Ekphrasis as a Basis for a Framework for Creative Design Processes

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This paper introduces the notion of ekphrasis in the arts as a basis for developing a framework of creative designing. Ekphrasis is the transformation of a concept from one medium or domain (e.g. sculpture) to another medium or domain (e.g. music). When used in design, ekphrasis enables the use of new processes afforded within the new domain that can produce new concepts not available in the original domain. We show how five known mechanisms of creative designing – emergence, analogy, combination, mutation and first principles – can be included in a general framework as instantiations of ekphrasis. This framework is developed based on the function-behaviour-structure (FBS) ontology and its application to affordances.

Introduction

Design researchers have sometimes drawn on the world of art as a source of inspiration for explaining or illustrating concepts of designing, mainly in the area of design creativity. Most of the metaphors presented in these studies remain on an informal level. Recently, the artistic concept of ekphrasis has been formalised and used as a basis for a computational model of creative designing [1, 2]. Ekphrasis is the transformation of a concept from one medium or domain to another medium or domain [3, 4, 5, 6, 7, 8]. Take as an example the mythical story of King Arthur and Excalibur, the foundation of the rightful sovereignty of the British. The precise nature of the story and what it exemplifies is not of interest here. What is of interest is that the story is depicted in multiple other forms. It is expressed as a painting in Figure 1(a), as a sculpture in Figure 1(b), and as a movie in Figure 1(c). All three are examples of ekphrasis where the nature of the domain of expression allows for different expressions.

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Fig1. King Arthur and Excalibur represented as (a) a painting, (b) as a sculpture, and (c) as a movie

Ranjan et al. [9, 10] showed that the cross-domain interpretation of artistic ideas, i.e., ekphrasis, can be tested empirically and that such a cross-domain interpretation of artistic ideas can be the basis of a form of creativity. In Gero's [1, 2] model of ekphrasis, novel design concepts are the result of two instantiations of ekphrasis: One instantiation transforms the design representation from the original domain of designing to a new domain, leading to new processes that can operate on that representation. A second instantiation transforms the results of executing the new processes back into the original domain, leading to the production of new design concepts in that domain. Here the notion of a "domain" is understood as an agreed area of knowledge, which may include technological domains [11] and representational domains on a symbolic level.

In this paper, we extend Gero's [1, 2] model of ekphrasis by deriving a generic framework based on the function-behaviour-structure (FBS) ontology and its application to representational affordances. These affordances are defined as the action possibilities of a designer when interacting with a design representation; e.g., calculating the area of a building when being shown a floor layout representation. We show how five known mechanisms of creative designing – emergence, analogy, combination, mutation and first principles – can be viewed as instantiations of this framework. This has the advantage that creative design processes and techniques that traditionally have been studied separately can now be treated in a uniform way. Insights in creative designing may thus be more easily transferred across different methods and different domains, as they can be described using the same foundational model.

This paper is organised as follows: Section 2 presents foundations of design creativity using a state space view of designing. Section 3 develops an ontological framework of ekphrasis that is then extended to represent creative designing. Section 4 applies this framework to the mechanisms of emergence, analogy, combination, mutation and first principles. Section 5 concludes the paper with a discussion of potential future work.

Creative Designing

Boden [12] distinguished between "historical" (or h-) creativity and "psychological" (or p-) creativity. For h-creativity, novelty is evaluated in relation to the history of humankind. The first steam engine was an example of a h-creative design. P-creativity implies novelty only with respect to the lifetime of an individual, for example a novice architect designing a high-rise office building for the first time.

An extension of Boden's classification has been proposed by Suwa et al. [13] who added the notion of "situated" (or s-) creativity. S-creativity is defined with respect to the situation rather than to the outcomes of the process. A design or design concept 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. The concept of creativity used in this paper is the one of s-creativity.

S-creativity allows a characterisation of the design process as either routine or non-routine [14, 15]. *Routine designing* is when the state space of possible designs is well defined, fixed and bounded at the beginning of the design process. Designing then consists of finding a specific set of values for known design variables and known ranges of values. This corresponds to a view of designing as search. No creativity is involved in this idealised view. *Non-routine designing* can be either innovative and creative. *Innovative designing* assumes a well-defined, fixed and bounded set of design variables but modifies the ranges of values to be outside the norm. *Creative designing* introduces new design variables, so that the state space of possible designs is extended. Variables can be introduced additively, leading to an expanded design state space, or substitutively, leading to a shift of the design state space that may be disjoint from the original one [15]. A summary of this view of routine, innovative and creative designing is depicted in Figure 2.

Five processes have been proposed that can lead to extensions of the design state space [15]:

- Emergence: is the process of making implicit features in a representation explicit.
- Analogy: is the process of extracting useful concepts in an existing design and introducing them into the current design.
- Combination: is the process of forming a new concept from two or more separate ones.
- Mutation: is the process of arbitrarily altering an existing concept.
- First principles: is the process of using foundational concepts as the basis for designing.

