Grammars of creation.
Mapping search strategies for radical innovation

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ABSTRACT

Radical innovation creates discontinuity in the competitive environment and, in some cases, open new industries. The origin of radical innovation is poorly understood, although a large literature deals with its consequences. Some authors stressed the importance of challenging established boundaries of markets, by addressing non-customers and developing products around new functionalities.

This paper goes a step beyond by addressing the cognitive foundations of radical innovation. It uses insights from design theory in engineering science, complex problem solving in artificial intelligence, applied ontology in philosophy, ethnographic research, economics of technology and history of technology to build a framework for understanding the nature of radical change. Links with other fields (mainly in social sciences) that have explored the nature of creative processes are developed.

First of all, it elaborates on the notion of function space, i.e. the abstract characterization of possible uses of artefacts. It argues that this space is subject to an internal dynamics, that designers, industrial researchers and innovation managers try to identify and map.

Secondly, it proposes a simple but general framework for defining heuristic strategies for search into this space. It proposes the categories of local search, recombination, analogy and abstraction as useful way to characterize general search strategies. It discusses each of them in the light of the literature and offers a rich series of mini case-studies to illustrate the underlying logic.

The paper uses abstract conceptual categories but offers many practical and managerial insights into the largely under-explored field of radical innovation.

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1. Explaining radical innovation

Radical product innovation can generate entire new industries, as in the case of the PC, low cost airlines, or mobile communication, but also can sustain the long term competitive advantage of innovative firms in established industries, as in the case of i-Pod in the music industry, Cirque du Soleil in the entertainment industry, or Geox in footwear. It is largely acknowledged in the literature that radical or discontinuous product innovation requires a substantially different managerial approach than incremental innovation or continuous improvement (Veryzer, 1998a; McDermott and Colarelli O’Connor, 2002).

This literature has examined to the so called “fuzzy front end”, i.e. the early conceptual stage of product development, a stage dominated by goal ambiguity, uncertainty, oscillation between different solutions, and significant conflict in product development teams (Reid and De Brentani, 2004). One of the main results is that the distinction between radical innovation and incremental innovation has its roots in the fuzzy front end. In the field of new product development several contributions have also examined product acceleration, that is, how to manage group conflicts and divergence under time stress and goal pressure (Cooper and Kleinschmidt, 1994; Eisenhardt and Tabrizi, 1995; Moorman and Miner, 1998).

Despite these efforts and important conceptualizations, the nature and origins of radical innovation are still largely unknown. We know that a significant role is played by endogenous technological evolution, but the interplay between the understanding of customer needs and the opportunities offered by technology must still be subject to a thorough theoretical analysis. Furthermore, the evidence suggests that technology push is not the only (and sometimes not even the most important) determinant of radical innovation. This theoretical situation is somewhat problematic, given the increasing emphasis placed by the strategic literature on the importance of novelty and discontinuity.

Back in 1990 Henderson and Clark defined radical innovation as one involving both architectural reconfiguration and technological change (Henderson and Clark, 1990). Christensen has proposed that disruptive innovation often takes place by addressing non-markets (Christensen, 1997; Christensen and Raynor, 2003) and by identifying the signals of change generated by opportunities from nonconsumers, overshoot consumers and undershot consumers (Christensen, Anthony and Roth, 2004).

More recently, a large stream of managerial literature has emphasized the importance of mastering breakthroughs, as opposed to incremental innovation or efficiency gains. Kim and Mauborgne (2005) have stressed the notion that radical innovators redesign the distribution of customer benefits, rather than trying to match the performances of best-in-class companies. In the same line, Ridderstrale and Nordstrom (2006) have suggested that companies should not follow the benchmark of others but try to depart from established directions.

In this line of thinking, Sheth (2007) has showed how dominant companies are vulnerable to entrants that adopt radical innovations and warned against the fatal risk of complacency and self-indulgence. In order to support the ability of companies to think about deviation from rules, improbable events and discontinuity, Mathews and Wacker (2002) have developed the notion of deviant’s advantage, Taleb (2007) has proposed to dismiss predictive and rational management based on assumptions of normal distributions, and Cholle (2007) has suggested a managerial approach based on intuitive intelligence.

Another stream of literature has suggested that radical innovation is based on creativity in problem solving and has examined the determinants and contextual factors of creativity, based on cognitive psychology and social psychology and on a long tradition of research into the origins of scientific, technical and aesthetic novelty (see Amabile, 1996 for an authoritative survey and
Hemlin, Allwood and Martin (2004 on recent evidence). Somewhat related with this tradition is the large flow of practical suggestions on how to enhance creativity in problem solving (e.g. De Bono, 1992; Couger, 1995; Van Gundy, 1997), as well as the specialized literature on creativity tools in organizational decision making (e.g. McCrimmon and Wagner, 1994; McFadzean, 1998).

In the literature it has been suggested that radical innovation involves deep cognitive changes such as concept shifting (Seiden, 2007), or pattern recognition from customers (Veryzer, 1998b; Colarelli O’Connor and Veryzer, 2001). We suggest that these phenomena can better be understood and explained by referring to an abstract formulation of the problem of artificial, i.e. of intentional creation of novelty. In this paper we try to expand the literature, building a conceptual link between management of new product development and formal theories of artificial. In order to reach this goal we will need to address very abstract questions, questions that will turn to be of immense practical value only at the end of the journey.

More specifically, we suggest that creativity in product development does not depend on generic cognitive or organisational rules to generate “new ideas”, but on deeper search strategies (or heuristics) that explore what we label the function space. What is at stake in radical product innovation is a deep change in the abstract relation between a complex set of functions and a number of physical (or intangible) structures implementing these functions. These are the largely unexplored cognitive foundations of radical innovation.

In this paper we offer a theoretical framework for examining this issue, building upon an articulated background in various fields, such as design theory in engineering science, complex problem solving in artificial intelligence, applied ontology and informal logic in philosophy, ethnographic research, economics of technology and history of technology. In doing so we ask the reader to trust the author, for the first ten pages, that the abstract notions developed will ultimately lead to useful concepts for analysis of innovation in the real world.

The paper is structured as follows. We first introduce and discuss the notion of function space as an abstract concept to account for search strategies and heuristics. We then discuss the grammar of search, that is, the heuristic rules that any type of search in this space must follow. We then introduce a categorization of general search strategies, offering many practical examples drawn from case studies of innovative firms. A call for extension of the framework and further accumulation of empirical evidence concludes the paper.

2. How can you describe an object?

Let us start with a simple observation. Any innovation involves objects, either physical objects (car, oven, headphone) or intangible objects (parcel delivery service, legal procedure). The general question “where stuff come from”, and in particular, “where new stuff come from”, is attracting highly qualified interest, ranging from applied ontology in philosophy (Casati and Varzi, 1999; Varzi, 2001; 2005; Ferraris, 2005) to sociology and anthropology of design and consumption (Norman, 1988; Molotch, 2003), to computer science (Smith, 1996). It is likely to be an interesting question for innovation studies as well, although they rarely start their investigation at such a high level of abstraction.

How can objects be described? Among many others, this question was clearly addressed by Polanyi in Personal knowledge (Polanyi, 1958), wrongly famous only for the notion of tacitness.

In articulating this relation, Polanyi addresses a classical problem in the philosophy of scientific explanation and develops a distinction which has a more general validity. Take an object as the reference point. How many different descriptions are possible for any given object? There are many possible descriptions regarding its physical structure, depending on the scale of observation (object,
parts of the object, molecules, atoms), the aspects described (geometry, materials, physical properties such as mass or weight, etc.), the coarseness of description and the like. Ultimately, all descriptions of this type have the same logical nature and are mutually reducible to each other, shifting the frame of reference. Let us call them structural descriptions. A structural description regards an object according to its structure or form, or it contains structural properties of the object. Quite generally, structural properties are related to two main elements: materials and shape. In doing so a structural description includes an object into one or more classes of objects that share the same properties. There are many classes to which an object may be ascribed according to its properties: the class of all objects with the same weight, with the same shape, made of the same material and so on. The number of classes is an open question, but for all practical purposes let us assume that it is a large number. Being a description based on physical properties, and being physical objects finite by definition, this number would be probably finite, but for all practical purposes it may be considered very large.

