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# CREATIVE SYSTEMS THAT GENERATE AND EXPLORE

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**Abstract:** This paper describes *generate and explore* as a paradigm for models of computational creativity. It describes the difference between search within a conceptual space and exploration in changing conceptual spaces. Three types of exploration are described and existing examples of them are presented. It describes generate and explore as a potential basis for generating utility, novelty and surprise in models of computational creativity. The paper identifies the role of interpretation in creative systems and ways that it can lead to exploration.

***Keywords:*** *computational, creativity, situated, interpretation, exploration*

## 1. Introduction

Studies of designers thinking aloud repeatedly show that designers change their conception (or framing) of the design task during the process of designing (Cross, 2004; Dorst & Cross, 2001; Schon & Wiggins, 1992; Schön, 1983; Seelig, 2012; Suwa, Gero, & Purcell, 2000). Since design is an activity constrained by the designers' own conception what it is that they are doing (Gero, 1990), this shifting of the frame allows the designer to produce designs that were previously inaccessible.

More formally, a system can be described as having a space of possible designs (a state space). Creativity can occur through search of this space, where the frame does not change, producing designs that are distinguishably similar as the product of what could be described as a single grammar. Creativity can also occur through exploration, where the frame does change, which potentially produces deisgns that are both novel and dissimilar to existing designs produced by the system (Boden, 1991; Gero, 1990, 1994).

Some models of computational creativity can be described through the paradigm of *generate and test* in which a space of possible designs is searched through a cycle of generating and then evaluating the product of generation (Langley, 1987). Many useful designs have been produced in this way, such as a genetic programming system that can lead to patentable designs (Koza, 1992; Koza, Al-Sakran, & Jones, 2005). A limitation of this paradigm is that it does not capture the movement between different frames for creative activity.

A different paradigm is proposed: *generate and explore* that describes systems that generate designs within a frame and also move between different frames. Models that generate and explore are capable of changing the space of possible designs in some way. The two paradigms differ in multiple ways. For example, generate and test assumes a space of possible designs that is unchanging and is useful for comparing techniques for search within a space. Generate and explore in contrast assumes a space of possible designs that changes and is useful for comparing ways in which this exploration can occur.

In this paper, the space of designs that a creative system is capable of producing, without limits upon time, resources or experiences, will be referred to as its universe. This space is bounded by limits upon the structure of knowledge within the system, such as language. Within a particular state of the system it can access a smaller space within this universe, based upon the experiences that it has had (or its knowledge) and the notions to which it is currently attending. This reduced space will be referred to as the conceptual space of the system.

The claim being made is that systems that generate and explore are appropriate for modelling human-like phenomena of creative design. The paper explains the role of interpretation in creative systems and ways that it can lead to exploration. Figure 1 illustrates the movement between conceptual spaces during creative activity, inspired by studies of designers engaged in creative activity, in which unexpected discoveries during interpretation lead to a changed framing of the design problem (Kelly & Gero, 2014; Suwa et al., 2000; Suwa & Tversky, 1997). The rectangle in Figure 1 represents the universe of the designer. Each ellipse represents the conceptual space within which the designer searches for a solution. As design activity progresses, designers are observed to search within a conceptual space as well as explore the universe by shifting their conceptual space.

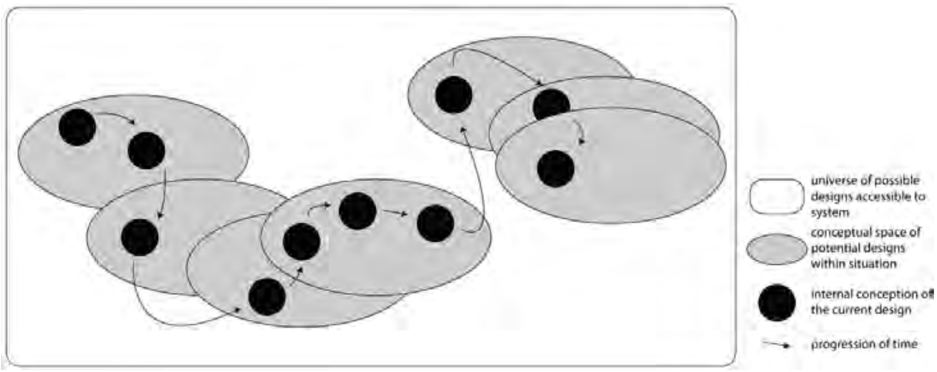



Figure 1 Movement between conceptual spaces during creative activity (after Kelly & Gero, 2014)

## 2. Systems that generate and explore

The distinction between search and exploration has significance within systems that operate (reason/generate/act/interpret) within a subset of the states within which they are capable of operating. The knowledge of the system, learnt from experience within the universe of the system and stored, will be denoted as $U_!$. At a point in time, a system attends to parts of $U_!$ at the expense of others. This implies a conceptual space $C$ within which the system operates. This conceptual space can change when something causes the system to attend to different parts of $U_!$. For example, a designer that has been fixated upon a theme might pay attention to another theme.

