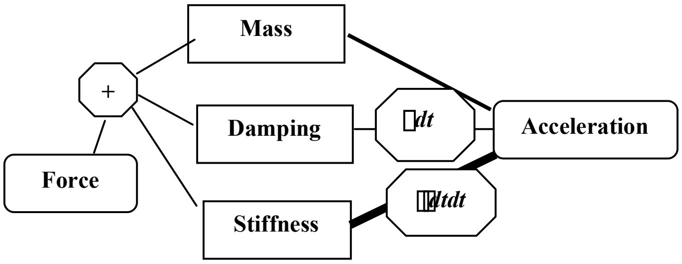
$$\square t(C_i(x, t) \square\ E_i(x, t)),\ 1 \le i \le n \tag{10}$$

Table 1. Classification of Abduction Modified from [8]

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	Extrapol-ative 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	↑



(b) Electric Circuit System



(a) Lumped Mass System

Fig. 2. Two Isomorphic Systems

in which $\Rightarrow$ means “an implication stronger than material one, e.g., counterfactual or law-like implication.” Now assume that “all these empirical laws are themselves correlated in the following way”:

$$\forall x(\forall t(C_i(x, t) \Rightarrow E_i(x, t)) = \forall t(C_j(x, t) \Rightarrow E_j(x, t)) \quad 1 \leq i < j \leq n. \tag{11}$$

In such a case, there must be a unifying explanation for all of these propositions; this creates a new theory.

An example given by Schurz [8] 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, $M(x)$. We may say:

$$\forall x(M(x) = \forall t(C_i(x, t) \Rightarrow E_i(x, t))). \tag{12}$$

From this, we actually create metallic character that unifies those theories about behaviors such as heat conductivity, electricity conductivity, flexibility, elasticity, etc.

Abduction for (Factual) 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]. Indeed, first order existential abduction generates an entity that performs the given requirements. So, we name this abduction *abduction for (factual) creation*.

While philosophically this analogy seems valid, computationally (or from the design point of view), we can see that factual abduction does not really lead to creative and innovative design. First, it generates *trivial* facts from a known set of axioms and theorem (i.e., requirements) in a domain which 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 (2) to (4). To computationally perform this type of abduction, obtaining formula (2), we must be given a knowledge base that contains *a* and *a* should satisfy $C(a)$, before even we design. This means that we should know the solution before we design and that design boils down to search problems or constraint solving.

Figure 3 depicts this situation. First, we are given axioms as background knowledge and theorems as requirements. Factual abduction generates facts that describe a design solution. If given different requirements (i.e., a different enclosing domain), we arrive at different design solutions. However, these domains are already implicitly defined by axioms!

One another important mode of abduction is *theoretical-fact abduction* that generates new initial or boundary conditions that describe the yet-to-be-found design solutions. While this abduction does not directly generate design solutions, it will generate conditions that these solutions should satisfy. In the design context, these conditions can become new sub design problem or additional requirements. Therefore, it is also of great relevance to design.

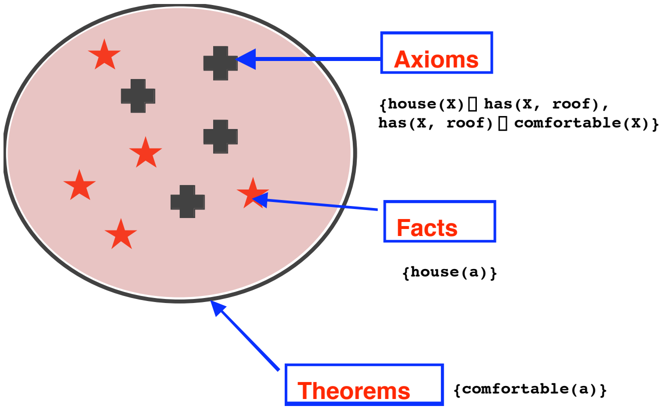
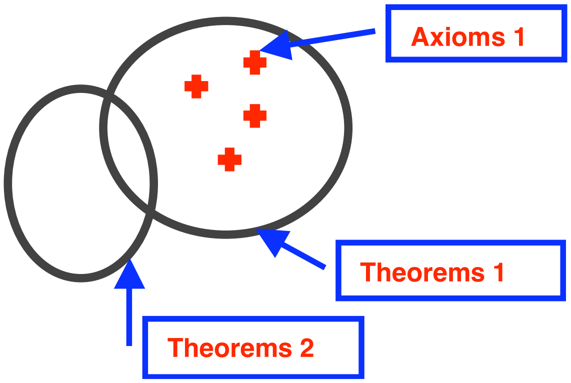


