Creative Designing: An Ontological View
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ABSTRACT
This paper presents an ontological account of creative design. It identifies processes and activities in designing that can produce novel design concepts to change the state space of possible designs. Activities that foster creativity are integrated in an ontological framework of design, the situated function-behaviour-structure (FBS) framework. This provides a foundation for locating these activities across the design steps. An important outcome of this approach is that most steps of designing can be shown to contain opportunities for creativity.

Categories and Subject Descriptors
I.2 Artificial Intelligence, J.6 Computer-aided engineering

General Terms
Design, Human Factors, Theory

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Design, creativity, ontology

1. INTRODUCTION
Designing is often seen as the prototypical example of a creative human act. By definition, it is concerned with “creating”, be it new products, systems, processes or organisations. Novelty, however, is not inherent to the thing being created; rather, it is a notion relative to what has been known to exist previously. As a consequence, whether or not a design is characterised as being creative ultimately depends on subjective experience. Boden [2] has introduced the distinction between “historical” (or h-) creativity and “psychological” (or p-) creativity. H-creativity is a stronger form of creativity, where novelty is evaluated in relation to the history of humankind. For example, the first steam engine was a h-creative design. P-creativity implies novelty only with respect to the history of an individual. A novice architect designing a high-rise office building for the first time can be viewed as producing a p-creative design. H- and p-creativity are often understood as describing the social and the individual aspects of creativity, respectively.

Suwa et al. [23] have extended Boden’s classification by adding the notion of “situated” (or s-) creativity. This kind of creativity is defined relative to the process of designing rather than to the outcomes of this process. A design or design feature is viewed as s-creative if it is introduced for the first time in the ongoing design process. S-creativity is independent of any post hoc ascriptions of creativity to the product of designing, and thus independent of the location of the knowledge required for these ascriptions. The concept of creativity used in this paper is the one of s-creativity. S-creativity can also be either p- or h-creative.

S-creativity allows characterising designing as either routine or non-routine. Routine designing describes the case where the state space of possible designs is well defined, fixed and bounded at the outset of the design process. All design variables and their ranges of values are known in advance. Designing then only consists of finding a specific set of values. This maps onto a view of designing as search. Design optimization is often regarded as an instance of routine designing. No creativity is involved in this idealised view of designing. Figure 1 shows the state space of routine designs.

![Figure 1. The state space of routine designs as a subset of the state space of possible designs](image)

Non-routine designing can be subdivided into two further groups: innovative designing and creative designing. Innovative designing assumes a well-defined, fixed and bounded set of design variables but manipulates the ranges of values to be outside the norm. Figure 2 shows the resulting state space of innovative designs.

Creative designing introduces new design variables, which extends the state space of possible designs. Variables can be introduced additively or substitutively. The former results in an expanded design state space as depicted in Figure 3. The latter results in a shift of the design state space, which, in the extreme case, may be disjoint from the original design state space.
Research in creative designing can be separated into two strands. One strand of research is concerned with developing computational processes that can extend the design state space. Here, five classes of processes have been suggested [11]: emergence, analogy, combination, mutation and first principles. Another strand of research deals with the human behaviour involved in changing the state space of possible designs. Here, creativity is viewed as part of more general design behaviour including cognitive and physical activities carried out by the designer.

A paradigm that characterises designing in terms of the activities performed by human designers is situatedness. Its foundational concepts go back to the work of Dewey [6] and Bartlett [1]. Their ideas have strongly influenced the more recent notion of situated cognition [3]. From the situated perspective, designers perform actions in order to change their environment. By observing and interpreting the results of their actions, they then decide on new actions to be executed. This means that the designers’ concepts may change according to what they are “seeing”, which itself is a function of what they have done. One may speak of an “interaction of making and seeing” [22], which strongly determines the course of designing by modifying the design state space.