Thus a structural description is a very rich one, since it allows many levels and permits the connection with many other structural descriptions. In general, it is possible to generate many descriptions that have the same logical nature, i.e. can be transformed into each other provided a sufficiently rich vocabulary is developed. Thus a description in terms of molecular structures can be transformed into a description in terms of atomic structures provided the chemical and physical laws relating the two levels are specified.

Question is: is this the only admissible type of description?

According to Polanyi there is another type of description, which is called functional description. In this type of description, the object is considered in relation to its behavior or effect, not structure. To describe the behavior of an object it is necessary to specify the conditions under which the behavior is observed. A behavior under a general class of conditions is called a function. So we say that the function of heart is to pump blood. Or the function of a hammer, under the conditions that a force is exerted on the wooden body around a fulcrum is to push a nail in the wall. Why do we use such term in our descriptions? The nature of this description is much less clear than the other and requires careful articulation.

To begin with, logical positivists such as Hempel (1959) tried to subsume the functional description as part of the nomological-deductive explanation, where the function is inferred from the underlying causal relations (i.e. because a muscular structure shaped like a heart invariably produces pumping, we say it has the function of pumping). A functional explanation is a deductive explanation in which the condition is the effect produced by the object, and the cause (the function of the object) is inferred by necessity. It is important to recall this approach, because most economic analysis follows it, downplaying the distinction between causal and functional explanation.

This strategy has logical flaws, however, as Polanyi clearly notes. There are always many ways in which a given cause may be produced: for example blood may be pumped by an artificial heart or by a system of valves. An inference from the effect to the presence of the cause is not logically binding.

At the same time, once one has started to describe an object according to its function, immediately it becomes clear that it may have many other functions, perhaps less trivial. A hammer can be used to keep a door open, or to support the body of a plant, or to press a stack of paper sheets so they do not fly away in the room. In describing these functions it is necessary to change the conditions under which the behavior is observed. Once one has generated some examples of plausible functions for the object several questions arise, such as: how many functions are there for an object? And: what is the relation between describing an object according to its function and describing it according to its structure?
The number of functions is an open question, but there is nothing logically absurd in admitting they are potentially a large number. Of course not all changes in conditions are admissible, so not all functions are plausible for an object. Ultimately, functions must be described in terms of physical variables. “Pushing a nail into the wall” can be translated into “exerting a pressure of X kilograms per square millimeter following a movement with angle k on axis Y around a fulcrum at the bottom of the object” or the like. Thus we may agree on the intuition that the number of functions must be finite but very large. Then why do we identify only a few? We suggest that this question is a fundamental one to understand radical innovation.

A promising way to answer this question is proposing that functions are the result of a selectional process, similar to that assumed in evolutionary biology. In this way a function is ascribed to an object not in virtue of its actual or possible functions, but in virtue of the fact that that function must be the result of a selectional process occurred in the past, with some ancestors. This also explains why we tend to identify a small number of functions to objects, even though there may be others. The realized mapping we observe (the fact that a hammer is normally used for pushing nails in the wall) must result from a process of selection among many possible mappings.

This points to the final question. Given that the descriptions according to functions and according to structures are different, the relation between the two cannot be logically binding. This is the fundamental contribution of the critique to Hempel’s attempt to reduce functions to deductive reasoning. There is nothing logically compelling in establishing a relation between a structure and a function. There has to be a translation or mapping between the two.

The statement that functions and structures call for logically different types of descriptions is supported also by Nicholas Rescher. In his view, the information contained in a structural description does not logically imply the information in a functional description (Rescher, 1996).

These views point to an important point, i.e. that functional descriptions are ultimately written in physical terms. Any function can be described as a statement in physical language. In other words, functional and structural descriptions must be compatible, since ultimately the behavior of the object must be realized in the physical world. Still, the crucial point is that these representations are logically different.

3. Function space and structure space

Interestingly, this notion has strong correspondence with the way in which engineering disciplines reflexively represent and model themselves.

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2 This restriction makes it problematic to use the notion of function to cover aesthetic properties. It is possible that beauty can be described in physical terms (and indeed a long tradition in architecture and history of art suggests that this is exactly what is needed). It is also possible that the “effect” of beauty on human beings can be related to measurable physiological reactions. Recent research on modern art (such as Pollock’s paintings) suggests that beautiful pieces have a clear structure that can be described mathematically. But we still know very little about all that. This is unfortunate, because significant part of innovation takes place in industrial design, that combines functions and aesthetic or experiential properties. McCarthy and Wright (2004) started to explore this connection. How functions and beauty interact, or the relation between reproducible form (industrial design) and unique form (art), are clearly areas for future research in the economics and management of innovation.

3 This is the main reason for our departure from the approach taken by the pioneering work of Rikard Stankiewicz on the economics of design and technology. Stankiewicz (2000; 2002) proposes the notion of design space as a unitary space in which workable solutions evolve in the form of engineering principles realized into operands, together with solution embodiments in objects. Operands are demonstrated solutions and allow search to take a cumulative dynamics. While this is an attractive way to give an account of the evolutionary dynamics of technology, we prefer to keep functions and structures separate from a logical point of view. This gives more flexibility in explaining how operands come to the light.
There are three main streams of literature within engineering disciplines that are relevant for our purposes. The first is the systematic effort of some authors, mainly in continental European countries, to build a general theory of design. In this line of research, experienced academic engineers try to identify common types of problems across all specialized disciplines and to build up a systematic catalogue of procedures used to solve them (Pahl and Beitz, 1984). This literature goes much beyond practical applications such as House of Quality or Quality Function Deployment, that typically assume the functional description of artifacts as given and try to optimize the physical deployment.

The second stream of literature is more pragmatic, since it was originated by an effort to develop an artificial intelligence approach to design (Tong and Sriram, 1992; Sriram, 1997).

Here the practical problem was how to automate design problems and develop software programs that could substitute for human problem solving. It turned out that many design problems could not be automated at all, but the reason for that impossibility was far from clear. This difficulty fuelled research into the abstract nature of design problems. In this direction this pragmatic line of work had important connections with the tradition of analysis of problem solving heuristics and procedures in cognitive science.

Finally, there are also a number of ethnographic studies, which describe in detail the heuristics and problem solving procedures used by engineers and designers in field tasks (Ferguson, 1992; Bucciarelli, 1994).

In design theory, the distinction between structural and functional description plays a central role (Pahl and Beitz, 1984; Ullman, 1997; Ulrich and Eppinger, 1995; Hubka et al., 1988). Theories of design as specialized problem solving (Brown and Chandrasekaran, 1989; Coyne et al., 1990) show that the reasoning behind design is based on heuristics about the likelihood that a given structural configuration can implement a desired set of functions, of the form “generate and test”. There is no logical necessity in this reasoning, insofar as there are a large number of alternative ways to implement the desired functions. This notion is made even more explicit in the axiomatic theory of design (Suh, 1982).

Let us summarize the main arguments of these contributions by introducing some notions. For the sake of clarity, let us use some naive graphical representation.

Two remarks. First, in the following we will refer to function space as defined mainly from an artificial or engineering point of view, assuming intentionality. The same arguments apply, mutatis mutandis, to natural function spaces. Second, we will refer mainly to physical elements in the structure space. The same arguments apply, mutatis mutandis, to immaterial technologies such as information and communication technology or services.

Let F be the function space, or the set of all possible functions. This space contains all possible behaviors of objects under any conceivable condition, subject to the constraints that they can be implemented in the physical world. This means that the function “moving at speed higher than light” is not included in the function space.

Let us remark that functions are not needs. The latter are defined in discursive terms by human users of objects. Functions are defined in physical terms, as behaviors under specified conditions, which are connected to a general effect. The question how needs are interpreted by firms and are transformed into requirements for functions is a crucial one, and we will address it in the final part of the paper.