Fig. 3. Factual Abduction

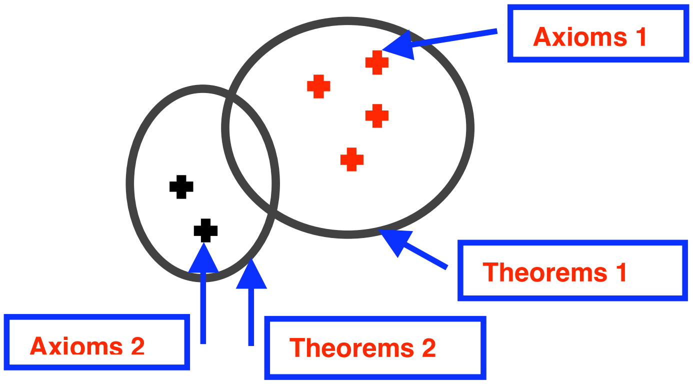
Abduction for Integration

While abduction is a crucial concept as discussed in the previous section, abduction also plays another important role in integrating multiple theories [6]. 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 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.

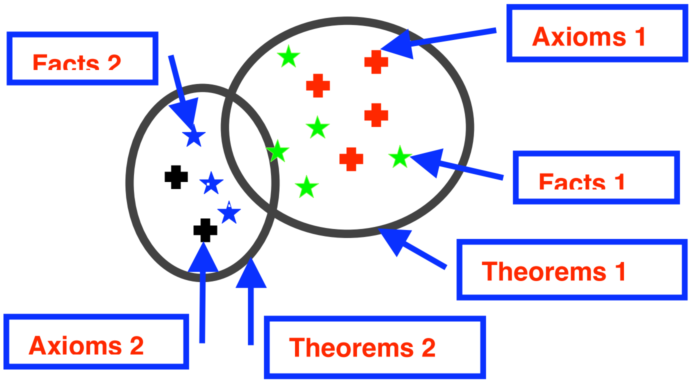
Figure 4 depicts abduction for integrating theories. First, we are given axioms 1 as background knowledge and the combined domain of theorems 1 and 2 as requirements (Fig. 4 (a)). However, we may notice that there is no way to arrive at design solutions that can cover the domain designated by (potentially) theorems 2 with only axioms 1 (hence theorems 1). Computationally, this check can be performed by conducting



(a) Initial Requirements



(b) Incorporating Axioms 2



(c) Factual Abduction to Obtain Facts

Fig. 4. Abduction for Integrating Theories

all possible factual abduction to see if the results of abduction cover the entire domain of theorems 1 and 2.

Results of this check may request us to incorporate a new theory, i.e., axioms 2 that may be able to cover this domain (Fig. 4 (b)). 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 (Fig. 4 (c)). Logically, this situation can be represented as follows.

$$\mathbf{A_1 \cup F \not\vdash Th_1 \cup Th_2}$$

$$\mathbf{A_1 \cup A_2 \cup F \vdash Th_1 \cup Th_2} \qquad (13)$$

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 [8], this *abduction for integrating theories* seems to be carried out by combination of modes of second order existential abduction.

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, law abduction or second-order existential abduction.

Our group has developed a prototype of a computational tool, called *Universal Abduction Studio 1* that actually integrates different theories based on analogical abduction. Interested readers may refer to [9].

REFRIGERATOR DESIGN

To test the ideas described in the previous chapter, let us consider a conceptual design of refrigerators [15] (this example was inspired by [16]). While refrigerators are originally simple devices, today we can find a variety of sophisticated designs depending on such requirements as capacity, cooling temperature and humidity, how to store and handle food, and where to use. Some examples of refrigerators that can be found include 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 consider the most fundamental refrigerator design which has only one cooled space. In this paper, we employ the terminology of Suh's axiomatic design [16] to represent the relationships between functional requirements (FRs) and design parameters (DPs). (Naturally, the same could be demonstrated with other design methodologies such as [12].) 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 [16], this is a decoupled design that is not necessarily a good design.)

