Towards an anticipatory view of design

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Anticipation indicates the capacity to act in preparation for a certain effect or future state of the world. Although the link between anticipation and design has not received particular attention in design research, it is a fundamental one. In the paper we review the concept of anticipation and discuss its meaning for design research. We further argue that in order to develop an anticipatory view of design it is necessary to move beyond long-established paradigms and abstractions such as those of machine, evolution and control. Based on a conceptual and methodological framework proposed by Robert Rosen we elaborate such an anticipatory view that establishes the uniqueness of design compared to these paradigms.

Keywords: design theory, design problems, epistemology, modelling, anticipation

Anticipation is generally associated with the ability of looking ahead (or looking forward), but it also refers to an action or decision that is taken in preparation for some future event. Cambridge Dictionary Online (2006) defines anticipation as follows: 'to imagine or expect that something will happen, sometimes taking action in preparation for it happening'. The Oxford English Dictionary (2006) lists several definitions of anticipation which link it with the idea of possessing or realising something in advance (actually or virtually); taking action that meets beforehand, provides for, or precludes the action of another; but also with a priori knowledge, precognition, preconception, and expectation. Similarly, many different conceptions and definitions of anticipation are found in domains as diverse as philosophy, psychology, cognitive science, biology, and computer science.

In this paper, the meaning and role of anticipation in design is explored. While anticipation has been recognised as an important issue in design from the early years of design research (see for instance Fuller, 1963) it is also fair to claim that there is no general treatment of anticipation in design. In fact, it is a rather ignored topic in comparison to issues such as learning and creativity. The aim of the paper is to motivate the view that anticipation and design constitute a special kind of relation, which we can use to uniquely identify design.

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In particular, the paper proposes an abstract (but precise) construction, which provides a theoretical and methodological framework for exploring the nature of design and its possible interpretations. The value and contribution of this endeavour is that it allows comparisons to be made with other general epistemological frameworks in design research, and helps explore and overcome certain limitations in expressing the nature of design.

In the following, a review of different approaches to anticipation in various fields is offered first so as to highlight central arguments and problems. In the second part, various conceptions of anticipation in the field of design are explored. This leads to the third section where the suggested anticipatory view of design is laid out. The third section uses algebraic notation in order to discuss different paradigms that have influenced design research and demonstrate their limitations. In particular, the section includes an investigation of three concepts: the concept of *machine*, which is generally associated with computational and information processing systems; the concept of *evolution*, which is generally associated with the 'natural' principles of variation, heredity and selection; and the concept of *control*, which is linked to purposeful behaviour. The section further examines how the limitations of these abstractions can potentially be overcome through adoption of an anticipatory paradigm. The paper concludes with a summary and discussion.

1 Approaches to anticipation in various fields

Anticipation is an appealing but also difficult idea, as it seems to violate fundamental principles of time, causality, or construction of abstractions. This is because it implies circularity: how can future states of the world affect present time, or how can the effect of an action determine the action in advance of its realisation? As we will see, this problem is normally resolved by assuming a capacity to construct an implicit or explicit representation of future states, or effects, before the actual realisation of the action that produces them. However, anticipation is not only a time related problem. In the history of philosophy and logic, an abstraction – such as for instance the idea of 'whiteness' – is often believed to be constructed from specific examples (i.e. different whites perceived). From this perspective, anticipation seems to imply the paradoxical capacity to generate abstract ideas without having specific instantiations of these ideas.

So, while the core definition of anticipation seems to be generally accepted, the assumptions about the nature of anticipation vary substantially. For example, anticipation has been defined as a particular kind of dynamics (e.g. Dubois, 1998), as a particular pattern of causal relations (e.g. Rosen, 1985), or as a particular relationship between wholes and parts (e.g. Van de Vijver, 2000). Additionally anticipation has been studied in relation to different types of systems: biological (Rosen, 1985), physical (Dubois, 1998), cybernetic (von

Glasersfeld, 1998), cognitive (Riegler, 2001), social (Leydesdorff, 2005), or artificial systems (Butz et al., 2003a).

Here we will mainly examine the predominant approaches of Rosen and Dubois: Rosen is considered to be the 'father' of anticipatory systems since his treatment introduced the concept in relation to the study, modelling, and control of complex systems, while Dubois reintroduced the concept in the scientific community in recent years. We will also briefly explore anticipation in relation to the concept of agency in cognitive science and artificial intelligence. In any case, we will distil some important arguments for the understanding of anticipation in the context of design, and highlight links with other related concepts such as expectation or autonomy.

1.1 Rosen's view of anticipation

Rosen's concept of anticipation, which has biological roots, is tied with the reinstatement of the 'lost' cause of Aristotelian logic: the *final cause*. Briefly, the old Aristotelian categories of causation (called material cause, formal cause, efficient cause and final cause) constituted four distinct ways of answering 'why-questions'. Material cause refers to matter, the primitive substances or components by which something is constructed; while formal cause refers to the form which these take, the shape or structure of something. Efficient cause refers to the agent or producer of an entity; and final cause refers to the end, the purpose, or function for which the entity comes into existence. We can take the simple example of a hut. The material cause of the hut is the stuff used to build it: straw, clay, wood, etc. Formal cause is the shape of the hut and its structural characteristics. Efficient cause refers to the agent that transformed the materials into the specific form, the builder or designer. Efficient cause may also refer to the procedure, method, or principles by which the hut became realised. Final cause refers to the function that the hut serves, for example to provide shelter from the sun or rain. According to Rosen, explanations of the fourth kind have been excluded from science because they have been taken as a direct violation of the traditional notion of causality. How can the function of the hut, which only becomes realised after the hut is built, become a cause of its creation? Yet, he suggested that finality was the only kind of explanation that could be offered to anticipatory behaviour, which is manifested at all levels of biological organisation, from the molecular level up to the human level.

There are two aspects in Rosen's work worth exploring. The first has to do with his definition of anticipatory systems which profoundly influenced the contemporary understanding of anticipation, and the second has to do with his formal elaboration of a certain class of systems called metabolism—repair (M, R)-systems. The elaboration of (M, R)-systems is considered to be useful here because it offers a formal treatment of anticipation as a systemic capacity. Transferring this to design, we have both a formal expression of anticipation that we can extend for our purposes, and also a methodology that we can use to study design.