A fundamental property of the function space is hierarchy. Functions can be hierarchically decomposed, down to elementary units. A functional hierarchy is an iterative decomposition of a high level or macrofunction into more elementary sub-functions (see for a simple example Figure 1). The achievement of lower level functions is a requisite for the achievement of higher level ones. Sub-functions are either intrinsically related to the main function as necessary elements, or are generated by the extension of conditions for behavior. Thus the function “transmit voice from and to a mobile device” is naturally decomposable into several main sub-functions (transmission, reception, recording etc.), each of which has a tree-like structure down to elementary functions such as “switch on/off” or the like. It is important to note that the detailed functional tree is a very large one in most cases. A full functional tree of a moderately complex device contains a few or several hundred sub-functions, all of which must be satisfied for the main functions to be implemented.

This tree-like structure may be further refined if one adds new conditions under which the same function must be performed, e.g. the device must work without recharging for 3 days (see conditioning below). The hierarchical tree has not a natural vertex. Any node in the tree is a function itself and may be considered the vertex of a new hierarchical tree in the space of functions.

In the engineering literature, a certain effort has been put in trying to build up common vocabularies and general catalogues of functions and in developing models for connecting functions to known solutions (see for example Kirschman and and Fadel, 1998; Hirtz et al.; 2004; Kitamura, Kasai and Mizoguchi, 2001).

Let S be the structure space, or the set of all possible structures. This includes all natural structures and all conceivable artifacts, the latter subject to the constraints that they do not violate physical laws. This means that the structure “chocolate bar at 300° C” or the structure “an engine exhibiting motum perpetuum” are not included in the structure space. As Galileo Galilei once noted, a mouse of the size of an elephant would not be possible, because the geometry of the mouse

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**Figure 1** A functional hierarchy of a power plant (portion). From Kitamura, Kasai and Mizoguchi (2001)
skeleton would not resist a large weight. Therefore a very big mouse is not part of the structure space.

At a very general level the main elements of structure are shape, or form, and material. Because of their form and material artifact have some properties or behaviors, and due to these exhibit certain performances. More detailed descriptions of structures can be given, depending on specific areas. For example, in mechanical engineering a complex structure like a car is said to have a macro-function (e.g. to transport people), delivered thanks to an internal working (e.g. combustion engine) and implemented by drivers through a specific mode of use (e.g. driving). In delivering the function, cars exhibit behaviors that are necessary to implement the function (e.g. vibration of the engine) and effects that are not necessary (e.g. noise emission). In materials technology a rather general representation is a flow-block diagram that links processing technologies to physical structures (microstructural subsystems such as crystal grain sizes), and these structures to properties they control (such as strength and toughness). Finally, properties lead to a desired performance, that is needed in order to implement functions when the material is used in an artifact. A representation in the field of steel technology is offered in Figure 2. Although all these qualifications are important, and are indeed necessary to articulate the design process, we make abstraction from them. All relevant definitions are summarized in the notion of structure space.

As in the case of functions, an essential property of the structure space is hierarchy. Physical entities are organized according to a multilayer structure ultimately dependent on the scale of matter (Smith, 1981; Kline, 1995). But while the functional hierarchy has not a fixed topology, in the sense that any node may generate sub-trees, in the structure space the hierarchy is rooted in the physics of matter and in the related orders of magnitude.

The discussion so far has lead us to postulate that these spaces have different logical nature, so they must be represented independently by human beings in their mind. The separate representation of functions and structures is most likely at the origin of the technical capabilities of mankind, which is highly distinctive of the species, and that has probably evolved slowly in the natural history. One of the reasons is that it requires the development of an operational memory of sufficient size (Boncinelli, 2006). Recent neuro-physiological research on mirror neurons suggests that humans recall the function of an action (e.g. picking up a cup of coffee) even when the physical realization of the action is experimentally interrupted, i.e. maintain a functional representation independent on the causal representation (Rizzolatti, 2005).

It is likely that this capability is peculiar of humans. Animals can learn simple functional relations from repetition of causal actions, but cannot develop machines. Biologists studying the differences between men and monkeys show that, although the latter are able to solve correctly elementary problems of functions (e.g. filling the blank card between an apple and a cut apple with the card representing a knife), they are not able to solve problems that require maintaining a representation of the functions for a certain time interval (Tomasello, 1999; Premack and Premack, 2002).

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5 This is beautifully shown by biologists interested in scale properties of animals. See for example Griffin (1962) and more recently the general reconstruction of Bonner (2006).
Historians of technology emphasize that the distinctive capability of humans to manipulate nature is rooted in the learning of general schemes of functions, starting from the initial rudimentary creation of artifacts, then to their combination in more complex artifacts, finally to the application of energy (Leroi-Gourhan, 1943; 1945). The appearance of language greatly improved the ability to transmit knowledge on these schemes (Leroi-Gourhan, 1962).

Thus human beings have the distinctive ability to represent functions (perhaps large classes of functions) as independent from objects. Their learning does not only take place in the space of structures, resulting from repetition of causal observations, but also in the space of functions, representing them in abstract way. Let us represent (naively) this situation as in Figure 3. It is then important to understand which is the relation between functions and structures.

First of all, a correspondence between a point or a region in the structure space and a point or region in the function space is called mapping. What is the implication of the realization of a new mapping? Once a new mapping has been generated, the efficiency of searching in close regions greatly increases, leading to a wave of new cumulative refinements. A new mapping is usually associated to a sequence of further improvements that take place in the neighborhood. This implication is consistent with evolutionary accounts of history of technology, that present technological evolution as a collective effort of trial and error (in our language, of successful or unsuccessful mappings), even for small and apparently insignificant objects such as paperclips and screwdrivers (Petroski, 1992; Rybczynski, 2000; see also Richerson and Boyd, 2005). While this account is generally accepted, it leaves open the question of how a new mapping is generated. As we will see, a pure random search is an extremely inaccurate representation.

Second, how many mappings are possible for any given point in the two spaces?

Following our previous discussion, there are always many points in the structure space that can implement any desired function. At the same time, each structure has many possible functions. Consequently, although we observe objects that have a well defined set of functions, there is always a many-to-many correspondence between the two spaces (Figure 4).
Formally, the two spaces do not enjoy properties of holohedral isomorphism, nor of merohedral isomorphism (Polya, 1945, 46). Holohedral isomorphism, or simply isomorphism, is the property that there is a one-one correspondence between the objects of the two systems S and S’ preserving certain relations. It means that if such a relation holds between the objects of one system, the same relation holds between the corresponding objects of the other system. On the other hand, merohedral isomorphism, or homomorphism, implies that there is a one-many correspondence between the objects of the systems S and S’ preserving certain relations.

The mapping between S and F, in our case, is a many-many correspondence, lacking the inner order and predictability of any type of isomorphism. At the same time, it is clear that this correspondence is definitely not a random matching between pairs of points in the structure and function space. The potential mapping is highly structured.
Let us refine the argument about the precise relation between the two spaces. A structure implementing a function is ultimately subject to a physical description. This description will include a causality relation of the sort: “the structure of heart produced the pumping of blood”. The flow diagram illustrated for materials science in Figure 2 can be read from the left to the right as follows: “the matrix structure of material K, obtained through a process of tempering and solution treatment, produces certain properties of toughness and hence delivers the performance required”. Would it be possible to go backward from the effect to the cause, i.e. from the right to the left? If yes, would it be possible to collect an exhaustive list of all possible structures that produce a desired effect?

In other words, is the mapping reducible to a search within all possible causal explanations? If this were possible, one would build a complete catalogue of all possible causal relations, then would ask what is the desired effect and would generate (almost automatically) all possible mappings.

Unfortunately, this is not logically possible. The mapping can never be derived only from knowledge of structures. The reason is that causality relations are not of deductive type, so that it is always possible to conclude whether the set of all possible conditions for a given effect is closed. Causal relations have to be established inductively. Now, in inductive logic, there is not a process by which it is possible to construct the set of all possible causes for an effect (Copi and Burgess-Jackson, 1996; Gustason, 1994). Causal relations must be collected one by one and checked separately. So the catalogue is never guaranteed to be complete. The mapping can never be automated.

