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RESPONSE TO KEYNOTE

The whittled design space

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Abstract

The paper by Woodbury and Burrow is examined using four criteria: completeness, discrimination, alternative approaches, and combining exploration in different problem domains. Although the paper covers significant aspects of the search space literature it leaves out some relevant aspects of the cognitive approach. It fares much better in terms of discriminating important concepts and alternative approaches to the modeling of the design search space. The *structure–function–behavior* model is suggested as an analogy for the central parameters of the search space paradigm. The Woodbury and Burrow paper reveals more than what has been accomplished up to now in the design search space area, but its task still remains incomplete.

Keywords: Alternative Approaches; Combining Explorations; Completeness; Discrimination; Structure–Function–Behavior Model

1. INTRODUCTION

When considered in the context of systematic studies of the design process and its formalization, "design space" is an age-old concept. The design methods movement of the 1960s has been one of the first concerted efforts of exploring a problem domain, which we can retroactively call the design space. These early efforts, at best, chipped away at a difficult and poorly formulated problem. Attempts at exhaustive and quantitative solutions did not go far (Jones, 1970; Wade, 1977). Simple-minded formalizations merely revealed the complexities of the real challenge and led to abandonment of these approaches even by their own authors (Alexander, 1964). More serious and less ambitious steps were taken with the entry of artificial intelligence and cognitive science approaches into the fray (Eastman, 1970; Akın, 1986). These removed more layers of ambiguity and misdirection from the larger research effort of understanding the architecture of the design search process. Clear explanations have not been easy to come by. From a distance, all of these efforts appear as *whittling* away at the bark of, say, an old growth trunk. If the paper by Woodbury and Burrow represents taking an axe to it, then it promises to reveal more than has been accomplished before, but the trunk would still remain massive and vast.

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2. ANALOGY

The attempt to formally describe the concept of design space (taken in its phenomenological sense, as that which the formalization effort targets) is laudable and significant. I imagine that Woodbury and Burrow imagine such a feat can yield the goods; goods that have eluded many others attempting the same task, or other tasks of design formalization, which in fact, may be rendered through this one.

Analogous goals have been attempted in a variety of domains. Chess, medical diagnosis, mathematical discovery, and formal reasoning come to mind. Some of these are even computational cousins of this effort. Some attempts predate these efforts by centuries and do not even anticipate a world of machine computing.

What would be the example that benchmarks the ultimate success of formalized exploration spaces; one that would enable generations of future scientists and designers to pluck dozens of both tractable and intractable problems, as if they were an organized series of well-defined ordered search acts in structured "space?"

How about the discovery of the Periodic Table of Elements? Mendeleev's discovery has been nothing short of unveiling the *holy grail* of exploration to material scientists (physicists, chemists), who for many decades used this as their roadmap to elements both known and unknown. A brief excursion to 1868 may be instructive.

The motivation for Mendeleev was the construction of the table of contents of the second volume of his new text book on chemistry (Kedrov, 1966). In the first volume, he had already covered the halogens and the alkaline metals. It was not clear as to which group of elements should be covered next. In the absence of a logical structure to organize all of the 64 known chemical elements of the day, Mendeleev's exploration began with a search for a pattern that could govern all of the elements. One can view this as the pattern that structures the space of all elements.

Mendeleev started by comparing the atomic weights of elements. Although this was a good start for organizing the problem space at hand, there were two big obstacles. The first was the fact that the number of comparisons of atomic weights of all known elements was far too large to undertake exhaustively, not to mention the fact that the properties of these elements were too imprecise, owing to the poor methods of measurement available at the time, to make these comparisons accurately. The second obstacle was due to the chemical elements not yet discovered at the time, which made it difficult to see the global pattern in the data.

