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A NEW APPROACH OF INNOVATIVE DESIGN: AN INTRODUCTION TO C-K THEORY

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Abstract

In this paper we introduce the main notions and first applications of a unified design theory. We call it "C-K theory" because it stands that a formal distinction between spaces of "Concepts" (C) and space of "Knowledge" (K) is a condition for design. This distinction has key properties: i) it identifies the oddness of "Design" when compared to problem solving approaches ; ii) it distinguishes C-K theory from existing design theories like German systematic as C-K theory offers a precise definition of design and builds creativity within such definition. It does not require the too restrictive assumptions of General Design Theory [1] or Universal Design Theory [2]. It establishes that design reasoning is linked to a fundamental issue in set theory: the "choice" axiom. It models the dynamics of design as a joint-expansion of a space of concepts and a space of Knowledge needing four operators C→K, K→C, C→C, K→K. They compose what can be imaged as a "design square". These operators capture the variety of design situations and the dynamics of innovative design.

Key worlds : design theory, innovation, creativity.

1. Introduction. Why a new design theory ?

In this paper we present the main notions of a unified design theory. We call it "C-K theory" because its central proposition is a formal distinction between "Concepts" (C) and "Knowledge" (K). Design theories have been extensively discussed in the literature. So, what could be the claims of this new theory? What kind of improvement can C-K theory provide in design practice? In this paper we shall focus only on the theoretical aspects of C-K theory even if C-K theory was born from practical design issues in highly innovative contexts and is now used in numerous and well known innovative firms [3].This paper presents the basic elements of C-K theory and attempts to establish its validity and utility. Before, we will give an overview of the origins of C-K theory and of the main issues it wants to address.

C-K theory bears upon existing design theories, yet it re-interprets these theories as special cases of a unified model of reasoning. This model allows to solve two recurrent problems faced unsuccessfully by traditional theories:

- to offer a clear and precise definition of "design": this definition should be independent of any domain and professional tradition. It should give to "design theory" the same level of rigour and modelling that we find in decision theory or programming theory. This means that design theory should have robust theoretical roots linked to well recognized issues in logic. Design is one of the most fascinating activities of the mind, it would be surprising that a design theory had no relations with the foundational problems in logic or rationality that have been explored during the 20th century. We show below how C-K theory establishes such an important link.

- to offer a theory where creative thinking and innovation are not external to design theory but are part of its central core. This is a logical necessity: Design is a process by which something unknown can intentionally emerge from what is known. Usually this process seems contradictory with a well structured theory. The more a Design theory is rigorous and precise, the more it seems to exclude creativity and imagination. Yet, C-K theory aims to reconcile these two goals.

In the first part of the paper we briefly review existing theories and there ability to meet these issues. In the second part, we present the main notions of C-K theory. In the third part we begin to discuss the validation criteria for C-K theory, in particular we discuss the unifying power of C-K theory and how it is possible to interpret creativity with C-K theory in a new perspective.

2. Design theories: a short critical review

In this paper, our focus is the improvement of the type of Design theories which present a formal structure. We mean by "formal", the description of Design activity as a specific *form of reasoning* or rationality. The formal language used could be mathematical, meta-mathematical, computer oriented or simply taxonomic. The aim is to establish a model of thought [4] that defines design and offers constructive principles for designing. Yet, to identify more precisely the scientific background of this program a preliminary remark is necessary.

2.1. Design theories and the social shaping of design : the case of R&D.

For sure, Design is not only a mode of reasoning. It is also a human collective process shaped by history, culture, and social or organizational norms. *Yet, these two perspectives on design are not independent.* For instance, if Design is dominantly described as a three stages process (like in the German systematic), such formal scheme can be used as a work division norm, which finally shapes roles, skills and social identities. However, the distinction between architects and engineers is not only the result of different design theories, it is the legacy of a historical and social process that shaped two skills with different schools, cultures and professional organizations.

A comprehensive view of design should address both aspects. But, in this paper it is not our goal to offer such encompassing view[1]. However, it is worth mentioning one particular critical organizational issue that is supported by our approach (i.e. by C-K theory). The Design literature tends to accept the classic concept of R&D [2]. In this view, Research departments or Science labs are not perceived as design workshops or are not concerned by design theory. Research is described as creating new knowledge without any design purpose. This approach is valid only in special cases. Moreover a *design project can include scientific research work,* and we stand that the creation of new knowledge is a logical necessity in any design process ! Empirically, this is observable in many science-based industries like the pharmaceutical ones. In C-K theory it is a logical consequence as "knowledge expansion" (i.e. Research) is a primary axiom of Design

[1] We have discussed elsewhere the contemporary evolution of organizational principles for design in several companies [3].

reasoning. Therefore, C-K theory predicts the necessity of organisations where Research is not separated from Development or where new links between R and D have to be identified and implemented [3].