A number of activities related to potential design creativity have been studied that fit with the notion of situatedness. Most of them can be grouped into the following two classes:

- **Interpretation**: There is significant experimental evidence that the interpretation of sketches can be used as a source for modifications in the design state space. For example, Schön and Wiggins [22] found that designers use their sketches as a means to reinterpret what they have drawn, thus leading the design in a new direction. This extends the traditional view that sketches only serve as static, external memory aids. Suwa et al. [23] noted, in studying designers, a correlation of unexpected discoveries in sketches with the invention of new issues or requirements during the design process. They concluded that “sketches serve as a physical setting in which design thoughts are constructed on the fly in a situated way”. Many studies of creativity in design interpretation connect unexpected discoveries to the process of emergence – the process that transforms implicit features of the design into explicit ones, substitutively introducing new variables in the design state space. Consider, for instance, the shapes in Figure 4(a). They have initially been drawn with the intention to represent two overlapping squares. The three shapes in Figure 4(b) can emerge from this representation by considering the intersection and differences of the two squares.

- **Reflection**: Schön’s notion of reflection-in-action describes a practitioner’s activity of “thinking [about] what they are doing while they are doing it” [21]. It is connected to the idea of change, serving “to reshape what we are doing while we are doing it” [21]. In creative designing, reflection plays the role of a transformation of the current design state space using the designer’s memory. Specifically, reflection can be viewed as an instance of the idea of constructive memory, which holds that memory is not just laid down and fixed at the time of the original sensate experience but is a function of what comes later as well. Memories are constructed in response to a specific demand, based not only on the original experience but also on the situation pertaining at the time of the demand for this memory. Therefore, everything that has happened since the original experience determines the result of memory construction. Clancey [3] has exemplified constructive memory by a paraphrase of Dewey: “Sequences of acts are composed such that subsequent experiences categorize and hence give meaning to what was experienced before”. Each memory, after it has been constructed, is added to the existing knowledge and is now available to be used later, when new demands require the construction of further memories. These new memories can be viewed as new interpretations of the augmented knowledge.

These classes of design activities are orthogonally related to Gero’s [11] five computational processes. This means that any of these processes may occur in any of the two classes of design activities.

## 2. ACTIVITIES IN CREATIVE DESIGNING

### 2.1 The FBS Ontology

Gero [10] has proposed an ontology of design objects that provides three high-level categories for the properties of an object:

- **Function (F)** of an object is defined as its teleology, i.e. “what the object is for”. It can be described as the role that
the object plays in a superordinate system, including human users of that object. An example is the function "to wake someone up" that humans generally ascribe to an alarm clock. The set of functions used in a particular design process is a subset of the design state space, termed function state space.

- **Behaviour** (B) of an object is defined as the attributes that are derived or expected to be derived from its structure (S), i.e. "what the object does". It represents actions and performances of the object and comprises the criteria for evaluating that object’s design. An example of behaviour is "weight", which can be derived directly from a physical object’s structure (S) properties of material and spatial dimensions. The set of behaviour variables and their ranges of values used in a particular design process is a subset of the design state space, termed behaviour state space.

- **Structure** (S) of an object is defined as its components and their relationships, i.e. "what the object consists of". It represents the object’s "building blocks" that can be directly created or modified by the designer. Examples include molecule structures (created/modified by chemists), mechanical structures (created/modified by mechanical engineers), floor and wall structures (created/modified by structural engineers), spatial structures (created/modified by architects) and program structures (created/modified by software engineers). The set of structure variables and their ranges of values used in a particular design process is a subset of the design state space, termed structure state space.

Humans construct connections between function (F), behaviour (B) and structure (S) through experience and through the development of causal models based on interactions with the design object. Specifically, function (F) is ascribed to behaviour (B) by establishing a teleological connection between the human’s goals and the observable or measurable performance of the object. Behaviour (B) is causally connected to structure (S), i.e. it can be derived from structure using physical laws or heuristics. There is no direct connection between function (F) and structure (S) [5].

Designing is a process that aims to create the structure (S) of artefacts that meet a set of requirements stated as functions (F) and possible behaviours (B). As this mapping between function and structure can be established only via behaviour (B), that behaviour must satisfy two constraints: First, it must reliably describe the object’s “actual” performance under operating conditions, and, second, it must be consistent with the functions (F) required. One can think of behaviour (B) as being located in a field of tension between desirability, represented by function (F), and feasibility, represented by structure (S). Designed objects are successful only if their desired behaviour (constrained by function) matches their feasible behaviour (constrained by structure).

