Abduction for Creative Design

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Abstract

Creative design primarily comes from innovative combination of existing knowledge. While abduction is considered crucial for design in general, the paper also focuses on the role of abduction to integrate 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 creative design.

Introduction

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. *Abduction*, proposed by C.S. Peirce (Hartshorne and Weiss 1931-1935, Burks 1958), is considered to play a key role in design (e.g., see (Coyne 1988, Yoshikawa 1989)). Roozenburg and Eekels (1995) further proposed *innoduction* as a reasoning mode more appropriate than abduction. In our previous report (Takeda, Yoshioka, and Tomiyama 2001), we have proposed models of analysis and synthesis (as a part of design) that both include deduction and abduction, under an assumption that synthesis is largely a knowledge-centered activity. In particular, we pointed out that abduction can 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 innovative design.

Despite its importance to design, the design research community seems to fail building full understanding of abduction and its role in creative synthesis. Although within both the research communities of philosophy and AI (Flach and Kakas 2000), until recently there was no comprehensive model of abduction, Schurz (2002) has seemingly succeeded in compiling such models of abductive reasoning. Based on this classification, this paper tries to identify abduction that can be useful for innovative design.

The rest of the paper is organized as follows. First, we make a brief overview of abduction and introduce Schurz's classification of abductive reasoning. We then discuss roles of abduction in design. 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 innovative refrigerator designs.

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:

$$\mathbf{A}\ \square\ \mathbf{F}\ |\!-_{\square}\ \mathbf{Th}$$

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.

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**. In this formalization, there are two important structural elements of a theory; i.e., axioms and concepts, which define the target domain.

Models of Abuductive Reasoning

Schurz (2002) 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.

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

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

from

$$\mathbf{A} = \{C(x) \rightarrow E(x)\}$$

and

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

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. Schurz (2002) explains as follows: given a background law,

$\forall x(C(x) \rightarrow E(x))$: Whatever contains sugar tastes sweet,

and an empirical law to be explained,

$\forall x(F(x) \rightarrow E(x))$: All pineapples taste sweet,

we may obtain

$\forall x(C(x) \rightarrow F(x))$: All pineapples contain sugar.

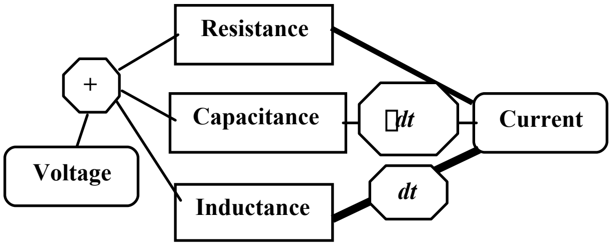
Second order existential abduction contrasts to the two categories of abduction in that it generates “at least partly new general property or natural kind of concept together with an at least partly new theoretical law.”

For instance, Schurz 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.”

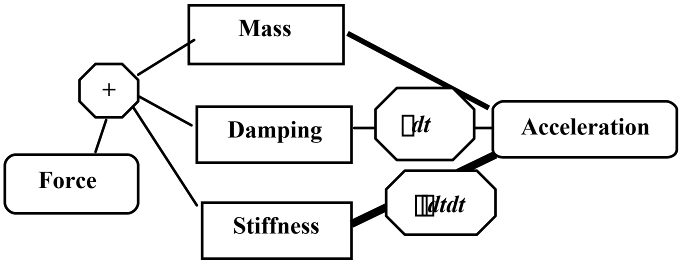
Table 1. Classification of Abduction modified from (Schurz 2002)

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	↑

Analogical abduction results from conceptual combination based on isomorphic mapping. An example is shown in Figure 1 depicting an electric circuit system and a lumped mass system. For the both systems, an identical



(b) Electric Circuit System



(a) Lumped Mass System

Figure 1: Two Isomorphic Systems

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, 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:

$F(x) \square\ G(x)$ (where F, G are observable properties)

to generate

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

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:

$$\square t(C_i(x, t) \square\ E_i(x, t)) \quad 1 \le i \le n$$

in which $\square$ 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":

$$\square x(\square t(C_i(x, t) \square\ E_i(x, t)) = \square t(C_j(x, t) \square\ E_j(x, t)) \quad 1 \le i < j \le n.$$

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 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:

$$\square x(M(x) = \square t(C_i(x, t) \square\ E_i(x, t))).$$

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

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 (Coyne 1988, Yoshikawa 1989). Indeed, first order existential abduction generates an entity that performs the given requirements.

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 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: Given:

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

and

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

obtain

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

as a design solution. To computationally perform this type of abduction, 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.

Figure 2 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. In the design context, this type of abduction generates new sub design problem or additional requirements. Therefore, it is also of great relevance to design.

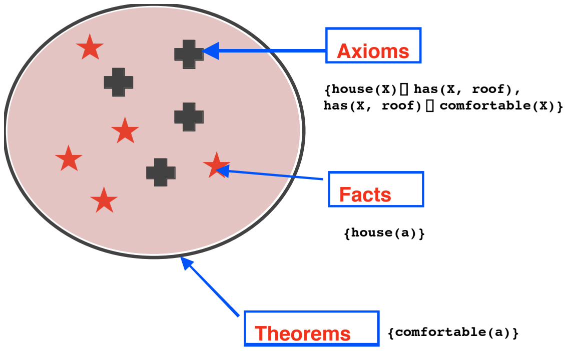


Figure 2: Factual Abduction

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 (Takeda, Yoshioka, and Tomiyama 2001). 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 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.