2.2. A short survey of design theories: Process and mapping theories.

The multiplicity of design theories offered in the literature is well known. A good survey of this variety is a difficult task. Moreover a clear synthesis of these theories is limited by the use of confusing or very similar notions. In a large survey, the authors [5] remarked that the existing definitions of design reflects such a variety of view points that they could only list key words: «*Needs, requirement, solutions, specifications, creativity, constraints, scientific principles, technical information, functions, mapping, transformation, manufacture, and economics*". This seems a realistic description of the state of the art. Therefore, we are left with the unique option to depict the main logics of these design theories. It has been already noticed that existing Design theories are either *process* or *product* oriented [5], [6]. We will keep this distinction for a brief critical review.

- **Process, stages and the recursive nature of design**: Process oriented design theories define design *stages* that have to be followed in order to achieve a design task. Thus the value and validity of such theories depend on the definition they offer about such stages.

The well known German systematic model [7] distinguishes three stages for any design process: the functional, conceptual, and embodiment design stages. Unfortunately, these levels often overlap. For example, it is not easy to formulate a functional property without already using a conceptual model. If we say that we want "to know what time is it ?": obviously the function (know the time) is already expressed through the conceptual notion of "time" as a measurable phenomena and this largely determines the conceptual design that will follow. In the German approach, the three stages are only *a heuristic* proposition, that can be useful in many engineering cases. So, are there universal stages in a Design process ? Watts [8] assumed levels of abstraction or concreteness and Marples [9] defined stages resulting from a decomposition of the main design problem in ad hoc sub-problems. These are not universal but contingent stages (and we will argue later against this idea of "decomposition").

Nevertheless, the idea of "stages", even if there are no universal stages in Design, outlines an important point. Design reasoning has the property of **recursivity**. Design does not only transform projects into solutions, but also *projects into projects*, or design problems into design problems. What could therefore be the end of a design process ? The usual answer is a "satisficing" solution [10]. But what proves that we can reach one ? Some authors solve the problem by setting axiomatically that a design problem has a finite number of stages [2]. Usually, it is said that Design stops when the designer "meets" the specifications of the problem. Yet this means that specifications are propositions that can be "met": but how ? What is the accepted tolerance about such "meeting" ? All process oriented theories have to clarify what is viewed as "an end" of the design process.

Finally, process oriented theories which do not specify a prescriptive definition of stages, are very close to standard Problem solving theory as defined by Herbert Simon. And Simon always claimed that "*design theory was nothing else than problem solving theory*" [11]. In his view, "Finding a problem space", "using search processes to generate alternatives", "adopting satisficing criteria" were the common components of both design theory and problem solving theory. This view has a major disadvantage: Design is no more *distinguishable* from other problem solving situations. Simon recognized the issue and repeatedly attempted to integrate creative thinking within problem solving theory. Hatchuel have argued [12] that this effort was an impossible one, as creativity cannot be just "added" to problem solving theory, it has to be built in the definition of the process. We will see that contrary to Simon's view, C-K theory leads to consider problem solving theory as a special and restricted case of Design theory.

- **Product oriented Design theory and "mapping" theories as specification theories.** All Product-oriented design theories are based on some specific properties explicitly required from the product to be designed. Therefore, product based theories are in fact *specification theories.* Suh axiomatic [13] is a good example of a specification theory that calls itself a design theory. Suh defines axiomatically two universal product attributes. These specifications only form new functional requirements that could be added to the primary functional requirements used to built the Suh's matrix. The same could be said from other theories [14]. Evolutionary design [15] is an interesting attempt to mix process and product but it is basically a problem solving theory where problems are discovered progressively.