### 3.2 Three Interacting Worlds

#### 3.2.1 The External World

It is a common assumption in most science and philosophy that we live in a world whose temporal and spatial dimensions constrain our actions and indirectly our thinking. This world surrounds us and is commonly viewed as being “there outside”. We therefore refer to this world as the external world. Even though the external world may be perceived differently by different individuals, it is reasonable to think of it as a common interface through which we can engage in interactions with other people or ourselves. This interface provides various interaction media, such as streets, telecommunication devices, air, paper, computational environments, or any other object or set of objects. This can be broken down further into molecules and atoms, pixels, bits, etc. Not every medium is available to everyone at any time. We have to choose which medium is the most appropriate to interact in effectively, depending on the specific situation and our cognitive and physical capabilities.

The external world does not only contain “real” objects, but also “representations of ‘real’ objects”. Examples for the latter include design drawings (iconic and symbolic representations of artefacts), and texts and utterances (linguistic representations of anything we want to express). While it is conceivable to interact with some of these representations as if they were “the real thing”, in most cases there are good reasons to distinguish between “real” and “represented”. However, we want to adopt the perspective of an omniscient observer modelling how people interact with the external world. Therefore, we are forced to use a language, a (meta-) representation for describing both “real” objects and representations of “real” objects. From this point of view, all “things”, real or represented, are treated as (meta-) representations, which only differ in their embodiment either in the (“real”) world of molecules and atoms, or in the (“representational”) world of symbols, icons or pixels. We thus refer to all things in the external world as external representations.

External representations can be categorised using the FBS schema presented in Section 3.1. We accordingly define three classes of external representations: external function (F), external behaviour (B) and external structure (S). This provides us with a universally applicable formalism to describe every instance of an external representation uniformly, including instances that are often referred to as “physical objects”, “virtual objects”, “processes”, “people”, etc.

#### 3.2.2 The Interpreted World

The assumption of an external world directly leads to the assumption of a counterpart, a world that is “inside” our minds and separate from the external world. We refer to this world as the interpreted world, and to representations within this world as interpreted representations. The process that transforms an external representation into an interpreted representation is called interpretation. The interpreted world is not only constructed from interpretations of the immediate external world, but also from our memories and reflections.

Using the FBS schema, we can define three classes of interpreted representations: interpreted function (F), interpreted behaviour (B) and interpreted structure (S). Figure 5 shows these three classes and their connections to corresponding classes in the external world. Both interpretation and reflection are modelled as “push-pull” activities [12]. This emphasises the role of individual experience in constructing the interpreted world, by “pulling” interpreted representations rather than just by “pushing” what is presented in the external world. It is the interaction of push and pull that may produce new representations that can be used to modify the design state space.
3.2.3 The Expected World

A world of observations, memories and scrutiny would be useless without the ability to relate their results to our current goals and perform actions to achieve these goals. Therefore we introduce a third world – the expected world. This world is located within the interpreted world and contains those interpreted representations that we take as our current goals or that we expect to be useful in achieving these goals. We refer to the representations in the expected world as expected representations. Analogously to the interpreted world, expected representations include expected function ($F^e$), expected behaviour ($B^e$), and expected structure ($S^e$), Figure 6. Focussing is the process that transfers representations between the interpreted and the expected world. This activity works in both directions: Some interpreted representations can be transferred into the expected world, while some expected representations can be transferred back into the interpreted world. This accounts for our ability to form new goals and drop previous goals. The set of expected representations corresponds to the idea of a design state space and its partial state spaces of a function state space, a behaviour state space and a structure state space.

4. CREATIVE DESIGNING IN THE SITUATED FBS FRAMEWORK

In Section 3.2.3 we have loosely referred to the expected world as the world of “design”, where functions are transformed into structure, via behaviour. However, the notion of designing must be understood in a wider sense, involving the interplay of all three worlds. The expected world is needed as a playground for design ideas based on our desires. The interpreted world is needed to supply the expected world with memories and reflections of previous designs and our perceptions and scrutiny of the current state of the (external) world. The external world is needed to make our designs “real” in the world we live in, which is the ultimate goal of every design process. Empirical studies of designers suggest that interactions between the three worlds occur throughout the process of designing.