1.1.1 Anticipatory systems

In Rosen's view, anticipation is coupled with the ability of a system to contain a model of itself and/or its environment. This ability enables the system to act not only according to its history, but also in response to possible or future states of the world. He gives some examples of systems where the existence of an internal model (whether 'wired-in' or constructed) allows the expression of future states to guide present action. In one such example he writes: '…if I am walking in the woods, and I see a bear appear on the path ahead of me, I will immediately tend to vacate the premises. Why? I would argue: because I can foresee a variety of unpleasant consequences arising from failing to do so.' (Rosen, 1985: 7). People customarily construct models which allow them to predict future situations, or consequences of future events, and on this basis to change their present course of action. But the ability to anticipate can also be found in 'lower levels' of (biological) organisation 'where there is no question of learning or of consciousness' (Rosen, 1985).

Rosen's characterisation of anticipatory systems is built on the coupling between a dynamical system *S* (running in real time) and another dynamical system *M* which is a model of *S*. The idea is that this model can 'go faster' than real time and therefore predict future states: 'by looking at the state of *M* at time *T*, we get information about the state that *S* will be in at some time later than *T*' (Rosen, 1985: 12). This prediction is then used to perform an action at present time. For Rosen, the idea of building and employing predictive models was a fundamental aspect of science in general. His definition of anticipatory systems with its associated premises was hence also intended as a framework for understanding, modelling and controlling (complex) systems.

1.1.2 The (M, R) model

An example that epitomises anticipatory ability is the metabolism–repair (M, R) model. The model aims to explain cell behaviour independently from material substance by adopting functional components as the basic units of analysis. An (M, R)-system is characterised by two fundamental biological qualities or functional components: a metabolic component, which can be represented as a set of mappings that convert inputs from the environment to outputs; and a repair component, which maintains and reconstitutes the metabolic activity. We will delve into the details of this model and the notation used in Rosen (1985, 1991), as these will be utilised to develop an anticipatory description of design in Section 3.

More formally then, let $f{:}A \rightarrow B$ denote a *functional* component of a system that transforms an input A to an output B. In particular f is a metabolic element that takes part in a metabolic network. This transformation or mapping *f* belongs to a larger set of physically realisable metabolisms that the cell can display denoted by $H(A,B)$. In other words, $H(A,B)$ is the set of all possible transformations from A to B. Any process that can generate copies of *f* must have its range in $H(A,B)$: if φ_f is the repair component, then this will be a mapping into this set. Hence the simplest (M, R)-system is given by:

$$\underbrace{\mathrm{A} \xrightarrow{f} \mathrm{B}}_{\text{metabolism}}\ \underbrace{\xrightarrow{\varphi_f} \mathrm{H(A,B)}}_{\text{repair}} \tag{1}$$

Rosen showed that this formalism already contains what is needed for the operation of another decisive genetic component: a replication mechanism. That is, the replication mechanism can be naturally derived by the mappings of metabolism and repair and represented by a mapping $\beta_b{:}H(A,B) \rightarrow H(B, H(A,B))$. The mathematical conditions for the existence of this mapping are nicely explained in Letelier et al. (2006). An abstract (M, R)-system can therefore be expressed by the following diagram:

$$\underbrace{\mathrm{A} \xrightarrow{f} \mathrm{B}}_{\text{metabolism}}\ \underbrace{\xrightarrow{\varphi_f} \mathrm{H(A,B)}}_{\text{repair}}\ \underbrace{\xrightarrow{\beta_b} \mathrm{H(B, H(A,B))}}_{\text{replication}} \tag{2}$$

This is the quintessence of a relational model in that the property of replication is entailed by the metabolism and repair mappings (or functions); it is constructed on the basis of these mappings alone, from the organisation of the system, and independently from any particular realisation of the living cell.

Let us briefly uncover the explanatory attributes of this diagram. For the simple mapping $f{:}A \rightarrow B$, the question ‘why *B*’ can only have two answers: in terms of material cause (‘because *a*’ – the value of *A*) and in terms of efficient cause (‘because *f*’). But *B* has no explanation in terms of final cause – there is nothing to explain *B* by its effects in this diagram, or to endow it with a function (any finalistic answers have to pertain to the external environment of the system). On the contrary, *f* and *a* can only be explained in finalistic terms because of their function in the diagram, that is to entail *B*. By extending the original mapping with the repair component the function *f* is efficiently entailed by φ_f :

$$\begin{tikzcd} \mathrm{A} \arrow[r, "f"] & \mathrm{B} \arrow[r, "\varphi_f"] & \mathrm{H(A,B)} \arrow[ll, dashed, bend right=60] \end{tikzcd} \tag{3}$$

Furthermore, by adding the replication mechanism the mapping φ_f can also be entailed; but it is the fact that *B* can entail β_b that eventually does the trick. In this last diagram everything is efficiently entailed and all final cause answers are found within the system. Note that only the initial input A originates from the environment.

$$\begin{tikzcd}
A \arrow[r, "f"] & B \arrow[r, "\varphi_f"] \arrow[rr, dashed, bend right, start anchor=south, end anchor=south west] & H(A,B) \arrow[r, "\beta_b"] \arrow[ll, dashed, bend right, start anchor=north, end anchor=north east] & H(B, H(A,B)) \arrow[ll, dashed, bend right, start anchor=north, end anchor=north east]
\end{tikzcd} \tag{4}$$

This for Rosen also exemplified the essence of an organism, a system closed to efficient causation, which is characteristically non-computable (contains non-simulable models). For a more comprehensive mathematical treatment of (M, R)-systems, see Letelier et al. (2006). It is worth noting that Rosen's notion of (M, R)-systems bears comparison with the notion of autopoiesis proposed by Maturana and Varela (1980). Autopoiesis is another characterisation of living systems, which is also made specifically in terms of a circular, self-referential, type of organisation − although the concept of anticipation is not explicitly taken into consideration. For a discussion on the relation between autopoietic and (M, R)-systems, see Letelier et al. (2003).

1.2 Dubois's view of anticipatory systems

Another prominent approach to research in anticipatory systems is advocated by Dubois (1998, 2000). Starting from a divergent position from that of Rosen, he suggests that anticipation is not a characteristic of biological systems alone (a trait of life), but is fundamentally present in all physical systems. In particular, he asserts that Rosen's notion constitutes a special form of anticipation as it is founded on model-based prediction ('weak' anticipation). He additionally discusses a formulation where anticipation as change of current state according to initial, as well as final conditions, is achieved at a system level ('strong' anticipation). His alternative interpretation is based on the concept of incursion (implicit recursion) by which future state is *computed* in a self-referential manner.

