"Realities" of Design

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In an article published in 1965, the Bauhaus teacher and designer, Johannes Itten, wrote:

The creation of a work of art often requires that the creative potential has at its disposition a multitude of possibilities to arrive at the simplest and clearest formulation. (Itten 65, p11)

The possibilities that Itten refers to are the inner creative resources of the artist. In order to train these resources Itten’s students worked on exercises to practice the links between perceiving, imagination and artistic media. Itten found the source of possibilities inside the artist; in recent years we have learned something about expressing possibilities externally.

Spaces of Designs.

Consider an arbitrary design. Whether it is a drawing, a physical model, or a data structure in a computer’s memory, it to some degree represents the objects it proposes, but it is not those objects. A design may be changed and such changes transform a design into another design. Through changes, designs derive other designs. If a design B can be created by a sequence of changes to a design A then A can be said to derive B. Derivation can be considered recursively, in the sense that derived designs can in themselves be changed in order to derive other designs. Typical designs may be changed in a variety of different ways - many designs can be derived from one design.

Designs may thus be intellectually connected to other designs through derivation. To use the terminology of graph theory, designs may be taken as nodes and derivations as directed arcs. Thus designs may be positioned in a graph of designs related to each other through derivational connections. Such a graph may be called a space of designs.

A process of design may then be characterized as moving (or searching, or exploring) through a (possibly changing) space of designs, following derivational connections between designs until the process is stopped.

Except in the most trivial of cases, no process of design can visit all designs in a space. In fact, the size of spaces of designs is typically astronomical, if not infinite. Spaces thus have a virtual existence. A space need not be enumerated (not all nodes need be visited) for it to be a meaningful concept in thinking about designs. It is the possibility of enumeration (generation) that gives spaces their interest.

Virtual Reality.

Regardless of the origin of the term, the notion of virtual reality has been with us for quite some time. I understand it to mean that a computer simulates some aspect of a phenomenon so as to give to a human a convincing experience of interacting (both perceiving and acting) directly with it. The phenomenon is given a virtual existence by the computer, thus the term virtual reality.

Each discipline, indeed each task, poses its own phenomena for virtual reality simulation. Virtual reality for pilots requires models of the instrumentation and control devices for aircraft and simulation of changing attitudes and accelerations as manoeuvres are performed. This is in addition to the visual virtual reality of landscape seen through the airplane’s windows. Virtual reality for fire-fighters would require not only some pyrotechnic thermal devices but also simulacra of water-spewing hoses which in turn...
can affect the "fire" if it was to provide a believable simulation of engaging a major fire at close quarters. Personal computer games are so popular because they involve people directly with the game, even though their rendering of a "realistic" environment is presently very poor. Design is no different - it would require its own unique virtual reality that gets people involved with design. Visual experience may play only a subordinate role.

The notion of moving, searching or exploring in a space of possibilities has a centuries long tradition in architectural thought and more recently a strong following in CAD. As a metaphor for design it reveals much and has coherence with other metaphors of design. Thus I contend that spaces of designs are a good metaphor for the "reality" in which designers work.

