REPRESENTATIONAL AFFORDANCES IN DESIGN, WITH EXAMPLES FROM ANALOGY MAKING AND OPTIMIZATION

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Abstract. Affordances in design can be understood as the action possibilities of a user interacting with a designed object. In this paper, we develop the notion of "representational affordances" to denote affordances provided by design representations to the designer as the "user" of these representations. A major characteristic of representational affordances is that they do not have to rely on existing representations but can drive the construction of new representations that may then afford different design actions. We describe representational affordances ontologically, proposing three affordance types: reflexive, reactive and reflective. We illustrate them with examples of analogy making and optimization.

1. Introduction

One feature that is common to most engineering design is that designers produce and interpret representations of their design (Ullman et al. 1990; McGown et al. 1998; Schütze et al. 2003). Representations may refer to different aspects of the same object, such as its function, behaviour and structure (Gero 1990). In addition, representations of the same aspect may use different modalities, such as drawings, sketches, diagrams, text, verbal speech and gestures. For example, a carburettor may be represented using natural language expressions (describing functions such as "ease of manufacturing"), mathematical or logical expressions (describing behaviours such as the physical principles that establish the process of carburetion) and graphical models (describing structure). One can further differentiate design representations within individual design aspects. For example, one may represent the geometry of the carburettor from various spatial perspectives and with various renderings, either zooming in on individual details or zooming out to highlight the overall shape. These representations may or may not include the carburettor's environment, such as fuel, air and adjacent engine components.

It is generally known that different representations allow or facilitate different cognitive actions (Scaife and Rogers 1996; Zhang 1997). For example, for analysing relationships within a dataset, graphical representations of this dataset are generally better suited than tabular representations (Larkin and Simon 1987). A study by Schwartz and Black (1996) shows that a change in the representation of two gears – from one with smooth to one with rough contacting surfaces – facilitates mental simulation of gear rotation. What kinds of representation are needed for different activities and purposes has also been an area of research in designing. Some of this research focuses on the issue of interoperability – the ability to exchange design information among stakeholders or design tools that use different representations of the same design. Other research concentrates on how designing can be supported by providing design representations that can stimulate the generation of design ideas or facilitate the elaboration of these ideas. These activities are generally called divergent and convergent, respectively.

Convergent design activities are enabled by design representations that serve as external extensions of the designer's memory. These representations often occur in form of sketches that "store" ideas in the conceptual design stages (van der Lugt 2005), or in form of calculations, drawings, simulations and checklists in the detailed design stages (Ullman et al. 1990). A number of computational tools are available for these design activities, often pre-defining the schemas and formats in which design data needs to be represented. Convergent activities are mainly used in routine designing.

Divergent design activities are supported by design representations that allow for the re-interpretation of design concepts. They can lead to the discovery of new concepts that are disjoint from the initial ones. This phenomenon has been referred to as "lateral transformations" (Goel 1995) and "focus shifts" (Suwa and Tversky 1997). Perceptual ambiguity in design representations, especially in sketches, has been found to be one of the driving forces in divergent activities (Suwa et al. 1999). Divergent activities can commonly be found in non-routine designing.

Existing research has shown how different classes of activities (divergent ones in particular) can be supported by design representations that differ with respect to modality, level of abstraction, domain specificity and other features (Sarkar and Chakrabarti 2008; Linsey et al. 2008). Craig et al. (2002) have provided a good example for how different spatial perspectives and layouts of source representations can affect analogy making. One of their studies describes a design representation that included a top view of two doors (as in an architectural layout sketch), while another representation included a side view of the same set of doors. Subjects who were shown the former representation were more likely to identify the rotational behaviour of the doors as a potential source mechanism for a target design problem. The explanation suggested by the authors is that all spatial relations in the top view are orthogonal to gravity, which facilitates the mental simulation of opening and closing doors.

In most instances of designing, the relationships between design representations and design actions cannot be generalised without taking into account a number of features that compose a particular design situation. A pre-dominant factor has been shown to be the individual designer. For example, Kokotovich and Purcell (2000) found that the effects of either 2D or 3D shapes on design creativity depend on the discipline in which the designer is trained. Ball et al. (2004) showed that different levels of abstraction at which cues for idea generation are represented stimulate creative design outcomes to different extents depending on whether the designer is an expert or a novice. A great deal of anecdotal evidence shows that different designers undertake their design tasks in different ways ending up with different designs, even when they are given the same representation of requirements. And the same designer is likely to produce different designs at later times for the same requirements. This is a result of the designer acquiring new knowledge during their interactions with the design task.

These studies and observations suggest that the relationship between design representations and design actions is a complex one, and that models of this relationship need to incorporate notions of experience, interpretation and goals. In this paper, we develop an extension of the concept of affordances – representational affordances – bringing all of these notions together. Our goal is to develop a foundation on which some of the issues discussed in this Section can be explored. The structure of this paper is as follows. First, we introduce the notion of representational affordances (Section 2). We then propose an ontology to describe an effect-based and a process-based view of representational affordances (Section 3). Using the process-based view we define three types of affordances: reflexive, reactive, and reflective (Section 4). We then apply representational affordances to two examples of designing: analogy making (Section 5) and optimization (Section 6). A discussion of implications and future work concludes the paper (Section 7).

2. Representational Affordances

The concept of affordance in design has been imported from cognitive science where it was first introduced by the perceptual psychologist, James Gibson:

> "The *affordances* of the environment are what it *offers* the animal, what it *provides* or *furnishes*, either for good or ill. The verb *to afford* is found in the dictionary, but the noun *affordance* is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment." (Gibson 1979, p. 127; emphasis is the author's)

Affordances in design are the action possibilities of a user when the user interacts with an object. They can be "directly" or "intuitively" perceived based on the structural features of the object, without requiring explicit use instructions. In this paper, we use the term "affordance" as shorthand for Norman's (2002) notion of "perceived affordance". Examples of affordances include "climb-ability" and "descend-ability" of stairs, and "sit-ability" and "stack-ability" of chairs. The "users" of objects may also include other objects. For example, a chair affords "stack-ability" not only to human users but also to other, identically shaped chairs that fit on top of this chair. Maier and Fadel (2009) call this an "artefact-artefact affordance", distinguishing it from an "artefact-user affordance".

Affordances emerge from the interaction of an object and its user in their specific situation. Maier and Fadel (2009) likened the relationship between objects and users to the notion of entanglement between quantum particles. The entangled relationship also implies that different affordances can be produced even if they are associated with the same object. This is because users may have different experiences and goals leading to different interactions with the object at different times (Heft 2003; Vyas et al. 2006).