More specifically, Dubois describes Rosen's anticipatory system S as a set of differential equations as follows (M denotes the predictive model):

$$\Delta S/\Delta t = [S(t+\Delta t) - S(t)]/\Delta t = F[S(t),\ M(t+\Delta t)] \tag{5a}$$

$$\Delta M/\Delta t = [M(t+\Delta t) - M(t)]/\Delta t = G[M(t)] \tag{5b}$$

His alternative proposition, where the future state of the system S and the model M at time $t+\Delta t$ are a function of this system S at time t and of the model M at a later time step $t+\Delta t$ (Dubois, 1998: 5), is written as follows:

$$\Delta S/\Delta t = [S(t+\Delta t) - S(t)]/\Delta t = F[S(t),\ M(t+\Delta t)] \tag{6a}$$

$$\Delta M/\Delta t = [M(t+\Delta t) - M(t)]/\Delta t = G[S(t),\ M(t+\Delta t)] \tag{6b}$$

Dubois uses the concepts of incursion and hyperincursion (incursion with multiple solutions) as a method to investigate and develop a series of formal models, ranging from control of feedback and chaotic systems, to the generation of fractals from incursive automata and digital wave equations.

Dubois' view in fact summarises the main discussion points in research relevant to anticipatory systems: whether anticipation is a unique characteristic of biological systems or extends to all complex systems (biological, natural, and artificial), and whether anticipation can be realised computationally. The question about computation has its roots in Rosen's argument that there is a parallel between natural languages and organisms, in the sense that they both possess semantic models of entailment that cannot be encapsulated in a syntactic formalisation, a formal system, or a machine (Rosen, 1991: 247). Thus, although the existence of some sort of internal model is commonly agreed to be necessary, some consider that purely syntactic representations are sufficient for producing anticipatory behaviour, while others consider that a semantic dimension is necessary. For a discussion on computability, language and anticipation, see Ekdahl (2000). On the other hand, most researchers prefer to focus on the question of how anticipation can be realised computationally, and what mechanisms or structures are more appropriate for achieving this. For instance, while some consider that anticipatory behaviour can be modelled using reactive (rule based or stimulus–response type) mechanisms, others consider that the internal model should necessarily involve functions such as expectation formation or learning (see for example the discussion by Castelfranchi, 2005). For a review and classification of anticipatory mechanisms, see Butz et al. (2003b). For a more comprehensive view of the work in the field one may consult the Computing Anticipatory Systems (CASYS) Conference Proceedings that appear annually since 1997 and are edited by Dubois, as well as the book edited by Butz et al. (2003a).

1.3 Anticipation and agency in cognitive science and artificial intelligence

Anticipation is often considered to be a characteristic attribute of agency tightly linked to concepts of intelligence, autonomy and adaptability (Christensen and Hooker, 2000; Ekdahl, 2000; Castelfranchi, 2005). Among researchers who explore relationships between anticipation and agency, there are many who see that anticipatory behaviour and other high-level cognitive capabilities (such as intentionality or sociability) can only be explained and constructed as the result of the dynamic, mutually constructive interaction between agent and environment. In other words, these abilities are the result not only of agent and environment properties, but also of the properties and dynamics of their interaction (Pfeifer, 1995; Christensen and Hooker, 2000). Taking this view seems to be important for formalising, and possibly constructing, systems that are able to produce the laws of their own operation. This is essentially the problem of formalising and designing self-referential systems. Rosen's (M, R) formalism, as well as Maturana and Varela's (1980) definition of autopoietic systems, offers a way to describe organisms as systems whose fabrication process is entailed within them. For associated views of autonomy as self-governance, and arguments on the relationships and differences with concepts of cybernetics and autopoiesis, see Smithers (1997) and Collier (2002).

Before we conclude with this section it is also useful to note that anticipation is considered as an important concept not only in relation to issues of individual agent intelligence and cognition, but also in relation to issues of coordination and cooperation in groups of agents. The ability to form expectations about the future, or 'look ahead' in time and space so as to forecast future conflicts and advantageous opportunities, has proven to be particularly useful in improving collaboration and social utility, as well as avoiding or resolving conflicts (e.g. Veloso et al., 1999; El hadouaj et al., 2000).

1.4 Summary

From all the works we reviewed, anticipation surfaces as an important aspect for understanding, modelling, or even constructing reality, and it is also strongly related to scientific investigation per se. In place of a summary it is important to reiterate that the discussion of anticipatory systems is closely linked to the general philosophical and technical problem of self-reference. The problem of self-reference is often discussed in set theoretic terms, which we will explain here in a non-technical way. According to set theory, any reality is perceived and changed in (finite) stages. For instance, in Dubois' notation, stages are represented by an index of time. Alternatively, stages can be thought as levels of abstraction from 0 to N where every level has all the necessary information (let us say components) to completely define entities at the next level. It is often assumed that an entity must be defined uniquely by these components which are defined at previous stages or levels of abstraction. Note that the difference between different stages, or levels of abstraction, can also be seen as a discrepancy between system and environment. Now, the general question of anticipation is the possibility to construct an entity using not only components at previous states or lower levels of abstraction, but also entities from higher (later) levels of abstraction. This is a typical situation in design and especially in creative design. It alludes to the problem of specifying design solutions together with the components of the design artefact. So for instance, an architect often decides the general layout of a building (the building as a whole) while also resolving the configuration of the internal spaces (the components of the building). In set theory and computer science these issues have been formally expressed in the theory of Hypersets (Aczel, 1988). But, as Dubois (1998: 8) argues, '… self-referential systems have today no theoretical well-established framework'. So the development of anticipatory models and representations remains an open question.

Let us now explore in more detail how anticipation relates to design in particular, and what is the specific answer design research has to offer (if it has one) in relation to the notion of anticipation.

2 *Design and anticipation*

The meaning and role of anticipation in design can be discussed from different perspectives. From a social perspective, design objects can be interpreted as anticipatory actions in preparation for a certain future situation. Designers often play this special social role: they instantiate ideas that fulfil needs or resolve problems in reference to a future state of the world. For instance in product design, devices such as video mobile phones or MP3 players are developed in anticipation of certain needs not previously expressed (or possibly only expressed with the introduction of the product!). Similarly, the design of socio-technical systems, such as buildings or urban areas, is specified by looking at the expected lifestyle of future users. The vision of a design science as a 'comprehensive anticipatory science' suggested by Buckminster Fuller is an example in this direction.

