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Abstract:

Research on design theory and research on abduction have long developed in two parallel streams without connections. However, some researchers have noticed that design and abduction might be fruitfully connected: they identified some forms of abduction in design processes and characterized the variety, and even uniqueness, of forms of abduction in design. Following this stream of work, this chapter includes an analysis of how design theory might help uncover some critical properties of abduction, and conversely, how this analysis might also help uncover particular facets of design, namely the logic of preservative generativity. More specifically, in recent years research on design theory has contributed to reconstructing a basic science, design theory, that accounts for the logic of generativity. Moreover, design theory developed without relying on the notion of abduction. Hence, design theory appears as an interesting scientific analytical framework to analyze the generativity logic of design abduction and, more generally, abduction in science. It leads to making two main propositions: (1) abduction descriptions actually tend to underestimate the potential of the generativity of abduction, making it a form of "bounded generativity", and (2) unbounding

generativity in abduction would lead to discuss the relationship between generativity and preservation in the construction of scientific hypotheses.

Keywords: Design abduction, Design theory, C-K theory, Generativity

I. Introduction: design theory to shed new light on abduction

Research on design theory and research on abduction have long developed in two parallel streams without connections. 19th and 20th century works on 'Konstruktionslehre' in Germany (König 1999; Heymann 2005) did not rely on abduction, although dealing with invention and knowledge creation. Conversely, in the same period, abduction research—be it Peirce's abduction or more recent works in philosophy of science—did not refer to design theory, although relating to 'discovery' and the introduction of new ideas in knowing systems (Fann 1970).

However, some researchers have noticed that design and abduction might be fruitfully connected: they identified some forms of abduction in design processes (March 1976; Coyne 1988; Coyne et al. 1990; Roozenburg 1993) and characterized the variety, and even uniqueness, of forms of abduction in design (Dorst 2011; Kroll and Koskela 2016). Following this stream of work, this chapter includes an analysis of how design theory might help uncover some critical properties of abduction, and conversely, how this analysis might also help uncover particular facets of design, namely the logic of preservative generativity.

More specifically, in recent years research on design theory has contributed to reconstructing a basic science, design theory, that accounts for the logic of generativity and is comparable in its structure, foundations and impact to decision theory, optimization and game theory in their time (Hatchuel et al. 2018). Moreover, design theory developed without relying on the notion of abduction (Ullah et al. 2011). Hence, design theory appears as an interesting scientific analytical framework to analyze the generativity logic of design abduction and, more generally, abduction in science. It leads to making two main propositions: (1) abduction descriptions actually tend to underestimate the potential of the generativity of abduction, making it a form of "bounded generativity", and (2) unbounding generativity in abduction would lead to discuss the relationship between generativity and preservation in the construction of scientific hypotheses.

The chapter unfolds in three part: (a) it is first shown that the two notions of abduction and design theory are in fact disentangled and this disentanglement itself enables using design theory as an 'instrument' to better understand generativity in abduction; (b) the authors' method is described next, consisting of analyzing abduction—formulations and illustrations—through a design theory lens; and (c) the results of this analysis are presented, followed by a discussion of the two propositions (abduction as bounded generativity, and unbounded abduction as a balance between generativity and preservation).

II. Abduction and design: disentangling the two notions

II.1. Abduction as the 'kernel of design'? The critical issue of generativity

A stream of works in design research has analyzed how abduction can be considered as the 'kernel of design' (e.g., Roozenburg 1993). These authors recognize that abduction, since Peirce, discusses the process of generating and selecting hypotheses to test in science—and is opposed to deduction—whereas design begins with a "desire" that is not satisfied by known artifacts and leads to generating a new artifact. But even if deduction and abduction seem to be two dissimilar types of reasoning, a correspondence can be established as follows (as explained by Roozenburg):

- an *existing* design can be described, and properties can be inferred by *deduction* (given are a design description *p* and a known rule *p*→*q* that connects this description to some property, therefore the design exhibits property *q*);
- the *design process* itself follows a pattern of reasoning that is considered '*analogous to abductive reasoning*' (Coyne et al. 1990): it begins with the desired performance (we wish to have *q*) and the designers rely on some rules (of the forms *p*→*q*) that relate shape, material, dimensions, etc. to the performance, to be able to get an artifact with design description *p* that will exhibit the performance *q*. This pattern of reasoning (the premises are *q* and *p*→*q*; the conclusion is *p*) can be considered abductive and could be found in AI and knowledge-based systems

from the 1980s (to perform diagnostic tasks in expert systems) and more specifically in knowledge-based design systems (Coyne 1988; Coyne et al. 1990) to design artifacts based on existing, known design rules, which is assimilated by Coyne et al. to 'cause finding'.

Note that the distinction between deduction and abduction also corresponds to a classical trope in design theory: the distinction between knowledge about existing designs vs design of new artifacts. Design theorists have shown that the design of new artifacts is not just deduction or 'applied science' but requires specific reasoning to make use of knowledge to design a desirable object—Redtenbacher elaborated his Konstruktionslehre on this distinction (Redtenbacher 1852; Le Masson and Weil 2013); in the 1970s, Rodenacker underlined that design could be represented as an 'inversion' of the experimental process (Rodenacker 1970), since, according to Rodenacker, experiment is going from a physical phenomenon to measurement to physical concept whereas construction is going from function to command signal to the final artifact.

Hence in this rough description, abduction appears as a name given to the phenomenon that should be described by design theory: a reasoning that goes from desired performance to a known artifact. It designates the issue but provides limited insight on the reasoning itself. At a more detailed level, some authors have tried to explicate more clearly what could be considered as 'the kernel of design': Roozenburg insists on the fact that design cannot be limited to the use of given rules, and the designer might have to conceive a new rule. Roozenburg refers to the distinction proposed by Habermas between explanatory abduction and innovative abduction (Habermas 1968); see Figure 1: in explanatory abduction, the rule ($p \rightarrow q$) is a premise whereas in innovative abduction, the rule is in the conclusion.