- **An interesting proposal: General design theory and its biased view of the knowledge process** [1], [16]. This theory deserves a special discussion. It is an attempt to build a rigorous and universal theory of design as "a mapping between the function space and the attribute space". Yet, all the modelling effort is concentrated on structuring the functions space and the attribute space so that a "good" mapping is always possible in situations of "ideal knowledge": i.e. situations where "all is known about the entities of a product domain". The paradox is that Yoshikawa defines as ideal, a situation where Design disappears. If we perfectly know the functions, the attributes and how to fit functions and attributes, what is left for design ? To sum up, in a perfectly and totally known domain there is nor design, nor designers. Yoshikawa recognized the issue and also studied "real knowledge" situations. In this second case, his model leads to interesting results: one of them called theorem 32, is noteworthy: "In the real knowledge a design solution has unexpected functions". This is a an interesting way to underline a fundamental property of design: *design cannot be defined without a simultaneous knowledge "expansion" process.* As "discovering unexpected functions" means obviously acquiring new knowledge. Yet, it is not a free learning process per se as it is embedded and oriented by the design process. However, Yoshikawa does not derive all the consequences of this result for a more complete definition of design: define the link between concepts and knowledge as the core issue of design and reject the concept of design in the world of "ideal knowledge" as misleading. Instead, he simply suggests that, within the "real knowledge world", Design is a heuristic process built upon a "refinement model" [16].

This is certainly a too short survey of existing theories and we may have forgotten some important proposal. Yet the difficulties of surveying Design theories is a good signal of the present advancement of field. At least, our survey indicates that improvements in Design theory should be obtained in three directions:

- Defining design as a form of reasoning where creativity is built-in its definition
- Defining design as a process where knowledge expansion is built-in its definition
- Defining design as a process whose output could be a new design issue.

In the following section we present the main assumptions of C-K theory which meets in our view these requisites and offers a wide variety of results.

3. The principles of Concept-Knowledge theory (C-K theory)

C-K theory has been initially proposed by Hatchuel [17] and developed by Hatchuel and Weil [18], [19]. The theory is based on the following interdependent propositions that will be presented here in the case of *an individual designer*. But the theory can be extended for collective design.

3.1. Assumptions and Definition of Design

1. We call K, a "knowledge space", the space of propositions that have a logical status for a designer D. This space is always neglected in the literature, yet it is impossible to define design without such referring space.
2. We call **"logical status of a proposition", an attribute that defines the degree of confidence that D assigns to a proposition**. In standard logic, propositions are "true or false". In non standard logic, propositions may be "true, false, or undecidable" or have a fuzzy value. A Designer D may use several logics . What matters in our approach is that we assume that **all propositions of K have a logical status what ever it is**, and we include here as a logical status all non-standard logical systems. In the following, we will assume for simplicity reasons that in K we have a classic "true or false" logic. But the theory holds independently of the logic retained.
3. We call **"concept", a proposition, or a group of propositions that have no logical status in K.** This means that when a concept is formulated it is **impossible to prove** that it is a proposition of K. In Design, a concept usually expresses a group of properties qualifying one or several entities. If there is no "concept" Design is reduced to past knowledge[2].
4. **Definition 1 of Design:** assuming a space of concepts C and a space of knowledge K**,** we define Design as the process by which a concept generates other concepts or is transformed into knowledge, i.e. propositions in K**.**

Comment 1: This definition clarifies the oddness of Design reasoning. There is no design if there are no "concepts": concepts are candidates to be transformed into propositions of K but are not themselves elements of K. If we say that we want to design "Something having the properties (or functions) F_1,F_2,F_3,…": we are necessarily saying that the proposition "Something having the properties F_1,F_2,F_3" is nor true nor false in K. **Proof:** If the proposition was true in K it would mean that this entity already exists and that we know all that we need about it (including its feasibility) to assess the required properties. Design would immediately stop! If the proposition was false in K the design would also stop for the opposite reason. It is important to remark that there is no concept per se but relatively to K. We call it the **K-relativity** of a design process. This definition captures the very nature of design and have important operational consequences.

[2] This distinction between C and K is essential to our definition of design. Even if we admit in K a very weak form of logic this distinction should be maintained. A design concept is a proposition that can't be logically valued in all logics assumed in K. Such strong axiom is a condition that avoids to reduce design to classic problem solving. If it was possible to give any logical status (L) to the concept this would mean that the proposition ("it exists an entity having properties P_1, P_2, P_3,.." have the status L) is a true proposition in K. This would open the way to several contradictions and probably to some circularity similar to Godel's classic incompleteness theorem.

