Capturing indeterminism: representation in the design problem space

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Models of problem solving hinge on the idea of the problem space. Current models of the problem space do not account for indeterministic processes, e.g. those which exist in the solving of design problems, which are inherently ill-structured. While maintaining the concept of the problem space, this paper proposes a modified description of representations in the design problem space, with the purpose of getting a handle on indeterministic processes that are typical of the front edge of designing.

Keywords: design process, design rationale, modelling, problem solving, representations

The distinction between well-structured and ill-structured problems has been proposed as early as three decades ago [1], and has gained wide acceptance among researchers of problem solving. The realization that design problems are ill-structured (or ill-defined, or non-routine, or wicked) has been slow in coming, but today there seems to exist a consensus concerning this observation [2–6]. Moreover, design problems, as a class, are seen as a prime example of ill-structured problems [5].

What are ill-structured problems, and why is designing seen as the solving of ill-structured problems? If we accept the notion that the process of problem solving consists of moving (applying operators) from an initial state to a goal state through intermediate states, we can use these constituents to compare well- and ill-defined problems. Convention has it that in a well-defined problem the initial state is given, the goal state is either specified or it can be determined using stop rules, and the operators are controlled by known algorithms. In an ill-defined problem, on the other hand, one or more of these constituents is either unknown or incoherent. The initial state is usually vague, and the goal state either unknown or ambiguous. Neither stop rules nor algorithms for operators are specified in advance. The solver

1 **Reitman, W R** 'Heuristic decision procedures, open constraints, and the structure of ill-defined problems' in **M W Shelly and G L Bryan** (eds) *Human judgment and optimality* John Wiley, New York (1964)
2 **Buchanan, R** 'Wicked problems in design thinking' *Design Issues* Vol 8 No 2 (1992) pp 5–22.
3 **Cuff, D** *Architecture: the story of practice* MIT Press, Cambridge, MA (1992)
4 **Gero, J S and Maher, M-L** (eds) *Modeling creativity and knowledge based creative design* Erlbaum, Hillsdale, NJ (1993)
5 **Goel, V** *Sketches of thought* MIT Press, Cambridge, MA (1995)
6 **Rittel, H J W and Webber, M M** 'Dilemmas in a general theory of planning' *Policy Sciences* Vol 4 (1973) pp 155–169.

of an ill-defined problem must generate and represent a great deal of additional information that he or she 'imports' into the problem space in order to construct states, including the initial and goal states, and in order to construct a path or paths that connect them. It is therefore unlikely that problem spaces for well- and ill-structured problems are similar, nor can we expect to find similar search mechanisms within them.

Design problems are ill-structured, because one never has sufficient information in the initial state and because the properties of the goal state are never fully specifiable in advance, and therefore many different goal states are conceivable and acceptable. In addition, to date—despite continuous efforts—no satisfactory algorithms have been proposed other than for limited partial sub-problems. It is, therefore, true that in design problem solving, solutions are almost never predictable. This turns designing into an indeterministic process which is difficult to model and even more difficult to prescribe.

1 Indeterministic design processes

A predisposition to importing information into the problem space is particularly pronounced in design problem solving. What makes this phenomenon especially fascinating and at the same time difficult to model, is the fact that 'imported' information obeys no rules whatsoever: it may come from any domain, be represented in any medium and penetrate any existing information structure at any point. The designer and especially the expert designer, has some control over adding information. He or she may deliberately look for it and guide its incorporation to an appropriate spot. But this control is limited and information may also be added inadvertently [7].