Anticipation can also be seen as a characteristic of the design process. As Smithers (2002: 7) notes, in the core of what is design(-ing) lies an apparent paradox: designing has to do with arriving at a solution to a problem which is not a priori specified. In other words, although design is driven by a need or goal, this goal (i.e. the final cause) is actually constructed by the very process of design. In this sense, designing involves the capacity to generate design solutions, in anticipation of a correspondence between the design solution and the desires and needs that motivate it. Moreover, during the design process small changes on parts of a design artefact may result in large effects for the artefact as a whole. In engineering, social, or artistic design such effects may be desirable, but may also be costly or even damaging. It is therefore important to anticipate these effects in order to drive the design process towards solutions that avoid or augment them.

Characteristic reasoning patterns in design also entail an anticipatory capacity. For instance, abduction can be seen to involve describing the structure of a hypothetical device based on the expected behaviour of this device. The generation of such a description implies the capacity to see forward, namely to observe that the realisation of such a description would produce the expected properties. Additionally, as we will see, reasoning about the structure of objects that satisfy certain functions (functional reasoning), or reasoning about the possible functions carried by objects (affordance reasoning), can also be seen to involve some sort of anticipation.

Finally, anticipation is discussed in relation to design as a general capacity or attribute of human intelligence (see Nadin, 2000). But let us now investigate in more detail how different design studies have incorporated different notions or aspects of anticipation.

2.1 Anticipation of emergent designs

One of the most fundamental subject matters in design research is creative design, which is often linked with the phenomenon of emergence. Is there a notion of anticipation related to this fundamental aspect of design? The answer is yes, although at first sight the relation seems to be a negative one. Emergence is commonly associated with a spontaneous discovery of some new attribute (form, structure, or function) of the design description or artefact, which has not been expected or anticipated. However, this view of emergence is increasingly being challenged within the design community.

For example, looking at visual emergence in design, Oxman (2002) puts forward a view of 'anticipated emergence' that contradicts the traditional definition. She suggests that the emergence of shapes is due to a process of resolution of shape ambiguities that relies both on perception, as well as cognition, and the ability to 'think with shapes'. According to her approach, emergence is therefore not accidental but it is canalised by high-level cognitive schemata, which guide the resolution of shape ambiguities.

Knight (2003) also examines the link between emergence and unpredictability and talks about the classification of emergent shapes in shape grammars into three classes: anticipated, possible and unanticipated. According to her view, anticipated emergence constitutes a key to analysis applications of shape grammars where the emergence of shapes is carefully predicted. Possible emergence involves the formation of conjectures about the emergence of shapes from (again intentionally) applied rules. Finally, unanticipated emergence, which plays an important role in conceptual and creative stages of design, involves the generation of shapes that are not premeditated in any way. Interestingly, Knight highlights that the classification of shapes into the aforementioned categories is 'relative to the knowledge and eye of the author or user of a grammar' (Knight, 2003: 135).

Likewise, starting from a classical example of visual emergence, where four squares are placed together so that a fifth square is produced from them, Brown (1998) notes that the appearance of the new shape is something that occurs even if we do have prior knowledge of the phenomenon, that is, emergence can be expected. On this basis he distinguishes between two types of emergence: the first, *directly identifiable emergence*, occurs when the identification of a new property can be traced back in the existing knowledge of a person; whereas the second, *indirectly identifiable emergence*, is linked to a discovery process of setting apart a property as interesting and hence worth remembering and classifying. Brown further suggests that identification of an emergent property comes about by way of analogical and/or functional reasoning, the latter being concerned with the use, or purpose, of a design artefact.

2.2 Anticipation in design agents

Working along similar lines, Gero (2003) links the notion of emergence to that of situatedness, proposing that what one 'sees' is affected by both the situation he or she is in (what is 'out there') and the previous knowledge available, which guides what one is 'looking for'. A fundamental characteristic of his approach is the notion of constructive memory. The driving idea is that memory is not only constructed by experience, but it is also re-interpreted and re-constructed in the light of the present situation. The concepts of situatedness and constructive memory are used for the development of a model of designing (Gero and Kannengiesser, 2004, 2006). The model considers situation as something that incorporates three different kinds of environments, the external world, the interpreted world and the expected world, which are linked to one another through the processes of interpretation, focussing and action. Notably, in this framework the formation of expectations is considered fundamental for both the formation of internal representations and the construction of memories. The differentiation between external, interpreted and expected world is tellingly reminiscent of the most classical and fundamental perception of anticipation, which considers that a model of the external world (or environment) constructed within a system (here design agent) could be used to form expectations about future changes and guide current action.

The ability of agents to interpret and act in the external world by constructing internal representations of this world based on memories, experiences and expectations, is generally associated with the ability for reflective reasoning (or the notion of reflection in action advocated by Schön, 1983). Reflective reasoning is important not only for individual agents but plays also a significant role in the context of distributed design. For example, Brazier et al. (2001: 137) argue that in distributed design where multiple agents need to combine their efforts to achieve a design solution, agents should be endowed with the ability to reason reflectively about additional aspects, such as the knowledge and experience of other agents, their expected actions and results, as well as the types and content of interactions.

Finally, Zamenopoulos and Alexiou (2003) also discuss a formalisation of distributed design as a coordination problem, which takes into account the need for knowledge construction and co-evolution of the problem and solution spaces, but also explicitly suggests that this constructive process entails formation, evaluation and re-interpretation of (expected) future design descriptions (what the authors call the 'memory of the future', Zamenopoulos and Alexiou, 2003: 193).

2.3 Summary

In this brief review of studies anticipation emerges as an important characteristic of design decisively linked to phenomena such as creativity and emergence. However, the typical association of anticipation with design as a cognitive process generally indicates a focus on individual design agents as the unit of analysis for design systems. In this sense, design abilities are fully embedded and embodied in a human or artificial design agent. That is, design abilities are coupled with, but external to the design situation or environment. Of course, the studies mentioned above recognise the significance of reflective action, the constructive role of the situation, or the social and distributed character of design knowledge and abilities, and take steps towards a re-evaluation of the boundaries between system (design agent) and its environment (external world). However, as we will argue in the following section, in order to develop an anticipatory account of design one needs to go beyond views based on traditional computational and formal paradigms.