Comment 2: traditionally design is defined by the intention to fulfill some requirements, or as a proposal to fulfill some requirements [5]. These notions have a practical meaning when for instance some client formulates a requirement and a designer answers by a proposal. In our framework the formulation of the "requirements" is a first concept formulation which is expanded by the designer in a second concept that is called the proposal.. The latter being a new design departure for the designer or for other design actors. Moreover, in our theory the logic of "intention" is built-in the definition of a concept. What would mean the intention to design if it concerns something that is already completely defined in K? We can even characterise the broad world "intention" in design as a class of endeavours or deeds that aim to bring a concept to some form of "reality" i.e. logical status in K.

As required earlier, **creativity is now clearly built-in the definition of Design**. A concept being nor true nor false, the design process aims to transform this concept and will necessarily *transform K*. All classical definitions of Design are special cases of our definition. If we say that we have to design a product P meeting some specifications S, we are implicitly saying that the proposition (Product having property S) is a concept ! But usually one forgets to indicate to which K should one refer a design problem. If we want to design a "flying bicycle", we formulate a concept relatively to the knowledge space available to almost everybody. But if we say a "flying boat", then it's a concept only for those who never heard about hydroplanes ! **K-relativity** is central for understanding how Design is shaped by different traditions. A "ready made artistic work" was a concept for Marcel Duchamp [20], a founder of modern art, but it was a false proposition for classic Art.

3.2. Space of Concepts, concept-sets and concept expansion: a new interpretation of the choice axiom in set theory.

Now that we have a well formed definition of Design, we can derive from it the process of designing. We need before other definitions of what we call a "concept-set" and "concept expansion". This is a crucial part of the theory and we will follow a step by step presentation.

1. **Concepts as specific Sets**: as said before, a "concept" C is a proposition which has no logical status in a space K (i.e. nor false nor true in K). It says that "an entity (or group of entities) verifies a group of properties P". This definition is equivalent to defining a set associated with C. This set will be called also C: it contains all entities that are partly defined by P. Yoshikawa [1,21], uses a similar notion called entity-concept. However our assumptions about this concept-set are quite contrary to his[3]. His concept-set aims to capture all the

[3] The Yoshikawa's. "set concept" or "entity concept" or "concept of entity" is the set that contains all the objects of a domain. This allows him to formulate theorem 5: "the entity concept in the ideal Knowledge is a design solution". This means that there is no disjunction between existing knowledge and the entity concept. In his model of real knowledge Yoshikawa has therefore difficulties to define his entity concept as it becomes impossible to say that the concept contains only design solutions. Lets take an example if we want to design "a flying boat" in the Yoshikawa's approach of an entity the design solution will have to be a boat in exactly the same definition than in the original set. This is precisely what we avoid in our definition of a concept. The design of "a flying boat" could possibly be an object which could not be defined as a boat in the first phase of the design project. This is also why the choice axiom in C is rejected. An other indication of the difference between our approach and Yoshikawa's one can be seen in his hypothesis that the entity concept can be associated to a functions space containing all the classes of the entity concept. This means that the power set of the concept set is also perfectly known. This is also contradictory to our rejection of the choice axiom.

existing objects of a domain and this is, in our view, in contradiction with the definition of design. Therefore, due to our definition of Design, C has the following strange property!

2. **Concepts are sets from which we cannot extract one element !** Why such a strange property ? If we say that we can always extract one entity from the concept-set, then we are in contradiction with our proposition that a concept has no logical status in K. **Proof:** if we could extract one of these entities, it would mean that the concept is true for this entity; hence it wouldn't be a concept but a proposition of K ! Yet, why not consider all those entities except this one ? This means that we change the first concept by a new required property (be different from the already existing entity). Now, the new concept also should show no element we can extract, otherwise we would repeat the same process ! Finally, being a concept impedes the possibility to have elements that can be isolated ! **This property of concept-sets corresponds to a well known issue in Set theory: the rejection of the axiom of choice axiom .**

3. **Proposition: In design, concepts are sets defined in Set theory without the "choice axiom":** The importance of the choice axiom in Set theory is paramount [22]**.** The choice axiom says that it is always possible to "find" an element of a set, and accepting or rejecting the choice axiom controls the nature of mathematics. *Our definition of Design appears now deeply rooted in the foundational issues of mathematics*. Design needs concepts and concepts are sets where we cannot accept the choice axiom. And yet, concepts are still sets ! We know from a famous theorem due to Paul Cohen in 1965 [22] that the choice axiom is independent from the other axioms of Set theory: **This means that while rejecting the choice axiom we can still use all basic properties and operations of sets for concepts!** [4]