We can apply the affordance concept to interactions between designers and design representations. Using this view, design representations can be said to afford possible design actions that we refer to as *representational affordances*. These affordances produce new design representations that may incorporate additional knowledge (Sim and Duffy 2003). For example, a CAD representation may afford the design action of generating an assembly plan that incorporates knowledge about available assembly methods and resources besides the geometric knowledge represented. Representations produced by a design action may again have representational affordances that can drive further design actions. This view is consistent with Gaver's (1991) concept of "sequential affordances" that "refer to situations in which acting on a perceptible affordance leads to information indicating new affordances" (p. 82). Sequential representational affordances capture the interplay between design representations and designers producing new design representations that has been observed in a number of studies (Schön 1983; Goldschmidt

1991; Gero 1998; Lawson 2005). A set of representational affordances may be "nested" within more complex ones (Gaver 1991).

Affordances of design representations are conceptually very similar to affordances of physical objects. They are not inherent in the design representation but in the interaction with the designer whose experience, perceptions and goals change dynamically. So what makes representational affordances special?

One distinguishing feature of designing is that it can generate the representations needed for reaching current design goals. This means that when an existing representation does not readily afford a particular design action, it can be re-interpreted to produce a more suitable representation. Designers are not just passive users of representations; they actively create their own world of representations, tailored to the design task and the situation at hand. Users of physical objects commonly do not have the capacity to generate their (physical) world but need to rely on the artefacts and natural objects that exist. As a result, the affordances they have access to (we call them *physical affordances*) are much more limited.

3. Ontological View of Representational Affordances

A clear understanding of representational affordances is facilitated by developing an ontological framework that is based on a common terminology with agreed meanings for a domain of discourse. The function-behaviour-structure (FBS) ontology (Gero 1990; Gero and Kannengiesser 2004) provides such a basis for the design domain. We propose an effect-based and a process-based ontological view of representational affordances.

3.1. EFFECT-BASED VIEW

One way to understand representational affordances is to describe their relation to the function, behaviour and structure of representations.

Structure (S), in the FBS ontology, is defined as the components of an object and their relationships. The structure of representational objects (i.e., representations) includes symbolic or iconic constructs and their relationships. For example, the components of a graph-based representational structure of a building include nodes (representing spaces in the building) that are interconnected by arcs (representing topological relationships between the spaces). The components of an iconic (geometric) representation of the building may include vectors (representing surfaces of the building's shape).

Behaviour (B) is defined as the attributes that can be derived from an object's structure. This can require external or exogenous effects to interact with the structure, which are often induced by the intentional actions of an agent. Typical exogenous effects interacting with representations are mental or physical operations, producing attributes (that means, behaviours) that describe the results of these operations. For example, the behaviour of a graph-based representation of a building may include features obtained by applying the exogenous effect of searching for specific patterns in the graph structure. The behaviour of a geometric representation of the building may include the total amount of space in the building, obtained by applying the exogenous effect of using mathematical operations on the represented geometry. Based on the general definition of behaviour in the FBS ontology as attributes, rather than just "activities" in a colloquial sense, representations can be viewed as having behaviours even though they do not "do" anything as such.

Function (F) is defined as an object'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 object. For example, a function one can ascribe to a graph-based building representation is to allow compliance checking in the early stages of designing. A function of a geometric building representation may be to allow engineering simulations such as thermal analysis.

Affordances are an agent's potential actions that interact with an object's structure and thereby produce object behaviours. These actions can be captured in the FBS ontology as exogenous effects resulting in behaviour. Figure 1 consists of two shapes that symbolise affordances and behaviour, respectively. For an affordance to produce behaviour, there needs to be a "fit" between the two. This fit can be illustrated by conceptualising behaviour as including an "input port" or "receptor" that metaphorically mirrors the shape of the affordance. In other words, we can define input parameters of behaviour that represent relevant aspects of affordances, and output parameters that represent measurable effects of these affordances. For example, relevant aspects of the "open-ability" affordance of a door include the amount and direction of force applied to the door. The output parameter associated with this input may include the speed with which the door opens when applying the force.

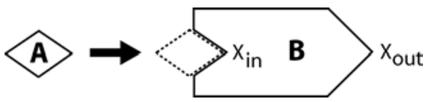


Figure 1. Behaviour (B) as a construct that provides input parameters (X_{in}) representing relevant properties of affordances (A), and output parameters (X_{out}) representing measurable states produced

In representational affordances, input parameters of behaviour represent design actions afforded by a design representation. Output parameters represent the effects of the design actions, and measures for their success with respect to a task-related goal. In the example of the graph-based building representation, an affordance that may be called "pattern search-ability" provides the input of a behaviour that includes graph features as output. An affordance of the geometric building representation may be called "space calcul-ability", which is an input to a behaviour that includes the total amount of space as output.

Behaviours establish a link between functions and structures. Desired functions can only be achieved through appropriate behaviours, and these behaviours are based on afforded interactions with structures. The notion of representational affordances allows not only producing the design actions needed to achieve a particular design goal (or representational function) but also creating the design representations needed to perform a specific design action. We will elaborate and illustrate this idea in the remainder of this paper.

3.2. PROCESS-BASED VIEW

A representational affordance can be viewed as part of a process that transforms a representational structure into representational behaviour. This is consistent with Maier and Fadel's (2009) view of physical affordances as transforming physical structure into physical behaviour. This Section develops a meta-cognitive framework that represents the processes involved in producing representational affordances.

Figure 2 introduces two "worlds": an *interpreted world* that represents current ("as-is"), past ("as-was") and hypothetical ("as-could-be") states of the world, and an *expected world* that represents desired ("to-be") states of the world for the current design interaction. The different states of the world(s) are mental models that within our meta-cognitive view are described as the functions, behaviours and structures of design representations. In the interpreted world, behaviour (B^i) is derived from a given or hypothetical structure (S^i), and function (F^i) is derived from a given or hypothetical behaviour (B^i). In the expected world, expectations are produced about what behaviours (Be^i) are needed to achieve desired functions (Fe^i), and what structures (Se^i) are needed to exhibit desired behaviours (Be^i). The expected world is a subset of the interpreted world, as indicated by their nesting in Figure 2. Accordingly, Fe^i, Be^i and Se^i are defined as subsets of F^i, B^i and S^i, respectively.

In addition to the transformations between function, behaviour and structure within the two worlds, Figure 2 shows a number of other processes:

- *Focussing* selects subsets of F^i, B^i and S^i to be used as Fe^i, Be^i and Se^i. Once selected, a subset is not fixed but can be changed by focussing on different F^i, B^i or S^i.
- *Comparison* determines whether or not an "as-is" state of the world is consistent with a "to-be" state of the world.

This process compares Be^i and B^i, as it is the behaviour level that provides measurable attributes for evaluating different representations.

- *Constructive memory* can produce new F^i, B^i and S^i. This process represents a richer notion of memory than simple recall via indexing. It includes the role of subjective, individual experience in constructing new concepts that are tailored to the agent's current situation (Dewey 1896; Bartlett 1932; Rosenfield 1988; Clancey 1997). Constructive memory can be modelled using the idea of intertwined data-push and expectation-pull (Gero and Fujii 2000), which is denoted in Figure 2 using a combined straight-and-returning arrow symbol.