Other bases for virtual realities might initially be thought to be more obvious. A very common and ordinary instance of virtual reality is one that provides the eye with what it might see by moving in some physical world. It can easily be said that such a visual virtual reality models a real world and thus would be more "real" in some sense than other more "conceptual" virtual realities. But a visual virtual reality is every bit as partial and metaphorical as any other virtual reality. It is partial in both what it presents and how it presents. When using a visual virtual reality you would only be experiencing part of what is needed to interpret a building fully. For example, you would not be given an experience of its role in the economy within which it works, nor would you be able to experience the ways in which people habitually used it. Instead you would be given what "the eye might see," and this in only a partial sense. Presently our understanding of biological vision and computer graphics technology can only provide images that are recognizably "unreal". Though both understanding and technology will grow, computer generated images will remain "unreal" to us for some time to come. A visual virtual reality is also metaphorical. It is based on a long-standing and useful notion of taking the eye as a perspective device. But the eye plays a much larger role in our interaction with the world. At best, the eye-as-perspective metaphor addresses only what happens in our fovea view; it certainly has little to say about our peripheral or night vision. The eye-as-perspective metaphor hides many aspects with which designers are deeply concerned. It preoccupies us with certain limited dimensions of the visual and experiential. In doing so, it directs our concerns away from aspects of architecture that are every bit as essential as vision. Lastly the eye-as-perspective metaphor is not strongly coherent with what we do in design. True, it can provide a simulacrum of the visual experience of a complete building, but tells little of very real designerly concerns of how the design for that building came to be and where it might be taken next. Even within its domain as a simulator of visual experience it is incoherent with design. To create a "real" visual simulation, there must be specifications for "real" material and "real" ways of joining materials. In short there must be a complete design. In absence of a complete design, there are few options and these lead in such directions as removing material completely (as in the Eisenman "foam-core" houses I-X) and the presumption of absurd and untenable completions (as happens when large energy analysis programs like DOE-2 are used). Designs are never complete, and "real" simulations based on incomplete designs will necessarily hide as much as they show.

A visual virtual reality might be appropriate for a client; designers have other concerns. Certainly the techniques of visual virtual reality will be important for architecture, but placing our main attention on them, or on any virtual reality of a finished design is not in the best interests of design. Further, design need not give visual virtual reality much attention; its appeal is universal, its development is thus assured.

Consider a visual virtual reality experience of a Victorian house. As you "turn" and "move" through the house you are provided with a "realistic" simulation of the visual experience of the house. This simulation might be computed with all the latest computer graphic capabilities, for example combined ray tracing and radiosity with extra detail computed at the point of your fovea view. When you "turn" a corner into another room, the room is, to your perspectival eye, there. Although it exists nowhere, you experience it; you are provided with a space of experiences through which to move. You are
making "moves" in an apparently physical world. Suppose you do not like what you see and wish to change some aspect of the design. What does the virtual reality you have been experiencing tell you about your options and possibilities?

Contrast this to a designerly virtual reality experience of the same Victorian house. This virtual reality positions you in a space of designs. You might move through any one design, experiencing it from many points of visual and conceptual view — this is the visual component of a designerly virtual reality and requires a certain amount of computer graphical sophistication. At any point you might decide that the design needs to be changed, for example you might wish to re-articulate the masonry.

You would reach out to the design with an "articulation tool," touch it in a few places and would instantly be shown several alternatives of articulation at those places.

You could move through any of these in turn, and use one or more of them for further explorations of design alternatives. At any time you would be positioned in a design space surrounded by virtually existing designs, all just a thought, touch and gesture away. The "reality" simulated would be a derivationally connected space of designs. You would be making "moves" in an conceptual world.

A designerly virtual reality presumes the existence of a visual virtual reality, but also requires much more — specifically the ability to travel, in apparent "real" time, in a virtual space of designs. The technology for the visual part of the virtual reality will take care of itself, for the motivation for it exists in almost every field. In the main designers and design researchers need not waste time and effort considering its further development. There are, of course, some exceptions, for example the fidelity of light source modeling required for museum simulation is high and unlikely to be treated outside of museum design. Design spaces are another matter as they are unique to the discipline of design. If anywhere, it is here that design and design research need to set goals for developing and using virtual reality.

Building a Designerly Virtual Reality.

The account of spaces of designs so far has only used the notions of derivation of designs from other designs and movement (search or exploration) through the implied spaces of designs. If computation is to be used to further develop spaces of designs, then the idea of a symbol structure must be used. Within a computer, all data and operations are expressed as collections of symbols, i.e., symbol structures and all representations must be built in symbolic terms. Designs are thus understood as symbol structures which to varying degrees represent aspects of a design. Changing designs occurs through operations to symbol structures.