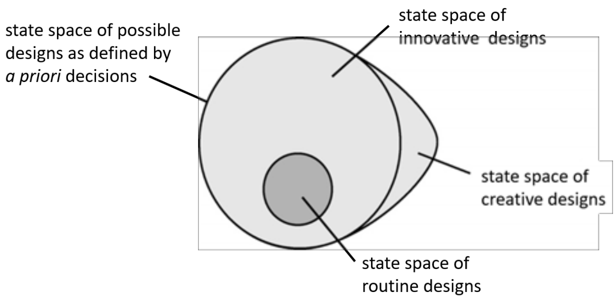


Fig2. The state spaces of routine designs and innovative designs as subspaces of the state space of possible designs (as defined by a priori decisions), and the state space of creative designs as its superset (here depicted for additive variable introductions).

Some of these processes have been studied separately from one another, often in different research domains and communities. Emergence is mostly the subject of research in visual cognition. Analogy, combination and mutation are studied within design creativity research. First principles are mainly used in physics-based approaches such as mechanical engineering.

This domain specificity makes the five processes difficult to apply in different domains, because every domain has its own set of representations that afford different processes operating on these representations [16]. A generic framework of creative designing that encompasses all five processes would therefore need to include transformations of representations across various domains. Ekphrasis, which is concerned with transforming concepts from one domain into another, can provide the basis for such a framework.

Modelling Creative Designing Using Ekphrasis

An ontological framework of ekphrasis can be developed based on the FBS ontology and its application to representational affordances [16].

An Ontological View of Ekphrasis

Here we provide a brief introduction of the FBS ontology and its use in representing affordance. More detail can be found in [16]. The FBS ontology has been developed to represent a wide variety of artefacts including physical objects, software, processes and organisations [17]. Recently this ontology has also been applied to representations in design, as the basis for a model of representational affordances [16].

Structure (S) is defined as the components of an artefact and their relationships. The structure of representations includes symbolic or iconic constructs and their relationships. For instance, a graph-based representational structure of a building may consist of nodes (representing spaces in the building) interconnected by arcs (representing topological relationships between the spaces). An iconic (geometric) representational structure of the building may consist of vectors (representing surfaces of the building's shape). An evolutionary representation of the building may consist of genes (representing the layout of the rooms).

Behaviour (B) is defined as the attributes that can be derived from an artefact's structure. External or exogenous effects may be needed to produce behaviour by interacting with the structure. These effects are often induced by the intentional actions of a user. Mental or physical operations typically establish the exogenous effects interacting with representations, producing attributes (i.e., behaviours) that describe the results of these operations. For instance, features of a graph-based representation are behaviours obtained by applying the exogenous effect of searching for specific patterns in the graph structure. The total amount of space in a geometric representation of a building is a behaviour obtained by applying the exogenous effect of using mathematical operations. A modified gene structure of the evolutionary representation of the building is a behaviour that may be obtained by applying crossover and mutation operators.

Function (F) is defined as an artefact's teleology ("what the object is for"). It is ascribed to behaviour by establishing a teleological connection between a human's goals and measurable effects of the artefact. For instance, allowing compliance checking in the early stages of designing may be a function of a graph-based representation of the building. Allowing engineering simulations such as thermal analysis may be a function of a geometric representation. Exploring alternative room layouts may be a function of the evolutionary representation.

Affordances are the potential actions of a user interacting with an artefact's structure and thereby producing artefact behaviours. In the FBS ontology, these actions can be captured as exogenous effects. Figure 3 shows two shapes symbolising affordances and behaviour, respectively. For an affordance to produce behaviour, there needs to be a "fit" between the two. Conceptualising behaviour as including an "input port" or "receptor", which metaphorically mirrors the shape of the affordance, illustrates this fit. Relevant aspects of affordances can be defined as input parameters of behaviour, and measurable effects of these affordances can be defined as output parameters. For example, the "open-ability" affordance of a door includes the amount and direction of force applied to the door. (We use the common "verb + -ility" convention for labelling affordances.) The speed with which the door opens when applying the force would be an output parameter associated with this input.

In representational affordances, the input parameters describe design actions afforded by a design representation. Output parameters represent the effects of the design actions, including measures for the success of the actions with respect to a task-related goal. Take the example of the graph-based building representation; an affordance called "pattern search-ability" provides the input of a behaviour that includes graph features as output. For the geometric building representation, an affordance may be called "space calcul-ability", viewed as an input to a behaviour that includes the total amount of space as output. For the genetic engineering representation, the affordances may be viewed to include "combin-ability" and "mutat-ability".

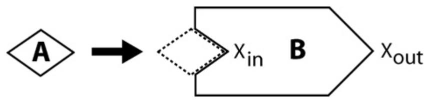


Fig3. Behaviour (B) provides input parameters (X_{in}) representing relevant properties of affordances (A), and output parameters (X_{out}) representing measurable states produced.

Ekphrasis can be viewed as a transformation of a representation from an original domain to a new domain from which new representational affordances can be derived. Using the FBS ontology applied to representations, we can describe this as follows:

$S^{dn} = \tau(S^{do})$ (1)

$B^{dn} = \tau(S^{dn})$ (2)

where dn = new domain, do = original domain, τ = transformation.