Explanatory abduction:

$p \rightarrow q$ (a given rule, IF p THEN q)

q (q is a given fact, a result)

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p (p is the conclusion, the case or cause)

Innovative abduction:

q (q is a given fact, a desired result)

$p \rightarrow q$ (a rule to be inferred first, IF p THEN q)

p (p is the conclusion, the cause, that immediately follows)

Figure 1: Explanatory abduction vs innovative abduction after Habermas (1968) and Roozenburg (1993)

Therefore, according to Roozenburg, design is not a combinatoric choice among disposable rules but rather the kernel of design is the generation of both rules and artifacts. This process of generating new rules and artifacts is called generativity (Eris 2003; Rogers et al. 2005; Zittrain 2006). Generativity appears as the critical feature of design (Hatchuel et al. 2011a), and abduction, if considered as innovative abduction, would refer to the fact that design theory should try to account for generativity as a rigorous reasoning process. Referring to abduction, Roozenburg implicitly underlines three main requirements that a design theory should satisfy:

- Requirement 1: it should be a reasoning—rational, logical, and more precisely, based on controllable logic;
- Requirement 2: in a way design theory should be 'more than' deduction;
- Requirement 3: design theory should account for generativity; not only the generation of (previously unknown) artifacts, but also the generation of new rules to design these artifacts.

This perspective is reinforced by further works on design and abduction (Dorst 2011; Kroll and Koskela 2016; Koskela et al. 2018), where the authors show that a design process can be described as a variety of abductive steps, connected into an exploratory divergent–convergent process.

II.2. The issue of generativity in abduction

How do works in abduction deal with generativity? It is well known that the distinction between explanatory abduction and innovative abduction corresponds to important debates in research on abduction. Many researchers have underlined that in the works of Peirce on abduction, Peirce had a clear ambition to meet the requirements above, but only partially succeeded. Peirce definition is well-known (Peirce C.P. 5.189, 1903): "[T]he operation of adopting an explanatory hypothesis, -which is just what abduction is,- [is] subject to certain conditions. Namely the hypothesis cannot be admitted, even as a hypothesis, unless it be supposed that it would account for the facts or some of them. The form of inference therefore is:

> The surprising fact, C, is observed
> But if A were true, C would be a matter of course,
> Hence there is reason to suspect A is true."

There is a rich exegesis of Peirce's definition (Frankfurt 1958; Fann 1970; Hookway 1995; Lipton 2000; 2004; Schurz 2008; Douven 2021; McAuliffe 2015; Roudaut 2017; Mohammadian 2019). Douven (2021) follows Frankfurt (1958) to remark that "this is not an inference leading to any new idea. After all, the new idea, the explanatory hypothesis A, must have occurred to one *before* one infers that there is reason to suspect that A is true, for A already figures in the second premise". McAuliffe (2015) brings some nuances and considers that "there is no reason to interpret this passage as evidence that Peirce viewed abduction as a method for adopting a hypothesis as true". The debates finally show that (a) it is unclear whether Peirce himself in fact limited "abduction" to hypothesis adoption, but (b) over time, large streams of works on abduction have assimilated abduction to hypothesis adoption and more specifically, to Inference to the Best Explanation (IBE), so that in the Stanford Encyclopedia of Philosophy "Peirce on Abduction" is now a supplement to the "Abduction" article that explicitly identifies abduction with IBE (Douven 2021).

It is interesting to underline that even in the IBE perspective, the question of hypothesis generation cannot be completely neglected: as explained by Douven (2021), "best" in IBE can hardly be understood in absolute terms since the inference is a choice among *conceived* hypotheses and "it is rather implausible to hold that we are this privileged [that we consider *all* potential explanations]" and we may well be led to believe "the best of a bad lot" (van Fraassen 1989).

Roudaut (2017) gives a nice example of the "bad lot" issue, and the question of the capacity to generate hypotheses: one typical example of IBE is the well-known demonstration of Neptune's existence by Le Verrier, who aimed at explaining anomaly in Uranus trajectory. In an abductive framework, the reasoning can be described as follows:

> fact: anomaly in Neptune trajectory;
> rule: Newton's theory being considered as true; the existence of a new planet would explain Neptune trajectory;
> result: Newton's equations and considerable computational effort enabled predicting the size and position of the new planet and this planet was finally observed by Johann Gottfried Galle at Berlin observatory working from Le Verrier calculations.

As recalled by Roudaut, less known is that Le Verrier also noticed an anomaly in Mercury perihelion; following the same pattern of reasoning, he proposed the existence of another planet, Vulcano. But "Vulcano was not here to be discovered" (Roudaut 2017, p. 53); Mercury perihelion is today explained by General Relativity, which was of course unknown to Le Verrier and his contemporaries. Hence Le Verrier was actually doomed to search in a bad lot.

Therefore, be it central or marginal, "hypothesis generation" remains an open question in research on abduction.

II.3. Advances in design theory: accounting for generativity without relying on abduction

In design research over the last decades, design theory was developed to make theoretical propositions that meet the above-mentioned requirements. Several research works have contributed to design theory, step-by-step increasing its capacity to account logically for generativity (Hatchuel et al. 2011a; Le Masson and Weil 2013). General Design Theory (Reich 1995; Yoshikawa 1981; Takeda et al. 1990), later developed in the Coupled Design Process design theory (Braha and Reich 2003), has extended knowledge-based design system methods by relying on topological approaches. C-K design theory can be considered as an extension of the Simonian approach to account for 'expandable rationality' (Hatchuel 2002).