Generation $G$ can be formulated as a function of conceptual space $C$ that produces a design $\alpha$, Equation 1. In systems that generate and explore it is necessary that $C \subset U_!$. This is distinct from systems that generate and test where it is possible (but not necessary) that $C = U_!$.

$$G(C) \rightarrow \alpha \tag{1}$$

Generate and explore is further distinguished by a second function $\Gamma$ that produces a new conceptual space from the current conceptual space, Equation 2.

$$\Gamma(C_i, U_!) \rightarrow C_{i+1} \tag{2}$$

One reason for moving between conceptual spaces is that in models where $U_!$ is large, combinatorial explosion may make it computationally advantageous to restrict $C$.

### 2.1 Changing conceptual space

For illustrative purposes it serves to adopt a 'classical' view of creative systems as having a conceptual space represented by a number of variables. For example, a potential design developed by a system can be described by a number of design variables (Gero, 1990).

In this understanding, the language and structure of the system define the potential variables of the system as the set $V_U$. The experiences of the system limit the variables to a subset of these, the set $V_{U_!}$. Finally, the current conceptual space limits the variables to a subset of these, the set $V_C$. These relationships are expressed by Equation 3.

$$V_C \subseteq V_{U_!} \subseteq V_U \tag{3}$$

The conceptual space may further define a region within this space where design is occurring, represented as limits upon variables of the type $v_i \in V_C: x < v_i < y$.

The ways in which changes to conceptual space may occur can be listed as: (i) changes to the limits upon variables (expansion or reduction of space within the same variables): (ii) changes to the context in which the system conceives of variables; and (iii) and changes to the membership of $V_C$.

A simple example serves to demonstrate these three changes. Consider a designer designing a chair. One variable amongst others within $V_C$ is for the *number of legs* represented by $n$. Within their current conception of the design task (perhaps based upon past experiences) they are working within the limits such that $n \in \mathbb{N}$ and $1 \leq n \leq 4$. Within this example a narrative can be contrived to describe the three types of changes.

1) **Changes to limits of variables.** The variable for *number of legs* can be extended such that $1 \leq n \leq 6$ or perhaps the boundary case $0 \leq n \leq \infty$. In this new conceptual space the chair may have 0 legs.
2) **Changes to the nature of variables.** The variable may be reconceived by the system such that $n \in \mathbb{N}$ becomes $n \in \mathbb{R}$, where $\mathbb{R}$ is the set of real numbers. In this new space the chair may have 4.5 legs.
3) **Changes to the membership of the set of variables.** Perhaps in response to 1., the system introduces a new variable for *number of strings connecting chair to ceiling* and ceases to attend to the variable for *number of legs*.

This list represents a catalogue of ways in which changes to conceptual space may occur, however it does not give examples of how they occur (computationally) nor begin to give an account for how they occur in designers (phenomenologically).

## 3. Exploration through interpretation

The elements of a system at a point in time can be listed as: (i) a knowledge structure (implying $U$); (ii) experience (implying $U_!$); and (iii) a conceptual space (implying $C$). It has been proposed that generation occurs within $C$ due to the likelihood that in most systems $U_!$ is too large for effective search. The question remains: How does $C$ change?

One proposed response is that the past experiences of the system are utilised during interpretation (Kelly & Gero, 2014). The notions that are not a part of $C$ implicitly have a location in relation to $C$ are shown in Figure 2. This relationship between notions and the space defined by $C$ may be defined in a number of ways. For example, it could by the Euclidean distance of a notion from $C$ or it could be defined in terms of the number of connections away from $C$.

Whilst certain notions are contained within $C$ (forming explicit expectations), the notions outside of $C$ have an implicit relationship with the conceptual space. Interpretation can be described as a process that utilises both explicit and implicit expectations that are able to change $C$. Other work has explored how this can occur through expectations that change during interpretation (Kelly & Gero, 2014). Interpretation can be conceived of as a 'pull' from the explicit expectations to construct what is expected, as well as a ‘push’ from the data to be recognised regardless of expectations (Gero & Kannengiesser, 2004).