B^{dn} and B^{do}, and S^{dn} and S^{do}, respectively, are typically disjoint (i.e., $B^{dn} \cap B^{do} = \varnothing$, and $S^{dn} \cap S^{do} = \varnothing$) because they are based on the unique knowledge representations available in a domain. However, there may be exceptions as domains can overlap in various ways [18]. We will provide examples of such overlaps later in this paper. F^{dn} and F^{do} are non-disjoint (i.e., $F^{dn} \cap F^{do} \neq \varnothing$) because they are associated with the concept to be conveyed that transcends the different, domain-specific representations. Figure 4 uses a state space view to show the relations between the function, behaviour and structure of the representation before and after the ekphrasis.

This ontological framework can be illustrated using the example of an artwork being represented as a poem, as shown in Figure 5. Thus, the original domain (do) in this example is art, and the new domain (dn) is poetry.

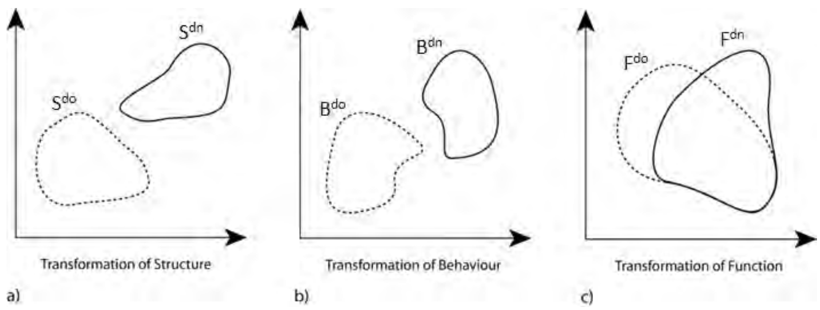


Fig4. Ekphrasis as transformations of structure, behaviour and function: (a) Structure is transformed into a disjoint state space, (b) behaviour is transformed into a disjoint state space, and (c) function is transformed into a non-disjoint state space.

The original structure (S^{do}) of the artwork "Equinox" shown in Figure 5 is a composition of blocks, cogwheels and paint. It is transformed into the new structure (S^{dn}) of the poem "Autumn Window", which can be viewed as a composition of words and sentences. The two representational structures are completely disjoint from each other, based on the disjoint types of structure elements available in the two domains.

"Equinox"; Mixed media on wood; 19" x 19"

Autumn Window

Sun and moon
come to an even stance,
blocks of time
tell when they each
can shine,
as clocks are re-set,
equinoctial points
intersect

the lines of light streak
across the room
earlier than last week,
passive orange and yellow tones
slip through my fingers

as I sit by the window,
reminisce about youthful
moments
when time never needed
to be wound,
it simply sprung
from season to season

now it drags
as leaves on the ground
crisp and crunchy,
crumble into brown pieces.

-Suzanne Bruce

Suzanne Bruce© Autumn Window

Fig5. Example of ekphrasis transforming an artwork into a poem (Artwork by Janet Manalo, poetry by Suzanne Bruce; http://www.ekphrasticexpressions.com).

The original behaviour (B^{do}) of "Equinox" includes attributes such as the distribution of paint and the area covered by the physical elements on the canvas. It also includes neurocognitive activities afforded by the artwork, such as spatial focussing, 3D object recognition or mental simulations. The new behaviour (B^{dn}) of "Autumn Window" includes different attributes that are specific to the domain of poetry, such as rhymes and rhythmic patterns. Similar to the artwork, this poem can also afford various neurocognitive activities. Yet, these activities are specific to the domains of poetry and text, and thus disjoint from those afforded by the artwork.

They include the syntactic and semantic interpretation of words and sentences, and the recognition of specific textual patterns and poetic styles. The original function (F^{do}) of “Equinox” can be interpreted as the goals of conveying or evoking emotional responses related to the concept of a beginning autumn, or more generally of seasonal change, to the viewer. The new function (F^{dn}) of “Autumn Window” is the same as the one of “Equinox”, yet the poem seems to augment it with the concept of a changing perception of time between youth and adulthood.

A Model of Ekphrasis in Creative Designing

We can develop an ontological framework of creative designing that is based on two consecutive instantiations of ekphrasis. A first ekphrasis E1 at time t_{E1} transforms the representational structure $S^{do}(t_{E1})$ in the original design domain (do) into a representational structure $S^{dn}(t_{E1})$ in a new domain (dn), and derives new representational affordances $B^{dn}(t_{E1})$ in that new domain. This is represented in equations (3) and (4):

$$S^{dn}(t_{E1}) = \tau(S^{do}(t_{E1})) \quad (3)$$

$$B^{dn}(t_{E1}) = \tau(S^{dn}(t_{E1})) \quad (4)$$

Executing these affordances produces a new representation in domain dn, which is interpreted as a new representational structure (S^{dn}) to be used as a basis for a second ekphrasis E2 at time t_{E2}:

$$S^{dn}(t_{E2}) = \iota(B^{dn}(t_{E1})) \quad (5)$$

where ι = interpretation of execution results.