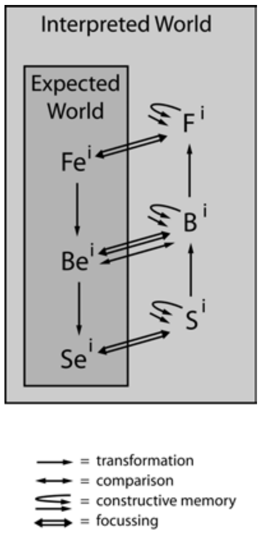


Figure 2. Function, behaviour and structure in the interpreted world (F^i: interpreted function, B^i: interpreted behaviour, S^i: interpreted structure) and the expected world (Fe^i: expected function, Be^i: expected behaviour, Se^i: expected structure)

Figure 3 is an extension of Figure 2. It adds the *external world*, which consists of things outside the agent and with which the agent's mental models can interact. In our meta-cognitive view, we conceptualize these "things" as the functions, behaviours and structures (F^e, B^e and S^e) of design representations. The external world also includes requirements on function, behaviour and structure (FR^e, BR^e and SR^e), representing constraints given from an external source (for example, a design project manager). We will not use them in this paper, but have included them for reasons of consistency with Gero and Kannengiesser's (2004) situated FBS framework. The process numbers are also taken from that framework; they are labels only and do not represent an order of execution.

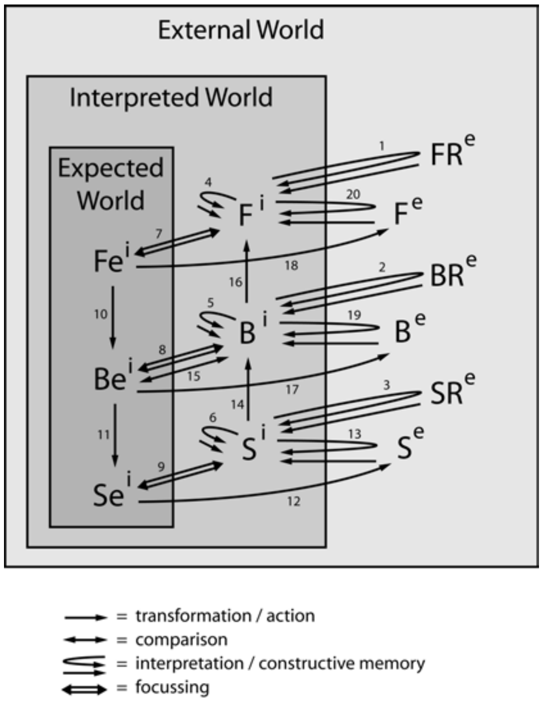


Figure 3. A process framework (consistent with Gero and Kannengiesser's (2004) situated FBS framework) that includes function, behaviour and structure in the external world (F^e: external function, B^e: external behaviour, S^e: external structure, FR^e: external requirements on function, BR^e: external requirements on behaviour, SR^e: external requirements on structure)

Adding the external world introduces processes connecting it with the expected and the interpreted world:

- *Action* produces F^e, B^e and S^e according to Fe^i, Be^i and Se^i. Action producing B^e is the execution of expected design actions. Action producing S^e creates a new external design representation or changes an existing one.
- *Interpretation* uses F^e, B^e and S^e to produce F^i, B^i and S^i using the same "push-pull" idea as for constructive memory: The results of interpretation are not simply "pushed" by what exists in the external world; instead, they emerge from the interaction of "push" and "pull". Thus, the same F^e, B^e and S^e can be interpreted differently at different times, leading to changes in the F^i, B^i and S^i generated.

We can now represent how representational affordances are produced. On a high level, this is a process that turns external representational structure (S^e) into external representational behaviour (B^e). This involves, at least, the following sub-processes, labelled according to Figure 3:

- Process 13: transforms S^e into S^i
- Process 14: transforms S^i into B^i
- Process 15: evaluates B^i against Be^i
- Process 17: transforms Be^i into B^e

These sub-processes compose what we may call the *affordance production process*. Other processes may be added depending on the extent to which the affordance interacts with the agent's situation that includes its experience, perceptions and goals. We can distinguish three types of representational affordances resulting from the different interactions:

- *Reflexive affordance*: applies to situations where there is a unique, pre-existing ("hard-wired" or habituated) response to a representation. No alternative affordances need to be considered.
- *Reactive affordance*: applies to situations where an action needs to be selected from a pre-existing set of possible actions, as no unique response is available.
- *Reflective affordance*: applies to situations where a new action needs to be constructed, as no existing action is available.

Section 4 provides a more detailed ontological description of these three types of representational affordances.

4. Types of Representational Affordances

Table 1 shows the processes involved in the three types of affordances. While the affordances all share the same affordance production process, they differ in the pre- and post-processing required.

Reflexive representational affordances require no pre-processing, as Fe^i, Be^i and Se^i are pre-existing and fixed. Be^i and Se^i provide a pattern to be matched by the B^i and S^i generated by the affordance production process. Optionally, the expected structure can be represented in the external world (S^e) (process 12). Because of the fixed, one-to-one mapping of S^e onto Se^i and the pre-existing affordance, there is a high confidence that the effects of action (process 17) will produce an output that by default meets the expected behaviour. Assessing B^e (processes 19 and 15) through a post-processing step is therefore only optional.

Reactive representational affordances are not based on pre-defined pattern matching but need pre-processing by selecting a set of known alternative structures (processes 9 and 11), behaviours (process 8) and functions (process 7). Optionally, a specific alternative Se^i can be transformed into S^e (process 12). These pre-processing activities make producing an affordance no longer an instance of pattern matching but of selection. Discussing any specific selection mechanisms is beyond the scope of this paper; such mechanisms may be implemented using standard techniques such as levels of grounding, recency and conflict resolution methods. The confidence in the effects of the selected action is lower than for reflexive affordances, which thus requires post-processing by assessing B^e (processes 19 and 15) and potentially re-selecting Fe^i, Be^i and Se^i (processes 7, 8, 9 and 11). This provides a basis for a new affordance production process.

TABLE 1. Reflexive, reactive and reflective representational affordances have the same production process but differ in their pre- and post-processing. Numbers refer to processes defined in Figure 3.