4. **Concepts-sets can only be partitioned or included, not "searched" or "explored"**: the practical consequence of rejecting the choice axiom is immediate: we cannot "explore" the concept or "search" in such sets ! **Proof**: how could we do that, if it's impossible to extract one element ! The metaphors of "exploration" or "search" are thus confusing for design. This explains why empirical studies are so embarrassed to find the "search processes" they look for in design activities [23]. Now, if we cannot search a concept what can we do *? We can only create new concepts (new sets) by adding or substracting new properties to the initial ones*. If we add new properties we partition the set in subsets; if we subtract properties we include the set in a set that contains it. Nothing else can be done in space C, but this is enough to reach new concepts.

5. **By adding or subtracting properties we can change the status of concepts. Proof:** Each time we make an operation like these, we may generate a new proposition of K. Let us consider "bicycles with pedals and effective wings" as a concept (relatively to our Knowledge space). If we subtract the property "have effective wings", we obtain "bicycles with pedals" which for almost all of us is not a concept but a true proposition (hence belongs to K) ! The reverse transformation is a partition of "bicycles with pedals" into two concept-sets: "bicycles

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[4] One may thinks that by rejecting the choice axiom any set operation on C will be refused. This is not the case. What is forbidden is the possibility to extract or find **one** element of C, but all others operations on sets are still possible. That is why there is a complete branch of set theory that is still possible without choice axiom [22]. Usually the choice axiom is famous for creating celebrated paradoxes like the Banach-Tarski paradox where one sphere can be divided in pieces that allow to make two new identical spheres. Such paradoxes are obtain not when sets are manipulated through there properties, but only when a single element is supposed to be found in the manipulated set.

with pedals and effective wings" and "bicycles with pedals and no effective wings". The former is now a concept for those (including the authors) who never saw "flying bicycles" (different from "flying motorcycles" which already exist) and cannot say if they will ever exist. **These elementary operations are all what we need to define at a high level of generality the process of design** !

3.3. Disjunctions and conjunctions: The dual dynamics of design

The process of adding and subtracting properties to concepts or propositions is one **central mechanism of Design**: it can transform propositions of K into concepts of C and conversely. Let us define more precisely these processes.

1. We call "**disjunction"** an operation which transforms propositions of K into concepts (going from K→ C); and we call "**conjunction"** the reverse operation (going from C→K).

2. What usually appears as a design solution is precisely what we call a "**conjunction"**. What does that mean? It means that we have reach a concept which is characterised by a sufficient number of propositions that can be established as true or false in K. This also means that we have now reached a definition of an entity which takes into account all existing knowledge and fulfills a series of properties clearly related to the initial concept. This is precisely a good "definition" of the entity that we wanted to design. And defining the object we want to design is equivalent to saying that we have designed it!. Another important remark is that this definition is still associated to a set of entities in K but we can now accept the choice axiom in this set . **Finally in our theory designing a concept is transforming a set where the axiom of choice is rejected into a set where it is accepted**. Yet this last set exists only in K. Why do we need the choice axiom here? Precisely to be able to speak of **one** solution, but it is possible to assume that design never ends in one solution but in a set-solution in K: the classic idea of geometrical tolerance in mechanical design is exactly the same idea. We never design one geometrical object but a set of geometric objects defined by the interval tolerance.

3. **Definition 2**: Design is the process by which K→C disjunctions are generated, then expanded by partition or inclusion into C→ K conjunctions.

4. **Proposition: the space of concepts has a tree based structure: Proof:** A space of concepts is necessarily tree-structured as the only operations allowed are partitions and inclusions and we have to assume at least one initial disjunction (this a classic result in graph theory). Several Design theories has used the tree structure to represent design reasoning [9] but they misinterpreted it as a decomposition process. A tree structure appears because we can only add or subtract properties. Yet adding properties to a concept seems to decompose a concept into sub-concepts: this is an illusion, as in design the tree is necessarily an "expansion" of the concept. To understand this point we need to distinguish between two type of partitions: respectively, **restricting and expanding partitions.**

5. **Definition of restricting and expanding partitions:** If the property we add to a concept is already known (in K) as a property of the entities concerned, we call it a **restricting partition**; if the property we add is not known in K as a property of the entities concerned, we have an **expanding partition**. In other words, restricting means detailing the description with already known attributes, while expanding means adding a new topology of attribute.