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} x & 0 \\ x & x \end{bmatrix} \begin{Bmatrix} S \\ C \end{Bmatrix} \qquad (14)$$

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.

$$\begin{Bmatrix} FR11 \\ FR12 \\ FR21 \\ FR22 \end{Bmatrix} = \begin{bmatrix} x & 0 & 0 & 0 \\ x & x & 0 & 0 \\ 0 & 0 & x & 0 \\ x & 0 & x & x \end{bmatrix} \begin{Bmatrix} E \\ A \\ Cd \\ Tc \end{Bmatrix} \tag{15}$$

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. More recent innovative designs include having smaller doors instead of a single big door, drawer-like design with cooled compartments for separate vertical access, or even having a smaller door in the big door. If we neglect efficiency and emphasize access, an extreme design case of a box with a top opening without a lid that can often be seen in supermarkets for frozen food. Another extreme is a design with frontal sliding doors made of glass for the display purpose but with better cooling efficiency than open box design.

These design examples do not mean, of course, representative of creative design, but are intended to demonstrate how different combinations of knowledge result in different designs that can potentially be innovative. In these design examples, the knowledge describing accessibility was combined with the knowledge about the behavior of cooled air for better, new designs for supermarkets. This combination process is exactly the result of abduction to integrate these two pieces of knowledge.

ANALYSIS OF KNOWLEDGE USE

Following the discussions in the previous chapter, here we analyze the refrigerator design examples more formerly. We can indeed logically interpret these examples, using techniques of qualitative physics, in particular, of naïve physics [17, 18]. In particular, we will focus on how different combinations of knowledge can logically done and yield different design solutions. This will help formalization of abduction for integration as well.

Knowledge about Cooling

First, let us consider design knowledge we used for embodying FR21 with Cd (formula (15)).

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

This sounds somewhat fundamental and might be accepted as a piece of fundamental knowledge. However, below we would like to point out that even such seemingly fundamental knowledge is a result of combination of more fundamental knowledge. To obtain TH1, we first need knowledge about heat transfer.

HT1: Heat is transferred through conduction from an object of high temperature to one of low temperature, if they contact each other.

This can be logically formalized using first order predicate logic as follows. Notice, however, that we may need more carefully treatment about temporal aspects and causality; to do so, one may use more sophisticated logic systems such as temporal logic than standard first order predicate logic.

HT1[2] = {contact (A, B) ∧ temperature (A, Ta) ∧
temperature (B, Tb) ∧ $Ta>Tb$ → heat_transfer (A, B)} (16)

The contact relationship is usually transitive and reflexive. So we know:

C = {contact (A, B) ∧ contact (B, C) → contact (A, C),
contact (A, B) → contact (B, A)}. (17)

When heat transfer happens, the object with higher temperature gradually cools down and the object with lower temperature also gradually heats up, and eventually they arrive at equilibrium. However, here we assume (for the sake of simplicity) that the heat capacity of an evaporator of a cooling cycle is sufficiently large, so that the temperature of the evaporator can remain the same, while this might not be the case for ice. In our case, after heat transfer, the object touching the cooling source gets cooler.

HT2 = {time (T0) ∧ heat_transfer (A, B) ∧ evaporator (B)
∧ temperature (A, Ta) ∧ temperature (B, Tb) ∧ $Ta>Tb$ →
time (T1) ∧ temperature (A, Tb) ∧ $T0 << T1$} (18)

In addition, we need to have knowledge about cooling sources. Such factual knowledge about entities and their functionalities are organized as follows [19]:

FK1 = {ice (X) →
cooling_soruce(X) ∧ temperature (X, 0°C)} (19)

FK2 = {evaporator (X) → cooling_soruce(X) ∧
temperature (X, 0°C)} (20)

Now, assuming that we use air as a medium to transfer heat and that the temperature of any cooling source is substantially below normal room temperature, i.e.,

AS1 = {cooling_source (C) ∧ temperature (C, Tc)
∧ food (F) ∧ temperature (F, Tf) ∧ $Tf > Tc$ ∧ air (A)
∧ contact (C, A) ∧ contact (A, F)}, (21)

We now obtain from (16) to (21) our formalized knowledge:

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[2] **HT1** in bold denotes a set of logical formulae, whereas HT1 in roman typeface denotes its plain text version.