Methodologists have been attempting to systemize the incorporation of new information into design processes for a long time. In recent years computational technologies have permitted the creation of relevant databases and methods of indexing, accessing and searching them, so as to tap information and knowledge that can be useful in design problem solving. Most of the knowledge in question is declarative (as opposed to procedural) and the various forms of databases (libraries, precedents, etc.) are domain-specific. Currently, models of the design process build heavily on knowledge bases, including some procedural knowledge. Few of these models can be described as computational counterparts of procedures used by humans and if so, only in simple, moderately ill-defined situations. They are counterparts in the sense that they solve problems, but they reach a solution using a different path than that used by a human mind. A review of this line of work is beyond the scope of the present discussion, but

7 **Goldschmidt, G** 'Doing design, making architecture' *Journal of Architectural Education* Vol 37 No 1 (1983) pp 8–13.

risking a gross over-generalization, we dare say that much of it is reductionist in the sense that it deals with indeterminacy by attempting to circumvent it. In other words, the goal is to transform ill-defined problems into well-defined problems. On rare occasions are models or computational tools proposed that confront the 'messiness' of a search that we associate with the solving of ill-defined design problems [8,9].

The question we deal with, however, is not whether human processes of problem solving, especially when the problems are ill-structured, can be simulated or emulated computationally. Rather, we are interested in the indeterministic nature of ill-structured problems and the cognitive processes that render them manageable. More specifically we would like to ask what representations are made in typical instances of design processes and how do these representations figure in design problem solving. To answer these questions, we first consider the notion of problem space—the locus in which problem solving activities take place.

2 Problem space

The metaphoric space in which the problem solver represents states of the problem, from an initial state through intermediate states to a goal state and the operators that are applied to them, is called problem space (the term is associated primarily with Newell and Simon [10]). Operators may come with a number of control functions, e.g. evaluation, transformation and problem-specific heuristics. Although the notion of a problem space was conceived in the context of computer simulation paradigms of problem solving, it was adopted by most students of problem solving, regardless of their approach to computation [11]. One of the advantages of using the concept of a problem space stems from its inclusiveness as a framework for development and comparison of problem solving models. We have seen that the difference between well-structured and ill-structured problem solving is easily described in terms of the problem space, i.e. the completion and coherence of states, and the degree to which operators are specified. In an ill-structured problem, the route to the goal state must be discovered, while the goal state itself is not entirely clear (and the initial state lacks information). An 'insight' that insinuates a solution occurs when at some point a trajectory is discovered that leads to an acceptable goal state, which is thus being determined.

In connectionist-oriented models, states in the problem space are described as nodes and operators as links among them. The result is a network that resembles a semantic network. Figure 1 is an illustration of such a network [12]. Models of trial and error as a common, low-end problem

8 **Coyne, R D, Newton, S and Sudweek, F** 'A connectionist view of creative design reasoning' in **J S Gero and M-L Maher** (eds) *Modeling creativity and knowledge based creative design* Erlbaum, Hillsdale, NJ (1993) pp 177–209
9 **Gross, M D** 'The electronic cocktail napkin—a computational environment for working with design diagrams'. *Design Studies* Vol 17 No 1 (1996) pp 53–69.
10 **Newell, A and Simon, H A** *Human problem solving* Prentice Hall, Englewood Cliffs, NJ (1972)
11 **Habraken, N J** *The appearance of the form* Awater Press, Cambridge, MA (1985)
12 **Holyoak, K J** 'Problem solving' in **D N Osherson and E E Smith** (eds) *Thinking* MIT Press, Cambridge, MA (1990) pp 117–146

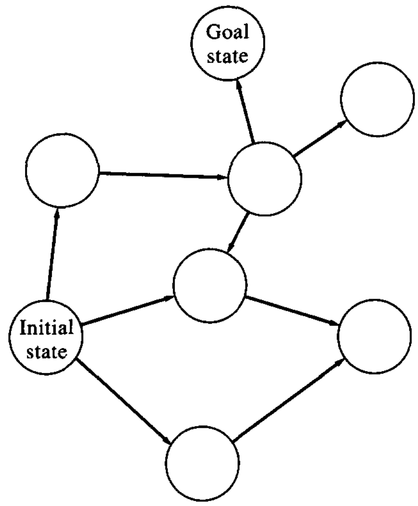

Figure 1 Fragment of problem space [12]. Copyright MIT Press

solving strategy, and models of spreading activation as a higher-end strategy, can be portrayed conveniently with this type of problem space representation. Means-ends models of problem solving, on the other hand, are easier to represent in the form of lists, where sequences of states are juxtaposed in parallel with lists of operators that interconnect them.