Mendeleev started comparing *groups* of elements based on their atomic properties and ordered them according to their atomic weights. This reduced the space of comparisons considerably and started yielding some consistent patterns. His second breakthrough came when he made a modification in his representation of the elements to save time. He was under pressure to go on a journey the next day and hand-written lists of the elements became too cumbersome to manage. Thus, he decided to use cards to represent elements ordered in a two-dimensional matrix space, with one dimension representing the ordering of atomic weights and the other general chemical properties (valences, and so forth) of the elements. The cards containing the identities of chemical elements were organized by Mendeleev in the same orthogonal fashion as the playing cards of the solitaire called *Patience*, according to suit and value.

This enabled Mendeleev to reduce the amount of clutter present in his problem representation. Despite the unknown elements, the new representation also made clearer the organizational principle of the resulting construct: "properties of elements stand in periodic relationship to atomic weights." One of the greatest contributions of the Periodic Table has been to facilitate, based on its underlying logic, the further study of the known but poorly understood elements as well as the discovery of ones that were unknown to scientists.

Mendeleev's discovery both provides an apt analogy for the present task at hand and exhibits certain patterns that can constitute a set of useful guidelines for making such discoveries. Mendeleev was

- working with a *complete* command of the knowledge in his field,
- *discriminating* the "noise" in the data so that the critical patterns are evident,
- identifying *alternative* approaches to the problem and considering the most manageable ones first, and
- deriving general principles from specific relationships to *combine* exploration in different problem domains[1] with the problem at hand (Kedrov, 1966).

Based on this line of reasoning, we can define the task proposed by Woodbury and Burrow as one that would commence with a complete understanding of the literature in the field of design, eliminate the noise in this body of sources, identify alternative approaches to the solution to be proposed, and combine insights from other domains to structure and synthesize a solution. The first one takes a lot of hard work, the second a discerning focus, the third an inclusive foresight, and the fourth, nothing less than brilliance coupled with good fortune. Lest you think this final factor leaves things to chance to an extent greater than that which would be warranted in the case of geniuses like Mendeleev, his familiarity with the solitaire game *Patience* and the circumstances surrounding his determined, almost obsessive, concentration on his task, over a very short period of time, were nothing short of serendipitous.

Consequently, the specific assignment I gave myself, in discussing the paper entitled "Whither Design Space?" by Woodbury and Burrow, has been to consider the presence of these four conditions in their documented exploration.

3. COMPLETENESS

Woodbury and Burrow draw from an impressive canvas of literature representing research done in various domains of spatial design ranging, impressively, along dimensions of both chronology and discipline. They sample broadly from linguistics to generative algorithms, from Simon's early work in the 1950s to his and other latest in the area. They define a comprehensive scope for spatial design particularly within the confines of a *spatiovisual* world.

They also hint at things that may be missing from this world. Early on, while discussing the paucity of research on the design space, they remark: "It may be that the current state of our knowledge of representation and generation is inadequate to the task" (Woodbury & Burrow's section 1). I agree with this assessment. In discussing the "prosaic" use of spreadsheets as a part of practice, they hint at the limitations that are implicit in these applications for assisting in the creation of formal representations for design spaces

[1] In the original text, the term used is problem spaces. I opted for substituting the word "domain" for it to avoid confusion in my arguments, because I use this concept to guide the exploration of a formal representation for problem spaces. Domain is a problem–space–neutral term referencing roughly the same semantic area.

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(Woodbury & Burrow's section 2.1). I agree with this assessment also. There are many more hints in the paper (Woodbury & Burrow's sections 3.3 and 3.8), at the shortcomings of formalisms and applications developed by many a design space explorer, including, to their credit, their own work, which share a thread with these two points.

The observation that the underlying media in all of these approaches is primarily spatiovisual is worth restating. Owing perhaps to the central metaphor of space, in the term "design space," and the primarily visual orientation of architectural design fields, to an obsessive degree I might add, all of the constructs reviewed or proposed are laden with graphic representations. The nongraphic content of design, often included in the form of design requirement models, are all but nonexistent. This is the blind spot of research in architecture, and indeed research in design computation. The situation is more than ironic, if you consider that computing is a medium particularly suitable for symbolic representation and processing, which are more suitable for nongraphic expressions. This preoccupation with graphics appears to be nothing short of disciplinary idiosyncrasy.