HT1 **HT2** **C** **FK1** **FK2** **AS1** **F** |–
Th {food (F) temperature (F, 0°C) time (T1)}. (22)

Notice that the first part of formula (22) (i.e., **HT1** **HT2** **C** **FK1** **FK2**) denotes combination of different axioms in the sense of Fig. 4. As a result of this combination, theorems **Th** derivable from (22) now include our design requirements (food(F) temperature(F, 0°C) time(T1)). From these requirements, we can now perform factual abduction for formula (22) and obtain

F = {evaporator (X)} (23)

as a design solution. Even for this kind of small example, we had to "integrate" various knowledge sources, such as **HT1**, **HT2**, **C**, **FK1**, and **FK2**, by union operations (assuming that a set union operation is equivalent to a logical conjunctive operation). In fact, through simple forward chaining, we obtain:

HT1 **HT2** **C** **FK1** **FK2**
{evaporator (X)
contact (X, A) temperature (F, 0°C) time (T1)} (24)

which is equivalent to TH1.

Notice that in this simple example the knowledge integration algorithm was not complicated (see formula (13)). It needed forward chaining to derive (24) and second-order existential abduction (fundamental common-cause abduction) for the derivation of assumptions **AS1** in (21), which was accumulation of all the prerequisites in all of **HT1**, **HT2**, **C**, **FK1**, and **FK2**. Further studies are needed to generalize these operations, though.

The reasoning above does not address enclosed space, because FR1 addresses only food storage and its accessibility. We all know that without enclosure this design would be very inefficient. To solve this problem, we further require knowledge about gas flow under gravity, such as:

GF1: Under gravity, cold air sinks below warm air.

GF2: Gas flows in open space and does not flow out from a enclosed space:

and knowledge about heat loss and insulation, such as:

HL: Heat loss inevitably happens through heat conduction, heat radiation, or heat circulation, depending on the material, if there is a temperature difference.

IN: If a space is to be cooled efficiently, then the enclosure of the space must contain insulation.

Using these pieces of knowledge, we know that an enclosed space with good insulation is necessary, but this of course creates another problem that is accessibility; this is also the subject of FR11 and FR12 in formula (15).

Knowledge about Space and Accessibility

Here we discuss knowledge about space and accessibility, but for the sake of simplicity and the space reason, logical expressions are omitted. First we discuss spatial knowledge.

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" [19].

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 pieces of knowledge, 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. (25)

SK3 SK5 "direction is vertical"
"vertical direction should be open" |– **Th** SK9. (26)

Having this kind of knowledge (SK8 and SK9) allows us to design an enclosed, insulated space with a door for horizontal access (formula (25)) or with a lid or a door for vertical access (formula (26)). This will address FR11, FR12, and the cooling efficiency problem and we may arrive at a traditional refrigerator design or one for supermarkets through factual abduction.

Once again, abduction indeed integrated theories: in obtaining (25) and (26), we combined different kinds of knowledge. This was done by forward chaining and second-order existential abduction as was the case for (22).

KNOWLEDGE STRUCTURE

The analysis of knowledge used in conceptual design we discussed in the previous section showed that combining such rather trivial theories can lead to interesting design solutions (such as refrigerators with a top opening even without a lid or with a sliding door). In this example, we integrated heat transfer knowledge, mechanism knowledge, gas flow knowledge, heat loss and insulation knowledge, and spatial knowledge. Some of these are relevant to each other, while mechanism knowledge and heat transfer knowledge, for example, are irrelevant to each other. Integrating such (at least superficially) irrelevant theories and different customer's requirements resulted in different design solutions.

In integrating theories, we can identify two issues that we did not mention. One is how to identify those theories superficially irrelevant but interesting enough to arrive at design solutions, such as axioms 2 in Fig. 4 (b), from a number of theories available for design. This requires a further study on second-order existential abduction and its application to searching candidate knowledge to be integrated.

