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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 designs that are both novel and dissimilar to existing designs produced by the system (Boden, 1991; Gero, 1990, 1994). Exploration distinguishes the activity of creating a space in which to search, from the search of that space (Gero, 1994). This is distinct from common usage of the term explore, such as in Finke et al's (1992) "Geneplore" model in which exploration refers to a number of different types of search.

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 however is that it does not capture the movement between different frames for creative activity.

A different paradigm that is a fit for models of creativity is that of *generate and explore* that describes systems that generate designs within a space of possible designs and also move between different spaces. 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 construct of the universe is drawn from the nomenclature of Wiggins (2006) and is useful for conceiving of the space of a system in the broadest sense; the limitations of what it is capable of representing given that it has a defined language and limited space.

The system within a particular state can access a subset of 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.

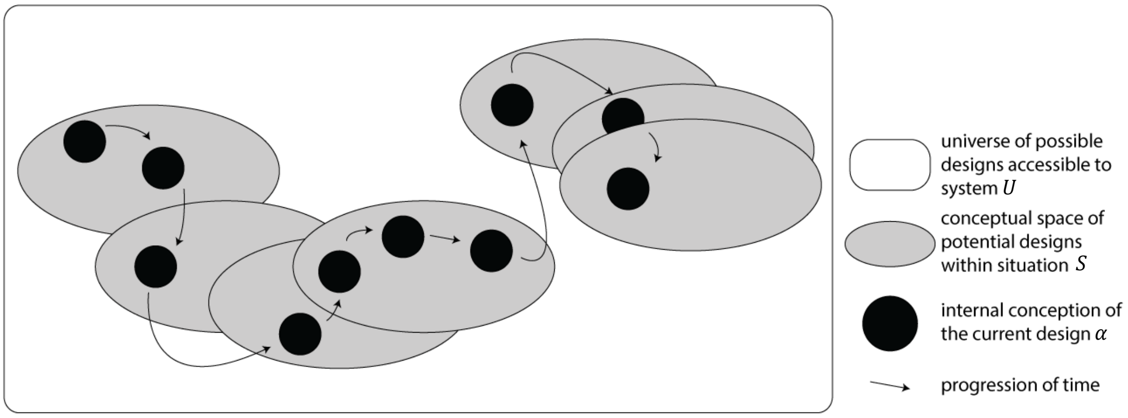


Figure 1 Movement between conceptual spaces during creative activity (after Kelly & Gero, 2014)

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 environment of the system and stored, will be denoted as $U_!$ (after Wiggins, 2006). $U_!$ changes as the system has experiences. At a point in time, a system attends to parts of $U_!$ at the expense of others. This implies a conceptual space S within $U_!$ 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. In systems that generate and explore it is necessary that $S \subset U_!$. This is distinct from systems that generate and test where it is possible (but not necessary) that $S = U_!$.

Generation G can be formulated as a function of conceptual space S that uses concepts to produce a design element α, Equation 1.

$$G(S) \rightarrow \alpha \quad (1)$$

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

$$\Gamma(S_i, U_!) \rightarrow S_{i+1} \quad (2)$$

(2) 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 potential variables of the system, perhaps infinite, can be designated as the set V_U. The experiences of the system limit the variables that the system has knowledge of to a subset of these, the set $V_{U_!}$. The current conceptual space limits the variables to a subset of these, the set V_S. These relationships are expressed by Equation 3.

$$V_S \subseteq V_{U_!} \subseteq V_U \quad (3)$$

Within the current conceptual space S, a region where design is occurring can be identified by variables, the context of those variables and the limits upon these variables of the type $v_i \in V_S : x < v_i < y$.

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. Where search allows for these changes within S, exploration allows for movement elsewhere within $U_!$.

A simple example can demonstrate these three changes. Consider a designer designing a chair. One variable amongst others within V_S is for the *number of legs* represented by n. Within their current conception of the design task (perhaps based upon past experiences) the designer is 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 context 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

In systems that generate and explore there is then a difference between 'what the system knows', the experiences represented by $U_!$, and 'what the system knows now', in the smaller space S. There are many implications of this distinction of situatedness (Clancey, 1997). Most salient here is that in some systems (e.g. the case of human cognition) $U_!$ is extremely large, making combinatorial explosion an issue for search by generation within $U_!$. The suggestion for models that generate and explore is that generation, with its need for combination, can occur within the confines of S, so long as the system can move towards a useful S. The question remains: how does this movement occur?

One proposed response is that movement of S can occur during interpretation, which lends itself to parallel processing and can be done within the much larger space of $U_!$-in-the-context-of-S (Kelly & Gero, 2014).

For parsimony all units of knowledge represented in the system will be referred to as concepts. The concepts that are not a part of S (that are outside of it) implicitly have a location in relation to S, shown in Figure 2. This relationship, between concepts outside of S and S itself, may be defined in a number of ways. For example, it could by the Euclidean distance of a notion from S or it could be defined in terms of the number of connections away from S.