As a departure point for the studying of ill-structured problem solving, we postulate that a network type of representation of the problem space has considerable advantages, since we must assume that states are tentative and that we cannot predict in advance how, if at all, they might be interlinked by operators. Furthermore, if we accept that ill-structured problems are 'insight' problems, then we may describe the process of solving a problem as hinging, at least partially, on an expansion of the network of states and operators beyond the boundaries of the initial problem space. Three illustrations of the expanded problem space concept, by Habraken [11], by Rosenman and Gero [13], and by Takala [14] are shown in Figure 2.

We submit, however, that the habitual network model, consisting of representations of states and operators that interconnect them [as depicted in Figure 1 and Figure 2(c)], is not entirely satisfactory as it does not account for indeterministic processes. The nature of our reservations will be clarified in the next sections.

2.1 Representations

The nature of representations of states and operators has received limited attention in problem space models. Regarding designing, we shall make the following distinctions:

13 **Rosenman, M A and Gero, J S** 'Creativity in design using a design prototype approach' in **J S Gero and M-L Maher** (eds) *Modeling creativity and knowledge based creative design* Erlbaum, Hillsdale, NJ (1993) pp 111–138

14 **Takala, T A** 'Neuropsychologically-based approach to creativity' in **J S Gero and M-L Maher** (eds) *Modeling creativity and knowledge based creative design* Erlbaum, Hillsdale, NJ (1993) pp 91–108

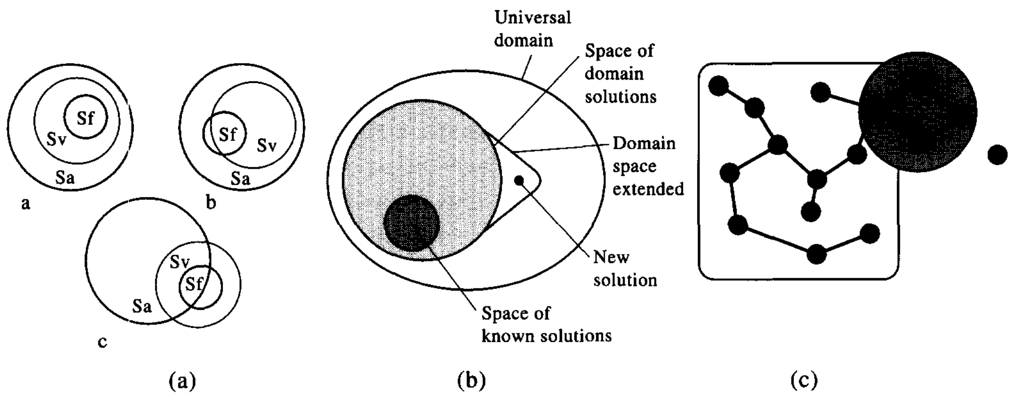

Figure 2 Illustrations of extended problem space **(a) Habraken [11] (b) Rosenman and Gero [13] (c) Takala [14]. Copyrights (a) NJ Habraken, (b) and (c) Lawrence Erlbaum Associates, Inc.**

2.1.1 Internal and external representations

Representations in the problem space can be internal or external. Under current theories, internal representations are the essence of cognition and imagery is the locus of much of our internal representation activity. External representations can be visual or verbal (by 'verbal' we mean expressed in words, in oral or written form). External and internal visual representations use different arrays of symbol systems [5]. External visual representations are expressed mostly in drawings (but there are other modes, e.g. three dimensional models). There are many types of drawings: two dimensional orthogonal projections, e.g. plans or sections, three-dimensional descriptions of objects or spaces, abstract diagrams and graphs, and personal 'shorthand' notations consisting of ad hoc graphic 'utterances' devised by the designer for his or her private use. We are interested in the early, conceptual phases of designing, in which designers habitually make sketches. The nature of sketches and intensity of the sketching activity are both task and designer dependent. Goel [5] points out that the symbol systems used in sketching display some properties that are not identical to those used in non-sketching external representations and these in turn differ from the properties of internal representation symbol systems. Although representation is a central issue in cognitive theories, these differences have not been addressed in the literature. This leads Goel to propose that present theories of cognition do not fully account for certain types of cognitive activity, e.g. those we witness in designing, as a prototypical example of ill-structured problem solving. He therefore outlines a design problem space which has some unique properties; e.g. deferment of commitment and personalized stop rules.