As shown in (Hatchuel et al. 2018, p. 5), research works on design theory "have reconstructed historical roots and the evolution of design theory, conceptualized the field at a high level of generality and uncovered theoretical foundations, in particular the logic of generativity". Especially, C-K design theory helps to draw some lessons on the ontology of design and hence on generativity (Hatchuel et al. 2013; 2018). In C-K theory (Hatchuel and Weil 2003; 2009; Le Masson et al. 2017b; 2020), design is modeled as an interaction between two spaces, the space of knowledge (K), composed of propositions characterized by the fact that they *all have a logical status* (true or false), and the space of concepts (C), where propositions *are interpretable but undecidable with respect to the actual existing propositions in space K*. Concepts are of the form "C_i = *there exists a (non-empty) class of objects X for which a group of properties* $p_1, p_2, \dots p_n$ *is true in K*". A design starts with a concept C_0, a proposition that is undecidable with respect to the initial K space. The theory formalizes how this undecidable proposition becomes a decidable proposition. This is realised by two processes, *expansions* in K (new propositions are added to K by deduction, learning, experimentation, remodelling, etc.) that can continue until a decidable definition for the initial concept is obtained in K* (the expanded K space), and *partitions* in C (it is possible to add attributes, known in K space, to the concept to promote its decidability). Partitions are called restrictive when they rely on properties usually associated with the object *X* in K; partitions are called expansive when they rely on properties that are not normally associated with the object *X* in K. Figure 2 is a diagram summarizing the C-K design theory.

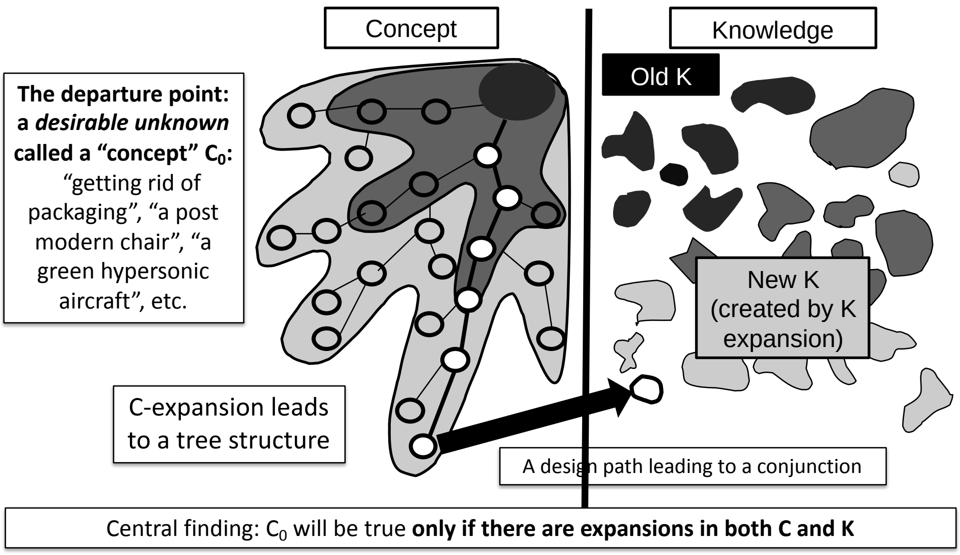

Figure 2: Diagram summarizing the C-K design theory (Le Masson et al. 2017, p. 140). There are four main operators: K→K = classical deduction, inference, modeling, optimizing actions; K→C = disjunction, from the known to the unknown; C→C = refinement, control of partitions; C→K = conjunction.

Figure 3 is a very simple example to illustrate the different C-K notions. For real case examples see for instance (Le Masson et al. 2017).

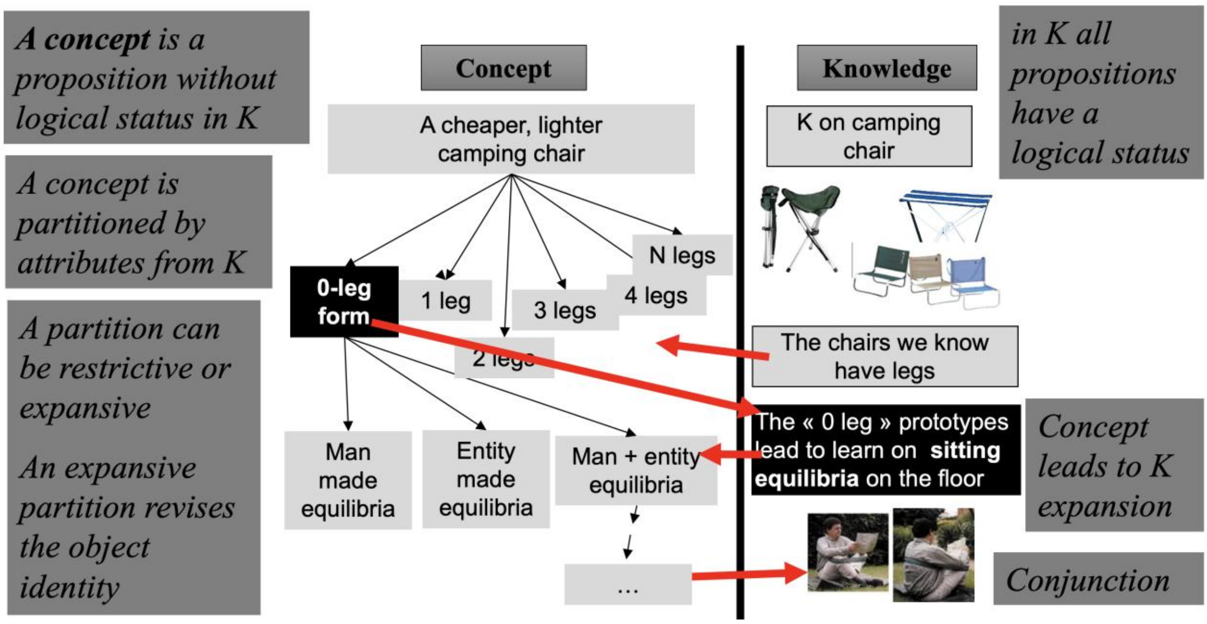

Figure 3: A very simple case to illustrate the main notions of the C-K design theory (after Le Masson et al. 2017, p. 137)

It has been shown that C-K theory cannot be assimilated to one simple abduction (Ullah et al. 2011). Still, C-K design theory meets the three main expectations listed earlier:

- Requirement 1: It is a rational, logical process. In particular, it has been shown that C-K theory can be seen as the interaction between two logics, an intuitionistic logic (in C) and a classical logic (in K) (Kazakçi 2013). it is known today that these two logics can interact, for instance in a topos structure, where sheafification corresponds to the mathematical transformation of a structure with an intuitionistic logic (the presheaf) into a structure with a classical structure (the associated sheaf) (Prouté 2016).
- Requirement 2: It is more than deduction. in C-K theory, deduction is one of the K→K operators (and statistical inference as well).
- Requirement 3: It accounts for strong generativity. Specifically, it has been shown that there is deep correspondence between C-K design theory and mathematical models of generativity, such as field extension (mathematical construction of new fields from existing ones (Kokshagina et al. 2013)), forcing (mathematical construction of new models of sets with 'interesting properties' (Cohen 1963; 2002)), or topos sheafification (mathematical construction of sheaves from preasheaves in a topos (Mac Lane and Moerdijk 1992; Hatchuel et al. 2019)). More generally, it is possible to account for various generativity regimes, designated C-K/K*, depending on the structure K* imposed on K: if K=K* that is a set theory structure, then C-K/set has the generativity of forcing; if K=K* that is a toposic structure, then C-K/topos has the generativity of sheafification.

Meeting these requirements facilitates addressing critical issues related to generativity in design: What is the quality of the generativity? Are there biases in generativity? Is it possible to tune generativity? Is it possible to improve generativity? Can one teach how to overcome impediments to generativity? Advances in design theory have paved the way to a large research program on these questions, traversing many research fields, and also very relevant for practitioners (see syntheses of some results in Agogué and Kazakçi (2014); Hatchuel et al. (2011b); Agogué et al. (2014); Hatchuel et al. (2015); Le Masson et al. (2017); Hatchuel et al. (2018)).

II.4. Disentangling design theory and abduction opens avenue for research

So far, some critical results on design theory and abduction have been recalled:

a) Design theory and abduction developed in two different, parallel streams so that the two notions can be disentangled;
b) Still, authors have noticed that there is innovative abduction (in the sense of hypothesis generation and adoption) in design;
c) Design theory today proposes models of generativity, generally applied to the so-called "desirable unknown";
d) Hypothesis generation remains an open issue in abduction.

Hence, design theory appears as an interesting scientific analytical framework to analyze the generativity logic of design abduction and (innovative) abduction in science. This paves the way to a research program: can design theory be applied to abduction to help uncover some facets of hypothesis generation? One can easily figure out possible outcomes. One might better qualify what exactly "innovative abduction" is and better address questions such as: Is there good/bad 'innovative abduction'? What is a rigorous, reliable 'innovative abduction' and can one control the 'quality' of innovative abduction; the control of the quality and rigor of reasoning being a critical issue in scientific methods? Can one help improve innovative abduction, and can one train scientists to carry out better innovative abductions? And there might also be interesting results for design itself, since applying design theory to the field of hypothesis generation might help uncover specific forms of design.

In the remainder of this chapter, an illustration of this research program will be presented: abduction is analyzed through the lens of design theory, with two strong restrictions: (a) the authors choose to rely on C-K design theory (other investigations could be made with additional formulations of design theory); (b) the authors choose a couple of very specific formulations of abduction (the variety of definitions and models of abduction are not addressed). These specific formulations of abduction are hence 'cast' into C-K design theory or, to use another metaphor, these abduction formulations are analyzed in light of design theory.

It is expected from this 'casting' (or this 'lighting') to learn about (innovative) abduction, to wit:

- what is the unknown in (innovative) abduction?
- can one evaluate the quality of the generation process in (innovative) abduction?
- are there specific features in the generativity logic of (innovative) abduction?

III. Abduction through the lens of C-K design theory: bounded and preservative generativities in science

III.1. Method: analyze abduction with design theory

An analysis of abduction formulations with C-K design theory is conducted. Note that many papers have already used C-K design theory as an analytical framework for generativity cases; see for instance Reich et al. (2012) and Kroll et al. (2014). The authors therefore follow here an established procedure. The method unfolds as follows:

(a) Choice of the abduction formulations to be used as 'object of analysis':

We use two formulations, one related to explanatory abduction; the other related to (design) abduction and associated with innovative abduction. These formulations can be considered as a reference in their respective fields: the first one appears in the Abduction entry of the 2021 revision of the Stanford Encyclopedia of Philosophy (Douven 2021); the second one is given by Kroll and Koskela (2016, p. 130), and is a synthetic reformulation of design abduction as proposed by Roozenburg (1993) and largely diffused and reused since then. It may sound strange to rely on a formulation deeply related to explanatory abduction to analyze the generativity logic; however, this is deeply justified because: (i) works on innovative abduction actually consider that the generation will be followed by an explanatory abduction (e.g., Schurz (2008)), hence the formulation gives us the 'final situations' targeted by an innovative abduction; (ii) it has already been noted that even in IBE, the issue of generativity cannot be neglected; (iii) the formulation is general and formal enough to be a good starting point for C-K analysis.

The explanatory abduction definition is given by Douven (2021). It is actually the third and last formulation in a series, and is considered to take into account the limits of the first two:

“given evidence E and candidate explanations H_1,... H_n, if H_i explains E better than any of the other hypotheses, infer that H_i is closer to the truth than any of the other hypotheses" (ABD3 in (Douven 2021)).

The second formulation (design abduction) is given with a hypothetical example of designing the first ever kettle; the general formulation and the example can be synthesized as follows:

“given the function *q* (e.g., boil water), ’discover’ the rule ‘IF form + way of use THEN function’, $p \rightarrow q$ (e.g., IF hemisphere and metal + fill water and place on burner THEN boil water), and immediately get the second conclusion *q*, which is a solution to the design problem (e.g., hemisphere and metal + fill water and place on burner)” (from Kroll and Koskela (2016) and Roozenburg (1993)). Note that Roozenburg's formulation is used here although Kroll and Koskela eventually proposed a modified, two-step formulation of this design process.

(b) Analytical framework:

In practice, an analysis based on C-K design theory consists of answering well-defined questions: What is the concept at the outset of the generation process (i.e., what is C_0, why is it a concept, what is unknown, etc.)? What is the knowledge available at the start of the process? What are the knowledge expansions in the generation process? What are the partitions applied to the initial concept?