<table>
<tr><th>Type</th><th>Pre-Processing</th><th>Affordance Production Process</th><th>Post-Processing</th></tr>
<tr><td>Reflexive</td><td>No pre-processing required, as Se^i, Be^i and Fe^i are pre-existing
• Optionally, producing external structure: 12</td><td rowspan="3">• Input: S^e
• Transformation: 13, 14, 15, 17
• Output: B^e</td><td>No post-processing required
• Optionally, assessing the affordance: 19, 15</td></tr>
<tr><td>Reactive</td><td>Any of:
• Selecting Se^i: 9, 11
• Selecting Be^i: 8
• Selecting Fe^i: 7
• Optionally, producing external structure: 12</td><td>• Assessing the affordance: 19, 15
• Optionally, re-selecting Se^i, Be^i and/or Fe^i by new pre-processing</td></tr>
<tr><td>Reflectiv e</td><td>Any of:
• Constructing Se^i: 6, 9
• Constructing Be^i: 5, 8, 10
• Constructing Fe^i: 4, 7, 16
• Reflecting on new structures: 11, 12, 13, 14</td><td>• Assessing the affordance: 19, 15
• Optionally, re-constructing Se^i, Be^i and/or Fe^i by new pre-processing</td></tr>
</table>

Reflective representational affordances need pre-processing for constructing Fe^i, Be^i and Se^i (via processes 4, 5, 6, 7, 8, 9, 10 and 16). Pre-processing may also include generating and re-interpreting novel representational structures in the external world (processes 11, 12 and 13), which corresponds to Schön's (1983) notion of "reflective conversation". Affordances derived in the transformation may therefore be fairly novel, and their effects may then be associated with fairly low confidence. As a result, post-processing is required that assesses the outcomes of the affordance (processes 19 and 15). There may also be the need for re-constructing any of Se^i, Be^i and Fe^i, using any of the processes listed for pre-processing. This can result in a new affordance production process.

Sections 5 and 6 illustrate the three types of representational affordances and the ontological processes involved using examples of design analogy making and design optimization. We will particularly focus on how the design agent's interactions with different design situations can turn representational affordances from reflexive to reactive, and from reactive to reflective. While Table 1 lists many processes that may be involved in the different affordance types, we will focus on the processes operating on representational structure rather than behaviour or function. This is to highlight the main characteristic of representational affordances: the ability to produce the representations needed to afford suitable interactions with the design situation.

5. Representational Affordances in Analogy Making

Analogy making is commonly viewed as a two-stage process (Gentner 1983): (1) A "matching" stage, identifying common features of the target design and a potential source representation, and (2) a "mapping" stage, transferring knowledge from the source representation to the target design. We will use an example of analogy making where the target design is a pinball game for smartphones. One issue to be solved through analogy is to develop a new mechanism for the movement of balls through a set of various types of bumpers on the playfield. A potential source representation for such an analogy is a model of the solar system that is external to the design agent and thus S^e. Figure 4 shows an image of the solar system that includes planets, a comet and orbits. This representational structure can afford "map-ability" to the target problem in one of three ways: reflexively, reactively, and reflectively.

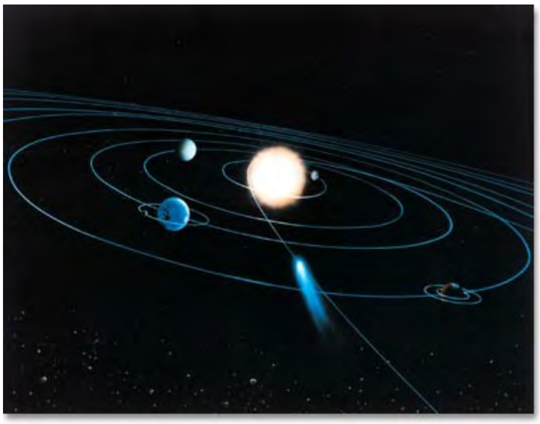


Figure 4. An external representation of the solar system

5.1. REFLEXIVE

Producing reflexive representational affordances involves no pre-processing. All expected functions, behaviours and structures are viewed as pre-formulated and fixed. This is the result of the designer being habituated to using solar-system analogies in previous design episodes. Fe^i is to “support the conceptual design stage”. Se^i is a representation of objects connected by force vectors as shown in Figure 5. The large spheres (representing planets) in this representation are assumed to be stationary, while the small sphere (representing a comet) is assumed to be moving. Optionally, the designer may produce an external sketch of this conceptual model (process 12). Be^i includes an expected representational affordance that maps planets onto round bumpers and comets onto balls, and expectations of the resulting trajectories of balls in the pinball game.

The reflexive affordance is produced by interpreting the external model of the solar system (S^e) to be consistent with Se^i (process 13), deriving a behaviour (B^i) (process 14), matching it against Be^i (process 15) and generating B^e (process 17). In our example, B^e includes characteristics of ball trajectories in the target design after implementing the analogical transfer. Subsequent interpretation (process 19) and evaluation (process 15) of this behaviour, in an optional post-processing step, may either support the reflexive affordance or reveal the need for producing a new affordance that may be reactive or reflective.

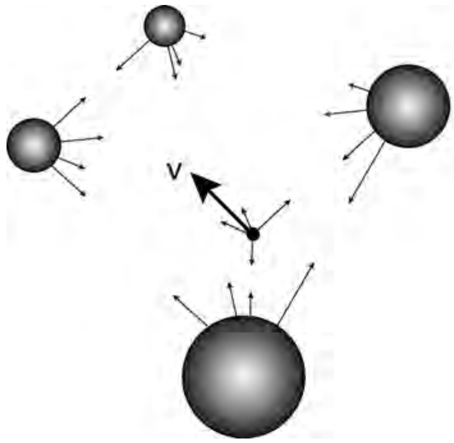


Figure 5. An interpreted representation of the solar system as a set of stationary planets and a moving comet with velocity vector v (dashed arrow), connected by force vectors (solid arrows)

5.2. REACTIVE

We base our illustration of reactive affordances on the assumption that the design agent assesses the outcomes of the reflexive analogy as unsatisfactory. For example, the pinball trajectories achieved by using this analogy may be too similar to existing pinball games. One way in which a new analogy may be produced is by expanding the range of alternative representations of the solar system model (process 9) that then give rise to different affordances. This expansion consists of representations that are already known to the agent. Figure 6 shows a representation of the solar system that introduces the movement of planets on different orbits. The agent selects this representation as a new Se^i (process 11), and optionally produces an external representation of it (process 12). In this example, we assume that Be^i is left unchanged; i.e., it includes an expected representational affordance that maps (the now orbiting) planets onto round bumpers and comets onto balls. Similarly, Fe^i remains unchanged.