This argument can also be defended along the lines of theory of causality (Glymour and Cooper, 1999; Pearl, 2000). Given a causal structure, is it possible to reason back from an effect to all possible causes? The theory shows that this is possible only under very severe assumptions, that are normally violated in design problems. In most cases what one can obtain is a set of non-causal factors, rather than the complete list of causal factors. This points to a fundamental property of mapping: knowledge about physical structures can enumerate exhaustively only all mappings that are not feasible, but never all those that are.

From a cognitive point of view a mapping is a projection from a space into another. There is no logical necessity for such projection. Knowledge of the structure space has limited the admissible region, leaving however a large number of open possibilities. Mapping follows possibility, not probability.

This means that design problem solving cannot be reduced to inductive thinking. It is rather a form of abductive thinking, that does not move from antecedents to consequences, but makes the reverse path, from desired consequences (functions) to possible causal factors (structures). In this perspective, design is not the object of logics, but rather of informal logics or, under a different perspective, semiotics. In fact, the way in which functions are projected onto physical structures resembles the process of attribution of meanings to signs, or semiosis (Eco, 1990, Morand, 2004; see Peirce 1878; 1901).

This conclusion is consistent with developments in artificial intelligence applied to engineering problems. Only trivial problems of routine design can be completely automated. For advanced tasks, automation is always partial and is reduced to well known portion of the process. Finally, there is no successful experiment in the automation of concept design (Sriram, 1997).

Another way of formulating the same idea is that design is a NP-hard problem. There may be approximately optimal algorithms to solve well defined types of design problems, but a general algorithm which is able to produce optimal design algorithms does not exist at all.

The literature in cognitive science has examined design activity as a particular form of complex problem solving. Problem solving may refer to well structured problems (e.g. algebra problem or chess game) or ill-structured problems (Newell and Simon, 1972; Dorner, 1977; Newell, 1990). Design is an extreme case of ill-structured problem solving, in which the statement whether the system is in the final state and the problem is solved (i.e. QED in algebra, or killing the king in
chess) is not well defined. At the same time, design is also a very information-intensive and computationally demanding activity, because a large number of alternatives must be explored (i.e. generated and tested) (Goel and Pirolli, 1992; Gero and Maher, 1993). In this type of activity, a general finding is that the performance of experts is largely superior than novices. Experts are able to move iteratively back and forth between functions and structures, and up and down the product hierarchy, much more rapidly than novices. In addition, due to the hierarchical nature of the two spaces, the feasibility of any given product innovation requires the exploration of the complete function tree. While the design work on product components is usually done in the detailed design stage, expert designers are usually able to identify the possible bottlenecks very early in the conceptual design stage. Although there is a significant tradition that addresses design as a form of expert problem solving, it is true that this literature has given important contributions to well-structured problems, but has failed to identify regularities in ill-structured problems.

A less structured approach, is based on the notion of wicked problem, as proposed in social planning (Rittel and Weber, 1984; see also Budgen, 2003). Wicked problems are such that a solution to one of its parts simply changes the nature of the problem. In Herbert Simon’s terms, these types of problems are non-decomposable. These problems are unique, have no definitive formulation, have no stopping rules, have no immediate and ultimate test of a solution, and do not have an enumerable (or an exhaustively describable) set of potential solutions. This characterization clearly applies to conceptual design and to design processes oriented at radical innovation.

Having firmly established this point, we are lead to ask whether there are still regularities in the way in which mappings are realized. In other words, how is the new mapping generated?

This question has fully addressed by a research tradition centered around TRIZ (Theory of Inventive Problem Solving), a methodology invented by Soviet scientists on the basis of a systematic scanning of several million patents and popularized in 1991 by the US company Invention Machine. This methodology proposes up to 40 Inventive Principles (essence of ideas in inventions) and 76 Inventive Standards (standard solutions corresponding to various situations) (Cascini, 2005). Simplified versions such as USIT (Unified Structured Inventive Thinking) use 32 solution generation operators (Nakagawa, 2004).

These methodologies can deliver a uniquely useful contribution to managerial processes of product development. However, they suffer from a common limitation: they require a very long learning curve to be implemented. In practice, one should be able to formulate explicitly all problems at a very detailed way in order to apply inventive principles or standards, or to apply formal problem solving techniques. This is not consistent with the way individuals reason in the fuzzy front end, in which ambiguous formulation, vague ideas in natural language and raw sketches dominate the representation. Secondly, these approaches do not support a distinction between radical and incremental product innovation. In order to do this, some notion of distance in the search space should be introduced. According to the scheme stylized in Figure 4, a radical innovation is one in which either (a) a given function is mapped in a region of the structure space distant from current mappings, or (b) a new function (i.e. a function in a region of the function space distant from current functions) is mapped for the first time. On the contrary, incremental innovation takes place in regions close to the points in both spaces linked by the current mappings.

Intuitively, these definitions make sense. In order to make them more rigorous, it would be necessary to establish metrics for both function and structure space, which is our current research interest.

Before reaching this point, however, it is interesting to examine which cognitive strategies may lead innovators to search in regions that are distant from those where they have most experience. In other words, it is useful to identify a few general and robust cognitive strategies that may support the exploration of distant regions. These strategies are not simple events of problem solving, or
solutions tools. Rather, they are cognitive orientations or attitudes, that motivate, support and guide the difficult activity of search in distant regions of function and structure spaces.

3. Innovation beyond problem solving

3.1 Counterfactuals

The creative activity involved into mapping points from one space to the other is cognitively very demanding. This is even more so if search is not confined in the region close to existing and working mappings, but extends to distant regions, either in the function or in the structure space.

It is important, looking at Figure 3, to note that what we observe is usually only one mapping, that is, the realized mapping embodied in a given artifact. The fact that the relation between structures and functions is not isomorphic is in sharp contrast with this common sense experience. In fact, our experience is only a tiny fraction of all the admissible mappings.

A realized mapping embodied in an artifact is the outcome of a selectional process in which several competing mappings have been materially or conceptually tested, and only a few survived. Thus any object can be seen as the final point of a natural history that takes place within a many-many potential mapping. That is, objects would be subject to a classical variation-selection-retention cycle (Campbell, 1960), at the end of which objects are fine tuned with desired functions. The whole mapping possibilities are accessible only upon historical reconstruction, or rigorous counterfactual reasoning.

This is particularly true for everyday objects. What we observe in everyday life is a fixed association between structure and function, that appears obvious and does not require conscious inference and categorization. A chair is immediately perceived as something on which one can sit. For the same reason, all objects that share the same characteristics of “being adapt for sitting”, like a bed, are naturally perceived as similar to chairs, even though they are not members of the same object category. This gives them the important property of affordance- people find it natural to associate a function to an object because its physical constitution invites, or affords, a specific use.

The property of an object to show immediately its potential uses was first discussed by the psychologist James J.Gibson (1977; 1979). The affordance of an object is the set of real or perceived properties that determine the way it can be used. The fact that objects are repetitively used in everyday life confers to them a natural association with their possible uses; in this perspective a good design is one that gives users the most natural material and cognitive affordance (Norman, 1988; 1992; Molotch, 2003).

Affordance has enormous economic advantages. First, it helps to economize on cognitive resources in everyday life. We need to assume, in daily life, that each object has just the functions that are ascribed to it by everybody, in an intuitive way. Should we ask each time whether any given object is the best way to implement its functions, or whether these functions might be implemented by different objects, our life would be impossible to live. If we had to start all our days by asking which are all the possible structures that can implement a shaving function before deciding to use a razor blade, our life would be a little bit painful. We do not usually think to counterfactuals. Second, it allows better communication and coordination among users. If we find a Black and

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6 The need for counterfactual reasoning is an element in common with abductive reasoning in situations such as criminal investigation. Here we know the final outcome (a killing) and we need to identify the causal agent (the killer) among many possible and plausible agents, without the help of deductive reasoning. The (potentially infinite) series of causal chains leading to the final outcome can only be reconstructed via counterfactual reasoning, testing them against available evidence. See on these issues the classical discussion of Sherlock Holmes in Eco (1990); see also Gustafsson (1994).
Decker under the Christmas tree, it is unlikely that the intended goal of our wife is to kill our boring neighbour.