2.1.2 Conceptual and figural representations.

In most design fields the ultimate goal is to envision new entities, mostly artifacts, that fulfil a function such that a description of the entity and the way in which it functions meets with the approval of the parties concerned (clients, users, manufacturers, peers, etc.). In most cases, approval or at least assessment towards approval, is sought before the actual entity comes into existence: it is examined on the basis of its representations. A sufficiently full and coherent external representation can therefore be seen as the goal state in the design problem space. Intermediate states would then have to be inner or external representations of candidate elements of the entity that is being designed, and of anything that could be relevant to reasoning about the new entity and its functioning. Representations that portray physical elements of a new artifact, or of an existing artifact that is elicited for the sake of reasoning, depict figural attributes of artifacts. Such representations are therefore figural. Representations that regard attributes that are not physical, and do not directly pertain to forms or figures, are conceptual; e.g. a drawing of a shape that has specific proportions would be a figural representation of the shape; an expression of a wish for 'perfect proportions' would be a conceptual representation.

Designers (and other problem solvers) make representations of both kinds, as we can discern when inspecting external representations, e.g. sketches and concurrent verbalizations (recorded in protocol form, for example). The figural–conceptual classification is reminiscent of the pictorial–descriptional classification used in the imagery debate. The debate is over the nature of visual imagery, and it hinged on a more general question of whether cognition can be seen as being entirely computational or not. Today, there appears to be considerable agreement that both these modes co-exist in imagery. Likewise, we postulate that inner representations in the process of designing are also of the two types, figural and conceptual.

As we have direct access to external representations only, we can refer to sketches and verbalizations made while designing as the representations of which states and operators in the design problem space consist. We postulate that these external representations also reflect inner representations, although they are definitely not identical to them (e.g. Olson [15] shows that negation cannot be represented in visual imagery). It could be tempting to encode drawings as figural representations and verbal commentary as conceptual representations. We do not have this division in mind. Rather, we propose that both sketches and verbalizations may belong to these two modes of representation. We shall further propose that in designing it is essential to use both, alternately, resulting in multiple representations of

15 **Olson, D** *Speech and writing: towards a psychology of literacy* Globerson Memorial Lecture, Tel Aviv University, March 13, 1996

states and operators in the problem space, for the purpose of coping with indeterminism.

2.2 The structure of representations in the design problem space

Moves in the problem space are the small steps in which reasoning proceeds: i.e. they are representations of states and operators. Moves consist of arguments, with which the problem-solver reasons; in the case of design, arguments may be figural or conceptual. Representations are often continuous, in the sense that one sentence, or one image, may represent more than one argument, or may even pertain to several consecutive moves. Furthermore, representations are not restricted to a single vein: internal or external, verbal or visual— any combination of these modes and modalities may appear concurrently. The concurrent appearance of verbal and visual representations in problem solving is not unique to designing, but it is particularly frequent in designing, as compared to the solving of other types of problems. Evidence of the irregular appearance of different types of representations in designing (and possibly in ill-structured problem solving in general), leads us to treat them similarly. In this view, states and operators are symmetrical, in the sense that their status and their function in the problem space are equal. In current network models, states and operators have different functions and are treated differently: each operator links two states. Graphically, an operator is described as a line, perforce connecting two circles which stand for states. Our proposition does not require that each operator connect two states. Rather, states and operators, denoted by similar (graphic) symbols, crowd the problem space and form links among themselves, regardless of whether they are states or operators. Links among them, according to this model, are not independent representations, but have a different status. In other words, operators cease to be links; a link, we maintain, is not a cognitive operation, but its result.