One reason why interpretation is a good choice for the process in which exploration occurs is that interpretation is well suited to parallel processing, as it moves from a single source to a single internal representation using a space of possibilities. In contrast, generation is concerned with the production of a single artefact from a space of possibilities (combination).

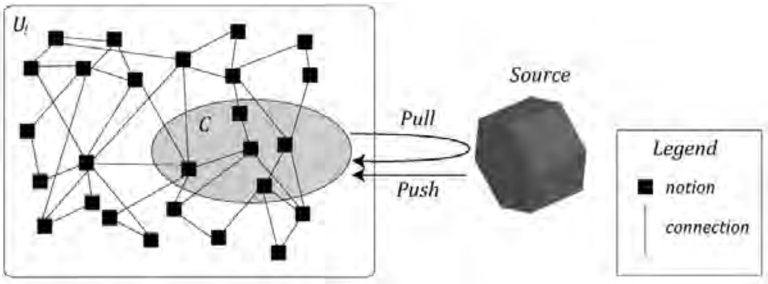



Figure 2 Implicit expectations as notions proximal to explicit expectations within the knowledge structure

### 3.1 Changing space

The three types of change to $C$ described in Section 2.1 can take place then through the changes to notions making up $C$. Notions may be introduced or removed from the conceptual space such that variables are extended, changed or introduced.

One way of conceiving of notions is as concepts that arise from perception through abstraction (Barsalou, 1999, 2005). A detailed account of how notions may be represented geometrically is presented by Gärdenfors (2000). Figure 3 depicts the way that concepts can be formed as convergence zones over information in perceptual domains.

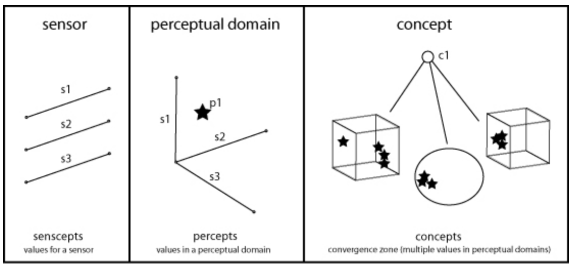



Figure 3 A concept represented as a convergence zone of points in conceptual space.

New notions introduced to the conceptual space and the removal of previous notions may introduce changes to the space through extension of variables, changes to variables and new variables at the expense of others.

Each notion $c \in U_!$ is taken to be a prototype with defined variables and limits upon those variables based upon past experiences. The collection of notions making up a specific space $C_1$ then has a set of variables $V_{C_1}$ that can be related with those variables in each $c \in C_1$. This implies a function $\Upsilon$ within the system capable of producing $V_C$ from the conceptual space, Equation 4.

$$\Upsilon(C_1) \rightarrow V_{C_1} \quad (4)$$

Consider then that a transformation occurs during interpretation that changes this conceptual space, through use of Equation 2, perhaps through the introduction of a new concept to the conceptual space:

$$\Gamma(C_1, U_!) \rightarrow C_2 \quad (5)$$

Depending upon the definition of $\Upsilon$ within the system, the new set of variables $V_{C_2}$ may exhibit any one of the three changes described in Section 2.1. Creative systems that generate and explore can experiment with the way that $\Gamma$ and $\Upsilon$ are implemented.

## 4. Computational models of generate and explore

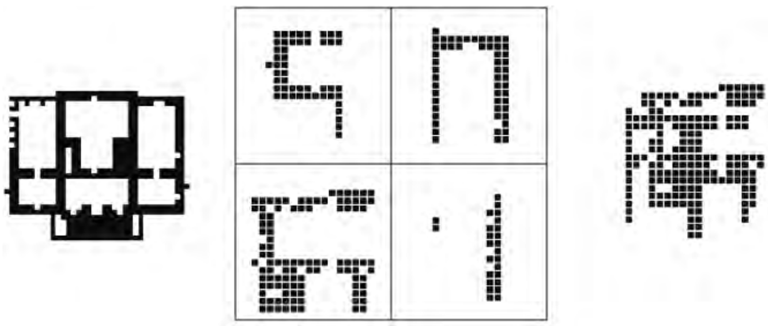
### 4.1. Changing limits of variables through interpretation

A generate and explore system was implemented in the domain of floor plans (Kelly & Gero, 2014; Kelly & Gero, 2011). The system holds concepts at two levels of abstraction in linked self-organising neural networks. The system was trained on floor plans by three architects, such that it holds knowledge of relationships between 16x16 pixel feature maps that make up floor plans, Figures 4(a) and (b).