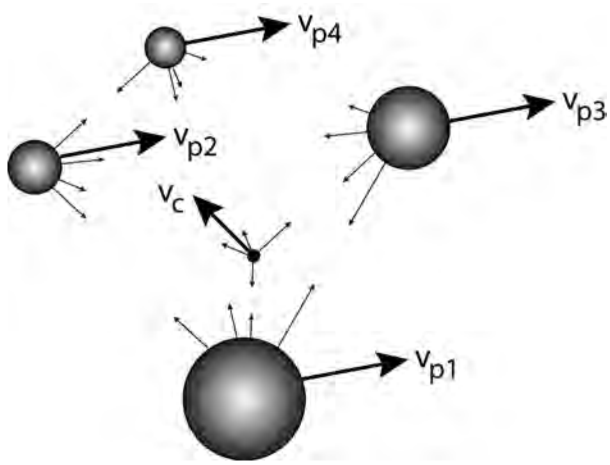


Figure 6. A new interpreted representation of the solar system as a set of moving planets with velocity vectors v_{p1}, v_{p2}, v_{p3} and v_{p4}, and a moving comet with velocity vector v_c, connected by force vectors

The reactive affordance is produced by interpreting the external model of the solar system (S^e) to be consistent with the new Se^i (process 13), deriving a behaviour (B^i) (process 14), comparing it with Be^i (process 15) and generating B^e (process 17) that includes new ball trajectories. After interpreting (process 19) and evaluating (process 15) this behaviour, the agent may accept the affordance or produce a new reactive affordance. In the latter case, the agent may select new Be^i (process 8) including a new affordance that maps planets to bumpers of all shapes rather than only round bumpers.

5.3. REFLECTIVE

In the case where previous representational affordances have produced unsatisfactory results, the agent can choose to look at the solar system in different ways. In our example, the agent may look for other theories of gravitation as a basis for producing a new expected representational structure (Se^i) of the solar system. For example, the agent may construct a memory (process 6) of the "rubber sheet" model in Einstein's general theory of relativity as an alternative source representation. According to this model, as shown in Figure 7, the mass of an object warps the space around itself, affecting other objects depending on their distances and masses. We assume that the agent has never before used this idea to represent the solar system, which makes it a reflective act. The agent adds this representation as a new alternative Se^i (process 9), selects it as a structure instance (process 11), and turns it into S^e (process 12). The agent interprets it (process 13) and derives a new B^i (process 14) that includes as a new affordance a mapping of the objects onto balls and round bumpers, and a mapping of the rubber sheet onto the playfield of the pinball game. This set of processes is an instance of Schön's "reflective conversation" (Gero and Kannengiesser 2008). Here we assume Fe^i to remain the same, although new functions may be constructed in other design examples (often derived from a new behaviour, via process 16).

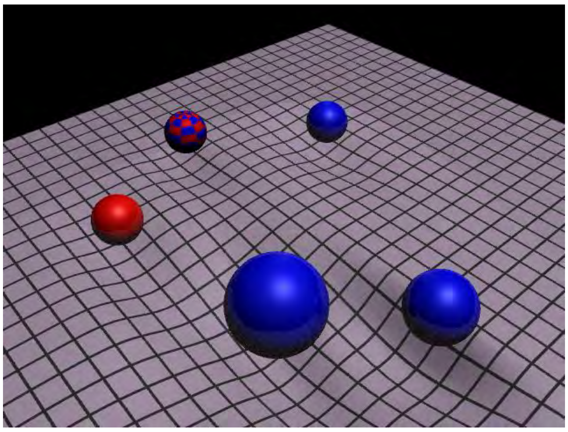


Figure 7. A new interpreted representation of the solar system as a set of objects warping space (Einstein's "rubber sheet" metaphor)

The reflective affordance is produced by interpreting the external model of the solar system (S^e) to be consistent with the new Se^i (process 13), deriving a behaviour (B^i) (process 14), comparing it with Be^i (process 15) and generating B^e (process 17) that includes interactions of balls with bumpers and their resulting trajectories. After interpreting (process 19) and evaluating (process 15) this behaviour, the agent may or may not accept the affordance. If a different affordance needs to be constructed, a number of processes are available to do so, as listed in Table 1. In our example, we assume that no alternative affordances are needed but that a change in Se^i occurs (process 6) that augments the internal representation of the comet's movement with a tail of gas or dust. This cues the construction of an additional task-related goal (F^i), to "support developing concepts for visual effects" (process 4), that is introduced in the expected world (process 7) to drive the construction of a new affordance (process 10) that maps various visual effects from the solar system to the pinball game.

5.4. DISCUSSION

Most models of analogy implicitly assume a view of source representations as being fixed before being used as input for analogical matching with a target representation. By applying our framework of representational affordances, we have shown that analogical matching is more like a process of match-"making": If the required match is not available for the current design objective, it may be generated by interpreting the source representation in different ways depending on the current design situation (Gero et al. 2008). Figure 8 summarises the different interpretations of the solar system that were used as source representations in our example. Each of them affords a different "map-ability" into the target representation, thus producing different design concepts for the pinball game.

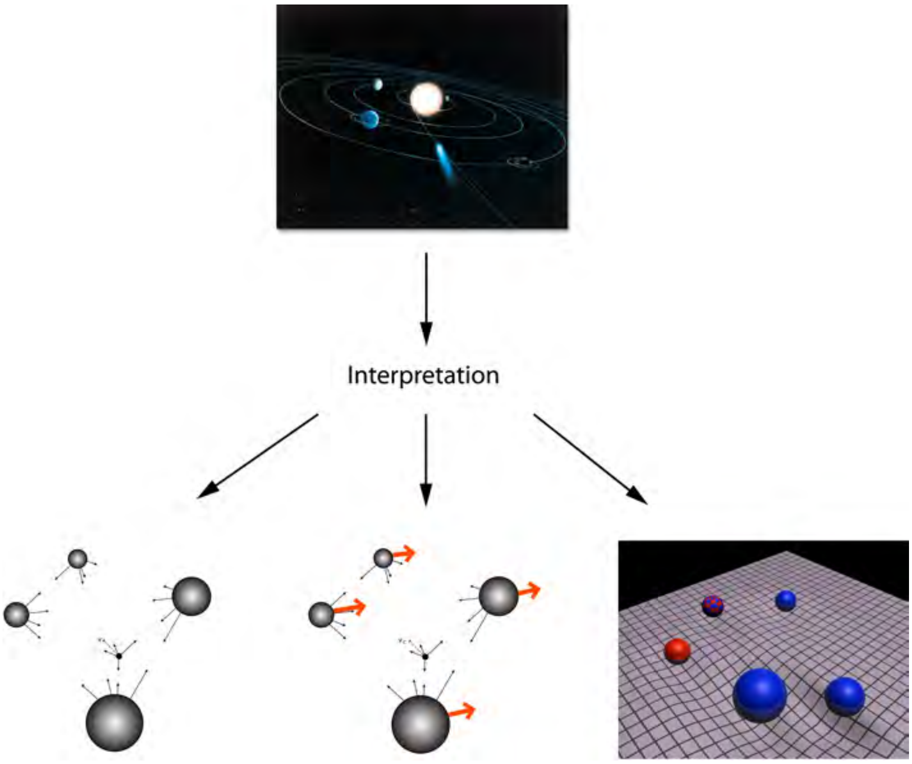


Figure 8. Different representations of the analogical source, affording different "map-abilities" to the target

Our framework is consistent with recent studies by Tseng et al. (2008) on the role of open goals (i.e., goals associated with current design tasks that have not been completed) in the interpretation of source representations for analogy making. They found that open goals allow designers to more easily identify deep similarities between source and target representations that are dissimilar on the surface (Holyoak and Koh 1987). Our framework allows mapping open goals onto expected functions, and provides a set of processes relating them to expected structures that may then generate appropriate source representations. Analogies that are based on deep (or distant) similarities between source and target representations, such as in crossdomain analogies, can therefore be assumed to often involve reflective representational affordances. On the other hand, once these similarities have been learned by the agent and applied in a number of design episodes, they will become more readily accessible, resulting in the affordance becoming reactive and then reflexive over time.