Gero and Kannengiesser [13] have presented a framework of designing – termed the situated FBS framework – that is based on the three worlds. A graphical representation of this framework is shown in Figure 7. In addition to using external, interpreted and expected $F$, $B$ and $S$, the situated FBS framework uses explicit representations of external requirements given to the designer by another person (e.g. a customer). Specifically, there are external requirements on function ($FR^e$), external requirements on behaviour ($BR^e$), and external requirements on structure ($SR^e$).
The situated FBS framework specifies a set of 20 activities. Their numbering in Figure 7 does not prescribe a fixed order of execution. All 20 activities can be mapped onto a set of eight fundamental design steps [10], which will be presented in the remainder of this Section as creative designing is articulated through this ontology.

4.1 Formulation and Creativity
Formulation produces an initial state space of potential design solutions (structure state space) and a set of criteria for assessing these solutions (behaviour state space). This step uses a set of goals (function state space) and constraints that are given to the designer by external specification or are constructed based on the designer’s own experience. In the situated FBS framework, this design step is composed of activities 1 to 10, Figure 8.

Interpretation, represented by activities 1, 2 and 3, produces function, behaviour and structure variables based on external requirements. However, this is not a simple reproduction of what is given to the designer. Any two designers will be likely to interpret the same requirements differently, depending on their individual experiences. As a result, they produce different sets of variables for the function, behaviour and structure of the design. This ability is also needed to resolve ambiguities that frequently occur in externally represented requirements, especially in function requirements that are usually represented in informal ways.

Reflection, represented by activities 4, 5 and 6, is used in formulation to produce additional, implicit requirements that have not been explicitly given to the designer. Most implicit requirements are constructed by default and are often accepted as common knowledge. For example, the function of a window “to provide daylight”, though not explicitly stated, can be considered common knowledge. Other requirements are more clearly based on the individual designer’s experience. Cross [4] provides the example of an expert engineer performing the task of designing a device that allows fastening and carrying a backpack on a mountain bike. Based on the engineer’s personal experience as a cyclist, an implicit constraint on the structure of the device was constructed, namely to select its location (and thus the location of the backpack) as low as possible for better riding control.

The transformation of function into behaviour (process 10), often seen as the main activity in the domain of requirements engineering, can be supported by analogy processes. For example, Maiden and Sutcliffe [17] present examples of behaviour specifications of a flexible manufacturing system (FMS) based on similarities with the domain of air traffic control (ATC). Figure 9 depicts key features to infer the similarities between the two domains, which can be used to derive and match functions of FMS and ATC systems. Specifically, functions such as “prevent collisions” and “ensure movements according to the pre-defined plan” can be seen as general goals of both systems. Behaviours of one system can then be mapped onto the other.

4.2 Synthesis and Creativity
Synthesis generates a design solution in terms of a point in the structure state space, and subsequently produces an external
representation of that structure. In the situated FBS framework, this design step is composed of activities 11 and 12, Figure 10.

![Figure 10. Synthesis.](image1)

Synthesis does not modify the design state space. Synthesis uses the variables produced by formulation without adding new ones. In our definition, all techniques and strategies used for searching a design solution operate on the values of structure variables rather than on the structure variables themselves. This view excludes a direct association of creativity with the design step of synthesis. The connection between synthesis and creativity lies in the interpretation of synthesised structure.

4.3 Analysis and Creativity

Analysis derives behaviour from synthesised design structure. In the situated FBS framework, this design step is composed of activities 13 and 14, Figure 11.

![Figure 11. Analysis.](image2)

Creativity is generally not desired in analysis, as the primary purpose of this design step is to prepare for the evaluation of the design solution against the pre-determined set of criteria, i.e. within the bounds of the current design state space. However, it is often during the act of analysis that new design issues and ideas emerge that may lead to additions to the design state space. One driver is the interpretation of structure (activity 13), providing the potential for the process of emergence to occur. Examples presented by Jun and Gero [15] are concerned with the emergence of shapes through re-representation of external structure. The wide range of drafting tools available may support re-representations, such as 2D-, 3D-, “fly-through-” and simulation models. Each of these models can enable the discovery of specific types of design issues.