The system cycles through a sequence of generation followed by interpretation, where exploration can occur during interpretation. The conceptual space $C$ is defined by four concepts currently attended to by the system, e.g. Figure 4(b). Generation is a naïve process by which the system utilises these explicit concepts (16x16 pixel representations) within the conceptual space and randomly places them within a 24x24 pixel 'canvas', Figure 4(c).

The system then interprets what it has produced, by a saccade across the canvas interpreting 16x16 sized perceptual 'chunks' and attending to the internal representations produced. In most cases the same 4 concepts that were used for drawing are found within the canvas, however in some cases the system finds 'unexpected' elements in what it has drawn. These come from the implicit expectations that are not a part of $C$ but are implied by $C$, and through interpretation are brought into $C$. Figure 5(a) shows examples of 4 parts of the canvas that have been paid attention by the system. One of these, the lower left, has come from implicit expectations.

Using the formulation from Section 2.1 each conceptual space $C_i$ that the system occupies implies a limited range of potential designs with variables $V_{C_i}$ given the method of generation $G$. When, through interpretation, the sytem changes to $C_{i+1}$ the limits to these variables change.



(a) (b) (c)

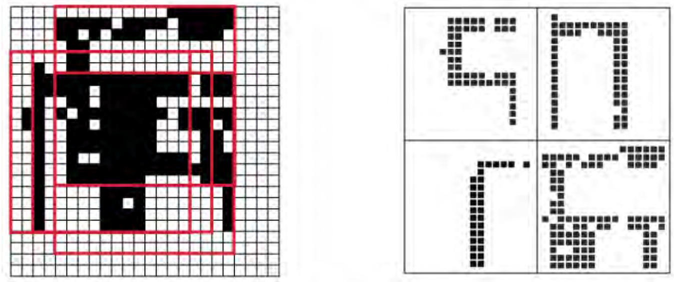
Figure 4 (a) A representation of the original floor plan; (b) a set of four 16x16 feature maps as current $C$; and (c) the representation produced through $G(C)$.

### 4.2 Changes to the nature of variables

Two examples serve to demonstrate how the computation of changing variables may occur.

#### *4.2.1 Salience weighting*

Gärdenfors' (2000) describes *salience weighting* as the way that different concepts can weight the variables that define them differently. Geometric dimensional scaling is used to distort the way that measurements within the conceptual space are carried out. Figure 6 shows an example of three concepts in conceptual space before and after dimensional scaling. The conceptual space has been partitioned using Voronoi tessellation. These divisions indicate which regions of the space are associated with each concept. When a point in space, $c_x$, is interpreted using an AS A relationship it is associated with the region in which it lies (Pylyshyn, 1977). The dimensions of this space map onto the dimensions of the sensors of the system. The concepts here each represent regions within this space. The 2D space in Figure 6 might represent one perceptual domain of related sense data (e.g. colour through hue and saturation) and a concept might bring together many such domains (e.g. form, colour, sound, smell).



(a) (b)

Figure 5 Interpretation within the system occurs through a saccade from top left to bottom right: (a) the four areas used for construction during interpretation marked by red boxes; (b) the concepts constructed through interpretation, where the lower left comes from implicit expectations.

In the partitioning of space before scaling $c_x$ is interpreted as an instance of $c_1$. However, if the $x$ dimension is scaled due to a greater salience than the $y$ dimension then it leads to a different partitioning of space, such that the same $c_x$ would now be classified as an example of $c_3$. The example shows how salience weighting can be used in two dimensions, and by extension into *n* dimensions.