Although typically infinite, virtual spaces of designs may be finitely and often compactly described. Spaces are typically defined by some of their members and a set of operators that can act recursively upon those members. A space comprises all designs that can be created beginning with a starting design (or designs) and by recursively following all possible derivational arcs. It should be obvious under this definition that changes to either initial designs or to operators will define new and most likely different spaces of designs. A particular process of design may be recorded as a sub-graph of the entire design space. Until a design is visited (generated) in a process of design its existence remains virtual, that is, only implied by the possibilities of recursive application of operators.

Conceiving of designs as symbol structures and design processes as recursively defined sub-graphs of a space of designs allows the creation of mathematically formal means to characterize designs and design processes. Under the banner of grammar, much formal mechanism has been created in this vein. Recently, computer systems operating on spaces of designs and producing (by themselves or with human interaction) complex and convincing designs have been devised. These systems create, or more precisely, discover designs.

Consider a space of designs; it is a graph in which nodes denote designs and arcs denote transformations between designs. Remember that a concise description of the graph can be achieved by describing some initial designs and the possible transformations that take one
design to another. If designs can be described at all, describing initial designs are not problematic - they are just designs. Describing the transformations is another matter. If each transformation in the entire virtual space of designs had to be individually described nothing would be gained. If initial states and operators are to yield concise descriptions of spaces of designs, then the operators must be expressed so that one operator describes a large (possibly infinite) set of transformations in the space of designs.

This is where rules, being the main device of grammar, come in. A rule specifies a condition under which it may be applied and an action which it effects. These two facets of a rule are customarily expressed separately as a Left Hand Side (alternatively a precedent) and a Right Hand Side (alternatively a consequent). For example, consider the rule below:

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Left Hand Side  Right Hand Side
(precedent)     (consequent)
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In English this rule says that whenever you have a solid rectangle (specified by the precedent of the rule), you can place another rectangle of the same shape and size but rotated by 90 degrees above it (specified by the consequent of the rule).

Whenever a way to position (transform) the precedent such that it is part of a design is found, the precedent (and therefore the rule) is said to match in the design. Once a match is found, the rule can apply to the design by removing the precedent in its matched position from the design and adding the consequent in the same position. Given an initial design comprising a single rectangle the example rule can be applied in four different ways (shown below) if the precedent of the rule is considered to match the entire rectangle and if identity (i), translation, rotation (r) and reflection (m) may be used in the matching process.

The rule can apply in turn to each of these new designs, but this time in eight different ways to each design. In the figure below, the alternatives are divided into two groups of four, showing respectively rule applications based on matches with the vertical and horizontal rectangles.

This process can be continued, applying the single rule in each of its possible matches, to
each new design in the developing space. The result is a space of designs. Choosing one path through the space (one sequence of rule application decision) yields a particular design. But all the other designs are waiting out there, ready for discovery, one need only find paths to them.

Initial designs and rules; these are the core of grammars. Grammars typically contain one other component, an alphabet of symbols, divided in turn into a terminal alphabet and a non-terminal alphabet. Alphabets are needed to provide a library of possible symbols on which to compute, and the division into two alphabets permits specification of halting conditions—a fundamental control of derivation processes. Derivations terminate when all of the non-terminal symbols have been removed by the application of grammar rules.

Grammars thus describe spaces of designs. In grammatical terms, these spaces are languages; of which there are two types. Derivable or extended languages comprise all designs that are generable by a grammar. Terminal languages or just languages comprise all designs with no non-terminal symbols that are generated by a grammar.

There exist many accounts of grammar systems for designs. These include precise definitions of grammatical systems, something that I have omitted here. Readers interested in the formal aspects of grammars are advised to refer to the primary sources.

Computer Programs for Grammars.

Grammars are theoretical devices interesting in their own right and for the designs and spaces of designs that one can derive with them. Their interest though is limited by the techniques we have at our disposal for their application. When we must apply grammar rules by hand each derivation takes a long time and is error prone. Asking questions concerning the relation of one design to another through manually created derivation sequences that generate them certainly appeals to some, but becomes quite tedious for me. It is useful to have a computer program that accepts grammar rules and assists us in piloting through the space of designs implied by those rules; such programs are absolutely essential for creating a designerly virtual reality. Generically such programs are called grammar interpreters.