A second ekphrasis transforms this representational structure back into the original domain (do), as a basis for further representational affordances that allow continuing designing in the original domain:

$$S^{do}(t_{E2}) = \tau(S^{dn}(t_{E2})) \quad (6)$$

$$B^{do}(t_{E2}) = \tau(S^{do}(t_{E2})) \quad (7)$$

This model of creative designing based on double ekphrasis is shown conceptually in Figure 6. This model can be extended using additional processes according to the FBS framework including the situated FBS framework [17]. For example, the process of evaluation can be added to address comparisons between multiple behaviours resulting from a set of transformations from structure to behaviour.

Ekphrasis could be applied iteratively to move from the original domain to a new domain and then from the new domain to a second new domain, before returning to the original domain.

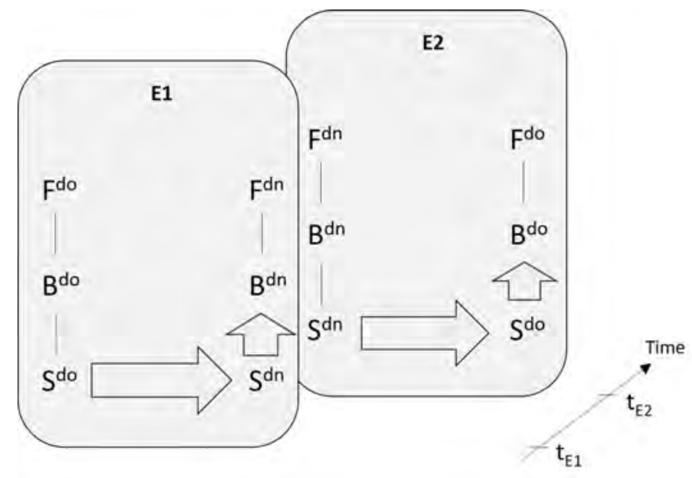


Fig6. Creative designing based on two instantiations of ekphrasis, E1 and E2, at times t_{E2} and t_{E2}

Processes of Creative Designing as Ekphrasis: Results

In this Section, we show the results from how the processes that can extend the design state space fit in the model of creative designing based on ekphrasis.

Emergence

Emergence makes implicit features of a representation explicit. An example of shape emergence is shown in Figure 7. Initially, only the three triangles in Figure 7(a) were drawn. Implicit in this representation is the shape of a trapezoid that in this example of emergence was made explicit in Figure 7(b).

The primary shapes (i.e. the triangles initially drawn) can be conceptualized as a representation in the domain of line segments (drawn between vertices). This representation is thus a set of line segments and vertices: $S^{do}(t_{E1})$ = (line segments, vertices). They afford perceptive activities of searching triangles in the representation: $B^{do}(t_{E1})$ = (searching triangles). This supports the designer's goal of reasoning about two-dimensional spaces in a building

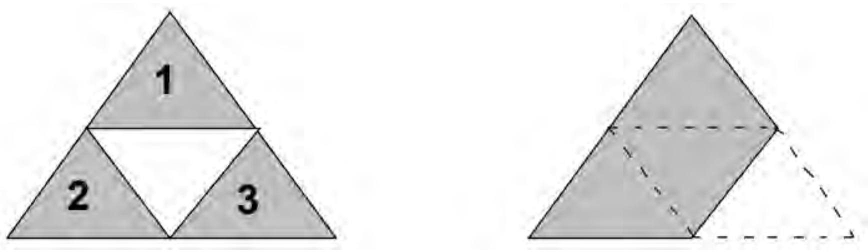


Fig7. An example of emergence: (a) Three equilateral triangles, which are the only shapes explicitly represented; (b) one emergent form of a trapezoid moving that shape from being implicit to being explicit. (image taken from [19])

design: $F^{do}(t_{E1})$ = (to reason about spaces in a building design).

The first ekphrasis transforms $S^{do}(t_{E1})$ from its original domain – the domain of line segments – into a new domain: the domain of maximal lines [19]. Maximal lines are lines that embed at least one line segment and do not belong to the domain of line segments [20]. Consequently, the new representational structure $S^{dn}(t_{E1})$ is a set of maximal lines:

$S^{dn}(t_{E1}) = \tau(S^{do}(t_{E1}))$ = (maximal lines) (8)

The maximal lines in $S^{dn}(t_{E1})$ have various intersections that do not exist in S^{do}, which affords searching shapes that were not necessarily intended initially:

$B^{dn}(t_{E1}) = \tau(S^{dn}(t_{E1}))$ = (searching shapes) (9)

The differences between the two domains in terms of representational function, behaviour and structure are summarised in Table 1.

Table 1 Differences between representational F, B and S across the domain of line segments (do) and the domain of maximal lines (dn) during ekphrasis 1

Ontological category	**Original domain (do)**	**New domain (dn)**
$F(t_{E1})$	to reason about spaces in a building design	
$B(t_{E1})$	searching triangles	searching shapes
$S(t_{E1})$	line segments, vertices	maximal lines

The trapezoid shape resulting from the search, as shown in Fig. 7(b) is then interpreted as a new representational structure being used as the basis for a second ekphrasis:

$S^{dn}(t_{E2}) = \iota(B^{dn}(t_{E1}))$ = (emergent trapezoid) (10)

The second ekphrasis transforms $S^{dn}(t_{E2})$ back in the original domain, turning the intersections into vertices, and the maximal lines into line segments between these vertices:

$S^{do}(t_{E2}) = \tau(S^{dn}(t_{E2}))$ = (line segments, vertices) (11)

This affords the cognitive activity of searching trapezoids, yet now in the original domain:

$B^{do}(t_{E2}) = \tau(S^{do}(t_{E2}))$ = (searching trapezoids) (12)

Analogy

This process uses ekphrasis to express a design in domains in which similarities with the original domain can potentially be found. A popular domain for finding analogies is biology. An example of a biologically inspired design is the roof of the Munich Olympic Stadium, shown on the right-hand side of Fig. 8. Its tensile structure reminiscent of cobwebs (left-hand side of Fig. 8) was a departure from traditional stadium roofs built using massive concrete.