Exactly for the same reasons, radical innovation is difficult. Innovation starts by breaking this strong association, and working on both sides of the open relation- what other functions can be implemented by this structure, what other structures can implement this function. However, this breaking (well known in the literature on creativity under the name of breaking of functional fixation or rigidity) is not the whole story. This literature has clarified a difference between expertise and innovation. The former translates in better performance in solving problems within given classes, the latter involves solving unknown problems. We go beyond this distinction and focus here on a particular case of creativity- the ability to conceive radically new products and services and to map successfully complete functional trees onto structural trees. We are not talking of creativity as production of new ideas, but production of new mappings.

As we shall see, from a cognitive point of view the important point is that innovators try to keep in mind- individually or organizationally- a large number of potential mappings. Their working space is not restricted to the actual mapping and its neighborhood. They are able to build mental representations that, at the same time, have high degrees of operational precision, but incorporate counterfactuals. They are able to work iteratively, moving from the consideration of radically alternative solutions down to details of selected mappings and then back to analysis of alternatives.

Because this is cognitively extremely demanding, innovators follow some search strategies that give promising results without forcing to explore all possible solutions exhaustively. These search strategies are based on a common feature- they allow the exploration of the function space at an abstract level. All engineers and designers are able to work in the structure space given a functional requirement, mainly by exploring the regions close to existing mappings. Radical innovation requires the exploration of distant regions in the structure space. But it would be impossible to explore the structure space extensively, as well as to select promising regions by random search. Something else it at stake.

3.2 Search in the function space

We propose that search in the structure space for radically new solutions is guided by a parallel search in the function space, i.e. an intentional activity of representing the general characteristics of functions and the constraints associated to them. Search in the function space is not immediately aimed at obtaining a specific solution for a given problem, but preliminarily at understanding the classes of admissible solutions. Given the hierarchical nature of the function space, search goes up and down the functional hierarchy.

It is search in the function space, as different from search in the structure space, that gives origin to radical innovation. The latter involves searching for solutions to known problems- indeed, it is a form of ill-structured problem solving. The former involves abstract knowledge of classes of admissible solutions. It may be activated by specific problems, but is also motivated by the discipline of scientific categorization and generalization, as well as by personal and intimate knowledge of a large number of design problems by creative engineers and scientists, and even by personal obsession of entrepreneurs.

It is search in the function space that makes it possible to search in distant regions. If exploring distant regions would be left to individual risk taking under conditions of random search, it would not be pursued, or would be extremely rare. On the contrary, radical innovators are led to explore very distant regions following conjectures generated by their search in the function space, including the possibility of totally new functions.
From the economic point of view, the key point is that search in the function space enormously increases the effectiveness and efficiency of search in the structure space, and ultimately of the innovative process.

In this perspective, search in the function space (and then radical innovation) is no longer an example of problem solving, be it ill-structured.

The degree of novelty of an ill-structured problem can be described with respect to two dimensions: the problem domain and the repertoire (Newell, 1972; Newell and Simon, 1990). The problem domain describes the nature of the problem solving, or its semantics. A domain may be totally new for the problem solver, or have some similarity with known domains.

The repertoire is the cumulated and collective set of rules or procedures that have proved successful in solving particular problems. It is stored in individual memory, as well as organizational and collective devices. In addressing a new problem the problem solver may utilize the existing repertoire or add new rules. Any time a solution is found using existing rules it reinforces the repertoire; any time the repertoire fails to deliver a solution there will be some search activity to add new rules. In the specific context of design problems, the repertoire of solutions is formed by validated engineering principles and the cumulated design knowledge, that is, the mappings that have proved to work.

We propose that radical innovation takes place when innovators abandon the current status of either one or both of these classical dimensions of problem solving. When both problem domain and repertoire of solutions are new, we are no longer in a problem solving situation.

![Mapping repertoire](image)

### Figure 5 A taxonomy of search strategies in radical product innovation

4. Search strategies

Based on the above discussion we introduce the general heuristics used to generate incremental innovation (local search) or radical innovation. We propose a simple matrix to represent several search strategies (Figure 5). Instead of entering into a detailed discussion of individual design rules (such as the inventive principles or standards of TRIZ) we suggest a simple but powerful characterization of general heuristics, or rules for search in the function space.

4.1 Local search or improvement
When the problem domain is close to the existing one and the repertoire is the same, we do not have radical innovation, but rather Improvement. In terms of the structure-function framework, this corresponds to local search in the regions close to the existing mappings. This may take place by exploring slightly different technical solutions in the structure space, or extending locally the required functions in the function space. From a cognitive point of view, the search strategy associated to incremental innovation is not extremely demanding, because successful rules are applied to domains that are similar to those already experienced. Expertise is all that is required. In this case expertise and creativity are often not distinguishable.

Local search is guided by the intrinsic features of both function and structure space and as such does not require cognitive capabilities of the higher order. Once a successful mapping has been found, it is often the case that the physical configuration of the structure can be modified incrementally and locally. As an example, if physical structures have different sizes, one can try systematically all size variations in order to accommodate functions more finely or in a more effective or efficient way. Or the extension of conditions for the mapped function simply tells what sub-functions must be implemented. This type of search is dictated by the need for satisfying the intrinsic dynamics of conditioning, that is, adding new conditions to the functional requirements.

This type of innovation is very frequent. It has large economic value, because it may generate families of products that extend the life cycle of radically new design and allow the capture of large streams of profits. Product extensions, product families, product portfolios are all included into this category. Many of the TRIZ inventive solutions fall in this category.

No abstract search in the function space is required here.

4.2 Recombinant search

Incremental search does not require the shift from the current mappings. Search takes place in the neighborhood of existing mappings and therefore capitalizes on validated knowledge. Radical innovation, on the other hand, requires the exploration of new regions in the two spaces: new functions and new structures. How can this search be guided, given the large cognitive complexity of the activity?

An important heuristics is Recombination, that takes place when existing solutions in the problem domain are assembled in a novel way. Recombination is not a simple combinatorial activity, that takes place more or less randomly by testing the potential for combining existing mappings. Recombination takes place in the function space- existing mappings are examined in terms of their functional content, and different functions are put together in an innovative way. This enlarges the repertoire of solutions, even though the problem domains remain the same.

Recombination takes place in several ways:

- integration of several functions, once provided by separate objects, into unitary (usually more compact, or less expensive, or lighter) objects;
- addition of new functions (often radically new), once not associated to the principal object;
- redistribution of functions across product components or systems of products (architectural innovation): functions once dispersed across separated elements are concentrated, or viceversa; functions are distributed differently.

The degree of innovativeness resulting from recombinant search is highly variable, from modest to very significant. Box 1 presents some examples.  

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7 In the following boxes a blend between information on largely international known companies and brands, and on niche players is carried out, the latter also using unpublished materials from interviews and personal communications.
The notion of recombination is not new, of course. In *The wealth of nations* Adam Smith suggested that the ability to combine productively ideas drawn from different fields is typical of great men, and particularly of philosophers. The idea that recombination is a significant part of innovative processes has been repeatedly suggested in the literature (Zander, 1992; Kogut and Zander, 1996; Langlois and Robertson 1996; Hargadon, 2003). According to this literature, large companies have the capability to combine and recombine existing technological knowledge stored in their organizational memories. It is also well known from the TRIZ literature that a significant part of technological knowledge as embedded into patents is in reality a combination of previous knowledge. If one interpret the claims of patent application forms as describing a design principle, it is actually a way of representing a proposed mapping, although it lacks many details and refers to a limited portion of the entire functional tree.

We add to these contributions a number of important qualifications.