The other issue is that we need to understand relationships among theories. For instance, we see that theories SK1 through SK9 share certain concepts and form an ontology about space and accessibility; e.g., SK1 is a super theory subsuming SK2 and SK3. These pieces of knowledge have such *knowledge structure* that allowed them to be integrated performed by abduction. In fact, SK1 through SK9 has shared common concepts, such as space, path, and object. Since SK3 is a special case of SK1, SK3 does not even have to be integrated. On the other hand, the design example integrated heat transfer knowledge, gas flow knowledge, and spatial knowledge. However, these do not share concepts and are fundamentally irrelevant to each other. They can only be integrated, because they dealt with an identical entity, which was, in this case, an insulated enclosure.

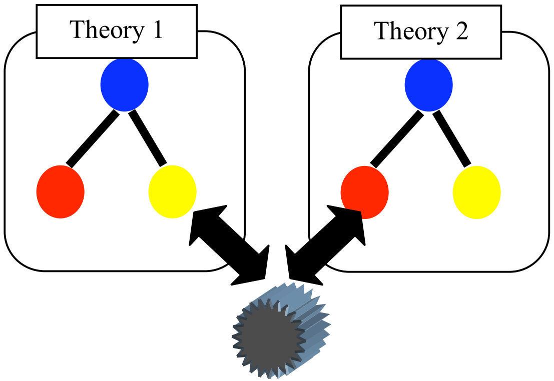
This means that knowledge integration requires well-structured and organized knowledge ready for integration. The set-up signified by formula (1) has two important structural elements of a theory; i.e., axioms and concepts, which define the target domain. Thus, knowledge structure of theories boils down to structural and ontological relationships among those elements. Depending on these different types of relationships among theories, algorithms or computational mechanisms of abduction for integration can be different.

The structural relationships between these two theories can be categorized as follows (see Fig. 5).

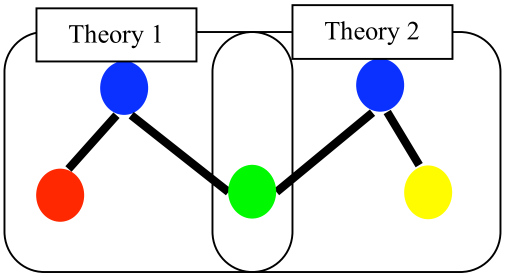
1. The axioms of the two theories are irrelevant to each other, and the concepts used in the theories are irrelevant as well, but they share the same entity.
   Example: The same entity can be a spring in strength of materials as well as a coil in circuit theory.
2. The two sets of axioms are irrelevant 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. In this case, obviously there is no need to integrate theories.
   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 (Fig. 2). Obviously, in case of isomorphic relationships, there is no need to integrate theories.

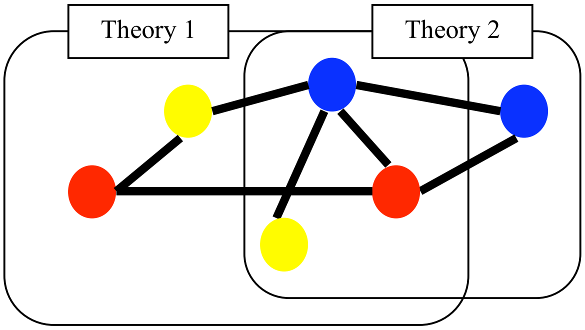
Besides those structural relationships among theories, we can find ontological relationships among concepts. In Fig. 5, we have already seen a case in which two theories sharing an identical concept. In addition, we may have such relationships as part-of, super-sub, and is-an-instance-of. These ontological



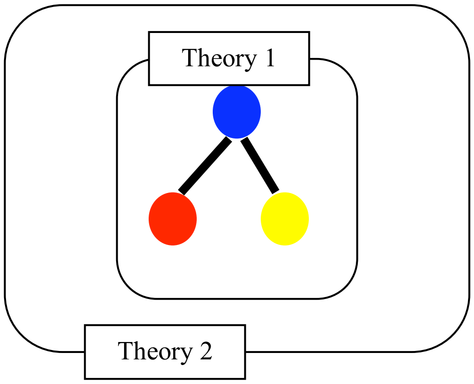
(1) The axioms of the two theories are irrelevant to each other, and the concepts used in the theories are irrelevant as well, but they share the same entity.



(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 share (at least, a portion of) concepts.



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

Fig. 5. Relationships Between Two Theories

relationships among concepts also determine the relationships among theories, thus resulting in knowledge structure.