The initial design is represented as an optimisation problem consisting of geometric parameters of a massive stadium roof and an associated fitness function: $S^{do}(t_{E1})$ = (geometric parameters of massive stadium roof, fitness function). This representation affords the use of suitable optimisation techniques: $B^{do}(t_{E1})$ = (applying optimisation techniques). This supports the designer's goal of generating a design with optimised performance (e.g. a roof with minimal weight): $F^{do}(t_{E1})$ = (to generate a roof design with minimal weight).

Fig8. Example of analogy: The roof of the Munich Olympic Stadium was inspired by natural structures such as cobwebs

The first ekphrasis transforms $S^{do}(t_{E1})$ from the domain of the built environment into the domain of biology:

$S^{dn}(t_{E1}) = \tau(S^{do}(t_{E1}))$ = (problem represented biologically) (13)

This problem representation affords search activities to find solutions in the biological world, for example by using a biomimetics database [21]:

$B^{dn}(t_{E1}) = \tau(S^{dn}(t_{E1}))$ = (searching for biological solutions) (14)

The differences between the two domains in terms of representational function, behaviour and structure are summarised in Table 2.

Table 2 Differences between representational F, B and S across the domain of the built environment (do) and the domain of biology (dn) during ekphrasis 1

Ontological category	**Original domain (do)**	**New domain (dn)**
$F(t_{E1})$	to generate a roof design with minimal weight	
$B(t_{E1})$	applying optimisation techniques	searching for biological solutions
$S(t_{E1})$	geometric parameters of massive stadium roof, fitness function	problem represented biologically

The result of the search for biological solutions in this example are the cobwebs shown in Figure 8. The phase in analogy-making that is concerned with finding such an analogous solution is commonly called "matching" [22]. That solution is interpreted as a new representational structure to be used for a second ekphrasis:

$S^{dn}(t_{E2}) = \iota(B^{dn}(t_{E1}))$ = (structure of cobwebs) (15)

The second ekphrasis transforms $S^{dn}(t_{E2})$ back in the domain of the built environment, formulating it as a modified optimisation problem that contains some of the design parameters describing cobwebs. This is what research in analogy in design refers to as the "mapping" phase [22]. We can write:

$S^{do}(t_{E2}) = \tau(S^{dn}(t_{E2}))$ = (geometric parameters of cobwebs, fitness function) (16)

This structure affords the use of standard optimisation techniques in that domain:

$B^{do}(t_{E2}) = \tau(S^{do}(t_{E2}))$ = (applying optimisation techniques) (17)

This optimisation results in the roof structure shown in Fig. 8.

Combination

Combination brings together two known concepts to form a new concept [23] that is an intersection between existing but commonly incompatible frames of reference [24]. For example, the concept of a chair can be combined with the concept of a cradle to form the new concept of a rocking chair, as shown in Fig. 9.

Using our model of ekphrasis, the process of combination in this example can be represented as follows. The initial design is assumed to be a geometrical representation of a chair: $S^{do}(t_{E1})$ = (geometry of a chair). This representation affords the use of various methods for detailing the design, such as deciding on the exact dimensions, materials, coatings and colours of the chair: $B^{do}(t_{E1})$ = (detailing the chair design). The designer's goal associated with this representation is to produce a design that satisfies any given requirements: $F^{do}(t_{E1})$ = (to generate a chair design).

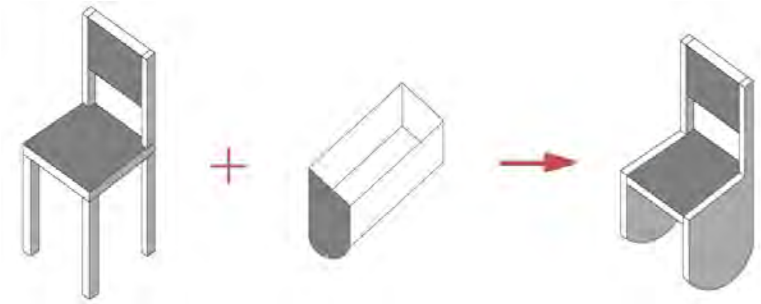


Fig9. Example of combination: Combining a chair with a cradle to create a rocking chair [25]

The first ekphrasis transforms $S^{do}(t_{E1})$ from the domain of chairs into the more general domain of furniture, leading to a more general representation of a system that provides support.