III.2. Analysis

a. One formulation of explanatory abduction analyzed with C-K framework

Douven’s formulation of explanatory abduction is analyzed (see Figure 4):

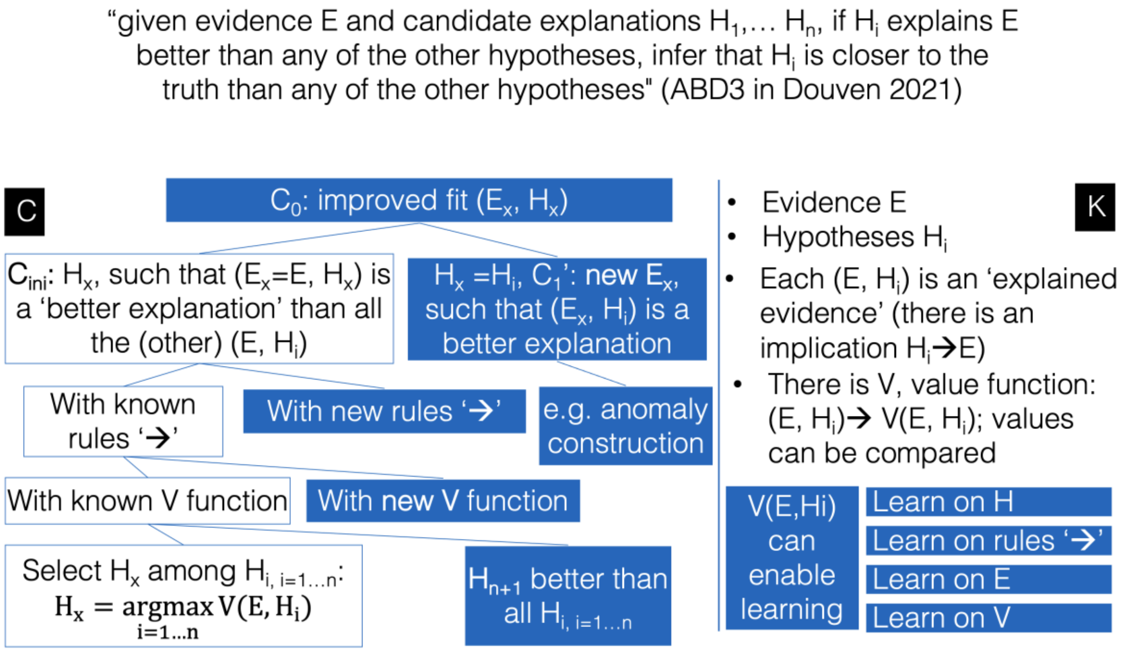

Figure 4: C-K analysis of Douven's abduction formulation. The dark-shaded boxes (with text in white) refer to the knowledge expansions and design partitions that are 'blocked' by the definition of explanatory abduction but could be opened in an innovative abduction perspective. On the left-hand side is the design path imposed by the definition.

1. Evidence E as well as hypotheses H_i are in K (known, given).

2. The abduction process consists of finding the "best explanation" (of E by a hypothesis H) among the given hypotheses that are all explanations. The desired unknown is hence C_{ini} = an "explained evidence" that is the best, a pair (E, H) where H 'explains' E better than all other given hypotheses.

3. To formulate this concept, one therefore needs to have in K:

- a model of 'explanation', i.e., the (acceptable) implication(s) to go from one H_i to E. This means that the hypothesis H_i is composed of possible complex implications that actually make E an (acceptable) consequence of H_i.
- a value function V associated with "better explanation": each pair of "explained evidence" can be evaluated and the values compared to identify an optimum. This value function is known to be a complicated issue (see Peirce considerations on economic evaluation, as discussed by Mohammadian (2019) and McAuliffe (2015)). Note that a single-dimension value function is

in itself a restrictive evaluation function, since it impedes multi-criteria evaluation.

4. Based on known implication rules and a known value function, the design consists of computing the value of each "explained evidence" and choosing the one that maximizes the value (see the design path on the left-hand side of Figure 4, linking white-colored boxes).

5. The C-K framework helps understand the following points:

- *What is supposed to be known in this formulation*: not only E and H_i, but also the implications that enable to relate each H_i to E and the value function V with some restrictive property.
- *The design paths (in C)*: there is a very clear, simple design path imposed by the formulation—the C-K framework makes visible the paths that are 'blocked' (impeded) by the formulation—these design paths are therefore the ones that could be re-opened by an (innovative) abduction. From a design perspective, the concept "an explanation for E" could actually lead to several partitions:
    - obviously, a new hypothesis H_{n+1}
    - but also new implication rules (associated even with known hypotheses!)
    - and new value functions associated with what is a "good explanation" (e.g., multicriteria evaluation functions).
    - Moreover, one could consider that the evidence itself is partially unknown and could require new investigations, new analyses, to get a more 'interesting' fit with the hypotheses. 'Interesting' could mean 'better positive fit', but in this partition path one could also find the situation where one deepens the investigations on E because E is an anomaly that shows that all given H_i are false! The case of Röntgen publications on X-rays (proving that the X-ray is not one of the radiation types known at Röntgen's time) would fall in this path (Röntgen 1895).
- *The knowledge expansions (in K)*: these are also blocked by the formulation but could be considered in the perspective of innovative abduction:

- Of course, all learning on hypotheses, value function, implication rules and evidence.
- Interestingly enough, this learning can be considered in relation to the explanatory, closed abduction process itself: in explanatory abduction the reasoner is supposed to calculate the value of each "explained evidence", so he or she produces knowledge at this stage. This knowledge can be used then for selecting the best explanation (as mentioned in the explanatory abduction formulation) but it can also be used to push exploration in other directions: What if the value of all the "explanations" appears low? Perhaps this would push to generate new hypotheses? Or maybe this will push to change the value function? Or to revise/deepen the implication rules? Or to reanalyze the evidence itself, possibly to consider it as an anomaly for hypotheses $H_{i,i=1...n}$!
- Clearly, this new knowledge would then push towards a new design of (E_x, H_x). This process, where tests, prototypes and proofs of concept lead to new expansions, is illustrated and described in detail by Kroll et al. (2014) and Jobin et al. (2021).