It is not the fact that there is no research in the area. It is, however, the fact that there is a lack of powerful paradigms that represent the design space of *requirements*. Furthermore, those that interface the graphic and nongraphic entities exactly in the way designers formulate and use them during design (Özkaya et al., 2004) are absent. This is a missed opportunity for design research in general and for the Woodbury and Burrow paper specifically.

Any attempt that models requirements alongside physical entities of design inevitably needs to address the duality of information types. Specifically, it must distinguish between requirements and physical entities; define the symbiotic relationship between them; and provide for the distinctions of storing, displaying, and computing within either set simultaneously.

The typed feature structures (TFS) paradigm adopted in the Woodbury and Burrow paper hints at this duality but primarily remains a homogeneous representation. Requirements and other nongraphic information are relegated to labels at best (Woodbury & Burrow's section 3.8). The bifurcation between generation and evaluation is another manifestation of the singularity of view. The role of evaluation in TFS is not clear. Do paths and tendrils (Woodbury & Burrow's fig. 10) grow from and append to one another due to some evaluation mechanism? If so, how does this influence the "morphology" or "genetic code," to introduce yet another metaphor, of the space that is created? These are questions that may posit interesting venues of development of TFS in the design realm.

4. DISCRIMINATION

This is where the Woodbury and Burrow paper shines. It takes an immense scope of a problem and brings it down to succinct enumeration of concepts and ideas. It begins by structuring and justifying a paradigm for formalizing the quasi-formal and certainly softer definitions of the design space found in the literature. It proposes a multitiered abstraction of this space and a specific approach that structures all of these tiers (Woodbury & Burrow's section 1). It sets a premise that suggests a convergence between the type–procedure–operation hierarchy and the action–amplification–computation operations (Woodbury & Burrow's section 1). It then goes on to specify the *action* domain through three central properties: representation, size, and intention (Woodbury & Burrow's section 2). The bulk of the discrimination effort exhibited by the authors is dedicated to the next category of operations: *amplification* (Woodbury & Burrow's section 3). It subsumes eight dimensions (representational prowess, codification, the explicit space, implicature, speed, backup, recall, and replay) that present an insightful and comprehensive view of design spaces. *Computation* in comparison to amplification takes a back seat in its generality. Clearly, this is not given detailed coverage by the authors, at least in this paper. They primarily refer to work that they have published elsewhere without getting into details. They conclude by proposing an approach to resolve remaining issues, through analogy, homology, and taxonomy.

This is a long, optimistic, and fairly written paper. Some of the more obtuse passages and expressions notwithstanding, it does an excellent job of discriminating thoughts, constructs, and relevant models for the design space. It accomplishes more through the parsimonious and powerful TFS model than those adopted in earlier attempts. It manages to explain and meaningfully connect a vast space of research gathered from diverse disciplines.

Digressing for a moment into the self-conscious realm let me observe that Woodbury and Burrow, wittingly or not, fall prey to the cognitive parameters by which we all abide. Many of their enumerations and categorizations number in conformance with George Miller's (1956) maxim: "the span of STM, 7 ± 2." This is certainly acceptable as we all conceive and communicate within these cognitive parameters and exceeding them is neither expected nor useful. The connection is not lost, at least on me, that the paper does not take a particularly *cognitive* view of the phenomenon under examination (design navigations within a space metaphor), which is the focus of the next section.

5. ALTERNATIVES

Woodbury and Burrow pay attention to cognitive factors in design. They not only display a basic understanding of designers' cognitive parameters in building their arguments, but they also take it into account in making proposals. Yet, this view of the world of design spaces does not rise to the level of a significant alternative to their central paradigm.