3 Towards an anticipatory view of design

The nature of design (and the role of anticipation in design) can be studied by focussing on different aspects or levels of abstraction. For example, design can be studied by focussing on the structure of design tasks, the logic of design reasoning, cognitive processes and representations, knowledge level representations, and social parameters of design. This paper considers that design can also be usefully studied by looking at an abstract (mathematical) space within which design methods, knowledge or entities are developed and realised. This follows the conceptual and methodological approach proposed by Robert Rosen. The core issue that we will particularly try to address is the uniqueness of the design paradigm in contrast to paradigms such as machine, evolution or control.

The premise behind our treatment is that design arises in response to a particular situation: when/where there is a desire, need or an idea that something should or could be different in a world W, but the means to achieve such a change are not immediately known (see for instance Archer, 1965; Mitchell, 1990; Smithers, 2002). In particular, the situation can be described as an inconsistency that emerges between beliefs about the past, current, and future states of the world, and the expressed desires or needs regarding the states of the world.

To express this more formally, we use the logic–theoretic distinction between *theories* and *models*. Theories can be defined as (desired or observed) descriptions of the organising principles of a world W, and models can be defined as (desired or observed) instantiations of a world. Models are often considered to assign specific semantics to a theory. On the other hand, theories are considered to describe families of models in W, where each model constitutes an instance of the theory. A theory is in correspondence with a model when it is possible to deduce the properties of the model from the theory, and respectively, it is also possible from the family of models to induce the theory. In this sense, a theory can be seen as a 'universal model', an archetypal model able to encode the principles of a class of models. More specifically in design, theories often represent ideas (e.g. analogies, principles or parameters that specify a solution space), requirements (e.g. criteria, properties or evaluation strategies), and plans for the resolution of a problem. Models constitute in turn interpretations of ideas into specific design descriptions, alternative configurations in a solution space, or instantiations of actions for carrying out design tasks. It is worth mentioning that the terminology is similar to that used in logic and model theory, so the concept of model here is different from that used in science. A detailed model-theoretic treatment of the distinction between theories and models in design can be found in Mitchell (1990).

With the help of the distinction between theories and models we can express the situation where design arises more clearly. The need to design can be thought to arise when desires about the world generate expressions of theories or models that do not follow the correspondence between theories and models as this is established by the belief system. Take for instance the desire for 'an air conditioning system that exploits natural resources in order to create certain environmental conditions'. A problematic situation arises when the available theory concludes that the desired properties (i.e. certain environmental conditions) cannot be achieved with known models of air conditioning systems; and/or the known models do not have the desired property of being able to exploit natural resources. The broken correspondence between theories and models explains why the means to achieve a design change 'are not *immediately* known'. In our view, and to borrow Smithers' argument (Smithers, 2002: 7), this broken correspondence 'neither specifies what is required, nor defines a problem to be solved' and it is 'what makes designing a particular kind of activity'.

In response to a problematic situation, design can thus be associated with the capacity to generate theories and models that bring beliefs and desires into correspondence. This may include the capacity to synthesise requirements, concepts, and plans of action (i.e. synthesise theories), as well as to generate specific instantiations (i.e. synthesise models) – see Smithers (2002). More importantly, design also involves the capacity to anticipate the correspondence between theories and models, which can only be verified by experimentation or the actual realisation of the design artefact.

Given the desire for a naturally heated building, the main concepts introduced in this section can be illustrated using Felix Trombe's design of a solar house as a motivating example (Ashley, 1983). One can imagine that his design involved the creation of a theory: *in order to naturally warm the air in a building, one should find a way to circulate the cold air over a naturally warmed surface*. It also involved the development of a model: that is *a double wall whose internal surface is built from a material that can act as a thermal mass and the external is* *made of glass*. The formation of the double wall induces certain properties (a belief theory about the thermal behaviour of the wall). According to this theory *the sunlight passes through the glazed surface and is absorbed by the internal wall. Heat can then be transferred by conduction, or by channelling the hot air through heat-distributing vents*. The essential feature of design is this capacity to develop a model (the double wall) in anticipation of certain properties (the thermal behaviour of the wall) that correspond to the formed theory (heating through circulation of cold air over a naturally warmed surface).

3.1 Some general notation and revised definitions

Let us adopt a general notation in order to explicitly express the ideas of this paper in relation to Rosen's main results. Statements about design (and anticipation) will be expressed in a language that involves *objects* (or *structures*) and *arrows* (or *transformations*) between objects, such as the following:

$$f : A \to B, \; g : B \to C \tag{7}$$

It also involves compositions of arrows, such as for instance $f \circ g : A \to B \to C$. In general, objects, arrows (and their compositions) can take a variety of interpretations. Arrows can be thought as causal relations between observables of type A and type B, dynamical transformations of inputs A (causes) to outputs B (effects), or abstract transformations of a language of type A to a language of type B.

3.1.1 Models and theories

We can use this notation to explicate the concepts of theory and model introduced above. Given the expression $f : A \to B$ the following definitions are considered: the objects A and B denote languages that generate theories, and the arrow f denotes a model that offers a specific interpretation of a theory A in B. For example, A may denote a language that generates theories about the connectivity and topological relations between activities in a building. B may denote a language that generates descriptions of geometric objects and their relations (e.g. floor plan configurations). Then f may denote a model that translates topological relations into a possible geometry. Therefore, the arrow f gives an instantiation of the theory of topological relations A, in the language of geometrical relations B.

3.1.2 Problematic situation and design

In the introduction of this section it was suggested that design arises in response to a problematic situation: when theories about the organising principles of a world do not correspond to available models of the world. A theory is in correspondence with a model when it is possible to deduce the properties of the model from the theory, and respectively, it is also possible from a family of models to induce the properties of the theory. How can this be expressed using the introduced algebra of arrows?