$S^{dn}(t_{E1}) = \tau(S^{do}(t_{E1}))$ = (support system) (18)

The new representation affords search activities to find forms for that support structure in the new domain:

$B^{dn}(t_{E1}) = \tau(S^{dn}(t_{E1}))$ = (searching forms) (19)

The differences between the two domains in terms of representational function, behaviour and structure are summarised in Table 3:

Table 3 Differences between representational F, B and S across the domain of chairs (do) and the domain of furniture (dn) during ekphrasis 1

Ontological category	**Original domain (do)**	**New domain (dn)**
$F(t_{E1})$	to generate a chair design	
$B(t_{E1})$	detailing the chair design	searching forms
$S(t_{E1})$	geometry of a chair	support system

The form of a cradle found during the search for forms is interpreted as a new representational structure providing input for a second ekphrasis:

$S^{dn}(t_{E2}) = \iota(B^{dn}(t_{E1}))$ = (form of a cradle) (20)

The second ekphrasis transforms $S^{dn}(t_{E2})$ from the domain of furniture back to the domain of chairs, by synthesising the design of a rocking chair that combines some structure features of a cradle with the initial chair design, as shown in Fig. 9:

$$S^{do}(t_{E2}) = \tau(S^{dn}(t_{E2})) = \text{(geometry of a rocking chair)} \qquad (21)$$

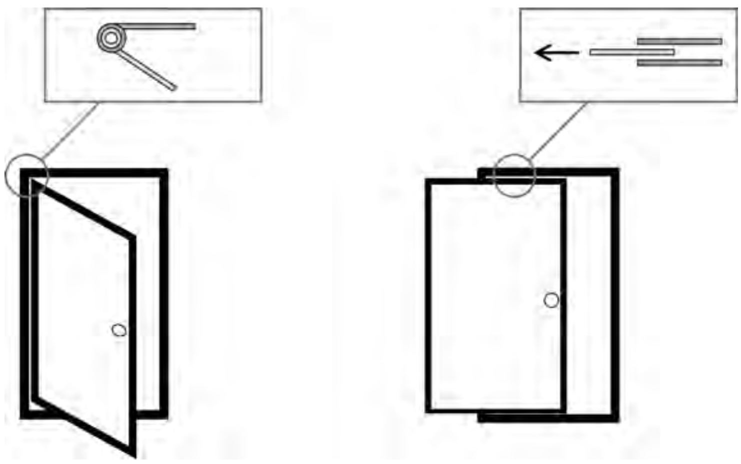
This structure affords the use of similar detail design methods as prior to the first ekphrasis:

$$B^{do}(t_{E2}) = \tau(S^{do}(t_{E2})) = \text{(to generate a chair design)} \qquad (22)$$

Mutation

Mutation alters an existing concept. It can occur either homogeneously by changing the value of a design variable or heterogeneously by changing the class of design variable [15]. Heterogeneous mutation implies moving from one domain to another. For creative designing, it is mostly the heterogeneous type of mutation that can produce a change in the design state space. An example is the mutation of a door's hinges into a slider, which results in a different approach for opening and closing the door: from rotational to linear movement, Figure 10.

As an instance of ekphrasis, this example of mutation can be represented as follows. The initial door design is a structure representation of a door opening mechanism using hinges: $S^{do}(t_{E1})$ = (structure of a rotating door), which affords detail design methods: $B^{do}(t_{E1})$ = (detailing the door design). The designer's goal associated with this representation is to produce a design that satisfies given requirements: $F^{do}(t_{E1})$ = (to generate a door design).



(a) **(b)**

Fig10. Mutation of (a) a rotating door into (b) a sliding door

The first ekphrasis transforms $S^{do}(t_{E1})$ from the domain of physical mechanisms into the evolutionary domain, involving genes that encode various structure features of the door:

$S^{dn}(t_{E1}) = \tau(S^{do}(t_{E1})) = \text{(genes)}$ (23)

With the intention to allow random changes in the genes, the new representation affords the mutation of some of the geometrical elements:

$B^{dn}(t_{E1}) = \tau(S^{dn}(t_{E1})) = \text{(applying mutation on genes)}$ (24)

The differences between the two domains in terms of the representational function, behaviour and structure are summarised in Table 4.

The result of the mutation in the new domain is a substitution of the gene encoding "angle" with a gene encoding "sliding length". This is interpreted as a new representational structure providing input for a second ekphrasis:

$S^{dn}(t_{E2}) = \iota(B^{dn}(t_{E1})) = \text{(mutated gene)}$ (25)

The second ekphrasis transforms $S^{dn}(t_{E2})$ from the evolutionary domain back to the domain of physical mechanisms, by using knowledge that the new "sliding length" allows moving the door in a linear direction:

Table 4 Differences between representational F, B and S across the domain of physical mechanisms (do) and the evolutionary domain (dn) during ekphrasis 1

Ontological category	**Original domain (do)**	**New domain (dn)**
$F(t_{E1})$	to generate a door design	
$B(t_{E1})$	detailing the door design	applying mutation on genes
$S(t_{E1})$	geometry of a rotating door	genes

$S^{do}(t_{E2}) = \tau(S^{dn}(t_{E2})) = \text{(structure of a sliding door)}$ (26)

This structure affords the use of detail design methods including the selection of a slider instead of hinges:

$B^{do}(t_{E2}) = \tau(S^{do}(t_{E2})) = \text{(detailing the door design)}$ (27)

First Principles

This process transforms a design from the physical domain into the domain of algebra, where new variables can be introduced using dimensional variable expansion [26, 27]. For example, the geometry of the beam shown in Fig. 11(a) is represented algebraically using two variables: length and radius. Both of these variables are then split into several variables (through a process called dimensional variable expansion), which – when transformed back into the physical world – describe beam segments of varying thickness, thus turning the original beam into a composite beam, Fig. 11(b).