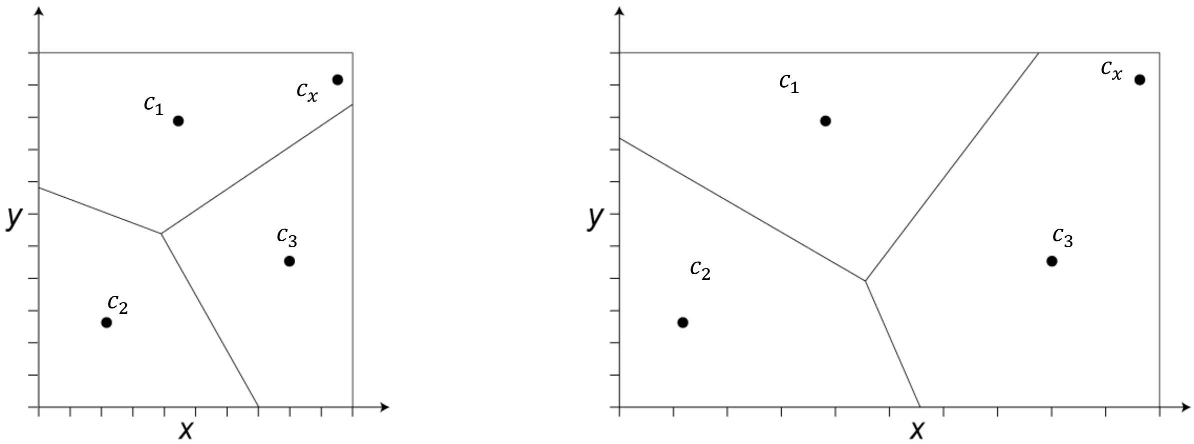



Figure 6: Point $\boldsymbol{c_x}$ is classified through Voronoi partitioning as an example of $\boldsymbol{c_1}$ prior to salience weighting of dimension $x$ and $\boldsymbol{c_3}$ after salience weighting (source: Gärdenfors 2000)

*4.2.2 Genetic expression in evolutionary design*

In evolutionary models of design a genotype represents the design variables. Genotypes are expressed as design phenotypes and some kind of a fitness function may used for testing generated candidates. This formulation is an example of generate and test, however an interesting variation has been proposed inspired by epigenetics, in which the transformation from genotype to phenotype can be influenced by what is in the genotype (Gero & Shi, 1999). In this example the nature of the variables may change depending upon Γ and ϒ. This is an example of exploration during generation rather than during interpretation as in the previous examples.

### 4.3 Changing of the parameters of conceptual space

Many systems have been developed that make analogies through the mapping of function, behaviour and structure of a source onto a target (Gentner, 1983; Gentner & Forbus, 2011). The production of analogies occurs within the process of interpretation of intrinsic or extrinsic source. Designers can be seen to introduce new variables into the design process through analogy making. For example, Vattam et al (2010) give an account of how designers use biological analogies to introduce new variables (using an analogy with the small intestine) into the conceptual space (in designing a water desalinator).

Systems that make anologies demonstrate the way that new variables can be brought into the conceptual space. In the interpretation of a source the conceptual space may be altered through the introduction of outside concepts that come from the experienced universe of the system. Typically this occurs through a partial mapping of a representation of the source onto a representation of the target. An outcome from this is that notions from the target in addition to the mappings can be brought into the conceptual space.

## 5 Discussion

This paper has introduced the paradigm of generate and explore as appropriate to developing models of computational creativity. Exploration has been identified as the movement of a system between different conceptual spaces or frames during creative activity. Interpretation has been identified as a process during which exploration can occur. The argument for generate and explore comes from this recognition of the role of interpretation in creativity; the motivation of this paper is towards models of computational creativity that model interpretation in human-inspired ways.

### 5.1 Models that explore through interpretation

In this paper, three ways in which the conceptual space of a creative system can change have been identified as changes to the limits upon variables, changes to the nature of variables and changes to the membership of the set of variables. Through the examples provided, it has been seen that the implementation of interpretation can model each of these types of exploration.

What is occurring in these examples? The common theme is that the difference between the conceptual space and the larger space of experiences facilitates exploration. The system brings its past experiences into the current activity with a resulting change to conceptual space. Three of the examples show ways that this can be achieved through the process of interpretation, whilst one provides a way that this can be achieved through generation. The assumption is that a change to conceptual space changes what the system is doing, such as how it will generate designs and how it will interpret stimuli in future.

The question of how a system explores can be re-represented as the question: How does a system goes about navigating its own knowledge? The paradigm of generate and explore looks towards systems in which this movement can occur through both generation and interpretation – and studies of human designers suggest that this exploration often occurs when interpreting.

### 5.2 Towards models that explore in a useful/novel/surprising way

The artefacts produced by models of computational creativity can be evaluated upon the basis of value, novelty and surprise (Maher, 2010). It is fitting to utilise this definition in the development of computational models of creativity and the way in which they explore. The three types of exploration were identified in Section 2.1, but why might they be utilised?

Exploration within a system can be considered *useful* if it leads towards a conceptual space within which a creative artefact can be found. If a system begins with one conception of a problem, and through creative activity reframes this problem in attempting to find a solution then this would be an example of useful exploration. Exploration within a system can be considered *novel* if it differs from existing types of exploration observed in models of creativity. For example, many existing models of creativity implicitly utilise a form of exploration. A novel type of exploration would be different to these. Exploration within a system can be considered *surprising* if the way in which it is novel is unexpected.

This work proposes a paradigm recognises the role of exploration in models of computational creativity.

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