b. One formulation of design abduction analyzed with C-K framework

A similar analysis is conducted of the formulation of innovative design abduction by Roozenburg (1993), also studied by Kroll and Koskela (2016) (see Figure 5):

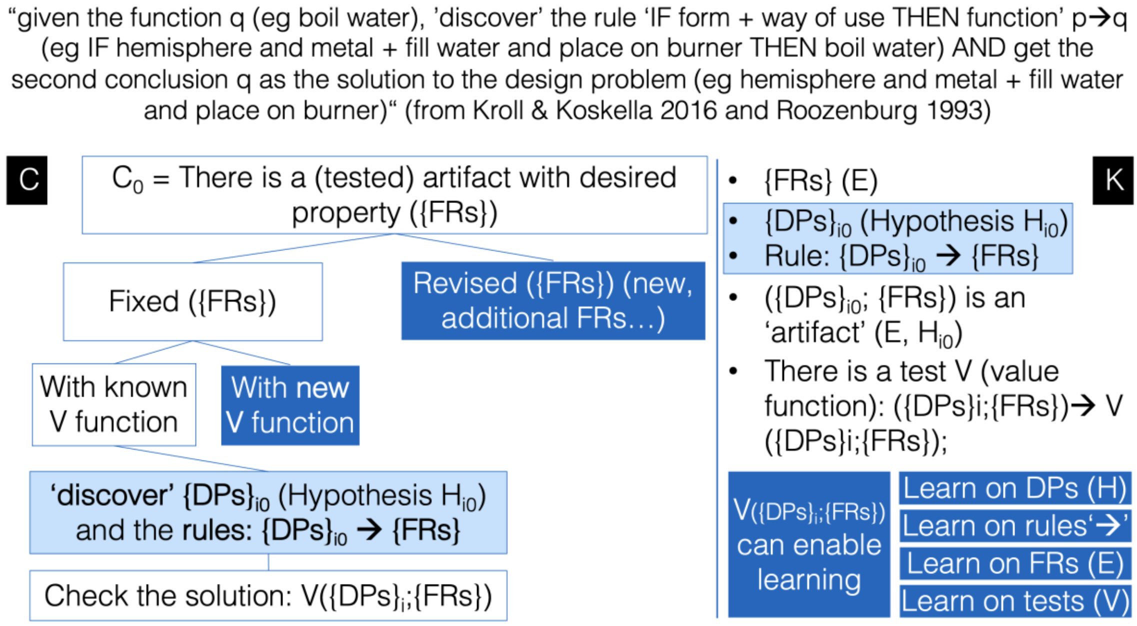

Figure 5: C-K analysis of Roozenburg's and Kroll and Koskela’s design abduction. FR stands for functional requirement; DP stands for design parameter. The light-shaded boxes (text in black) refer to the knowledge expansions and design partitions associated with the formulation. The dark-shaded boxes (text in white) refer to the knowledge expansions and design partitions that are rather blocked by the example.

1. In K is the expected ‘function’ as a list of functional requirements {FRs}.

2. The abduction process consists of designing an artifact that is made with ‘design parameters’ such as a form (but also matter, components, etc., i.e., means that are available to the designers) and also ‘design parameters’ such as ‘way of use’ (which is also a design parameter from the point of view of the user designing the artifact's usage) and the artifact satisfies the function(s). The desired unknown is hence an artifact that meets the requirements.

3. To formulate this concept, one therefore needs to have in K a value function (or a test) associated with “being an artifact”: each pair of ({DPs};{FRs}) will be tested to check that this is a valid artifact; valid here means, for instance, feasible, acceptable, usable, legal, or even profitable, marketable, etc.

4. Following the formulation: based on fixed desired functionalities {FRs} and with a known value function V, the design consists of:

- finding design parameters (either present in K or learnt/invented during the design process)
- and finding the rules that relate these DPs to the expected FRs (either based on available knowledge or based on newly created knowledge)
- in order to then design a pair ({DPs};{FRs}) that can be evaluated (tested) with the V function.

5. The C-K framework helps understand the following points:

- *What is supposed to be known in this formulation*: not only the artifact's function(s) but also the value function that enables to validate the artifact;
- *The design paths (in C)*: the definition of design abduction clearly identifies the paths related to *the exploration of design parameters and the rules associated with these parameters* to enable to relate these parameters to the function(s). Note that C-K analysis helps understand at least two additional paths:
    - new value functions associated with what is "an artifact". Some tests might be discovered in the design process: during the design process, the criteria for feasibility, testability, marketability, etc., might be revised. For instance, one could discover new testing and simulation techniques or new suppliers, etc.
    - one could also discover new functions. New expectations might be revealed, new stakeholders might be discovered during the design process. Hence, the value function itself could be designed.
- *The knowledge expansions (in K)*: The formulation explicitly implies learning on DPs and implication rules to move from DPs to FRs. Note that this 'learning' can mean a large variety of efforts, from identifying an existing, already known DP to the discovery of a new means of action. Moreover, the definition might also lead to learning on other dimensions, such as learning on function(s) and learning on value (test).

The analysis of abduction formulations with the C-K framework thus uncovers the knowledge conditions to activate such a design abduction and also enables to reveal the directions opened for generation. Note that these design directions are in fact larger (or at least more detailed) than the intuitive expectations of design abduction: innovative abduction is not just about generating design parameters and their associated rules, but design abduction can also be generative in functions and in tests.

IV. Results and discussion

The analysis of the two formulations related to abduction leads to three main results:

IV.1. Result 1: the unknowns in abduction – why scientific concepts are more than 'hypotheses'

It was expected that (innovative) abduction would generate *new* hypotheses. The detailed analyses of generativity processes associated with abduction formulations lead to enrich this perspective in several respects:

Result 1.a: the unknown that was found in the analyses is not limited to the hypothesis; it also relates to the 'value function' that helps to evaluate whether a hypothesis is good and better than another one. This refers to the methods, instruments, observations techniques, proof techniques that are accepted by current practices and epistemologies in a scientific community! And it is known that these epistemological instruments evolve over time (see how certain research communities have slowly accepted statistics and simulation as proof techniques).