6. Representational Affordances in Design Optimization

Design optimization is a process that aims to find the "best" design with respect to a set of criteria (Papalambros and Wilde 2000). This process usually requires formulating a mathematical representation of the design problem in terms of an objective function, a set of equality and inequality constraints, design variables, and design parameters. We have adapted an example from Papalambros (1994) and Papalambros and Wilde (2000) that is concerned with optimizing the design of a linear actuator. Here, the actuator's drive screw (shown in black in Figure 9) needs to be dimensioned with the objective to minimize material cost. We assume here that the initial, external representation of the drive screw (S^e) is the one shown in Figure 9. This structure can afford "search-ability" of an optimum design in one of three ways: reflexively, reactively, and reflectively.

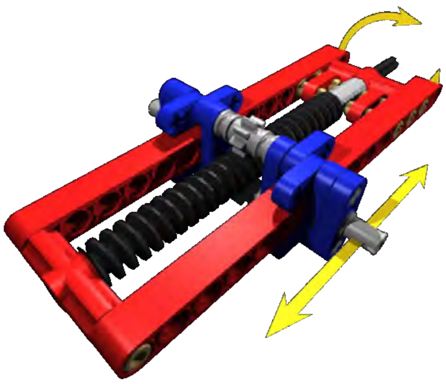
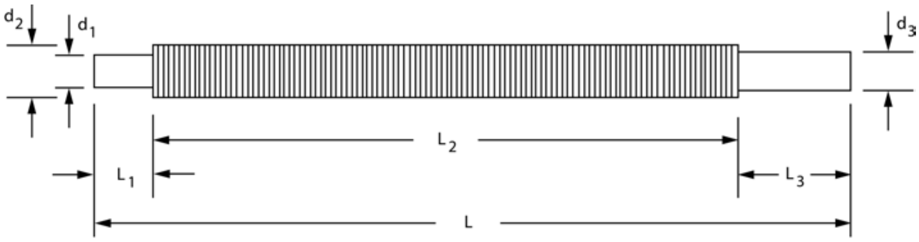


Figure 9. An external representation of a linear actuator

6.1. REFLEXIVE

Reflexive representational affordances are based on pre-formulated functions, behaviours and structures. To "support the detail design stage" can be viewed as a fixed Fe^i. The agent is also assumed to have expectations of a specific schematic and mathematical representation of the optimization problem, such as shown in Figure 10. These expectations are based on the agent's previous knowledge about optimizing drive screws for linear actuators. They are captured in our model by Se^i. The design agent may optionally produce an external representation consistent with Se^i, for example by inputting the mathematical problem formulation in an optimization tool. The agent also has expectations of a specific search method (say, Sequential Quadratic Programming (SQP)) that for the agent has previously proven effective in drive screw optimization. This method is the expected representational affordance of the problem representation, which we can describe as an input parameter of Be^i. The results expected from applying this method (such as the expected regions of the optimum design in the search space and the performance space, and the expected speed of running the search algorithm) compose the output parameter of Be^i.



Objective function: $f_o = \frac{c_m \pi}{4}(d_1^2 L_1 + d_2^2 L_2 + d_3^2 L_3)$

Constraints:

(g_1) $\frac{M c_1}{I} \le \sigma_{all}$

(g_2) $\frac{K T c_2}{J} \le \tau_{all}$

(h_1) $L = L_1 + L_2 + L_3$

(h_2) $M = F_a L / 2$

(h_3) $c_1 = d_2 / 2$

(h_4) $c_2 = d_1 / 2$

(h_5) $I = \pi d_2^4 / 64$

(h_6) $J = \pi d_1^4 / 32$

Design variables: $d_1, d_2, d_3, L_1, L_2, L_3$

Design parameters:
- c_m : *material cost per inch*^{3}
- M : *bending moment*
- I : *moment of inertia*
- T : *applied torque*
- σ_{all} : *allowable bending stress*
- τ_{all} : *allowable shear stress*
- K : *stress concentration factor*
- J : *polar moment of inertia*
- F_a : *force required during assembly*

Figure 10. A reflexively produced interpretation of the drive screw optimization problem

The external affordance is produced by interpreting the external representation of the drive screw (S^e) in a way that is consistent with Se^i (process 13), deriving behaviour (B^i) (process 14) and matching it against Be^i (process 15), and generating B^e (process 17) by applying the SQP method to the problem representation, using the optimization tool. Subsequent interpretation (process 19) and evaluation (process 15) of this behaviour, in an optional post-processing stage, is expected to but may not necessarily support the reflexive affordance.

6.2. REACTIVE

Reflexive representational affordances in design optimization can turn into reactive ones when they lead to unsatisfactory results, identified by interpreting and evaluating B^e. Unsatisfactory results may consist of the optimum being located outside the expected region in the performance space (i.e., the design under-performs), or the speed of search being unexpectedly slow. Modifying the expected affordance can eliminate these unexpected behaviours, here by selecting a different search method. Assuming that the agent can select from a range of known search methods, the resulting representational affordance will be a reactive one. This is captured in our model the selection of new Be^i (process 8).

Dissatisfaction with the current results may also create the need for choosing a different (expected) representation of the optimization problem, which is captured as reformulation of Se^i (process 9). For reactive representational affordances, this reformulation can produce objective functions, constraints, variables and parameters that the agent has been exposed with in previous optimization tasks. The agent then synthesises a different problem representation that forms a new Se^i (process 11), which can be externalised (process 12) by producing a changed problem formulation in the optimization tool. In our example, a "no-slip" constraint is added (with new parameters associated with it) that the agent remembers from a previous optimization task, Figure 11. Fe^i is assumed here to remain unchanged.

The external affordance is produced by interpreting the external representation of the drive screw (S^e) in a way that is consistent with the current Se^i (process 13), deriving behaviour (B^i) (process 14) and matching it against the current Be^i (process 15), and then generating B^e (process 17). Interpretation (process 19) and evaluation (process 15) may or may not support the expected affordance. Different Be^i and Se^i can be selected (processes 8, 9 and 11) using other combinations of previously known search methods and problem representations, respectively.