   Example: If we design a "system for stopping a car in case of extreme danger», we are not going to partition this set with known properties of "car brakes", we need to expand the concept by allowing new properties of the brakes or of the engine. The necessity of expanding partitions in Design explains why Yoshikawa (Yoshikawa 1981) finds "unexpected functions" for a "solution" but he misses the deep importance of this result in the definition of the design process itself.

6. **Creativity and innovation are due to expanding partitions of concepts:** This also reveals why creativity is built in our definition of design: concepts can be freely expanded provided we have available expanding properties. But where do these properties come from ? The unique answer is from K ! And this shows how the unknown comes from what is already known provided we accept the concept as a vehicle !

Now we have all the components needed to present C-K theory as a unified Design theory.

2.4. The four C-K operators and the "design square"

All preceding propositions define Design as a process generating **the co-expansion of two spaces**: spaces of concepts C and spaces of knowledge. Without the distinction between the expansions of C and K, Design disappears or is reduced to mere computation or optimisation. Thus, the design process is enacted by the operators that allow these two spaces to co-expand. Each space helping the other to expand. This highlights the necessity of four different operators to establish the whole process. Two can be called "external": from C→K and from K→C; and two are "internal": from C→C and from K→K. Let us give some indications on each operators. The four operators form what we call *the design square.* A complete study of these operators is beyond the scope of this introductory paper.

1. **The external operators**:
   - **K→C**: This operator adds or subtracts to concepts in C some properties coming from K. It creates "disjunctions" when it transforms elements from K into a concept. This also corresponds to what is usually called the "generation of alternatives". Yet, concepts are not alternatives but potential "seeds" for alternatives. This operator expands the space C with elements coming from K.
   - **C→K**: this operator seeks for properties in K that could be added or substracted to reach propositions with a logical status; it creates conjunctions which could be accepted as "finished designs" (a K-relative qualification). Practically, it corresponds to validation tools or methods in classical design: consulting an expert, doing a test, an experimental plan, a prototype, a mock-up are common examples of C→K operators. They expand the available knowledge in K while being triggered by the concept expansion in C.
2. **The internal operators:**
   - **C→C**: this operator is at least the classical rules in set theory that control partition or inclusion. But it can be enriched if necessary by consistency rules in C.
   - **K→K**: this operator is at least the classical rules of logic and propositional calculus that allow a knowledge space to have a self- expansion (proving new theorems).
3. **The design square, and C-K dynamics**

Figure 1 combines the four types of operators in what can be called the "**Design square**". It gives the fundamental structure of the design process. It also illustrates the importance of defining Design both on concepts and knowledge. This model avoids the classical logic of design stages from "abstract to concrete" or from "rough to detail". These are too normative positions: "details" may come first in a design if they have a strong partitioning power ;.and unexpected stages could result from a surprising knowledge expansion. The classical opposition between linearity and turbulence disappears: innovations could result from both.

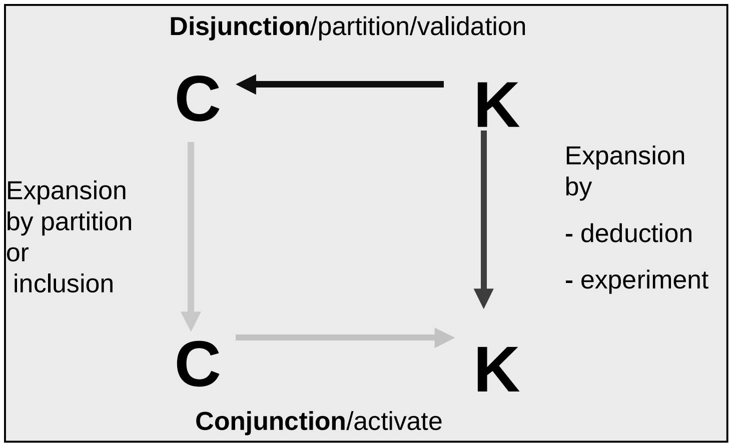

Figure 1. the design square

Another illustration of the C-K dynamics is given in Figure2. We recognize the tree structure in C, while the structure of K could be different. The analysis of the structure of K is a difficult one and it would be too long to discuss it here. We also see in this picture that any expansion in C is dependant of K and reciprocally. Any choice to expand or not in C is K-dependant. Conversely, any creation in K requires travelling by some path in C. Designs begins with a disjunction and will "end" conventionally only if some conjunction exists and is judged K-relatively as "a solution".