Grammar interpreters find matches and apply rules. In addition, they may have mechanisms to control the application of rules. To make them useful to humans they are given interfaces that support the creation and editing of rules, control of "travel" through their virtual spaces of designs, manual editing of designs, and simulation of individual designs.

As drawing media are to manual design so grammar interpreters are to a virtual reality for design. For example, consider pencil drawing. With it feedback is direct and immediate: graphite is laid onto paper by the passage of the hand. So it needs to be with grammar interpreters—users need to be able to directly experience consequences of their actions. Changes to both rules and to designs need to result in directly experienced changes to designs found by rule applications. Experience with the simple grammar interpreter DiscoverForm demonstrates the benefit of direct experience [Carlson 91a]. When a change is made to the underlying grammar it is immediately applied to the design generated by the grammar—enabling a user to base what is to be done next on the graphical effects just produced. Of course, to achieve immediate response requires speed. Towards this end, much remains to be done as very little is presently known of the time complexities of algorithms for grammars [Krishnamurti 81].

With a pencil, drawing can be fluid; the medium does not get in the way. We think of neither the parts of the pencil nor the composition of the paper, we simply draw. Similar fluidity needs to be provided in grammar interpreter interfaces and I propose here two principles of design towards this end. First, working with rules and designs should be as similar as possible. Non-parametric shape grammars are a ready demonstration of this idea, for with them designs and both the LHS and RHS of rules are simply labelled shapes—an interpreter could provide exactly the same editing capabilities for each. Second, the rule editing should be in an appropriate modality. For example, in the
program discoverForm[Carlson 91a] Carlson found that by programming rules through simple graphic interactions the notion of a rule almost disappeared in use. To use discoverForm is simply to explore.

When we draw we have expectations of the medium. For example, we quickly learn the kind of line qualities we can make with different leads, hand pressures, and speed. In the large, these expectations are met by the medium; it is predictable for us and holds few surprises. The same needs to hold with grammar interpreters; their basic workings need to accord with our intuitions. By way of negative examples, if there are known parts of a design space that are inaccessible with a grammar interpreter, users will become frustrated. Also, if an interpreter produces incorrect results, users will quickly lose confidence and interest. Much research effort in spatial grammar systems is spent aligning formalism with intuitive expectation. The famous shape embedding property so stressed in the shape grammar literature is an issue precisely because its presence makes the behavior of a representation accord with intuition. Without it, there frequently occur representational states that should be matched by rule LHS’s but are not. The various forms of rule parameterisation in grammars11 gives individual rules a broader and more intuitive scope of application. Sinty’s algebras of design can be seen as an attempt to make the broadest possible class of symbolic representations amenable to predictable computation (Sinty 90). Flemming’s generative rules for rectangular layout guarantee (amongst other properties) that all possible layouts can be generated and that a branch-and-bound search strategy will produce correct results. Heisserman’s unary operators on boundary representation permit arbitrary changes to object boundaries to result in well-formed representations of solids (Heisserman 91). In each of the above examples, the representation and the fundamental operations upon it provide a stratum upon which apparently well-behaved programs can be built - it would seem that carefully conceived and rigorously defined representations are necessary if grammars interpreters are to behave intuitively.

Beyond the analogies to manual media, grammars and their interpreters themselves present opportunities for enabling exploration of search spaces. Grammar interpreters are unlike pencil and paper in three ways. First, they simplify human action. Since rules imply spaces of designs, changing rules changes not one design, but many. Understanding the relations between rules and designs is crucial in making construction and use of grammars coherent, and is typically attempted by viewing rules as expressing principles or conventions that are exemplified by the designs that they partially generate. With this understanding, Flemming has formulated the criteria of correctness (or appropriateness, depending on context) and expressiveness for evaluating grammars [Flemming87a]. To the extent of possibility grammar interpreters need to make coherent the amplification of rules to designs.