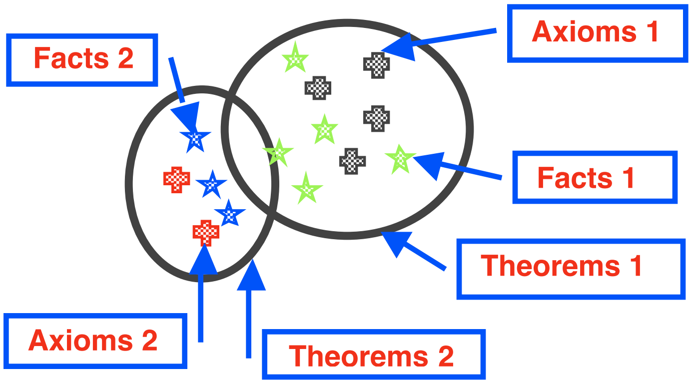


Figure 3: Abduction for Integrating Theories

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.

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.

Refrigerator Design

To test the ideas described in the previous ideas in the context of creative design, let us consider a conceptual design of refrigerators (this example was inspired by (Suh 1990)). 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 (Figure 4), advanced design with multiple compartments including drawer-type storage and even a door in a door (Figure 5), 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 like in Figure 6).

Figure 4: Traditional Refrigerator Design

Figure 5: Door-in-Door + Drawer Design

Figure 6: Showcase Design

Now let us analyze the most fundamental refrigerator design which has only one cooled space. In this paper, we employ the terminology of Suh's axiomatic design (Suh 1990) to represent the relationships between functional requirements (FRs) and design parameters (DPs). 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 Suh (1990), this is a decoupled design that is not necessarily a good design.)

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

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.

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

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 (Figure 4) 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 (Figure 5). If we neglect efficiency and emphasize access, a box with a top opening without a lid can often seen in supermarkets for frozen food. An extreme design case is shown in Figure 6 to maximize customers' convenience in supermarkets.

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 creative design.

Analysis of Knowledge Use

To further test our claim that abduction for integration is a key to arrive at creative design, in this chapter we analyze more formerly how this is done in the refrigerator design examples. We can indeed logically interpret these examples, using techniques of qualitative physics, in particular, of naïve physics (Hayes 1985, 1985a).

Knowledge about Cooling

First, let us consider design knowledge we used for embodying FR21 with Cd.

> 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 obatain 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 = {contact (A, B) temperature (A, Ta)
temperature (B, Tb) Ta>Tb heat_transfer (A, B)}

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)}.

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}

In addition, we need to have knowledge about cooling sources. Such factual knowledge about entities and their functionalities are organized as follows (Takeda *et al.* 1990):

FK1 = {ice (X) cooling_soruce(X)
temperature (X, 0°C)}
FK2 = {evaporator (X) cooling_soruce(X)
temperature (X, 0°C)}

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)},

our formalized knowledge should look like this:

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

We can now perform factual abduction and obtain

F = {evaporator (X)}

as a design solution. Notice that 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)}

which is equivalent to TH1.

However, 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 which is accessibility; this is also the subject of FR11 and FR12.

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” (Takeda *et al.* 1990).

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.

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

Having this kind of knowledge (SK8 and SK9) allows us to design an enclosed, insulated space with a door for horizontal access or with a lid or a door for vertical access. This will address FR11, FR12, and the cooling efficiency problem and we may arrive at a traditional refrigerator design such as Figure 4 through factual abduction.

Discussions

In the design example of refrigerator, we should pay a special attention to the 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 (Tomiyama 1995) and the descriptions of the solution gradually evolved, beginning with a space, an enclosed space, and then to an enclosed space with insulation. 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 such as Figure 4 through factual abduction.

To design a more sophisticated refrigerator shown in Figure 5, obviously we further need to introduce other types of knowledge, such as one about door size and cool air behavior. In case of a design in Figure 6, we further need knowledge about customer’s needs that is more important than efficiency.

This shows how we can introduce various types of knowledge results in innovative, creative 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 for integrating theories has many implications to design. The first is factual abduction to create an object that was not obvious 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. Design education should not only about factual knowledge, but also should be about relationships among factual design. It is also important to teach how to operate structured knowledge.

Conclusions

This paper assumed that creative design primarily comes from innovative combination of existing knowledge. Abduction is crucial not only to generate design solutions, but also to integrate various theories about design. By doing so, we might be able to obtain creative design solutions.

Based on Schurz’s classification of abductive reasoning, 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 computational algorithms. 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. There are many issues to be solved, including both theoretical and computational aspects. Regarding theoretical aspects, we believe clarifying structures of design knowledge is a key issue. Computationally speaking, this translates into appropriately structuring design knowledge. To integrate various knowledge systems, the authors' group has already proposed a mechanism called "model-based abduction." In addition, there remains an issue of computational algorithms for various abductive reasoning methods (Flach and Kakas 2000). Finally, even if design knowledge is well-structured, knowledge acquisition and knowledge management will be big problems to be solved.

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References

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

Coyne, R. 1988. *Logic Models of Design*. Pitman: London.

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*, 1-27. Dordrecht: Kluwer Academic Publishers.

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

[Hayes 1985]

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

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

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

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/).

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

Takeda, H., Yoshioka, M., and Tomiyama, T. 2001. A General Framework for Modelling of Synthesis – Integration of Theories of Synthesis. In Culley, S., Duffy, A., McMahon, C., and Wallace K. eds. WDK 28, Proceedings of the 13th International Conference on Engineering Design in Glasgow 2001, Book 1, Design Research – Theories, Methodologies, and Product Modeling, 307-314. Bury St. Edmunds and London: Professional Engineering Publishing.

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, 153-160. New York: ASME.

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, 329-340. New York: ASME.

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