Taking the previous example, the model f of theory a specifies a floor plan configuration in B, which can be denoted by $f\circ a$. On the other hand, a floor plan configuration b in B specifies a theory of topological relations of activities in A, which can be denoted by b^{f}. In general, a correspondence between theories and models implies the following transitions:

$$\begin{tikzcd}
& \text{Language A} & \text{Language B} & \\
\text{A theory } a & a \arrow[r] \arrow[d] & f\circ a \arrow[d] & \text{A model of theory } a \\
\text{A theory specified by configuration } b & b^{f} & b \arrow[l] & \text{A floor plan configuration } b
\end{tikzcd} \tag{8}$$

Note that arrows of the form $a \rightarrow b^f$ are defined in $[A \rightarrow H(F,B)]$, and arrows of the form $f\circ a \rightarrow b$ are defined in $[F \times A \rightarrow B]$. More succinctly, the generation of theories is said to be in correspondence with the generation of models if and only if any arrow of the form $a \rightarrow b^f$ can be uniquely defined from $f\circ a \rightarrow b$, and vice versa; namely the following isomorphism holds:

$$[A \rightarrow H(F,B)] \cong [F \times A \rightarrow B] \tag{9}$$

A problematic situation arises when a theory $a \rightarrow b^f$ does not uniquely correspond to the arrow $f\circ a \rightarrow b$. This can be expressed as lack of correspondence between models and theories:

$$[A \rightarrow H(F,B)] \ncong [F \times A \rightarrow B] \tag{10}$$

Design can thus be defined as the capacity to generate theories and models in anticipation of the correspondence between $f\circ a \rightarrow b$ and $a \rightarrow b^f$, namely in anticipation of the isomorphism (9). In the next sections it will be argued that the assumption of this correspondence is one the main problems that restrict the power of paradigms such as machine, evolution and control to capture the intuitive meaning of design.

3.2 Machines, evolution, control, and their influence in design research

Let us now consider the concepts of machine, evolution and control in more detail using the notation introduced above.

3.2.1 Machines

The term machine is used in ordinary discourse in connection with mechanical artefacts. However, in philosophy, science, and mathematics, the term has been used as a metaphor to express the fundamental working principles of reality, knowledge and thought. In particular, the concept of machine has been used for the definition of abstract notions such as *effective procedure*, *logical process* and *computing*. The best known example is the Turing Machine which was invented as a model of a universal computer capable to realise any possible logical process. For an introduction to machines the interested reader might consult Minsky (1972).

The machine abstraction has been an important epistemological basis for design, particularly due to the hypothesis that thought can be best modelled as an information processing machine (Stiny and March, 1981). The work of Newell et al. (1957) on human problem solving paved the way for the development of a cognitive understanding of design as information processing and its formalisation as a search process. This work has been influential for a very large number of empirical, theoretical or computationally-driven design studies (e.g. Eastman, 1970; Akin, 1986; Goel and Pirolli, 1989).

The advent of computing machines and the information processing paradigm have also been instrumental for the development of research in artificial intelligence. The rapid growth of artificial intelligence has naturally generated questions about the role of the machine paradigm in understanding intelligence in general, and design intelligence in particular (e.g. Cross, 1999; Liddament, 2000). Nevertheless, the relation between design intelligence and machines has been investigated at various levels of abstraction: at the level of information processing, the level of design tasks or the knowledge level – although the latter is not necessarily a machine abstraction in itself (Goel and Pirolli, 1989; Chandrasekaran, 1990; Smithers, 1998; Brazier et al., 2001).

The machine view of the world assumes that any logical process can be realised through a recursive application of a set of rules. A world is logically constructed *in ordered* stages, where new worlds are built from old ones (recall the discussion in Section 1.4). This logical process is defined on the basis of a complementary relation between a language (that generates imperative or permissive statements about a world), and a machine (that evaluates the statements, and produces an answer about whether a problem is solved or not). More precisely, a simple *machine* (or finite state automaton) is defined by a set of states f in F, a set of actions a in A, and transition rules of the form $f \circ a \rightarrow b$ defined in $[F \times A \rightarrow B]$. A *language* describes the behaviour of the machine, namely actions a that generate an answer b given the state f. Using the introduced notation, a language is defined by arrows of the form $a \rightarrow b^f$ in $[A \rightarrow H(F,B)]$. The complementary correspondence between language and machine is illustrated in diagram (11). In this diagram, a machine reads a language (substituting statements a for instructions b^f) and then evaluates the answer b (deducing the answer b from the rule b^f and the state f). In this sense, the specification of a machine and the specification of the behaviour of the machine have an optimum correspondence $[A \rightarrow H(F,B)] \cong [F \times A \rightarrow B]$ (for this argument see also Goguen, 1972).

$$\begin{tikzcd} H(F, B) \\ A \arrow[u] \end{tikzcd} \qquad \begin{tikzcd} F \times H(F, B) \arrow[dr, "\text{Evaluation}"] & \\ F \times A \arrow[u, "\text{Reading}"] \arrow[r] & B \end{tikzcd} \tag{11}$$

Language Machine

In design, a machine can be thought as an abstraction of the problem space. It represents a theory that determines and evaluates the principles of a specific model (a design solution) expressed in language *A*. Similarly, a language can be abstractly considered as the solution space, where the generation of alternatives is defined. On this basis, design is reduced to a search process for the best possible model that satisfies the constraint $[A \rightarrow H(F,B)] \cong [F \times A \rightarrow B]$.

3.2.2 Evolution

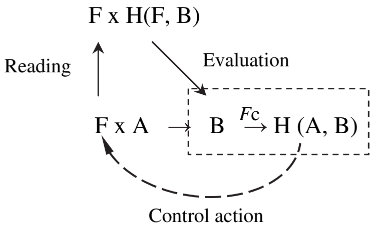
Based on the machine paradigm a plethora of different abstractions have been developed, which in general either refine or introduce more structure (restrictions) to the machine formalism. For example in evolutionary explanations, the objects of evolution are machines *M* together with their languages. According to the evolutionary perspective, the world is explained by a process of natural selection. Given a process that copies – under small variations – a population of machines *M* together with their languages, selection is taking place on the basis of to the correspondence between languages and machines; only languages that are readable (acceptable) by the machine *M* may possibly survive and reproduce. Similarly only languages that are realised by machines survive and therefore reproduce. In this way more complex machines and languages can be defined starting from simple ones – under constraints implied in diagram (12).

$$\begin{tikzcd} F \times A \arrow[r, "M"] \arrow[d] & B \arrow[d] \\ F' \times A' \arrow[r, "M'"] & B' \end{tikzcd} \qquad \begin{tikzcd} A \arrow[r] \arrow[d] & H(F, B) \arrow[d] \\ A' \arrow[r] & H(F', B') \end{tikzcd} \tag{12}$$

The concept of evolution has also been used in design in various ways, for example as an analogy for understanding the form and function of design artefacts (Steadman, 1979), or as a methodology for solving optimisation problems and generating novel forms (Frazer, 1995; Bentley, 1999). The evolutionary paradigm has been a useful abstraction for design. That is mainly because the generation of languages and the definition of machines are both entailed by the system itself. In contrast with the machine paradigm, theories (machines *M*) co-evolve together with models (languages), and this fits well with the view of design as co-evolution of problem and solution space (Maher, 2000; Dorst and Cross, 2001). However, the main difficulty arises in the explanation of functionality, or more precisely the explanation of functionality in anticipatory terms. In evolutionary explanations the function of a system is generally conceived to be a behaviour selected for its correspondence with a machine *M*. The correspondence between languages and machines (problems and solutions) drives the very meaning of natural selection; any mismatch is thrown outside the evolutionary process. However, as we saw, design is motivated by this very mismatch, and the process of design involves anticipating the correspondence between languages and machines, rather than using it as a constraint. In this sense, we can say that the correspondence between languages and machines (or models and theories) is an anticipated state that *emerges* out of the processes.