We are now ready to show the connection between the conceptual–figural classification of representations and the structure of the design problem space, in terms of relationships between states and operators. We shall do so by way of analysing a small excerpt from a design protocol.

2.3 The design problem space: an example

Our example is a short vignette from a design exercise. It is taken from a taped protocol in which Dan, a mechanical engineer, designs a bicycle rack for a particular model ('Batavus') of a backpack. Figure 3 shows the sketch made by Dan in this instance. Dan's verbal output includes 10 moves; each move contains one, two or three arguments, and all together this vignette is composed of 18 arguments, as follows:

Move	Argument	
1	1	alright so what we've got is erm I think that this detail here
	2	'cos it says any bike is what they want erm, er..er er
2	3	OK alright so we want something that's really clearly related to this backpack directly
3	4	alright which would mean that we want the backpack to snap into it
4	5	OK first thing is that to make it a proprietary product for the Batavus backpack the er
	6	this this this this frame here will have U-channels on it
5	7	OK mounted on it unfortunately
6	8	alright so we're gonna make it out of er...like a steel tube
	9	or an aluminum tube
	10	with a U-channel on it and erm
7	11	no we don't even need that
	12	what we're gonna have is we're gonna just have frames

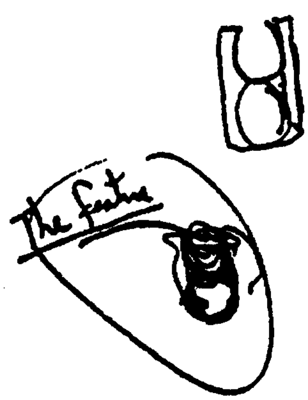

Figure 3 Sketch by Dan, from bicycle rack design protocol

8	13	gonna have a frame here end view
	14	and there's gonna be a er plastic erm clamp clip alright
	15	which the backpack will snap into
9	16	now why would the snapped backpack stay in there snap snapped into the thing erm
	17	when you might have large vertical loads
10	18	so we have one we have two times we want to have maybe four support points here

This episode occurs late in the design exercise, and in it the designer develops an idea for a clamp-clip that he calls the 'feature' of his bicycle rack design. This is a case of multiple representation, because of the verbal and visual representations that Dan produces simultaneously: in the course of two minutes he makes 10 verbal moves and produces a sketch that depicts the 'feature' twice. First very vaguely (Figure 3, bottom), then more coherently (Figure 3, top). If we code the arguments according to the type of representation they belong to, figural (F) or conceptual (C), we get the following sequence (by move):

Move	1	2	3	4	5	6	7	8	9	10
Argument	F-C-	C-	C-	C-F-	C-	F-F-F-	C-F-	F-F-C-	C-C-	F-

We observe that this sequence displays the following characteristics: (a) in most moves that include more than one argument, the designer uses both modes of representation; (b) moves start and end with either mode of representation; (c) the overall number of conceptual and figural arguments is equal: nine are figural, the other nine are conceptual. Similar characteristics were found in previous studies, concerning architectural designing [16,17]. What can we say about the problem space in which the designer Dan worked as he made these moves and, presumably, during the rest of the time he worked on the bicycle rack design?

As stated earlier the designer makes moves which are recorded in the problem space. The problem space includes representations of states and operators. We therefore conclude that moves are representations of states and operators: to make design moves is to represent states, operators and more states. Theoretically it may be possible that in inner representation, moves

16 **Goldschmidt, G** 'The dialectics of sketching' *Creativity Research Journal* Vol 4 No 2 pp 123–143.

17 **Goldschmidt, G** 'On figural conceptualization in architectural design' in **R Trappl** (ed) *Cybernetics and systems research '92, Proceedings of the Eleventh European Meeting on Cybernetics and Systems Research* World Scientific, Singapore (1992) pp 599–605 are sequentially ordered, i.e. each representation of a state is followed by a representation of an operator, and vise versa. External representations are not as regular and we record a number of consecutive representations of states, or operators, before the other type of representation is recorded (we believe that this is also the case in inner representation, but at present proof is still lacking). We propose that in essence, states in the design problem space are figural representations, while operators are conceptual representations. If true, this proposition is congruent with the pattern of arguments we detected in the vignette from Dan's protocol. How do we explain this proposition?