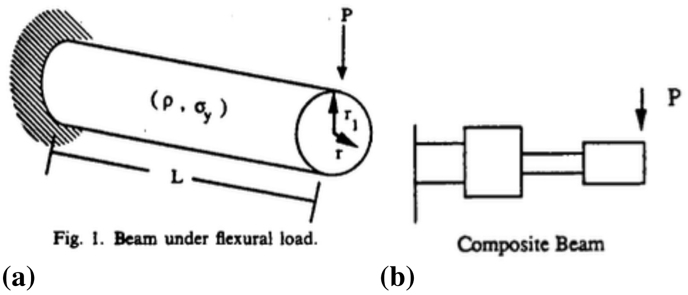


Fig11. Example of first principles (image from [27]): (a) original beam, (b) composite beam after dimensional variable expansion

The initial design is represented geometrically and physically: $S^{do}(t_{E1})$ = (beam shape, load conditions). This representation may initially afford searching for materials for the beam: $B^{do}(t_{E1})$ = (searching for beam materials). This behaviour supports the designer's goal of generating a beam design that can resist a specific load: $F^{do}(t_{E1})$ = (to generate a design for supporting/lifting loads).

The first ekphrasis transforms $S^{do}(t_{E1})$ from the domain of physics into the domain of algebra, using a set of algebraic equalities and inequalities:

$S^{dn}(t_{E1}) = \tau(S^{do}(t_{E1}))$ = (algebraic equalities and inequalities) (28)

This representation can afford various activities concerned with algebraic reasoning, one of which is dimensional variable expansion (DVE):

$B^{dn}(t_{E1}) = \tau(S^{dn}(t_{E1}))$ = (applying DVE) (29)

The differences between the two domains in terms of the representational function, behaviour and structure are summarised in Table 5.

Table 5 Differences between representational F, B and S across the domain of physics (do) and the domain of algebra (dn) during ekphrasis 1

Ontological category	**Original domain (do)**	**New domain (dn)**
$F(t_{E1})$	to generate a design for supporting/lifting loads	
$B(t_{E1})$	searching for beam materials	applying DVE
$S(t_{E1})$	beam shape, load conditions	algebraic equalities and inequalities

The result of applying DVE is a set of algebraic equalities and inequalities using new variables, which is interpreted as a new representational structure to be used for the second ekphrasis:

$S^{dn}(t_{E2}) = \iota(B^{dn}(t_{E1}))$ = (algebraic equalities and inequalities using new variables) (30)

The second ekphrasis transforms $S^{dn}(t_{E2})$ back into the physical domain, representing it as a composite beam with specified load conditions:

$S^{do}(t_{E2}) = \tau(S^{dn}(t_{E2}))$ = (composite shape, load conditions) (31)

This structure affords searching for materials, possibly different materials for different beam segments:

$B^{do}(t_{E2}) = \tau(S^{do}(t_{E2}))$ = (searching for beam materials) (32)

Conclusion

Emergence, analogy, combination, mutation and first principles have been known as processes for creative designing, as they can alter the state space of possible designs. However, most of them have been studied only as instances of designing in specific domains of design and computation. This has been an obstacle for understanding their commonalities and deriving a unifying framework for them. The previous section has shown that these five creative processes can be viewed as instances of a single framework of creative designing based on ekphrasis. Such a framework facilitates communication between researchers in different design disciplines and provides a new perspective to reframe existing ways of thinking about creative processes.

The main limitation of the approach is that the notion of a domain is not formally defined in the literature. Consequently, the instantiation of the ekphrasis framework for specific examples of creative designing can be difficult, as one domain may not always be clearly distinguished from another. For example, the domains of line segments and maximal lines (see section on emergence) may not appear fundamentally different from each other although mathematically they are disjoint indicating different domains.

Other processes can be investigated to fit into this framework, such as those listed in [28]. This would test its genericity beyond the five processes examined in this paper. An example is one of the oldest and most commonly known creative processes: Wallas' [29] model of creative processes consisting of the four stages of preparation, incubation, illumination and verification. The incubation stage is akin to the first ekphrasis in our framework, as it involves the designer directing attention to an unrelated domain before a creative idea emerges and is used within the original design domain. There has been some debate as to whether it is the domain being attended to or simply the break from the original activity (via forgetting) that leads to a restructuring of the problem domain [30]. In both cases, however, incubation can be seen as a transformation of a design representation from the original domain to a new domain that affords new cognitive behaviours.