3.2.3 Control

Other abstractions impose some kind of meta-structure on the machine metaphor. For instance in cybernetics, one of the fundamental problems is the existence of a formal process *Fc* within a machine *M* that can reduce the complexity of the environment (expressed by *B*) by producing the appropriate control action *F* (diagram 13).



(13)

In other words, the effect *B* in world *W* is endowed with a purpose or function. The function *Fc* regulates the environment (the machine *M*) by keeping the consequences *B* in some desired limits despite disturbances from external factors. This is also an interesting abstraction for design. Design can be interpreted as an action that modifies or creates an environment (e.g. a building) for a given system (e.g. a family) in order to create the appropriate conditions for the functioning of this system (e.g. in terms of lighting, accessibility or social security). Control and other cybernetic and system-theoretic notions have been influential for the understanding of the nature of design in the early days of design methods research (Archer, 1968), and still underlie epistemological studies of design (Glanville, 1994). The problem with the control view is that the purpose, or function of the resulting design, is externally defined. In particular, the function *Fc* is entailed by someone that is outside the structure of the above formalism.

In the same spirit, artificial intelligence generally assumes that the world *W* cannot be simply described by deductive steps: there is no such process *M* that can deductively prove *B*. The assumption put forward instead is that there is another process or language Fi at a meta-level able to define control strategies *Fc* that can heuristically prove *B* (diagram 14).

$$\begin{tikzcd}
F \times H(F,B) \arrow[dr] & & & \\
F \times A \arrow[u, "\text{Reading}"] \arrow[r] & B \arrow[r, "Fc"] & H(A,B) \arrow[r, "Fi"] \arrow[ll, dashed, bend left] & H(B, H(A,B)) \arrow[l, dashed, bend right, "\text{Evaluation}"']
\end{tikzcd} \tag{14}$$

In this context, design is often discussed as a search or exploration process which is driven by goals and constraints. The first arrow $F \times A \rightarrow B$ loosely corresponds to a machine that tests whether a given proposition is a design solution, the second $Fc{:}B \rightarrow H(A,B)$ is a control mechanism that drives the search process towards defined goals, and the third $Fi{:}H(A,B) \rightarrow H(B, H(A,B))$ is a problem-reformulation mechanism that generates alternative search strategies. Obviously the problem here is one of infinite regress, as we add more and more arrows in the machine structure in order to 'close' the formalism. This problem is further discussed in the next section.

3.2.4 Conclusions

We have now reviewed the general abstractions of machine, evolution and control using the introduced notation. In all these paradigms, the world was explained through a process whereby new entities are built out of old ones without reference to future anticipated states. At the beginning of the Section 3, a view of design was suggested that involves the capacity to build a representation of theories and their models in anticipation of a *correspondence* between beliefs and desires; that is, the capacity to entail theories and models (or machines and languages), but also to entail their correspondence. But in the paradigms exposed here the correspondence between languages and machines is not (indeed cannot be) entailed: it is a universal constraint, rather than an emergent state of the world *W*. Adopting therefore a machine-based paradigm in fact violates necessary conditions for the identification of design. In the following section we will discuss some general remarks for a possible characterisation of design as a unique paradigm.

3.3 The uniqueness of the design paradigm

The main theoretical and methodological contribution of Rosen's proposed (M, R)-system can be summarised in two points. Firstly, it offers an abstract mathematical structure for identifying anticipatory systems (and living systems). Secondly, it proposes a resolution of the infinite regress that occurs in self-referential systems by specifying the conditions for operational closure

(closure to efficient causes). As we saw, a system is closed to efficient causes if and only if every arrow (every model) is specified within the system. For the purpose of this study these are important theoretical and methodological results as they can help explain design as the capacity to generate models and theories *in anticipation* of their correspondence.

3.3.1 Design as a capacity to entail models

Let us have another look at the (M, R) formalism, this time explicitly in relation to design. For this purpose, the interpretations of arrows $f{:}A \rightarrow B$ given in Section 3.1 are presumed. In order to avoid cumbersome notation, but also for reasons that will be apparent in the next section, we assume that Rosen's results about B can generally be applied for A. On this basis, anticipation is implicitly defined as the capacity to specify a model f in preparation for certain effects in B (diagram 15).

$$\begin{tikzcd} A \arrow[r, "?f", ""{name=F, below}] & B \arrow[r, "\varphi_f"] & H(A,B) \arrow[to=F, dashed, bend right=60] \end{tikzcd} \tag{15}$$

The expression 'in preparation for' more precisely means that the model f is generated by a special arrow φ_f such that the properties of a configuration b are deduced by the theory a in A (i.e. $a \rightarrow b^f$) *before* the configuration b is derived by the model of the theory $f \circ a$ (i.e. before $f \circ a \rightarrow b$) – see also diagram (8). The correspondence between theories and models $[A \rightarrow H(F,B)] \cong [F \times A \rightarrow B]$ is therefore not given, but it is anticipated by the generation of the model f.

Rosen's (M, R)-system explains how this anticipatory capacity is possible. More precisely, the problem here can be framed with the question: how can the arrow φ_f be derived from the organisation of the above diagram? The key idea is that a theory generated in A implicitly describes the properties of function φ_f (and thus the system is closed to efficient causes). Rosen observes that this is mathematically possible under a certain condition (recall Section 1.1.2).

But how is this idea important in design? In order to understand its relevance to design it is useful to consider that the (M, R)-system embodies a form of abductive reasoning (for a discussion on abduction in design see March, 1976; Roozenburg, 1993). In particular, the identified condition postulates the representation of a deductive system before its actual realisation. Deduction simply implies that for any theory a in A there is a rule $f \rightarrow b$ (i.e. b^f), such that the result b can be deduced from the application of the model f and the rule b^f (diagram 16a). The arrow $ded{:}F \times H(F,B) \rightarrow B$ represents a deduction. Rosen's condition allows the existence of an inverse arrow $abd{:}B \rightarrow F \times H(F,B)$ (an abduction) such that certain models f and rules $f \rightarrow b$ can be derived from an (anticipated) configuration b (diagram 16b).