We recall that states and operators are interconnected in a network. We have shown elsewhere [18] why linkage is important: it supports a structured and productive process, which appears to be a necessary condition for arrival at a satisfactory design solution (such that the designed entity may gain approval). In further analysis we dwell on linkage between design decisions and the design rationale that supports them. During the process of designing, when decisions are at best tentative and commitment to them is withheld for as long as possible, design rationale is conditional. The designer develops partial candidate configurations and related concepts: concepts both generate configurations, or figural representations, and serve as criteria for their evaluation. Concepts therefore interconnect figural representations as operators interconnect states in the problem space. Likewise, figural images interconnect concepts as states interconnect operators. States and figural representations are both seen as descriptions of a condition, or phase of the problem or some subset of it at a particular moment. Operators, like concepts, make it possible to relate two states, or figural representations: only by coupling a figural representation (or a short sequence of representations) with a reasonable rationale, or raison d'être, can we react to it by another figural representation; e.g. let us look at moves 4 and 5 in Dan's vignette above, which includes arguments 5, 6, and 7. Argument 6 (F) which describes a frame with U-channels on it, is flanked by two conceptual arguments. Argument 5 (C) laid out the rationale for the configuration—the designer wishes to introduce a 'proprietary product' for the backpack he is designing for. In argument 7 (C) the designer assesses his tentative decision, saying that mounting the channels on the frame is unfortunate. Thus we get a sequence of interrelated moves: a concept or operator (propose a proprietary product), a state or a figural argument (frame with channels), and yet another operator or concept (assess frame with channels—not satisfactory).

18 Goldschmidt, G 'The designer as a team of one' *Design Studies* Vol 16 No 2 (1995) pp 189–209.

Sometimes a figure is predominant and concepts are matched to it, and at other times a concept is overriding, and figures are tried out to see if they fit. Therefore we have moves that begin with either argument modality. Sometimes the designer generates two concurrent figural representations (e.g. Dan's 'steel tube' and 'aluminum tube'; move 6, arguments 8 and 9). A rationale may be missing because it might have been stated earlier and need not be repeated (it may well be innerly represented). Likewise, a concept may be followed by another concept, when further articulation appears to be required (Dan's moves 2 and 3). For this reason moves consist of a varying number of arguments and manifest 'irregular' switches between representational modalities. In studies of longer design episodes than the vignette above, we have found [17] that 'the rate of exchange between modalities is more rapid at the time a design proposal is actually being generated, by comparison with instances of more generic reasoning about design...' (p 604). Likewise, Akin and Lin [19] identified three different types of 'activity modes' and showed that novel design decisions (as opposed to other design decisions) tend to involve a combination of all three activity modes in rapid succession. Despite the slightly different terms of reference used by Akin and Lin, we believe that the two types of analysis, which were carried out at the same grain, pertain to a similarly complex model of the design problem space. We depart from the simpler, commonly held model by proposing states and operators, both modalities of arguments, and links that interconnect them, instead of states, and operators that interconnect them.

2.4 Linkage and the extended problem space

Links among design arguments (or moves, depending on the purpose, and therefore the grain of the analysis) are important: we have shown elsewhere that they are indicative of the productivity level of the design process [18]. Certain components of productivity pertain to creativity, and links and their formation are therefore also relevant to design creativity. If innovative, insightful problem-solving is characterized by crossing the boundary of the problem space or by extending it, how does this description relate to an analysis of links among design moves or arguments?

Designs must be defensible, because of the need to gain approval for their creation (note the similarity to the social acceptance criterion for creative endeavors [19–21]). Coherence and completion are, therefore, utmost goals. To achieve coherence and completion, all components and elements of a design must reach 'good fit'. In other words, they must be closely interrelated. Therefore, one may describe the process of designing as one in which the designer tries to generate only such figures and concepts that can be linked to one another. Obviously, even experienced and creative designers generate moves that are poorly linked with other moves: these are 'futile' moves and their number decreases as design productivity rises.