Second, interpreters themselves can derive designs. Given a grammar, an interpreter can find some members of its language - creating the potential for a radically different type of dialogue than that possible with manual media. The potential is one thing, and taking advantage of it quite another, for grammar interpreters can produce far more designs than a human could productively consider. In this light, the layout system LOOS can be seen as a mechanism to eliminate from consideration all but a small set of distinct designs which cannot be formally rank ordered by the performances of its members. Presently very little of how to effectively structure dialogue with a grammar interpreter is understood.

Third, interpreters can potentially filter their output - a characteristic they share with all existing computer aids. For example, derived designs can be displayed in a variety of forms each of which may reveal (or conceal) some aspect of the design. In this characteristic, grammar interpreters are like more conventional notions of a virtual reality12. Since displaying designs well is one of the main achievements of conventional CAD, much is already known of how to effectively display designs and rules.

Some exemplary grammar interpreters (ones with some of these properties) have been implemented in research labs. Krishnamurti devised the first algorithms for and implemented the first non-parametric shape grammar
Several spaces of designs have been partially explored with the aid of grammar interpreters. At the time of writing, the most extensive explorations have been done with grammars that produce designs for Queen Anne style. Three such grammars have been implemented, the first by Ulrich Flemming et al. [Flemming 87b] and the other two by my graduate students at CMU, Shih Hai Chiang and Ching Yin. Flemming's grammar was implemented via a special purpose spatial grammar interpreter written in Prolog [Flemming 87a]. Chiang and Yin's grammars were both implemented in Genesis; they initially follow Flemming's but diverge significantly at some points and extend detail to a considerable degree. Figure 1 shows several Queen Anne house designs that are complete in their defining grammar (by Yin). Figure 2 shows several steps in a derivation sequence for one Queen Anne house design (by Chiang). Detailed explanations of these grammars will be given in a forthcoming publication. Typical designs from both grammars comprise about 250 boundary representation solid models. At present, Genesis generates these and similar designs, including display of all derivational steps in approximately two minutes.

Coherence with Design.

Designs may be produced by the artifice of grammar. Spatial grammars and the interpreters that compute over them are proof of this. But existence by itself seems insufficient support for directing serious research attention towards the creation of virtual realities of possibility offered by such devices. How coherent are the notions of derivation and grammar with what we know as design?

Several metaphors that describe movement along derivations in a space of possibilities have been developed. The notion of design as search is a basic metaphor that has become popularly identified with search situations in which the goals are predetermined and immutable. That such a restriction is untenable in general architectural situations is one of the major contributions of the so-called Design Methods theorists of the 1960's and 70's, but even within its confines, certain aspects of architectural design are illuminated by the metaphor, for
example, detailing building envelopes for airtightness as described by Brand (Brand 90). A grammar acted on by a control strategy in which the goals are invariant is an explicit and direct model of search that has been implemented on computers many times (but especially see [Flemming 89] in which each run of the system necessarily has a fixed goal structure).

Related to search, is the notion of exploration which is, according to Carlson, "...venturing forth without a definite goal in the hope of discovering interesting phenomena" [Carlson 91a]. Exploration explicitly takes away the fixed goal structures so problematic in the popular perception of search leaving questions of evaluation simply un-addressed. As a problem solving behavior it seems to me an extreme position, even further into the realm of the undefined than would be behaviors required, for example, for Rittel's famous wicked problems in which problems are at least stated though subject to reformulation. If grammars are taken as devices for stating possibilities and methods that can easily generate members of their languages are given then explorations of both the space defined by a single grammar and multiple spaces defined by altering grammar rules are enabled. Such is the premises of discoverForm, an interactive grammar interpreter over a simple case of structure grammars.

Simon's ill-defined problems [Simon 73] and Rittel's wicked problems can be thought of as arrayed between the extremes of popular search and exploration. Though I have not worked it through, derivational and grammatical notions would seem to be helpful to a precise formulation of these notions.