First of all, productive recombinations do not take place in the space of structures, but in the space of functions. Let $\Phi$ be the mapping of function $F_1$ on the structure $S_1$, and $\Pi$ the mapping of function $F_2$ on structure $S_2$. Both mappings realize their intended functions. Recombinant search begins by asking whether a combination of functions $(F_1, F_2)$ is interesting, and then proceeds by testing whether the two mappings might be combined together.

This gives an idea of the potential scope for a systematic collection of cases. The current exposition obviously suffers from over-sampling from Italian companies.
1. The i-Pod introduced by Apple revolutionizes the distribution of music. Pieces of music are downloaded from the Internet by paying a small fee and are stored in the device, that has a huge memory. A powerful battery allows the i-Pod to be used for a long time. An ergonomically friendly interface makes it possible to hear whatever sequence of pieces, and even to select random pieces. The i-Pod combines several existing technologies and an advanced concept of Digital Right Management in a highly innovative way.

2. The Echelon technology drastically changed the notion of control. The usual architecture of a control system is based on three separate subsystems- sensors, data processing, actuators. Since data processing requires the integration of information from various sensors, it used to be allocated to a computer (or an embedded software), physically separated from sensors and from actuators. The innovation introduced by Echelon allows all these functions to be implemented by an intelligent chip, that processes information and controls the actuation directly. This may be used for home automation, remote control, energy management and other applications. It required more than ten years to persuade users to adopt the new control technology.

3. In the industry of medical equipment for oftalmology a complex technology is used to throw light into the patient eye and collect data on biological parameters of cornea. Previous generations of equipment provided only analysis of data on a screen, that should be interpreted by the analyst. In order to store the data in a memory a complementary computer was needed, with appropriate interface. In order to print the results, a further peripheral was needed. While most producers worked hard in order to fine tune all these separate elements, following local search around the dominant mapping, ET Electronics introduced a new equipment that combined diagnostic, presentation, data storage, data analysis and printing functions into a single body. All components and interfaces are standard, removable and scalable, and the whole geometry has been deeply modified in order to accommodate the integration.

4. A new piece of furniture is gaining success in European markets, from a line product labeled Multi Pot, produced by Rotaliana. It is a opalescent vase with an internal lamp, that serves as a light and a beautiful furnishing element. In addition to that, on the bottom of the vase several sockets for plugging electric devices have been inserted. They can be used for recharging mobile phones, or PDA, or other portable devices. It combines aesthetic, illumination, carrying and electrical recharging functions into a compact design.

5. One of the problems in the distribution of soft drinks through vending machines is that different products have highly variable consumption patterns over time, so that provisioning is inefficient. Since vending machines are scattered around the territory and are located in urban environments, it is not possible to fill them frequently in order to eliminate shortages. A new concept has been developed by IBM. Products in the vending machines are stored in alleys that include a sensor. The quantity of products stored is registered and transmitted through a wireless technology to a database. A software is used to optimize the provisioning logistics. After the initial use of the new vending machines, distributors discovered that the database contained information of value to marketing services of large mass food producers, particularly on geographic segmentation and seasonal variability of demand.

6. The Sassicaia wine story. Around 1970 a noble from Piedmont married a Tuscany women from Castagneto Carducci, close to Livorno and moved in the countryside. He was fond of French wine. He then decided to import some small French vineyards for his pleasure and personal consumption. He then discovered that blending wine from the imported vineyards and local one could produce new flavors. Initially the combinations were not at all perfect. Peasants strongly resisted the combination, because French vineyards are smaller and require a different workers’ attitude for picking up grapes. Also wine tasters resisted. After 10 years of wine tasting with friends, a famous cook discovered the wine and found it irresistible. He promoted it worldwide. In the ‘90s it won the World Award as the best wine. It is now sold at more than 200 euros per bottle, depending on the vintage.

Sources: (1) Wired; Business Week; Newsweek, various issues (2) Thoma (2006)  (3) (4) Company websites  (5) IBM promotional material  (6) Personal communication of experts

Recombinant search does not simply combine structural elements. It is not simply searching in the space of physical parameters, but is the careful combination of mappings, i.e. of realized pairs of points in the two spaces. As such, it requires knowledge of both spaces. In practice, it is possible that a new mapping may be generated by the mere combination of physical structures, such as in Lego construction. But from the cognitive point of view even this combination is in reality based on the knowledge of functions performed by construction units, or assemblies of units.
Further, the combination of two mappings is not a trivial one. If it were, the mappings would already be part of some known function. Thus recombination follows a fundamentally different dynamics than conditioning, i.e. the progressive mappings of sub-functions dictated by the original mapping and by the adding of conditions for behavior.

Second, the creative combination of existing mappings may, in fact, generate completely new functions. The distributor machine case (case number 5 in Box 1) illustrates this point. Combining sensor, wireless and database technologies in the provision of beverages created the room for a completely new (and perhaps unexpected) function, i.e. the production of market information. This pattern is more general. Combining existing functions, mapping the new combination on the physical space and finding new effective mappings may open the way back to radically new functions. Thus radical innovation may arise from iterative paths back and forth between the two abstract spaces. As such, recombinant search may depart, although only partially, from traditional problem solving.

4.3 Analogical search

Recombinant search discovers new mappings using existing solutions in similar domain problems but combining them in creative ways. Analogical search identifies mappings between structures and functions that can be applied in different domains. A few examples are offered in Box 2.

Analogical search is defined by Polya (1945) as a general heuristics for solving problems. It requires the identification of a common deep structure between two apparently dissimilar problems. From a more procedural point of view, the two problems are not already available for comparison; instead what is required is the search for a problem that has the same deep structure of a problem at hand. In our case the heuristics identifies in the problem at hand a structure of the mapping which is similar to other known mappings. Similarity does not relate to either functions or physical structures, but to the way in which the mapping is arranged.

Analogical reasoning is a classical and largely explored field in cognitive psychology and cognitive science since long time (Dreistadt, 1969; Dorner, 1976; Gentner, 1983; Finke, Ward and Smith, 1992). A fruitful analogy identifies the deep structure of a problem or situation, below the surface of semantically different objects. Because individuals tend to process information differently due to variations in framing or semantics, the identification of fruitful analogies is a very challenging task (Holyoak, 1977; Gick and Holyoak K.J., 1980; Holyoak and Thagard, 1989).

To this general difficulty one has to add a more specific reason. Because F and S do not have isomorphic or homomorphic structures, the search for analogies is a very painful one and is subject to many mistakes. In general, since devising an insightful analogy is extremely difficult, it is considered the result of ingenuity and creativity.

A sub-class of analogical search makes use of antonymous concepts. Instead of searching for solutions to problems that have a similar deep structure, one might search for solutions to opposite problems, or problems that have an opposite functional structure. In most cases this does not lead to feasible solutions, but when a solution is found, it is generally highly creative. Looking at opposite solutions, in fact, usually involves a deep redefinition of the design problem, as it evident in the cases of UPS/DHL and of low cost airlines (see Box 2). This search may be also labeled negative analogy.

With regards to analogy, there are also important limits to mention.
Box 2

Analogical search in product innovation

1. Nike created a Department for creative solutions. One of the missions of the Department was to search for technological solutions in completely different fields. The underlying logic is functions: trying to discover similarities in functional problems in various fields. One of the products for which this approach has proved successful is the backpack for children. The main problem in this product is the ability to carry out heavy weight without damaging the posture of children. A careful ergonomic study revealed that this depended on the ability of the structure of the backpack to distribute mass and weight across the muscular area, and to alleviate regions of stress. The same functional problem is addressed in a drastically different field—the design of ejectable seats in fighter aircraft. Here the main problem is how to distribute the tremendous pressure generated by the explosion over the muscular regions without producing damage. Drawing a fruitful analogy with the problem of school backpacks, Nike has started to study and produce expandible tissues once used in aircraft applications.