19 **Akin, Ö and Lin, C** 'Design protocol data and novel design decisions' *Design Studies* Vol 16 No 2 pp 211–236.
20 **Heath, T** 'Social aspects of creativity and their impact on creativity modeling' in **J S Gero and M-L Maher** (eds) *Modeling creativity and knowledge based design* Lawrence Erlbaum, Hillsdale, NJ (1993) pp 9–23
21 **Hennessey, B A and Amabile, T M** 'The conditions of creativity' in **R J Sternberg** (ed) *The nature of creativity* Cambridge University Press, Cambridge (1988) pp 11–38

A breakthrough situation begins with a move that crosses the formerly outlined boundary of the problem space. If such a stray move remains solitary, it is likely to have no effect on the process. To be meaningful, it must be linked to moves within the problem space. The denser the web of links that the singular move (or moves) manages to weave, the more impact it is likely to have. If we imagined the boundary of the metaphoric problem space as being made of an elastic material, we could observe a dense cluster of links caused by 'breakaway' move(s) as pushing against the elastic boundary to make room for itself [Figure 2(b)]. The boundary may thus be stretched and the problem space is in a position to be extended.

3 Multiple representation

Some of the representations designers make are very close to one another. We postulate that with the exception of mere repetition, such close representations serve a constructive purpose. We will refer to this phenomenon, which is not unique to design of course, as multiple representation. How are multiple representations utilized? What needs are fulfilled by their juxtaposition or superposition in the design space, and what advantages do they offer in indeterministic processes?

Akin [22] points out that multiple representations of the same reality do not indicate that this reality is inflicted with inherent contradictions, but that 'realities have many different properties or attributes and each representation abstracts only a finite subset.' (p. 186.) In the early stages of designing, realities are quite tentative, but unless represented, they cannot be inspected for their potential contribution to the problem solving process at hand. We must distinguish between multiple representations as part of a design product, and multiple representations that a designer makes in the course of his or her search within the problem space. In the former case the multiplicity is meant to facilitate the communication of complex realities or ideas to a third party, whereas in the latter case they are meant to help the designer construct these realities. Multiple representation is a cognitive strategy that designers and ill-structured problem solvers in general adopt, because it facilitates the intricate process of creating links.

We postulate that multiple representation in the design process is related to the rhythmic switch between figural and conceptual arguments in the problem space. We have seen (Section 2.3) that, occasionally, several arguments of the same modality appear before a switch is effected. Short sequences of uni-modal arguments indicate that a single argument may not satisfy the cognitive system, which may not be ready to proceed to the next argument modality in the problem solving process. It therefore allows for multiple representation within the same modality. This leads to the

22 Akin, Ö *Psychology of architectural design* Pion, London (1986)

hypothesis that there are two types of possible links between consecutive arguments: a causal link is created when a switch in modality occurs. A link of the type 'multiple representation' is produced when no switch occurs (by this we do not mean to suggest that every pair of consecutive arguments are necessarily interlinked, or that links are formed only between consecutive arguments). The causal relationship between conceptual and figural arguments is part and parcel of our model of a problem space in which the two have a symmetrical status. But why multiple representation? Why is this phenomenon rather common? The roles multiple representations play in the 'micrograin' of the process appear to be quite similar to those their 'macrograin' counterparts play in the presentation of products. These roles include the following:

(1) Addition, completion. When one kind of a representation is not sufficient to convey certain information, another kind of representation may be summoned to supplement it. The additional representation could be of the same or of a different mode.
(2) Support, articulation, clarification, reinforcement. It is expected that information from more than one source, especially if its representations differ in mode, helps in memorizing information, possibly by providing more than one indexing option.
(3) Interpretation. The complexity of a situation or of an entity is sometimes hard to grasp when we have access only to a single mode of representation. This is particularly true if a rich interpretation of the situation or entity is required, e.g. in the performing arts. An exceptionally compelling example is the case of the theater director Robert Cordier, who accepted the difficult challenge of directing the play *Savage/Love*, by Sam Shepard and Joseph Chaikin (Theatre Marie Stuart, Paris, 1985). He took advantage of the fact that the plays were originally written in English, but were to be performed in France by a mixed group of English and French speaking actors. The performance presented each scene twice, once in English and once in French. This was not done in order to supply a translation to diversified audiences. Instead, it was a way to present two different interpretations of the script simultaneously (for further sophistication, the two interpretations were 'intermixed' across the two languages). This is a genuine case of multiple representation which, through the exposition of two lines of interpretation, created a rich, unified understanding of the whole.
(4) Transformation, modification, reformulation. We must resort to multiple representation when the represented entity is dynamic, a process: different phases of the process may be represented, mostly in the same mode, to create a continuum. When we adopt a wider perspective, we

may talk about the development of new ideas as reconfigurations of concepts familiar from elsewhere, within the same domain or outside of it. Schön calls this occurrence 'displacement of concepts' [23]. Schön refers in particular to the use of metaphors and analogy in generating new concepts, where familiar concepts from one context must be represented, transformed and abstracted, until they 'make sense' in a new context.

(5) Challenge, contradiction, conflict. Different representations which are not necessarily divergent interpretations of an entity or a situation, may serve as evidence of conflicting perceptions. Multiple representation may help in trying to bridge over a conflict or, conversely, in order to emphasize and sharpen it.

In designing, the dual verbal–visual representational system is especially conducive to multiple representation. Designers engage in intensive sketching, so as to arrive at multiple representations, either conceptual or figural (we should remember not to equate figural with visual and verbal with conceptual. These terms are by no means interchangeable). We know, for example, that sketching is helpful in certain types of transformational moves [24]. Multiple representations aid in structuring the problem space because they introduce prelinked states or operators. A rich array of representations may harbour clues that could eventually lead to the generation of a unique or breakaway representation; likewise it may make it easier (for a subsequent representation) to link such a remote representation to the main body of representations in the problem space, in order to achieve a breakthrough (Section 2.4). Therefore, we believe that multiple representation, which may at first sight seem to be a counterproductive or wasteful cognitive strategy, is actually a constructive device that is essential in indeterministic processes such as design problem solving.

To better understand the processes involved, we need a somewhat different model of the problem space than the one we hitherto subscribed to.

4 In conclusion

We have shown that given a different model of the design problem space, it becomes possible to advance a more coherent account of the process of designing, as a prime example of ill-structured problem solving. We have offered an alternative to the state-operator as node-link network that is the state-of-the-art description of the problem space. While maintaining the terminology and network approach, we have specified three rather than two types of components in the problem space. States and operators, which we equate with figural and conceptual representations (or arguments), have an equal standing and would both be considered nodes in a normative network. Links have a separate status and they are the third component of

23 Schön, D A *Displacement of concepts* Tavistock, London (1963)

24 Verstijnen, I, Goldschmidt, G, Hammel, R, van Leeuwen, C and Hennessey, J *Creative imagery of figural combinations: Synthesis can be done but analysis takes a sketch* (submitted) the space. In addition, we have proposed that the sequence of moves is rhythmic; in general modalities switch, and in a perfect and deterministic world we could probably expect a switch with every move. However, the world, at least the design world, is indeterministic and problem solvers cannot optimize their processes. Therefore, we witness phenomena like multiple representation, which causes irregularities in the rythmic process of representation in the problem space. We must, therefore, look at longer sequences of moves in order to assess the structure of the problem space.

It is our belief that the knowledge we currently possess about the intricacies of cognition and certainly design cognition, must lead to an increased acknowledgment of the enormous complexities that we face. We should therefore assume that the most profitable vein of investigation would be one that focuses on partial processes and questions, identifying variables and patterns of different cognitive manifestations of design behaviour. If we manage to represent the small particulars, we may in due time be able to link them together sufficiently to gain comprehension of the global whole.

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