Result 1.b: the unknown is not only related to the hypothesis and evaluation, but also to the evidence itself! Enriching the observation, the measures, the manipulations and experimentations on/with the evidence is actually part of the generativity process, with many smart reasoning steps to truly design an interesting 'explained evidence'. In particular, the demonstration of an anomaly is an interesting case of generativity in science, where one must design new observations to prove that an evidence does not fit with existing hypotheses.

Result 1.c: the hypothesis itself is a source of unknown that might have been underestimated. The analyses above show that the concept associated with 'innovative abduction' is not exactly 'a new hypothesis' but more precisely 'a hypothesis that better explains the evidence'. In C-K terms, one should distinguish between a hypothesis that is in K and comes with a set of rules that relates H to E and that can be evaluated by V, and a hypothesis that is in C that might be a partially unknown hypothesis in the sense that as a concept, some rules might be missing to relate the concept of H to E or to evaluate the concept of H. This formal nuance implies clear consequences: (i) contrary to intuition, it is not so self-evident to design such an hypothesis 'that better explains the evidence' – this analysis is in full coherence with Douven's argument "even if there is an infinity of hypotheses that account for a given fact, there may still be only a handful that could be said to give a satisfactory explanation of it" (Douven 2021); (ii) but one cannot go as far as saying that this would mean that available (known) hypotheses are necessarily the best ones, which would mean that there is no issue with 'bad lot' and hypothesis generation: it rather means that a hypothesis requires careful design! The design of a hypothesis is actually very hard work *since it also requires designing how the concept of hypothesis relates to the evidence (the rules, i.e., one or several theoretical constructions, previously explained evidence, etc.), and how the 'explained evidence' E will be evaluated*.

This analysis enables to discuss Douven's argument against the 'bad lot' issue (Douven 2021). Douven builds on Schupbach (2014): "given the hypotheses $H_{i,i=1\ldots n}$ we have managed to come up with, we can always generate a set of hypotheses which jointly exhaust logical space. Suppose $H_1,\ldots H_n$ are the candidate explanations we have so far been able to conceive. Then simply define $H_{n+1}=\neg H_1\wedge\neg H_2\wedge\ldots\wedge\neg H_n$ and add this new hypothesis as a further candidate explanation to the ones we already have. Obviously, the set $H_1\ldots H_{n+1}$ is exhaustive". Douven then goes further: he notices that H_{n+1} is hardly informative, it will not even be clear what its empirical consequences are. He gives the following example: suppose H_1= Special Relativity Theory; H_2= Lorentz' version of aether theory; then H_3 is "neither of these two theories is true. But surely this further hypothesis will be ranked quite low qua explanation […] and it is fully unclear what its empirical consequences are." Hence, H_{n+1} is not an interesting hypothesis and there is no real issue with 'bad lot'.

Based on the analysis of hypothesis generation, the reasoning above can be slightly modify: the proposition '$\neg H_1\wedge\neg H_2\wedge\ldots\wedge\neg H_n$' is actually *not* a hypothesis (technically this means that the collection of hypotheses is generally not stable by negation – such a stability would require much more severe mathematical conditions) precisely because it is unclear how it will relate to the evidence (what are the associated rules) and how it will be evaluated. But it could rather be formulated, in C-K theory, as a concept of hypotheses (C='there exists an hypothesis H_{n+1} that explains E better than all other $H_1 \ldots H_n$') that is still largely unknown and hence requires further partition and knowledge creation to actually design one (or probably several!) 'well-constructed' hypothesis, i.e., with well-identified rules to relate to E and well-identified value V(E, H_{n+1}).

Finally, results 1.a, 1.b and 1.c provide a rich representation of the 'unknowns' associated with generativity in science. They show that scientific concepts are much more than hypotheses! They also help to account for the variety of scientific 'results': a contribution to scientific progress is of course not limited to the proof of the fit between a hypothesis and an evidence, and design theory applied to 'abduction' helps enrich our understanding of this variety.

IV.2. Result 2: abduction as 'bounded generativity'

Based on decision theory, Simon showed that decision making processes in organizations or by a human were actually bounded: people and/or organizations did not make the 'optimal' decision, as defined by decision theory, but only a 'satisficing' one (Simon 1955; 1957). Similarly, based on design theory, which establishes a reference for generativity processes, abduction might be considered as a form of bounded generativity in the sense that it claims forms of generativity but in fact tends to underestimate the large set of generativity paths that design theory can formally associate with innovative abduction, e.g., hypothesis generation. More specifically, casting abduction in design theory led to identifying the following limits and biases:

Result 2.a: abduction appears as bounded when it comes to the value function (test, evaluation, etc.) and to the evidence (see the example of explanatory abduction in the previous section) or the functional requirements (see the example of design abduction also in the previous section).

Result 2.b: abduction is also bounded when it comes to the learning that is made at the evaluation stage: one seems to favor a form of selection ('adopt', 'select' the best hypothesis, validate an artifact) whereas this evaluation itself will produce knowledge that could be reused for further design.

Result 2.c: abduction is also bounded by the reasoning process itself: abductions tend to consider hypothesis generation as an 'emergence', whereas design theory clarifies that hypothesis generation is actually a complex design process that might involve multiple steps, such as characterizing the unknown to be addressed (i.e., formulate a concept of hypothesis), learning from tests and evaluations, elaborating on the evidence, learning on the rules that could help relate a hypothesis to the evidence, etc. Abduction simplifies and reduces this complex process of knowledge creation and concept partition. This result corresponds to the in-depth studies done on abduction and the design process that have already shown that it was necessary to consider several connected abductions to actually account for a design process (Kroll and Koskela 2016; Dorst 2011).

Result 2.c in particular leads to underline that hypothesis generation in science cannot be assimilated to abduction: among the complex steps that design theory led to identify in hypothesis generation, one finds especially regular deduction! Deduction clearly appears as an operator that is required to formulate and check the connections of rules that relate a hypothesis to the evidence. Neglecting deduction as an instrument for hypothesis generation is an example of how abduction can be a bounded generation. Design theory leads to show that 'abduction', in the broad sense of accounting for 'hypothesis generation', should in fact contain deduction, explaining why it is not possible to construct abduction as reversal of deduction.