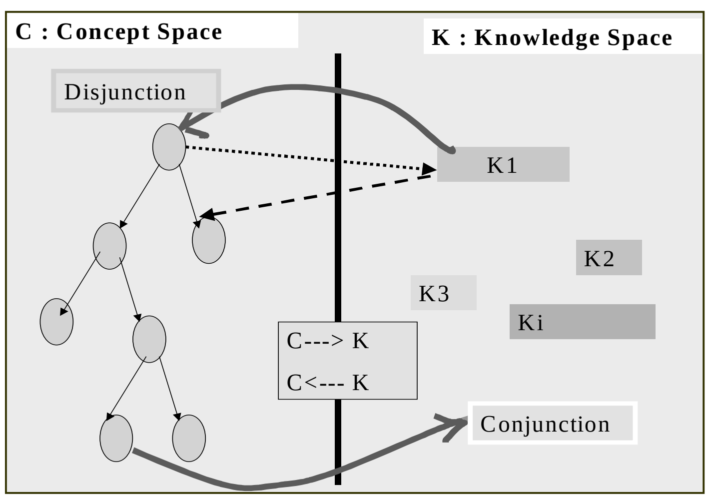

Figure 2. C-K dynamics

Considering the precise formulation of our assumptions and the dynamics of the four operators, we hope that the reader will be convinced that our approach is not a metaphor or a model of Design but a Design theory. At least, we have met our initial requisites: we have built-in creativity in the definition of design and we have established the process by which the co-expansion of knowledge and concepts becomes possible. Moreover C-K theory offers the following results:

- It offers **a universal form of reasoning** that describes how we can think about something we partially know and expand it to some unknown definition, while not being lost in the process.
- It allows to study **the conditions bearing on any design process**: How disjunctions or conjunctions are they possible ? What is the influence of our knowledge and learning processes on design ? A rigorous examination of these questions becomes possible and will be treated in forthcoming papers. We will limit ourselves in this paper to a first discussion of the power and applications of C-K theory.

4. Validation and implications of C-K theory

4.1.How can we validate a design theory?

It seems to us that the validation of a design theory is similar to the validation of other theories like decision theory or problem solving theory. In all these cases three criteria can be used. Each of them is probably not enough, however taken together they can be more convincing. i) First criteria: the theory constitutes a good unification of previous theories about the same object. ii) Second criteria : the theory clarifies hidden properties of its object that were not visible in the previous theories and this new insight contributes to embed the theory in a more universal body of knowledge. iii)Third criteria: the theory clarifies some pragmatic issues and even offers new ways to treat them with robust expectations.

4.2. C-K theory as a unified theory of Design

The first advantages of C-K are its rigour and its consistency. It offers the first definition of Design that captures the singularity and disturbing nature of Design: the dual concept and knowledge expansions. It has a precise formulation that allows strong control on the propositions of the theory, provided that one accepts Set theory and modern logic as valid knowledge (always the K-relativity…). Therefore, C-K theory appears as a unified theory in the classic scientific sense: **it captures in the same framework previous theories that looked initially different.** For instance, C-K theory is both a process and a mapping. It easily models all process-based theories and clarifies their implicit hypothesis. We can use C-K to clarify the implicit conditions on K that are assumed by the German systematic to be an acceptable method. It points out clearly why Suh's axiomatic is not a design theory as there is no concept and no knowledge described by the theory. Suh axiomatic is a command and control theory helpful in some design work. C-K theory also encompasses similar attempts like Yoshikawa's general design theory or Grabowsky et al., "universal design theory". Yet, to show it in detail would need a full paper. Finally, C-K theory synthesizes the knowledge acquired in the field of design theory in a consistent way and embeds it in modern set theory.

Even, if it is impossible to pretend that there is no other way to reach the same theoretical power, in this paper we have showed that C-K theory can successfully reach the first and the second criteria. It would be too long here to discuss it capacity to fulfil criteria 3. In practice, C-K theory is now used in several companies: i) to monitor the early phases of innovative design projects ; ii) to develop new organizational structures for innovation different from R&D organizations; iii) to memorize the results of a design works and its correlated knowledge expansions. We have discussed elsewhere how the C-K theory can be used as a useful guide for the organizing of innovation in “design oriented organisations” [3], [24], [25], [26]. However the following discussion of creativity can be seen as a first step in this direction.