Finally, the concept of affordances used as a basis for the proposed framework provides the potential of further studies. In particular, the distinction between reflexive, reactive and reflective affordances [16] may be useful for refining the framework in a way that considers the situatedness of designing. This may help address questions such as whether the new design variables introduced in a design state space are the result of either exploration or search in the new domain. Some of the examples in this paper suggest that search in the new domain (e.g. searching analogical solutions in a biomimetics database) may suffice to generate new design variables. The three types of affordances may be used to characterize the different modes of reasoning in the new domain.

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References

1. Gero JS (2017) Ekphrasis as a design method, International Conference on Engineering Design 2017, Vancouver, Canada, to appear
2. Gero JS (2017) Generalizing ekphrastic expression: A foundation for a computational method to aid creative design, in P Janssen, P Loh, A Raonic, MA Schnabel (eds) Protocols, Flows and Glitches, Proceedings of the 22nd International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2017, pp. 345–354.
3. Fowler DP (1991) Narrate and describe: the problem of ekphrasis. Journal of Roman Studies 81: 25–35
4. Goldhill S (2007) What is ekphrasis for? Classical Philology 102(1): 1–19.
5. Knapp JA (2011) Harnessing the visual: From illustration to ekphrasis, Image Ethics in Shakespeare and Spenser, Palgrave Macmillan, pp. 31–46.
6. Leader S (2014) Ekphrasis and its reverse, Academic Commons Program, Paper 11, http://digitalcommons.risd.edu/grad_academiccommonsprogram/11 {RISD paper}
7. Newby Z (2002) Testing the boundaries of ekphrasis: Lucian on the Hall. Ramus 31(1-2): 126–135.
8. Scott GF (1992) Ekphrasis. European Romantic Review 3(2): 215–224.
9. Ranjan A, Gabora L, O'Connor B (2013) The cross-domain re-interpretation of artistic ideas. arXiv preprint arXiv:1308.4706.
10. Ranjan A, Gabora L, O'Connor B (2013) Evidence that cross-domain re-interpretations of creative ideas are recognizable. arXiv preprint arXiv:1310.0519.
11. Alstott J, Triulzi G, Yan B, Luo J (2017) Inventors' explorations across technology domains. Design Science 3.
12. Boden MA (1991) The Creative Mind: Myths and Mechanisms, Basic Books, New York.

13. Suwa M, Gero JS, Purcell T (1999) Unexpected discoveries and s-inventions of design requirements: A key to creative designs, in JS Gero and ML Maher (eds) Computational Models of Creative Design IV, Key Centre of Design Computing and Cognition, University of Sydney, Australia, pp. 297–320.
14. Gero JS, Kannengiesser U (2011) Design, in MA Runco and SR Pritzker (eds) Encyclopedia of Creativity, Second Edition, Vol. 1, Academic Press, San Diego, pp. 369-375.
15. Gero JS (1996) Creativity, emergence and evolution in design. Knowledge-Based Systems 9(7): 435–448.
16. Gero JS, Kannengiesser U (2012) Representational affordances in design, with examples from analogy making and optimization. Research in Engineering Design 23(3): 235–249.
17. Gero JS, Kannengiesser U (2014) The function-behaviour-structure ontology of design, in A Chakrabarti and LTM Blessing (eds) An Anthology of Theories and Models of Design, Springer, pp. 263–283.
18. Tennis JT (2003) Two axes of domains for domain analysis. Knowledge Organization 30(3-4): 191–195.
19. Gero JS (1992) Creativity, emergence and evolution in design, in JS Gero and F Sudweeks (eds) Preprints Computational Models of Creative Design, Department of Architectural and Design Science, University of Sydney, pp. 1–28.
20. Stiny G (1980) Introduction to shape and shape grammars. Environment and Planning B: Urban Analytics and City Science 7(3): 343–351.
21. Deldin J-M, Schuknecht M (2014) The AskNature database: Enabling solutions in biomimetic design, in AK Goel, DA McAdams and RB Stone (eds) Biologically Inspired Design: Computational Methods and Tools, Springer, London, pp. 17–27.
22. Gentner D (1983) Structure-mapping: A theoretical framework for analogy. Cognitive Science 7(2): 155–170.
23. Nagai Y, Taura Y, Mukai F (2009) Concepts blending and dissimilarity: factors for creative concept generation process, Design Studies 30(6): 648–675.
24. Koestler A (1964) The Act of Creation, Hutchinson, London.
25. Rosenman MA, Gero JS (1989) Creativity in design using a prototype approach, Preprints Modeling Creativity and Knowledge-Based Creative Design, Design Computing Unit, Department of Architectural and Design Science, University of Sydney, pp. 207–232.
26. Cagan J, Agogino AM (1991) Dimensional variable expansion – A formal approach to innovative design. Research in Engineering Design 3(2): 75–85.
27. Aelion V, Cagan J, Powers G (1991) Inducing optimally directed innovative designs from chemical engineering first principles. Computers & Chemical Engineering 15(9): 619–627.
28. Howard TJ, Culley SJ, Dekoninck E (2008) Describing the creative design process by the integration of engineering design and cognitive psychology literature. Design Studies 29(2): 160–180.
29. Wallas G (1926) The Art of Thought, Jonathan Cape, London.
30. Segal E (2004) Incubation in insight problem solving. Creativity Research Journal 16(1): 141–148.