We can easily imagine that integration of theories becomes an issue for cases depicted in Fig. 5 (1), (2), and (3). In the refrigerator design case, the integration of heat transfer knowledge, gas flow knowledge, and spatial knowledge was only possible, because they formed the relationships depicted in Fig. 5 (1). This signifies the importance to understand knowledge structuring.

DISCUSSIONS

In the design example of refrigerator, we needed to pay a special attention to an enclosed space with insulation addressed both within the cooling efficiency knowledge and the spatial knowledge. For only the storage problem, the space does not even have to be enclosed. Indeed, simple shelves may suffice.

The design process was in fact a gradual refinement process [10] and the descriptions of the solution gradually evolved, beginning with a space, an enclosed space, and then to an enclosed space with insulation. (It is worth mentioning here that this gradual refinement process model can indeed deal with not only routine design but also creative design. Basically gradual refinement means design through synthesis-analysis cycles and a leap in idea generation at the synthesis stage is not excluded from the model.)

For each of this evolution (or refinement) process, a new set of knowledge was introduced. The final solution, an enclosed space with insulation is a fundamental common concept obtained by fundamental common cause abduction. It must also be mentioned that not only identifying such a common concept, but also theories associated with properties of this common concept is the key to fundamental common cause abduction; i.e., identifying relevant knowledge is another key element of this abduction.

In addition, as a consequence of this abduction, three theories necessary for designing refrigerators are effectively combined, *viz*., the cooling knowledge, the cooling efficiency knowledge and the spatial knowledge. This combination was necessary to arrive at a design through factual abduction.

To design a more sophisticated refrigerator, obviously we further need to introduce other types of knowledge, such as one about door size and cool air behavior. In case of an open top design, we further need knowledge about customer's needs that is more important than efficiency.

This suggests introducing various types of knowledge results in new design. While combining knowledge itself might be carried out by simple set union operations or logical conjunctive operations, we can easily foresee problems when theories involved within theories are not ontologically related or logically contradictory. This might be a future research issue.

Abduction has many implications to design. The first is factual abduction to create an object that was not obvious (but could be trivial) as a design solution. Second, it tells something about how to organize design knowledge. From the creative design point of view, the discussion above tells us that meta-level knowledge about relationships among different theories together with ontological relevance of concepts is more crucial than deeper knowledge about each of these theories.

This further has implication to design education. Traditionally, design education was all about how to design particular classes of artifacts. This is equivalent to teach deep factual knowledge. Design education then focused on process knowledge, such as design methods. The discussions about knowledge structure imply that, in addition to factual and process knowledge, we should teach relationships among factual design and how to operate structured knowledge.

Deeper understanding about design knowledge structure may improve engineering design education for the following two reasons. First, engineering design knowledge to be learned is increasing literally day by day. Appropriate knowledge structuring may result in reduced factual knowledge to teach. Second, it may help us develop a new educational method to improve creativity in design.

CONCLUSIONS

This paper assumed that innovative combination of existing knowledge is important to arrive at new design. Abduction is crucial not only to generate design solutions, but also to integrate various theories about design.

Based on Schurz's classification of abductive reasoning [8], the paper identified that abduction for integrating theories can be performed by second order existential abduction. Actual design to obtain a design solution can be performed by various forms of factual abduction. While Schurz's classification of abductive reasoning is seemingly comprehensive, unfortunately it does not contain generally applicable computational algorithms (although an early attempt to implement based on analogical abduction is found in [9]). Nevertheless, it is a valuable contribution to research in abduction for design.

The paper analyzed refrigerator design cases in the form of knowledge usage. It showed that introducing various knowledge sources is one of the central issues of design. Abduction for integrating theories is indeed a mechanism to do so.

This paper reports just a beginning of on-going research effort toward a formal computational model of design. There are many issues to be solved in future, including both theoretical and computational aspects. First of all, we need more complete understanding of abductive reasoning as well as its computational methods [7]. To integrate various knowledge systems, the authors' group has already proposed a mechanism called "model-based abduction" [6].

Second, we need to clarify computational mechanisms for abduction both for creation and for integration. In particular, how to identify most relevant knowledge to be integrated is a good research issue.

Third, we need to deepen understanding about knowledge structuring, including clarification of design knowledge structure and its computational methods. Even if design knowledge is well-structured, knowledge acquisition and knowledge management will be big problems to be solved. Knowledge structuring is important not only for advanced computational support but also for engineering design education as suggested in the previous section.