4.2. C-K theory and creativity: a new perspective.

C-K offers also a fresh critic on usual views about creativity. The dual C-K expansion process provides direct explanation of the empirical existence of *two major types* of “inventions”.

- **Type 1 creativity: C-k expansions (large C-small k) or "conceptual innovations"**: these cases need a significant conceptual expansion i.e a large number of successive partitions in C, whereas the knowledge K used is very common to many people. Therefore, most people are extremely surprised by the result. People’s reaction to such innovative design is typically: "why didn't we think of that before!" or "gosh, that's very clever", etc. These feelings are based on the fact that all the knowledge needed was already available, yet the concept had not occurred to them. C-K theory explains why these feelings are based on an illusion: knowledge has no design value without the concepts that it helps to expand! Thus this type of ordinary and common inventions require tenacity and patience: designers must agree to **suspend the logical status of some common propositions** for a time and accept several expanding partitions before obtaining any acceptable design**.**

- **Type 2 creativity**: **c-K expansions (small C-large K) or “so called” applied Science*:*** these cases involve sophisticated knowledge with a limited conceptual development. People are not surprised by mobile phones or televisions, they are completely fascinated! Not that they had never thought of long-distance communications, but because they had no idea how to get it. Also , except for a few specialists, they recognize the concept but they are not able to explain how it works. This second type of expansion is typical of the technological world in which we live. New knowledge is produced constantly and intervenes in design processes that are completely unknown to most of us. Facing this new objects, we suddenly discover unexpected combinations of simple concepts and complex knowledge. This model of creativity had an enormous impact on our views of design: many have the illusory idea that it simply involves an "application" of scientific knowledge. Therefore, the design process becomes invisible. This view has been very influential in the education of engineers: sound knowledge in the basic sciences would be all what is needed to be a good engineering designer!

All this allows to argue about the validity of classic creativity games like “brainstorming”. If one is involved in a C-k type innovation, brainstorming will be very disappointing as the most interesting ideas (i.e. C-K disjunctions) will appear either as too daring dreams regarding existing knowledge or as too prudent ideas whose innovative power would be visible only after several expansions. Thus C-K theory tells us that there are only **two consistent creativity games**:

- adopting **daring concepts** and **quickly leaving the creativity team** and room looking outside (new data, experiment, experts...) for new knowledge expansions;
- adopting **seemingly acceptable concepts** and working hard, continuously and with patience, to expand them towards an innovative design.

5. Conclusion: future prospects about C-K theory

In this paper we have presented the main elements of C-K theory and showed that this theory has several advantages. It gives a rigorous definition of design and establishes the deep link existing between design and a fundamental issue in Set theory. It also unifies existing design theories and offers a precise constructive definition of the design process. More over, with C-K theory design theory has immediate connections with all others knowledge theories or forms of logic. It can claim a universal value and several promising ways are opened to further research.

- **Improving the foundations of the theory**: C-K theory has been presented in this paper with **a limited mathematical development**. Yet there is a large area of investigation in this direction. The properties of K can be studied in more detail and the structure of the four operators presents very interesting features. We can attempt to characterize the conditions that warrant the existence of disjunctions and conjunctions ; and finally investigate the mathematical and computerized tools that could capture the C-K process.

- **Improving social and management research on design**: Based on our empirical industrial observations, the value of a unified design theory that can guide innovative projects has been assessed. C-K theory fits this program in a theoretical and rigorous way. We observe a good understanding of its principles by engineers, architects or artists as it offers a common language about Design that is not dependant of the type of skill and knowledge used. It also opens a new spectrum of research in the organization of design and innovation. **Qualitative and social research on Design practice** should be revisited as new investigations are suggested by C-K theory: for instance, what is the social acceptance of concepts and disjunctions in organizations ? how are they handled ? Does team work allow for long conceptual expansions ? What is the impact of knowledge codification on the ability to design ? C-K theory offers a clear set of universal notions that can help the social researcher to analyse a design process without being biased by too restrictive visions of Design.

The variety of these new research issues is certainly a good sign of the potential of C-K theory.

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