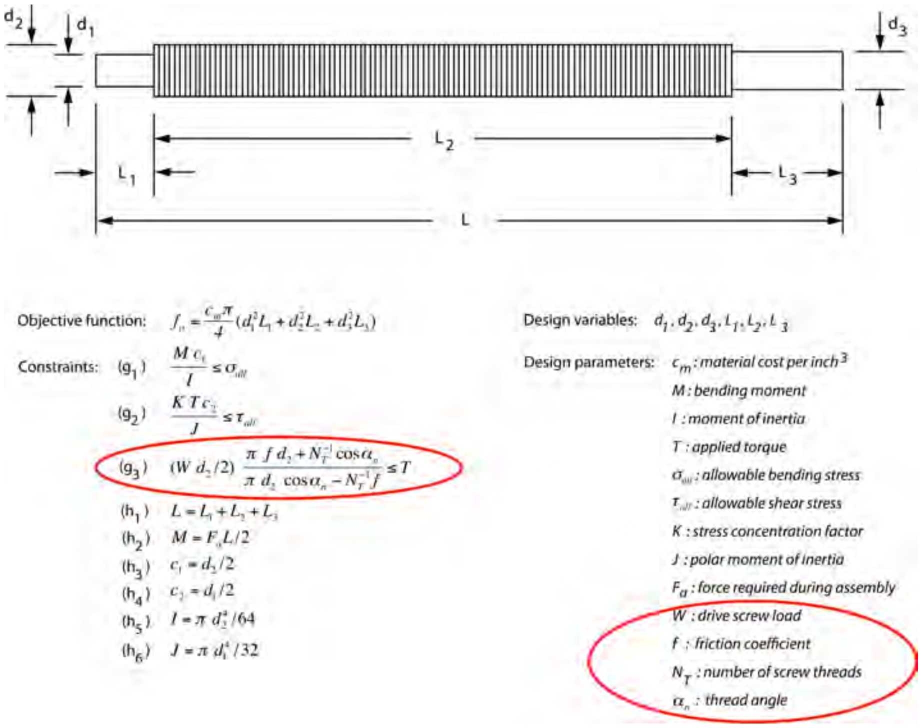


Figure 11. A reactively produced interpretation of the drive screw optimization problem, now including an additional constraint (g_3) and associated parameters (W, f, N_T and α_n)

6.3. REFLECTIVE

Producing new expectations may also operate on experiences that are not readily available through previous optimization tasks. This is captured by reflective representational affordances, which may involve any combination of newly constructed function, behaviour and structure.

Reformulating Se^i (process 9) reflectively is supported by strategies, documented in the design optimization literature, for re-representing (process 12) and re-interpreting (process 13) or re-constructing (process 6) problem formulations to facilitate their solution. For example, monotonicity analysis and dominance analysis are methods for discovering constraints that may be eliminated from the problem formulation, thus reducing the search space (Papalambros and Wilde 2000). Dimensional variable expansion (Cagan and Agogino 1991) can introduce new design variables by dividing the search space into multiple regions. In our example, a new design variable d_i is introduced that represents an inner diameter and turns the solid drive screw into a hollow one, Figure 12. This also changes the objective function and constraints h_5 and h_6.

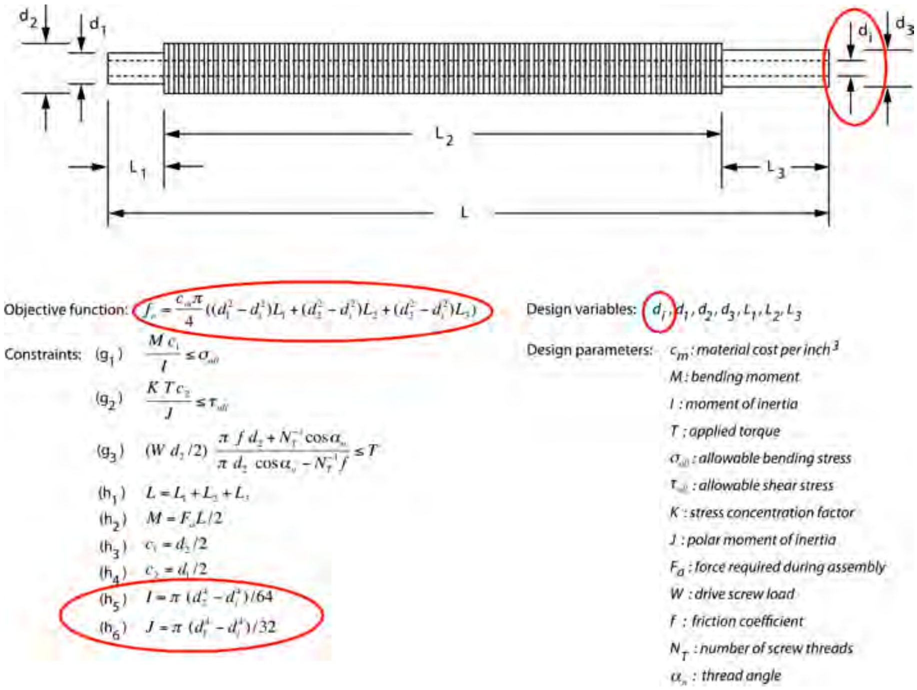


Figure 12. A reflectively produced interpretation of the drive screw optimization problem, now assuming the drive screw to be hollow instead of solid. This introduces a new design variable (d_i) and modifies the objective function and constraints h_5 and h_6

The hollow drive screw can be expected to significantly reduce the amount of material and hence the material cost. This corresponds to a construction (process 5) and reformulation (process 8) of Be^i by modifying the expected region of the optimum design within the performance space. Fe^i remains unchanged in this example.

The external affordance is produced by interpreting the external representation of the drive screw (S^e) in a way that is consistent with the new Se^i (process 13), deriving behaviour (B^i) (process 14) and matching it against the new Be^i (process 15), and then generating B^e (process 17). Interpretation (process 19) and evaluation (process 15) may or may not support the new Be^i. Unsatisfactory results may again provide the grounds for focussing on different Be^i (process 8) or Se^i (process 9). Satisfactory results, on the other hand, are a typical precursor for reformulating Fe^i (process 7). For example, a hollow drive screw design with minimized material cost may lead to the construction (process 16) of the new function to "allow exploring new design concepts for linearly actuated devices". One new concept to be explored may use the hollow space in the drive screw to transport liquids or gases in linearly actuated pumps.

6.4. DISCUSSION

Our framework of representational affordances supports a view of design optimization where the process of searching for the optimum design is only partially determined by the way in which the problem is formulated at the outset. Although a few mathematical methods and strategies for reformulating problems are well documented, the traditional view of design optimization does not include the notion that design representations and search methods emerge from their interaction with the experience, interpretations and goals of the designer (Gero and Kannengiesser 2006). Figure 13 summarises the different interpretations of the drive screw problem outlined in our example, each of which affords different "search-abilities" for the optimum design. As a result, both the process and the outcome of designing may change according to the specific design situation.