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REFERENCES

[1] Hartshorne, C., and Weiss, P. eds., 1931-1935, *The Collected Papers of Charles Sanders Peirce,* Vol. I-VI, Harvard University Press, Cambridge, MA.

[2] Burks, A., ed., 1958, *The Collected Papers of Charles Sanders Peirce*, Vol. VII-VIII, Harvard University Press, Cambridge, MA.

[3] Coyne, R., 1988, *Logic Models of Design*, Pitman, London.

[4] Yoshikawa, H., 1989, "Design Philosophy: The State of the Art," Annals of the CIRP, **38**/2, pp. 579-586.

[5] Roozenburg, N.F.M., and Eekels, J., 1995, *Product Design: Fundamentals and Methods*, John Wiley & Sons Chichester, MA.

[6] Takeda, H., Yoshioka, M., and Tomiyama, T., 2001, "A General Framework for Modelling of Synthesis – Integration of Theories of Synthesis," in Proceedings of ICED '01, pp. 307-314.

[7] Flach, P.A., and Kakas, A.C., 2000, "Abductive and Inductive Reasoning: Background and Issues," in Flach, P.A., and Kakas, A.C., eds., *Abduction and Induction*: *Essays on Their Relation and Integration*, Kluwer Academic Publishers, Dordrecht, pp. 1-27.

[8] Schurz, G., 2002, *Models of Abductive Reasoning*, TPD Preprints Annual 2002 No. 1, Schurz G. and Werning, M., eds., Philosophical Prepublication Series of the Chair of Theoretical Philosophy at the University of Düsseldorf, (http://service.phil-fak.uni-duesseldorf.de/ezpublish/ index.php/article/articleview/70/1/14/), to appear in Synthese (Kluwer Academic Publishers, Dordrecht), in 2003.

[9] Takeda H., Sakai H., Nomaguchi Y., Yoshioka M., Shimomura Y., and Tomiyama T., 2003, "Universal Abduction Studio–Proposal of a Design Support Environment for Creative Thinking in Design–," to appear in Proceedings of ICED '03.

[10] Tomiyama, T., 1995, "A Design Process Model that Unifies General Design Theory and Empirical Findings," in Ward, A.C., ed., *Proceedings of the 1995 Design Engineering Technical Conferences*, DE-Vol. 83, ASME, New York, pp. 329-340.

[11] Shah, J., 1998, "Experimental Investigation of Progressive Idea Generation Techniques," in *Proceedings of the 1998 Design Engineering Technical Conferences* (CD-ROM), DETC98/DTM-5676, New York, ASME.

[12] Pahl, G., and Beitz, W., 1996, *Engineering Design: Systematic Approach*, Berlin, Springer-Verlag, 2nd revised edition ed. Wallace, K.

[13] Altshuller, G., 1999, *The Innovation Algorithm; TRIZ, Systematic Innovation and Technical Creativity,* Worcester, MA, Technical Innovation Center.

[14] Takeda, H., Veerkamp, P., Tomiyama, T., and Yoshikawa, H., 1990, "Modeling Design Processes," AI Magazine, **11**/4, pp. 37-48.

[15] Meijer B.R, Tomiyama T., van der Holst B.H.A., and van der Werff K., 2003, "Knowledge Structuring for Function Design," to appear in CIRP Annals, **52**/1.

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

[17] Hayes, P.J., 1985, "The Second Naive Physics Manifesto," in Hobbs, J.R., and Moore, R.C., eds., *Formal Theories of the Commonsense World*, Ablex Publishing Corp., Norwood, NJ., pp. 1-36.

[18] Hayes, P.J., 1985, "Naive Physics Manifesto I: Ontology for Liquids," in Hobbs, J.R., and Moore, R.C., eds., *Formal Theories of the Commonsense World*, Ablex Publishing Corp., Norwood, NJ., pp. 71-107.

[19] Takeda, H., Hamada, S., Tomiyama, T., and Yoshikawa, H., 1990, "A Cognitive Approach to the Analysis of Design Processes," in Rinderle, J.R., ed., *Design Theory and Methodology –DTM '90–*, DE-Vol. 27, ASME, New York, pp. 153-160.