The significance of this is that the concepts outside S have an implicit relationship with S that is made use of during interpretation. Interpretation is defined as "a process by which the experiences of the system are used to create an internal representation from a source" (Kelly & Gero, 2014). This process involves a 'pull' from the concepts within S, which will be referred to as explicit expectations. In this way the system attempts to interpret the world using the concepts within S.

There is also a 'push' from the data to be recognised regardless of expectations (Gero & Kannengiesser, 2004). The system can use the concepts outside of S, which will be called implicit expectations, during interpretation. In this way, through a movement to implicitly expected concepts, the system can explore through movement to another S during interpretation (Kelly & Gero, 2014).

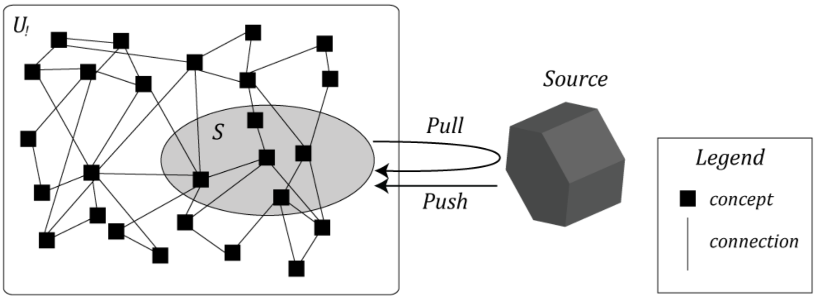


Figure 2 Implicit expectations as concepts proximal to explicit expectations within the knowledge structure

3.1 Changing space

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

Concepts are considered to arise through abstraction from sensation (Barsalou, 1999, 2005). A detailed account of how concepts may be represented geometrically is presented by Gärdenfors (2000). New concepts introduced to the conceptual space and the removal of previous concepts may introduce changes to the space through extension of variables, changes to variables and new variables at the expense of others.

Each concept $c \in U_!$, adopting again the classical view, can be taken as having a number of defined variables and limits upon those variables based upon past experiences. The collection of concepts making up a specific space S_1 can be used to produce the set of variables V_{S_1} where this set includes information about types and constraints. A function Υ within the system is defined as producing V_S from S_1, Equation 4.

$$\Upsilon(S_1) \rightarrow V_{S_1} \tag{4}$$

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:

$$\Gamma(S_1, U_!) \rightarrow S_2 \tag{5}$$

Depending upon the definition of Υ within the system, the new set of variables V_{S_2} may exhibit any one of the three changes described in Section 2.1. Creative systems that generate and explore are able to experiment with different ways in which Γ and Υ can be implemented.

4. Computational models of generate and explore

Three different systems can be used to give an example of each of the types of change to variables that can occur through exploration.

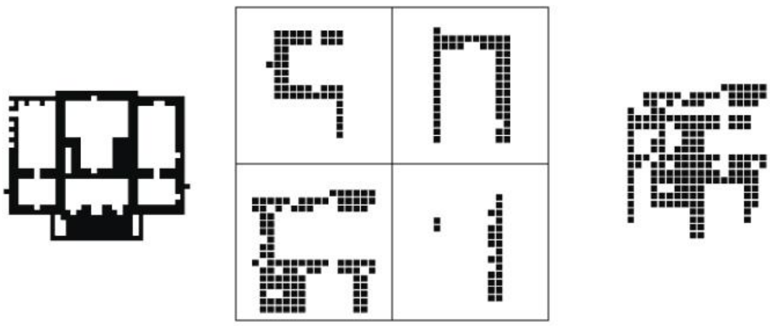
4.1. Changing limits of variables through interpretation

A generate and explore system was implemented in the domain of floor plans (Kelly & Gero, 2011; Kelly & Gero, 2014). The system is trained upon 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.

The conceptual space S is made up of four concepts currently attended to by the system, e.g. those represented in 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 internal representations produced correspond to the 4 concepts that were a part of S prior to drawing. In some cases, however, interpretation produces internal representations that come from $U_!$ outside of S. These come from the implicit expectations that are not a part of S but are implied by S, and through interpretation are brought into S. Interpretation was implemented in the system as a linear process of pull (from S) and push (activation of concepts outside but related to S) that repeats until an internal representation is produced (Kelly, 2011). Figure 5(a) show an example 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 S_i that the system occupies implies a limited range of potential designs with variables V_{S_i} given the method of generation G. When, through interpretation, the system changes to S_{i+1} the limits to these variables can change.