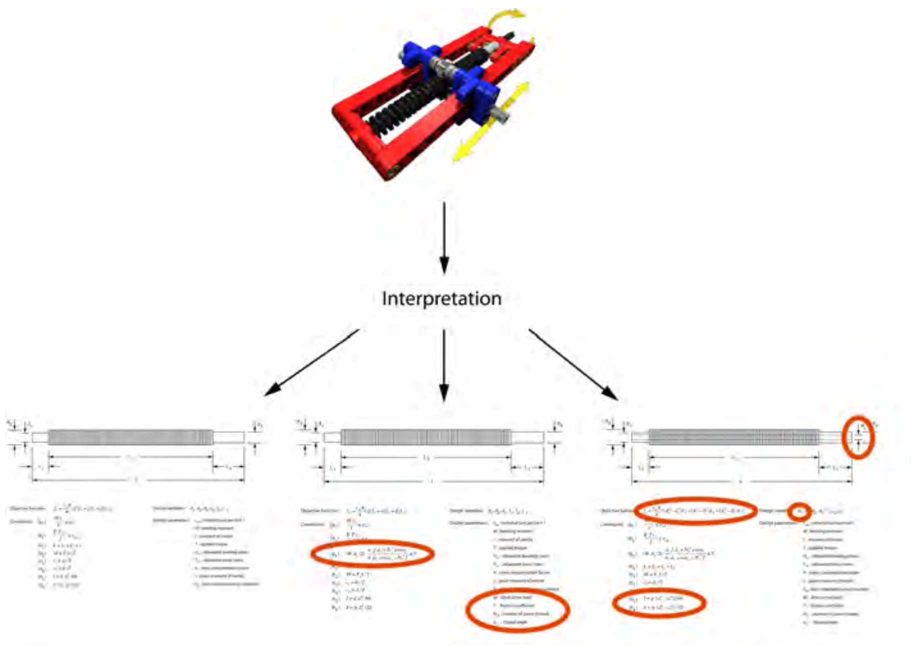


Figure 13. Different representations of the design optimization problem, affording different "search-abilities" for the optimum design

Searching for optimal designs often involves generating and identifying many sub-optimal design candidates and ineffective search methods. This provides plenty of opportunity for not only iterating the search steps but also reformulating the designer's expectations regarding appropriate problem representations, search methods and results. Representational affordances in most instances of design optimization are therefore likely to alternate between being reactive and reflective. Once the design agent grounds them by reusing them in a number of similar design situations, they will tend towards becoming reactive and then reflexive over time.

7. Conclusion

Representational affordances connect design representations and possible design actions not only with each other but also with the experience, the perceptions and the goals of designers. This can account for the differences with which individual designers interact with their designs in different situations. We have presented how representational affordances can be described in the FBS ontology and how they can be categorised as reflexive, reactive or reflective based on the effects of the current design situation. Each of these types involves different processes that are all captured in the FBS ontology.

We have applied our framework to two instances of designing from separate areas of design research: design analogy, and design optimization. They are often regarded as non-routine and routine designing, respectively. Routine designing is defined as a process that proceeds within a well-defined and fixed state space of designs (Gero 1990). Non-routine designing can be either innovative or creative: Innovative designing is defined as a process that involves modifying the state space of designs in terms of new alternative values for the same design variable. Creative designing involves modifying the state space of designs in terms of new design variables. By using the idea of representational affordances we were able to show that the common categorization of analogy as non-routine (creative or innovative) designing and optimization as routine designing can be incorrect. Analogy making can be carried out using reflexive affordances that do not alter the design state space. Design optimization, on the other hand, may involve reflective affordances that can lead to significant changes of the design state space. It is not the generic classes of design activities, such as analogy and optimization, that determine whether or not the initial design state space is modified, but the interpretation of that state space through the production of representational affordances. Reflexive, reactive and reflective affordance types correspond to routine, innovative and creative designing, respectively.

Figure 14 shows how the initial representations of optimization and analogy problems are connected to the three categories of designing not directly but via their interpretation within affordances. While initially the two classes of problems may be expected to afford activities with different impact on the design state space, they can be interpreted in reflexive, reactive and reflective ways, leading to categorizations as routine, innovative and creative designing on a case-by-case basis. Most importantly, what appears to be fixed at the outset of designing can change by interacting with the design situation. “Lateral transformations” (Goel 1995) or “focus shifts” (Suwa and Tversky 1997) can be viewed as transitions from reflexive to reactive and reflective types of representational affordances.

More research is needed to generalise these findings beyond design analogy and design optimization; for example, in areas of design configuration, design decision-making and design evaluation. Most interesting will be to examine cognitive processes such as mental simulation in the light of our framework. It may be possible to identify a form of design expertise that is independent of the amount of technical design knowledge: the ability to create new representations and explore their possible consequences. Representational affordances provide a basis for thought experiments that can then guide further research using cognitive or computational models.

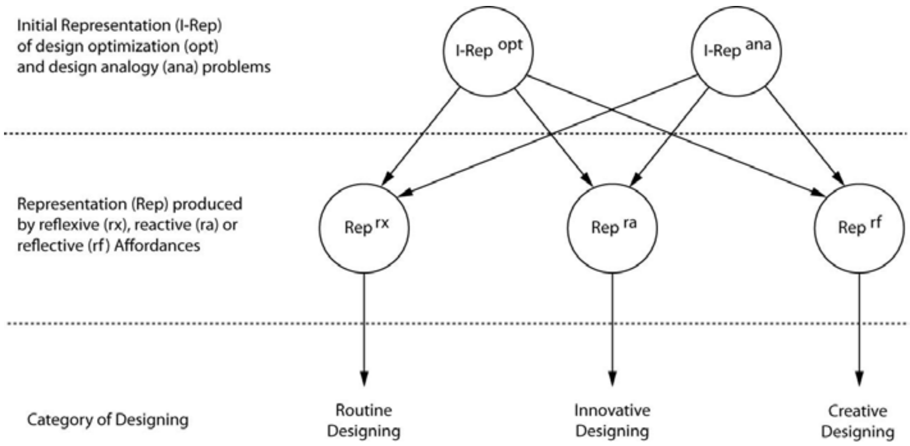


Figure 14. Representational affordances determine whether optimization and analogy are categorised as routine, innovative or creative design activities

The notion of representational affordances may lead to practical applications not directly related to designing but with a similar emphasis on interacting with representations. One application area may include virtual environments, such as in building design, where software agents or human avatars interact with representations of physical objects rather than with the objects themselves. Using representational affordances may allow more adaptive behaviours than would be possible using only physical interaction metaphors. Possible application areas for our work may also include information systems and their interaction with data representations of various domains. Affordances such as “interoper-ability” and “action-ability” may then no longer require fixed data formats or fixed process models, as representations may be generated as needed for the particular purpose in the particular situation.

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