In enumerating sources for "computational access to the design space," for instance (Woodbury & Burrow's section 1), they exclude perhaps the only source that treats the subject matter from a cognitive viewpoint (Akın & Sen, 1996). In discussing amplification, they overlook a body of literature that specifically deals with designer limitations (Flemming et al., 1997). These may not, in fact, be oversights. They may have been intentional exclusions, as the contributions of particular sources are assessed differently by different researchers. The demonstration of the alternative view then should be sought in the contents of the proposals included in the paper rather than its specific citations. Does the Woodbury and Burrow paper incorporate the cognitive view of the design space in its proposal? To examine this I considered their "path" diagrams in their figure 10.

The path diagrams are pictures of metaphoric paths that represent design exploration. Each tendril represents a "design event." Mapped into a literal space these events have certain characteristics such as beginning and ending points, lengths, and internal state sequences. There are interesting questions, in a formal representation, of preserving these properties as well as manipulating them to advantage while designing. Woodbury and Burrow discuss and discover important properties towards formalizing this concept while leaving out some of the important characteristics of cognitive events.

Reusing these tendrils in the course of design (which may be equivalent to reusing a particular sill detail, for instance) is represented as a mere "transplant" of the original tendril onto the body of the state space path. Within a cognitive framework this would play out differently. Cognitively speaking, an event (tendril) previously experienced is never the same, another time around. There would be economies of action, information, and representation that would be realized with repetition. There may also be parsing of paths into fragments or lateral connections between parallel paths, all of which have precedents in protocol analysis literature (Akın & Dave, 1986; Akın, 2002).

Furthermore, there are current formal models that go well beyond the much maligned copy–paste models of which Woodbury and Burrow are rightfully critical. It has been shown that the equivalents of their tendrils of arbitrary length, beginning point, ending point, and state sequence, can be formally represented from scratch as well as from prerecorded tendrils. Such a formalism was recently tested using cognitively based ethnographic records of design episodes (Akın & Moustapha, 2004).

6. COMBINED DOMAINS

A useful construct in studying design has been the structure–behavior–function (SBF) paradigm (Chandrasekaran & Milne, 1985), which can provide a valuable metaphor with which to fashion a formal ontology for design spaces. This metaphor would present numerous fruitful correspondences to constructs proposed in the Woodbury and Burrow paper, such as the "designer action," "amplification," and "symbolic representation" (Woodbury & Burrow's section 2), which correspond respectively to behavior, function, and structure. Because of the generality and power of its reach, however, the SBF model has been interpreted liberally in a variety of fields. Consequently, one of the immediate challenges in using it here is to define its components unambiguously.

Although a great deal has been written about it in the design domain (Gero & Kannengiesser, 2003), the genesis of the SBF model belongs to chemistry. Returning to this domain, let us consider the water molecule in Figure 1. It illustrates some of the central *structural* properties of water. Water is the simplest compound of the two most common reactive elements in the Universe. This structure results in specific *behaviors* that we can readily recognize.

For instance, when the temperature of water exceeds 100°C or falls below 0°C, under normal atmospheric pressure, it evaporates or, respectively icing occurs. In the latter case, crystallization takes place, increasing its volume. This is how ice can damage other materials that have fine cracks into which it can enter in liquid form. These behaviors, along with its structure, account for some of the very important *functions* it serves: we drink it, wash with it, swim in it, and cook with it.

Let us try to use this construct as the vessel into which we can place some of the concepts proposed by Woodbury and Burrow for design spaces. The "actions of the designer" would correspond to the *behaviors* encountered while observing designers in action. "Amplifying" these actions to serve specific purposes would give us the palette of purposes, or *functions*, designs serve. The constructs we would form through computable, symbolic representations, which correspond to design *structures*, would help us realize these amplifications.