Emergence during the analysis step is not limited to the structure level. New behaviour often emerges when using computational analysis tools that derive more performances from a given structure than necessary for the currently intended evaluation (activity 14). As an example, assume the designer of a new material flow system, interested in evaluating the speed of that system. The simulation tool used to perform the analysis calculates not only speed, but also machine utilisation. This can be seen as the generation of an additional, explicit behaviour variable that may be used to augment the behaviour state space. The creativity in this case can be seen in the interaction between the designer and the analysis tool.

The behaviour derived by an analysis tool may not be explicit; i.e. it has not been pre-programmed to be derived but can be constructed by the designer recognising patterns in the (visual) representations provided by the tool. This is the class of emergent behaviour that is typically studied in complex systems and Artificial Life research [14]. For example, Figure 12 shows the display of a Virtual Reality tool simulating pedestrian movement through an early design layout of a shopping mall [7]. Let us assume that this simulation has been used initially with the intention to derive average times for walking through the building. However, while executing the simulation model, the designer may discover a “jamming” behaviour emerging as a new issue in the design of the mall.

![Figure 12. Screenshot of a Virtual Reality simulation of pedestrian movement (taken from [7]).](image3)

4.4 Evaluation and Creativity

Evaluation assesses the design solution on the basis of the formulated criteria, i.e. by comparison of the behaviour derived from the design solution with the expected behaviour. In the situated FBS framework, this design step is activity 15, Figure 13.
In the context of evaluation, the term creativity is usually applied with a negative connotation; in a way similar to the analysis step. However, evaluation is often the precursor of a modified design state space, especially in the case of inadequate design performance that require major revisions of design concepts. In addition, evaluation is sometimes not a purely objective, mathematical comparison between two well-defined performances but relies on subjective judgement. This can also occur in case of conflicts between several “objective” behaviours. Saunders and Gero [19] have shown how evaluations of a design’s aesthetic value are based on subjective judgement that is the result of previous evaluations of aesthetic value.

4.5 Documentation and Creativity
Documentation produces an external representation of the final design solution for purposes of communicating that solution. This step is usually required to provide the builder, manufacturer or implementer with a “blueprint” for realising the design solution. In the situated FBS framework, this design step is composed of activities 12, 17 and 18, Figure 14.

Creativity plays no direct role here, because the ongoing process of design generation is usually terminated once the design has been released for documentation.

4.6 Reformulation Type 1 and Creativity
Reformulation type 1 modifies the structure state space. In the situated FBS framework, this design step is activity 9, Figure 15.

This design step is based on creative processes that may produce new structure variables. Any of three classes of input is needed for these processes: external requirements on structure, external representations of existing design structure, and interpreted structure representations.

The interpretation of external requirements on structure (activity 3) can bring about new structure variables in two cases. In the first case, modified external requirements are given to the designer after commencement of the design process. Here, the creativity is located in the environment in which the design process is carried out rather than in the design process itself. In the second case, the same external requirements as given at the outset of the design process are interpreted differently by the designer. This locates the creativity in the process of interpretation.

The interpretation of external design structure (activity 13) can involve creative processes that generate new structure variables. One example is the process of emergence that has also been described as a location of creativity in analysis. Another well-known example is the process of analogy. Here, an external structure is a source design exhibiting identical behaviour as the current (target) design. The matching and then mapping of the source structure onto the target structure is the creative element of interpretation.

Reflection on interpreted structure (activity 6) constructs new structure variables without the use of any external representations. This creative activity is frequently used across the design disciplines to lead the design process into new directions [21]. Reflection on structure is the best-studied type of the reflection processes.

For example, the domain of drug design uses reflection on structure to incrementally modify molecules to generate new drugs that meet specified behaviours. Here, reflection is often implemented as crossover (or combination) and mutation processes, embedded in design methodologies using Genetic Algorithms (GAs). GAs simulate biological evolution by applying crossover and mutation operators over populations of candidate structures. Candidates are selected using a fitness function that measures individual performances that correspond to the values of a given behaviour. Figure 16 shows examples of crossover and mutation operating on organic molecules.
4.7 Reformulation Type 2 and Creativity

Reformulation type 2 modifies the behaviour state space. In the situated FBS framework, this design step is activity 8, Figure 17.