2. Commerce Bank is an extremely successful bank based in New Jersey. Its innovative approach to retail banking was based on the idea that a bank outlet should not be seen as a financial services office, but rather as a shopping experience. The right analogy for a bank should be the attractive retail outlet commonly found in shopping centers. Based on this notion Commerce Bank started to redesign all interiors, emphasizing colors and attractiveness. Opening hours were changed in order to allow customers to visit branches on Saturdays afternoon. The branch layout was modified in order to give room to children, special toy machines were installed for them, and large parking areas were built around the facilities. Waiters were introduced at the entrance, in order to make people feel comfortable and avoid mistakes in addressing boxes. The result was that families started to visit branches over the week end, experiencing an exciting shopping atmosphere. All operational procedures were designed to minimize obstacles to customers and to reduce processing times. Sales and profit margins soared.

3. Baraclit is a medium-sized company specialized in prefabricated constructions. They developed a large family of components to be used in large constructions projects, often in foreign markets. Following an expansion process, the company acquired a small company specialized in a traditional, Tuscany-based construction material, called “cotto” (cooked). This is a difficult-to-produce and difficult-to-install material, made in thick, heavy and rather expensive bricks of natural matter. The market for cotto was stagnating, in part due to these difficulties of installation and to cost. Baraclit asked whether the cotto could be treated the same way as more conventional construction materials. This required a deep change in the way the product was conceived and engineered. The traditional brick technology has been abandoned, and thin layers of cotto have been deposed over a structural stratum of composite material. In this way, large prefabricated sections of grounds can be manufactured and sent to distant markets. Installation is easy and cheap, and does not require highly qualified manpower. This turned out to be a large success, leading to a surge in foreign orders.

4. The ancient family of Sella, who gave origin to the famous Minister of Finance of early Italian State, Quintino Sella, had a deep knowledge of photography. In XIX century one of the members of the family was the most famous photographer of mountains and alpine expeditions of the time, and author of a classical book. One of the difficulty of good pictures was how to make the color to be fixed on paper. Mastering this technology greatly improved the quality of pictures. Photography was, of course, a small business in terms of sales. In the same period, however, the large textile industry was fighting against a similar problem. Knitwear had poor quality because colors vanished when exposed to water. The Sella family started a great industrial tradition by transferring solutions from photography.

5. The US Post Service was traditionally managed under a monopoly with a public goal of serving all cities and areas in a uniform way (universal service). This led to consider accessibility to the service as the main functional requirement, and time to delivery as a subordinate goal. The entry into the market by UPS (ground delivery) and DHL (air delivery) drastically changed the landscape. These companies assumed time to delivery as the overall function and looked at sectors different from mail services, in which this function was implemented successfully, such as food logistics and military supplies.

6. The entry of low cost airlines is another example of negative analogy (search for opposite). While all the airline industry was taking for granted that cost of flight was impossible to reduce significantly, Ryanair started to assume it as a challenging constraint and searched for all solutions that could drastically cut all operational costs, mainly in other industries.

An important source of limitations for fruitful analogies is the fact that physical structure are not invariant to scale for many physical variables that are of interest in engineering applications. For example, the behavior of aircraft below and beyond sound speed is subject to fundamentally different phenomena, although the underlying physical variable is a continuous one. Analogies from solutions developed at Mach 0.8 cannot be applied at Mach 2.

Limits of analogies dictate the way in which competencies are constituted. As an example, both aircraft and space technologies deal with flying objects and solve the same general functional requirement. However, the lack of physical analogy in the behavior at different speeds involves a radically different set of structural solutions in the two fields. In practice, the two professional communities are separated.

The more distant (in the sense defined above) the functions incorporated in the new product or service, the more radical the innovation.

4.4 Search by abstraction

Innovation by recombination and by analogy are not new. They received lot of attention in the literature. We suggest a new category, that involves change in both problem domain and repertoire, and cannot be conceptualized as problem solving. Rather, it is entirely based on abstract search in the function space, as independent from particular problems at hand. We label it search by abstraction.

By abstraction we mean the explicit representation of all abstract conditions for a function to be implemented by any mapping. In search by abstraction there is not a test of a particular mapping, but rather the delineation of the general and abstract properties of any physical structure for them to possibly be mapped onto the function. These properties can be written in mathematical language and refer mainly to relations, rather than to specific quantities. Thus abstraction is not design, since it leaves unresolved the question of the precise mapping. But it has a tremendously powerful effect, which is to identify the class of admissible mappings and guide further search.

Search by abstraction in the function space is not motivated by a particular problem, but rather grows by generalization on abstract mappings. In some cases it is driven by the scientific understanding of underlying conditions for new mappings, as codified in engineering science disciplines. In other cases it is driven by scientific discovery, that may open the possibility of new functions. Yet in other cases it comes from entrepreneurial persistence in searching a solution for a completely new problem, defined in abstract terms.

Abstraction is a difficult but powerful cognitive strategy. It is based on the independence of functional representations from structural representations in human beings, but it requires an extraordinary determination to be carried out. In fact, the literature on engineering design suggests that designers do not love to reason in functional terms, but prefer to work directly on structures. Even more problematically, individuals are not able to keep several representations in parallel in their mind. Being able to think functionally for long periods, and to maintain several representations in mind is not a common attitude.

Several episodes in the history of technology and in product innovation confirm the importance of abstraction. See Box 3 for a few examples.

What is clear from these stories is that search in the neighborhood of existing mappings (e.g. around the basic geometry of conventional fighters in the case of Stealth, minicase no. 2), would have never led to the solution. On the other hand, random search would not allow a jump in a totally different region in the structure space with high probability. Or, if it happened by chance, it would never support the search around that region for long time. It was abstraction that allowed the team
to map the stealth function on a completely different regions and to persist in searching for the solution even against skepticism and unsuccessful initial trials.

Box 3

Search by abstraction in product innovation and history of technology

1. According to historians of technology, aircraft design was characterized by a long series of efforts by many talented amateurs, which however marked little progress in the maximum length of flight. The Wright brothers were able to produce a performance jump in a few years. The main point is that the Wright conceptualized the problem of flight from an abstract point of view and discovered that the two traditional functions of stability (i.e., the airplane should not break down or stall) and thrust were not sufficient. In order for the flight to be realized, a third abstract functions should be developed: i.e. control. Controlled flight was the key for the solution. For control to be implemented, however, the relations between mass and weight of the fuselage, position of engines, and control surfaces, had to be entirely redesigned. The reconstruction of Wright’s drawings and notes shows that they were aware of the deep design problems associated to this idea, although they lacked a formal engineering education. Their calculations and sketches were oriented towards the solution of an abstract problem, before turning to any realized physical implementation.

2. The goal of designing fighter aircraft that could avoid radar detection had been prominent in military technology since World War II, but had always defeated the best minds. When a contract was awarded to Lockheed for the development of a stealth fighter, a small group of engineers and scientists was created, under the most complete secrecy, which after many years produced the astonishing diamond-shaped black aircraft. After a period the director of the program published a non-technical account of that experience, which produced one of the most advanced results in flight technology. How was that the shape of the stealth so markedly differ from the one of conventional fighters? Most of research in the past had addressed the problem by refining the basic geometry of fighters, trying to reduce the detectability in an incremental way. In the team at Lockheed, a physician went through a paper of a Russian mathematician, recently translated into English. The paper was a mathematical treatment of the problem of minimization of reflection by bodies of whatever geometric shape. In developing the general conditions for any body to reduce detectability, it came up with the idea of diamond-like shapes. That discovery was a shock for the director, since no one had never designed a plane with that geometry. By persisting into this direction and defeating all skeptical views, the team was eventually able to develop the Stealth.

3. The invention of shoes that allow the transpiration of feet has introduced a remarkable dynamism in the footwear industry. The founder of Geox, Mauro Moretti Polegato, arrived at the invention after a long period of incubation. His obsession was to find a material with asymmetric properties with respect to water: let the vapor from natural transpiration of feet move away from the shoe, but not permit water to enter the shoe. In abstract terms, he was searching for a thin material with appropriate microscopic diameters. He went around for many types of materials, until he was able to develop a membrane with this property. Geox is now claiming they want to become world leader in leather shoe production. Total sales in 2007 will probably be close to 1 billion euro.

4. Starbucks drastically changed the way in which coffee is distributed, by building a whole new customer experience around it. It is designed around the notion of what a consumer would like most from a coffee, and it includes free space, no limit to time of stay, wireless computer access, and music distribution. Quite a different technology than just coffee.