Given $f \rightarrow b$ (i.e b^f)
And f
Deduce
b

$$\begin{tikzcd} F \times H(F, B) \arrow[dr, "ded"] & \\ F \times A \arrow[u] \arrow[r] & B \end{tikzcd} \qquad (16a)$$

Given b

Generate
f, b^f

$$\begin{tikzcd} F \times H(F, B) & \\ F \times A \arrow[u] \arrow[r] & B \arrow[ul, "abd"'] \end{tikzcd} \qquad (16b)$$

The existence of an inverse arrow can be seen to represent the anticipation of a deduction that satisfies the correspondence $[A \rightarrow H(F,B)] \cong [F \times A \rightarrow B]$. The condition formulated by Rosen therefore interestingly suggests that an anticipatory capacity is necessary for abductive reasoning, and this directly impacts on our understanding of design.

Anticipation can be perceived as a generic capacity that underlines the realisation of various reasoning patterns in design. To explore this more, let us assume that A is a language that specifies a theory of possible behaviours of a device, and B is a language that specifies its structural components. Anticipation is the capacity to specify the structural components in preparation for a specific behaviour. If A specifies a desired behaviour (or function) then the above reasoning pattern is in fact functional reasoning. If on the other hand A specifies a theory of devices and B a theory of functions (or a theory of potential functions derived by user—device interaction), then the above reasoning pattern is affordance-based reasoning. For a more detailed discussion of functional and affordance-based reasoning in design, see Brown and Blessing (2005) and Maier and Fadel (2002). Note that in general, the (anticipatory) specification of a model of a theory — in preparation for a certain effect in B — might be seen to refer to the description of an artefact (its structure, behaviour, function), or, equally, to the description of the process employed in order to complete a design task.

3.3.2 *Design as the capacity to entail theories*

Up to this point the emphasis has been on the identification of design with an abstract structure that is closed to efficient causes. The (M, R)-system identifies the principles of a system able to generate models in anticipation of a correspondence between theories A and models in the domain B. Yet, there is still something missing. In the beginning of the Section 3, the capacity to design has been identified not only with the generation of models (specification of the design objects), but also with the generation of theories (principles of design objects). If we go back to Rosen's original diagram (diagram 17) we can see that the material cause a in A remains unentailed; namely, the development of theories is still to be found in the environment E. It is clear that an additional closure condition needs to be formulated; this is the entailment of A.

$$\begin{tikzcd}
\mathbf{E} \arrow[d, dashed, "h"'] \\
A \arrow[r, "f", ""{name=F, below}] & B \arrow[r, "\varphi_f", ""{name=P, below}] & H(A,B) \arrow[r, "\beta_b", ""{name=Bb, below}] \arrow[to=F, dashed, bend right=60] & H(B, H(A,B)) \arrow[to=P, dashed, bend right=50] \arrow[from=2-2, to=Bb, dashed, bend right=60]
\end{tikzcd} \tag{17}$$

Our proposition is therefore to restrict the mapping β_b in those mappings whose image in $H(B, H(A,B))$ forms an isomorphism with A (diagram 18).

$$\begin{tikzcd}
H(B, H(A,B)) \cong A \arrow[r, "f"] & B \arrow[d, "\varphi_f"] \\
& H(A,B) \arrow[ul, "\beta_b"]
\end{tikzcd} \tag{18}$$

The closure can be generally inferred and explained by posing that Rosen's results about B are also applied to A – as discussed in the previous section. Hence we have that a theory in A effectively describes arrow φ_f (that is a method for the generation of new models), and a theory in B effectively describes arrow β_b (that is a method for the generation of new theories from models). In order to formally express this we need to move away from the simple algebraic notation (and set theoretic concepts), which is outside the scope of this paper.

Nevertheless, even in this simple notation it is possible to discuss two important results. First, the proposed diagram encodes all the necessary conditions for the definition and explanation of design presented at the beginning of the Section 3. That is, the proposed system entails a language for generating models of design objects in anticipation of an isomorphism between $[A \rightarrow H(F,B)] \cong [F \times A \rightarrow B]$. Moreover, it entails the generation of a theory under which these solutions are evaluated. This gives a clear characterisation of design using the paradigm of anticipation. It should be noted, however, that diagram 18 does not offer a model of design per se. It is a theoretical construction that can take different interpretations, each proposing a plausible model of design. Although the paper does not intent to give a specific interpretation, various alternatives can be envisaged from what we have discussed.

Second, it is possible to make some assertions about the meaning and role of anticipation in design. The use of abstract structures, and the general methodological approach, provided a precise basis for discussing the role of anticipation in design at different levels of abstraction. This included the study of design as a distinct reasoning pattern, but also as a distinct epistemological concept comparable to that of machine, evolution, or control.

4 *Summary and discussion*

In summary, the paper offered a review of the concept of anticipation and its meaning in the context of design. It further elaborated a comparison between a view of design as an anticipatory system with other important paradigms used in design research (i.e. the abstractions of machine, evolution, and control). The core issue was to develop such an anticipatory view able to uniquely distinguish design in comparison to the other paradigms. To that end, the concept of anticipation as defined by Rosen was used as a critical conceptual and methodological tool.

The paper opens a discussion on the possibility to uniquely identify the 'design paradigm' on the basis of an abstract structure – just like Robert Rosen did for living and anticipatory systems. But why is this endeavour useful? The answer is in fact three-fold.

First, the anticipatory view of design enables us to identify and address the limitations of other paradigms used in design research. The authors hope that the proposed view can be particularly useful in understanding the capabilities and limitations of computer-based realisations, which largely assume the machine paradigm. Second, the methodological approach facilitates the study, comparison, and possibly unification of different perspectives of design. In particular, the proposed formalism delineates the conditions for identifying design as a distinct 'problem', without committing to a specific interpretation of the processes, knowledge or entities involved in design. Finally, the proposed abstraction can also be used as an explanatory tool. Design research usually incorporates studies of 'what a designer does', 'what a designer thinks', or 'what a designer designs'. In comparison, the study takes some steps towards a theory of design which is developed by looking at the less studied question of 'how design emerges' or what are the conditions that explain the capacity to design.

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