Such an approach can well subsume the full complexity of designer's actions, their amplification, and their computable structures. The SBF metaphor can provide a clear set of the following:

1. criteria for categories into which known or to be discovered design phenomenon (just as in the case of the Periodic Table) can be placed, including design requirements;
2. formal relationships that structure the interaction between these categories, including partial and cognitively morphed events, or "tendrils," and

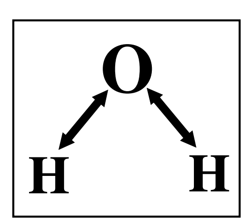

Fig. 1. The structure of the water molecule.

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3. semantic threads that reach into a plethora of formal and case based examples in different domains of problem solving and search.

Although the Woodbury and Burrow paper presents powerful ideas about the domain of search spaces, its implicit metaphor of "searching in a space" remains excessively generic and open ended. Consider the path metaphor. What evidence is there that the parameters that define the characteristics of a spatial path are the same as those that take place in design? A spatial path is defined by dimensions that are continuous. Space contains physical objects that obey the rules of physical dimension and continuity. They possess properties of mass, occupancy, and the physical laws of statics and dynamics. Is there any reason to believe that the properties present in the space of design are isomorphic to those of physical space? If not, then how far should this metaphor go in providing the guidance toward formalizing design spaces?

Conversely, their explicit mapping into the TFS model developed for computational linguistics (Carpenter, 1992) appears to be specific and well defined. This mapping begs the question of range. How successfully and to what extent can we map the world of design into the world of linguistics? The field of architectural design is populated with a fair number of language metaphors, similes, analogies, and the like. Some have captured the popular imagination of architects who are always eager to use loose reference, while, by and large, these efforts have failed to produce formal models of design that behave as they do in natural language.

A construct that provides both generality and power, such as the SBF paradigm, is more likely to provide a fruitful breakthrough, as Mendeleev was able to achieve. In summary, the SBF, when applied in a reverse engineering mode,[2] going from known behaviors to structures that accommodate these behaviors and associated functions, can help tap into the challenges and opportunities present in a very large body of relevant literature in a very diverse set of design domains: engineering, sciences, industrial design, and so forth. This may seem like an overly ambitious strategy at first; yet the ambitious agenda of creating a formal and domain-independent representation for design spaces needs an equally ambitious strategy.

[2]As one reviewer of this paper put it "the analogy of the water molecule seems to indicate that the structural properties of water result in specific behaviors that we recognize and that account for the functions that it serves. Projected onto Woodbury and Burrow's concepts, it could be interpreted as the structural properties of computable, symbolic representations, and their constructs give rise to specific processing techniques and methods (behaviors) that account for designer action amplification (functions)." At first (as suggested by this reviewer), the causality appears to be counterintuitive. Computable representations do not drive design behavior; they are created in response to them. Indeed, this is so. However, the requirement for creating these representations is to make sure that they are able to give rise to the appropriate behaviors and functions, that is, some sort of reverse engineering is required.

7. CONCLUSIONS

Woodbury and Burrow's work represents a significant step forward in understanding and formally describing design. Its use of the space metaphor, although unremarkable, is useful. Its utility arises principally from raising interesting questions rather than answering them. Here are some of them that provide food for thought.

1. Is it possible to formalize design, with all of its phenomenological complications, through a single, parsimonious model?
2. What role should metaphors play in developing such a model, during its conception, its formalization, versus its promotion through products like papers and prototypes?
3. What performance goals in the realm of design motivate and justify such efforts?
4. What role should human cognition play, if any, in defining these performance goals, not to mention the paradigm underlying these formalisms?
5. Can a comprehensive objective, such as this one, scale beyond the members of the inner group who produce it? What can be gained by broadcasting it to other researchers, such as the effort that this journal issue represents?

Although I am optimistic about the possibility of answering these questions positively and constructively, particularly the last one, I remain curious about the outcome, which should be manifest in this collection of articles.

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