5. Technogym has invented the business of wellness moving from conventional sport equipment. The innovation started from asking what would be the conditions for expanding the use of sport equipment beyond young performing people, following the general idea that everybody should have it. It led to developing new equipment, that changed the speed according to the parameters of the user, could be installed easily at home and not in dedicated gyms, and had not the appearance of sanitary machinery.

6. Maltese Falcon is an astonishingly beautiful sail boat with three high trees, produced by Perini Navi. The most remarkable feature is that sails are not visible but are hidden in the horizontal composite structures of trees. Sails fall down from these structures, entirely controlled by electronic actuators, instead of being pulled up with ropes. The main idea behind this boat was that not a full sailing team, but just a single individual should be able to maneuver and control the boat. This true obsession led the entrepreneur Fabio Perini to search for solutions that could make this possible.

7. Fluidodynamics and aerodynamics have provided since a longtime precise conditions for optimal design of airplanes. Long time ago, the great aerodynamicist Prandtl predicted that an optimal shape would have been very different from conventional airplanes, having wings tilted and connected on the rear, rather than orthogonal to the main axis of the body. He did not produce a proof of this statement, but researchers have now...
demonstrated that, indeed, the optimal abstract shape is Prandtl-type. Small manufacturers are starting to explore this concept and large constructors also have research in the field.

8. Bacteria meningitis of Type B had traditionally been difficult to fight, because researchers have for a long time been unable to identify, using biochemical techniques, molecules that can be used in a vaccine against all strains of the bacterium. Chiron Corp. radically changed the search strategy. Working in collaboration with the Institute for Genomic Research and using automated gene-sequencing machines, they decoded all the genes in the Type B bacteria, in excess of 2,000. Then they used high-speed computers to identify 350 new genes that coded for proteins on the surface of the bacteria. Finally they identified 7 candidate proteins that seemed to stimulate an antibody response capable of killing the bacterium. According to Rino Rappuoli, head of vaccine research at Chiron, “We have made more progress in the last 18 months than in the previous 40 years”.

9. Search by abstraction is also found in software design. E-ticketing in air travel, universal product codes and 800-number-based conference calls all originated from changes in the abstractions embodied in the underlying software. According to an authoritative approach to software design, in the field of software abstractions include declarations of the sets and relations, facts, and assertions. Important changes in software programs take place at this level, not of concrete writing of lines of code.

The same argument applies for the other cases: for example Moretti Polegato explains that he was obsessed with the problem of finding a material that would permit asymmetric flow of liquids: preventing water from entering the shoe, but allowing sweat to transpire out. Fabio Perini was searching for a design of a boat that could be maneuvered by a single individual, a bizarre requirement indeed.

In other cases, such as the Prandt-plane, the meningitis vaccine, or new software abstractions, radical innovation is originated by a planned search in regions of the structure space that are very far from those currently practiced by technical communities, on the basis of existing mappings. This search is dictated by an abstract representation originated in scientific knowledge, sometimes embedded into a mathematical formulation. It is important to underline that these representations, being based on causal models and not on abductive reasoning, do not provide directly the design solution. Science does not substitute for engineering. However, in these cases the search for design solutions in highly improbable regions of the structure space is made possible by an overall abstract representation.

Abstract innovators are much more than problem solvers. While recombinant search and analogy have repeatedly proposed in the literature as useful heuristics, search by abstraction is a completely new category, that deserves further conceptual and empirical exploration. And while recombination and analogy can rely on some existing knowledge of the domain or the repertoire, and are then less demanding, abstraction is cognitively extremely difficult. We suggest that abstraction is the most productive strategy to generate new functions, or real novelty. Recombination, analogy and abstraction are in ascending order of difficulty and impact, and in descending order of probability.

5. Implications and further research

We have presented a theoretical framework for characterizing cognitive strategies that may lead to radical product innovation. The framework is based on a conceptual reconstruction of various streams of literature and offers some useful insights for innovation. The paper gives contributions in different directions.

With respect to the fuzzy front end of conceptual stage, the paper helps to qualify two categories often used in the literature on creativity and product development (recombination and analogy) by placing them in the appropriate cognitive space. This may explain why simple creativity techniques
often fail to produce the expected results. These techniques take ideas, or solutions, as the building blocks and suggest how to manipulate them in brainstorming exercises. A common limitation of these techniques is that many ideas are produced in a smooth way, but very few of them have value. A strong implication of our approach is that creativity techniques should be explicitly applied to the search in the function space, not to ideas or solutions. Searching the function space is enormously more difficult. Individuals may generate many new ideas quite easily, but have difficulty in thinking in abstract terms for a long time. Representing explicitly the function space would greatly improve the impact of creativity techniques.

Second, in addition to recombination and analogy, already discussed in the literature, it proposes a new category (search by abstraction) that is extremely powerful in supporting difficult migrations from consolidated regions of knowledge to radically new mappings. This category may help to explain several puzzles in the theory of technological innovation, such as the punctuated equilibria dynamics of change, suggesting the origin of out-of-equilibrium discontinuity. At the same time it may give insights on the ability of companies to anticipate change by maintaining representations that are far from those currently employed in strategic management. Exploration does not take place cumulatively, or at the opposite, in a totally random way. The insight here is that what you need is a sufficiently abstract representation to explore in distant and improbable regions of the space, while keeping existing mappings for profitability.

Third, the broad heuristics identified may have interesting counterparts in problems of organizational learning and knowledge management. Our categories are complementary to the more commonly used categories of tacitness/codification, or exploration/exploitation. Incremental innovation makes use of existing domains and repertoires, and then does not introduce conflicting principles in the organizational structure. Recombination and analogies, on the contrary, are based on tensions in one of the two dimensions, that call for new organizational solutions and for a sound managerial justification. From a cognitive point of view, they introduce inconsistency. Building up new metaphors, images, or reference models is a way to manage these tensions. Still more complex is to manage radical innovation in the context of a powerful abstraction. Here the cognitive distance is very large. Perhaps the entrepreneurial mechanism is the only one able to support such a discontinuity, as sometimes suggested in the literature (Salavou and Lioukos, 2003).

Fourth, the conceptual framework is open to extensions in the domain of marketing science. Radical innovation involves the introduction to the market of objects that do not fit into existing perceptual and mental categories of customers. The cognitive psychology of categorization has shown how difficult can be the change of mental categories, as shown also in the new product literature (Veryzer, 1998; Seiden, 2007). Adding novel functions, or radically changing the bundle of functions of products may involve significant effort to build new categorizations. The more abstract the innovation, the more difficult this process.

The conceptual categories proposed in the paper are supported by illustrative cases. No effort has been done at this stage of the research to build a large sample of cases or to look for validity. Further research is needed to validate the framework, to explore its robustness and comprehensiveness, possibly to include other phenomena such as serendipity.

The papers does not try to make explicit all the potential links with the literature on strategic management of innovation, product innovation management, organizational learning and economics of innovation. As a matter of fact, many of the concepts recently introduced in these fields have a clear counterpart, that deserve a dedicated effort, in the cognitive analysis presented in this paper.

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8 This is what we have done by building a large functional base, with approximately 5,000 functional verbs, each of them organized in vertical lines (abstraction- instantiation, or father-son) and horizontal lines (synonymous-antonymous). The base has been built by using advanced lemmatization techniques applied to a large sample of technical documents and covers all functions in the mechanical and electromechanical fields. It is currently used for managing sessions of creativity in the conceptual stage in a variety of industries, as well as for fundamental research purposes. A very powerful use of the functional base is allowing the systematic examination of synonimous functional expressions (design by crossover) or of opposite expressions in the search for the productive analogy. Basically all heuristic rules can be implemented in such a base. See Bonaccorsi and Fantoni (2007) for details.
An effort to operationalize these strategies, using for example techniques such as semantic networks, clustering and data mining on functional information could be finalized. Finally, a series of testable propositions might be developed. The research agenda is therefore very rich.
References