This design step is based on creative processes that produce new behaviour variables. Any of four classes of input is needed for these processes: external requirements on behaviour, external representations of existing design behaviour, interpreted behaviour representations, and interpreted structure representations.

The interpretation of external requirements on behaviour (activity 2) can produce new behaviour variables in an analogous way as in reformulation type 1. Creativity is located either outside the system via modified requirements or inside the system via modified interpretation.

The interpretation of external design behaviour (activity 19) can produce new behaviours to alter the behaviour state space. This activity often uses emergence to reconceptualise current behaviours, which has mainly been studied in software requirements engineering [18].

Reflection on interpreted behaviour (activity 5) constructs new behaviour variables without the use of any external representations. It reconceptualises current behaviours in a similar way as interpretation. Its underlying mechanism can be assumed to be emergence, although little research has been done in this area.

The derivation of additional behaviour from structure (activity 14) can drive reformulation type 2 in the same way as described for the analysis step. Creativity here is fostered by the interaction between designers and computational tools. Another way to derive new behaviour from structure is via analogy. Consider the following example: A lamp designer, after coming home from work, looks at a book that still lies half open on his bedside table, Figure 18(a). He becomes aware that the front and back covers of the book can be thought of as defining an arched aperture that can be expanded or reduced by opening or closing the covers. This can be viewed as behaviour derived from an abstraction of the book’s structure. The designer realises that in the lighting domain this behaviour could be used as a physical mechanism to fulfil the function of dimming light. He finds this idea interesting and decides to change the design of a desk lamp he is currently working on by implementing this physical dimming mechanism instead of the originally intended electrical one. Figure 18(b) shows a CAD model of the new lamp. It incorporates behaviour and structure features of the book as the source design.

4.8 Reformulation Type 3 and Creativity

Reformulation type 3 modifies the function state space. In the situated FBS framework, this design step is activity 7, Figure 19.

This design step is based on creative processes that produce new function variables. Any of four classes of input is needed for these processes: external requirements on function, external representations of existing design function, interpreted function representations, and interpreted behaviour representations.
The interpretation of external requirements on function (activity 1) can produce new function variables in an analogous way as in reformulation type 1 and 2. Creativity is located either outside the system via modified requirements or inside the system via modified interpretation.

The interpretation of external design function (activity 20) can produce new functions to alter the function state space. Maiden et al. [16] have presented an example of designers of air traffic management software who combined existing software functions into new ones during a creativity workshop. Here, the two functions “to allow air traffic controllers to maintain an accurate mental model of the air space” and “to offer new types of situational display to air traffic controllers” were combined into the new function “to allow air traffic controllers to rewind and fast-forward aircraft movements to develop their mental models of the air space before taking responsibilities for decisions that they will make”.

Reflection on interpreted function (activity 4) constructs new functions without the use of any external representations. Little research has been done in this area.

The derivation of function from behaviour (activity 16) can result in new functions to be incorporated in the design. Schön [20] has presented the example of Scotch Tape, whose initial function was “to mend books”. However, the people buying this product invented additional functions, such as “to wrap packages”, “to hang posters on the wall” and “to curl hair”. These functions have been likely to be derived from the behaviour of removable adhesiveness. These unexpected functions subsequently led to adaptations of the product to different applications such as packaging, decorating and hair curling. Finke [9] has provided a number of other examples of functions that can emerge through reasoning about possible behaviours of a given object, Figure 20.

5. CONCLUSION

The ontological framework of creative designing, presented in this paper, supports the view of designing as the prototypical example of a creative human act. We have shown that there is the potential for creativity to occur at most steps in the design process. Reformulation (of all three types) is the design step that is most extensively based on novel discoveries and the construction of new issues during the ongoing design process. The design step of synthesis does not modify the design state space, and therefore does not directly include creative activities. This is in contrast to most other models of synthesis that view it as the major creative act in designing. This is because they do not differentiate in the same way between formulation and synthesis.

Locating design creativity in an ontological framework can enhance the development of better computational tools to support creativity. This is based on the independence of an ontological view of creative designing with respect to its embodiment. All creative processes and activities in designing can be located in human designers, their tools and the interaction between the designers and the tools.

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7. REFERENCES