IV.3. Result 3: towards unbounded abduction – facing the issue of preservative generation

Analyzing abduction in light of design theory shows that improved learning processes (in K) and more rigorous concept partitions (in C) would lead to a more systematic generation of hypotheses. Hence, a design theory-based abduction (in the sense of design theory-based hypothesis generation) could be an unbounded generativity (or at least a less bounded one). Building on results 1 and 2, this unbounded generativity would include a large variety of 'unknowns' (see result 1) and more specifically, would more rigorously address concepts of hypotheses (see result 1.c); it would also overcome the limits of bounded abduction (see result 2) and more specifically, include some forms of deduction in the hypothesis generation reasoning (see result 2.c). Consequently, hypothesis generation would become more systematic. This leads to new issues and criteria to be added to the hypothesis generation process:

Issue 1 of hypothesis generation: from the perspective of repeated scientific activity, one would wonder how a newly generated hypothesis will be helpful not only to explain a given evidence but also to support scientific generativity in the future! Hence, the criteria for evaluating a hypothesis would not be limited to their capacity to well/best-explain a given evidence, but also their capacity to be useful to generate other hypotheses and evidence! This is coherent with Poincaré claim: "we choose this geometry (i.e., this theoretical framework) not because it is more true but because it is more convenient" (Poincaré 1898, p. 63); see also Mohammadian (2019b).

Issue 2 of hypothesis generation: if hypothesis generation intensifies, then so does the control of generativity. The generation of new rules will necessarily raise the issue of whether this generativity will disturb well-established rules and 'explained evidence'. Design theory has long mentioned that expansions and the emergence of new pieces of knowledge might require a so-called 'knowledge re-ordering' (Hatchuel et al. 2013; Brun et al. 2016). In case of scientific constructions that aim at a global coherence and unification, this re-ordering effort might become critical. Consequently, it might be required that the newly generated hypothesis actually limits costly re-ordering and enables to preserve as much as possible the previously established results, or, in Peirce's words, to preserve the "consistency with well-confirmed beliefs". This is actually well-known in scientific production, where the greatest breakthroughs actually *also* relied on a preservation logic – Einstein's Relativity Theory, for example, preserved critical equations in physics, including Newton's ones at low speed (Damour 2005; Einstein 2011).

As an outcome, unbounded abduction would actually require models of preservative generativity. Recent advances in design theory enable to model the logics of creation heritage by injecting topos theory into C-K design theory (Hatchuel et al. 2019). These works might be useful to deepen the understanding of preservative generativity in science. The study of creation heritage with C-K/topos has pushed to explore new facets of design theory: injecting a topos structure in K-space of C-K enables to uncover how tradition preservation and innovation are not doomed to produce poor trade-offs, but they actually correspond to deep generative processes (corresponding mathematically to sheafification), where innovation occurs within tradition and tradition is inventively preserved in the generativity process. It describes forms of preservative creation, proving that innovation is not necessarily a creative destruction.

Conclusion: design theory to unbound generativity of abduction?

In this chapter the authors showed how design theory can contribute to Peirce's historical program to better model the logic of scientific knowledge creation. One could consider that for Peirce, abduction was more an unfinished program than a result: abduction was the name for the project to rationally (logically) account for generativity in science and in other fields where similar generativity would occur. More than one century later, advances in research on the logics of generativity—in mathematics, engineering design, cognition, etc.—have enabled quantum leaps in design theory, where recent advanced formulations such as C-K theory finally meet Peirce's requirements: design theory is a model of creative reasoning that accounts for generativity, goes beyond deduction and is logically grounded. Design theory developed without referring to abduction, but despite that (or, maybe, because of that), researchers have considered that studying design abduction could be fruitful not only to better understand design, but also to better understand abduction itself. In this chapter this logic was extended by applying design theory, formulated as C-K design theory, to analyze the generativity logics in two abduction formulations. This exercise led to three main results:

Result no. 1: it showed that abduction—seen as a logic of hypothesis generation—in fact addresses many unknowns with a strong generativity potential. In particular, it shows that the relevant unknowns are not embedded in the hypotheses themselves, but rather by the *concepts of* hypotheses, which require substantial design work to become testable explanations of the evidence.

Result no. 2: it also uncovered that even if abduction might explore these multiple unknowns, definitions of abduction tend to only very partially explore the full range of unknowns, so that abduction is a form of bounded generativity.

Result no. 3: finally, the exercise showed that an abduction that is based more explicitly on design theory would overcome the bounded generativity, and this would therefore lead to consider how this 'unbounded' abduction could be a *preservative generativity* that rigorously combines the creation logic of scientific discovery and the cumulative preservative logic of robust, reliable scientific knowledge.

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Figure Captions

Figure 2: Explanatory abduction vs innovative abduction after Habermas (1968) and Roozenburg (1993)

Figure 2: Diagram summarizing the C-K design theory (Le Masson et al. 2017, p. 140). There are four main operators: K→K = classical deduction, inference, modeling, optimizing actions; K→C = disjunction, from the known to the unknown; C→C = refinement, control of partitions; C→K = conjunction.

Figure 3: A very simple case to illustrate the main notions of the C-K design theory (after Le Masson et al. 2017, p. 137)

Figure 4: C-K analysis of Douven's abduction formulation. The dark-shaded boxes (with text in white) refer to the knowledge expansions and design partitions that are 'blocked' by the definition of explanatory abduction but could be opened in an innovative abduction perspective. On the left-hand side is the design path imposed by the definition.

Figure 5: C-K analysis of Roozenburg's and Kroll and Koskela's design abduction. FR stands for functional requirement; DP stands for design parameter. The light-shaded boxes (text in black) refer to the knowledge expansions and design partitions associated with the formulation. The dark-shaded boxes (text in white) refer to the knowledge expansions and design partitions that are rather blocked by the example.