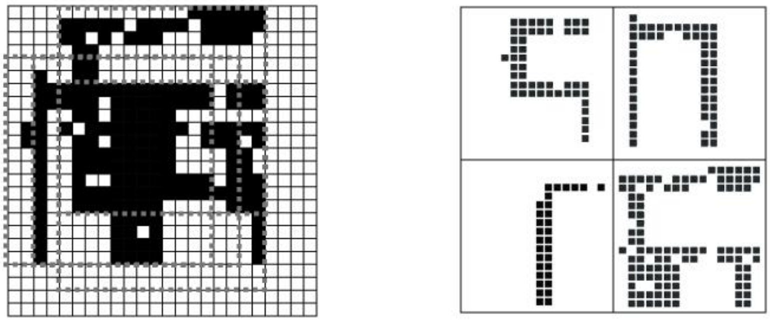


(a) (b) (c)

Figure 4 (a) A representation of the original floor plan; (b) a set of four 16x16 feature maps as current S; and (c) the representation produced through $G(S)$ (source: Kelly, 2011)

4.2 Changes to the context of variables

An example of salience weighting serves to demonstrate the computation of changing the context of variables during exploration. Gärdenfors’ (2000) describes *salience weighting* as the way that different concepts can weight the variables that define them differently. This is done by geometric dimensional scaling that distorts the way that measurements within the conceptual space are carried out.

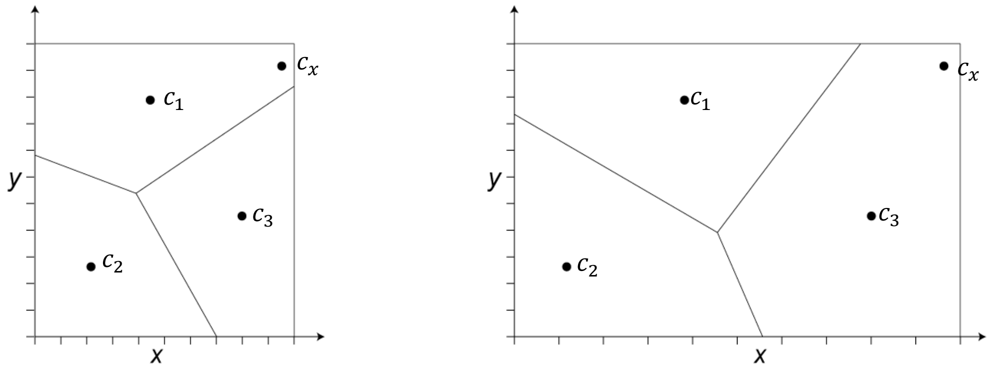


(a) (b)

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 dashed grey lines; (b) the concepts constructed through interpretation, where the lower left comes from implicit expectations (source: Kelly, 2011)

Figure 6 shows an example of three concepts, c_1, c_2, c_3, in conceptual space before and after dimensional scaling. The dimensions of this space map onto the dimensions of the sensors of the system. 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). This conceptual space has been partitioned into regions using Voronoi tessellation, taking the points in conceptual space representing each experienced concept as the centre of each region during tessellation (Gärdenfors, 2000). A point in space, c_x, representing incoming data from sensors in a system, might be interpreted using an AS A relationship, to be associated with the region in which it lies and in this way the concept associated with that region (Pylyshyn, 1977).

In the partitioning of space before scaling, Figure 6(a), c_x is interpreted as an instance of c_1. However, if the x dimension is scaled due to perhaps a greater salience than the y dimension then it leads to a different partitioning of space such as that shown in Figure 6(b), so that the same c_x would now be classified as an instance of c_3. The example shows how salience weighting can be used in two dimensions to change the context of variables, and by extension into *n* dimensions.



(a) (b)

Figure 6: A conceptual space following Voronoi tessellation where: (a) $\boldsymbol{c_x}$ lies within the region of $\boldsymbol{c_1}$; and (b) following salience weighting of dimension x, $\boldsymbol{c_x}$ now lies within the region of $\boldsymbol{c_3}$ (source: Gärdenfors 2000)

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 can occur within the process of interpretation of an 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 analogies demonstrate one way in which the conceptual space can change. In the interpretation of a source, S_i may move to S_{i+1} through the introduction of outside concepts that come from the experienced universe of the system $U_!$. Typically this occurs through a partial mapping of a representation of the source onto a representation of the target. An outcome from this exercise of mapping is that concepts from the target can change the conceptual space. The example from Vattam et al could be described as a conceptual space S that contains no notion a "small intestine". During interpretation an implicit concept, from the experiences of the system but outside of the current conceptual space, is attended to, changing the conceptual space.

5 Discussion

This paper has described generate and explore as appropriate for developing models of computational creativity. Exploration has been identified as the movement of a system between different conceptual spaces during creative activity. Interpretation has been identified as one way in which exploration can be computationally implemented. 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 context of variables and changes to the membership of the set of variables. Through the examples provided in Section 4 it has been suggested 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 and the examples show ways that this can be achieved through the process of interpretation. 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.

The suggestion is that models of creativity can explore through interpretation. There are many ways in which exploration can be implemented and examples have been described. There is a call for adopting the paradigm of generate and explore to produce different models of creativity, with attention to how these models explore. The specific implementations of exploration can be assessed for utility, novelty and surprise in the way in which they explore.

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