Another metaphor, which has recently become quite popular in CAD circles is that of puzzle-making which describes the work of architects as finding "...unique sets of combinatorial rules (the essence of the puzzle) that will result in an internally consistent fit between a specific kit of parts ... and the effects that are achieved when those parts are assembled in a certain way" [Archea 87, p. 41]. Without being formally precise, Archea could scarcely have given a more direct grammatical metaphor. Interpreted in the domain of grammar, Archea is saying that architects invent new rules.

In addition to direct metaphors involving movement through spaces of designs, several other strands of coherence within design theory can be found. A historical sketch of systematic notions of spatial design is given by March and Stiny (March 85). With the exception of their positions on questions of value, Alexander's pattern languages can be readily understood as informal grammars [Alexander 79]. Rowe presents a taxonomy of normative positions in architectural thought. He makes no claims of coverage for his taxonomy, but does maintain that each of its positions are "highly visible in contemporary theory and practice" [Rowe 87, p.124]. Each position is presented partly in terms of its "architectural devices", for example the functionalist position is partially described as having the "hallmarks of "explicit expression of a building's essential structure and process of fabrication" (Rowe 87, p.124). Put in grammatical terms "architectural devices" are vocabularies and rules. Rowe's positions seem to vary not in the importance they give to composition, but in perceived effects that can be achieved through compositional means. The first three chapters of Krier's book Architectural Composition, read as an informal introduction to grammar, with motivation from function, construction, historic building practice and cultural origins [Krier 86]. Several general expositions of essentially grammatical views of design have been made. In the most recent of these Mitchell constructs a view of architectural design that makes extensive use of logical models of thought and knowledge [Mitchell 90b]. In his account, grammars play the explicit role of characterization of a design world in which computations find states that satisfy given predicates expressed in terms of those states [Mitchell 90b, page 1791]. Mitchell's account is presented in generic terms, and he carefully points out that specific processes based upon it may take very different forms [Mitchell 90b, page 181].

Looking more directly at the design record it is easily seen that architects tend to create oeuvres or corpora of related designs. Exemplary is Frank Lloyd Wright, whose works (over more than 50 years) are identifiable and develop along threads of design ideas. Although we can often intuitively identify individual pieces of architecture that belong to the oeuvre of some architect and characterize common features of
architecture that typify members of a body of work, grammars provide us with an explicit way of describing and working with corpora of designs and of elegantly accounting for differences between corpora as a result of transforming grammatical rules themselves (Knight 83). Indeed much of the literature on spatial grammars has attended to the use of grammars to explain existing corpora of designs. Fleming, Knight, Mitchell and Stiny have been the main contributors in this regard, although there are a number of reports by others. Cumulatively these writings attest to the regularity of much of existing architecture and to what can be learned through post factum analysis by constructive means. A large part of the appeal of such analyses is precisely their constructive character - they address designerly questions about how things might be made in a way not to be found in other analytic forms.

At least one architectural practice, Pacific Architecture in Sydney Australia, David Week prop., has built notions of grammar directly into a way of doing work (Spence 87). For each of a number of housing projects in Papua/New Guinea the firm has developed an informal grammar that addresses notions of both function and construction. Along with direct experience of local context and an understanding of the history of local building and craft, these grammars have enabled the firm to propose projects very different from and arguably more preferred than typical contemporary building in the area.

Although the above account of the coherence of the metaphor is only a sketch, it appears that derivation and grammar have a strong coherence with threads of architectural history, theory and practice. I see several other facets of design with which coherence could be argued, for example the hermeneutical notions of dialogical design, issues of value in design and other linguistically inspired metaphors for design. In addition, a more extensive account of coherence would also have to describe what is hidden by the metaphor. These questions await another day.

Conclusion.

Derivational and grammatical ideas are now well-oiled machinery in design research. They enable a computational simulation of the world in which designers work; a world of designs, intellectually connected via derivational links. The metaphor for design that they present appears coherent with many aspects of design as we know it. They are thus a proper basis for virtual realities relevant to design. While researchers in other fields will almost certainly pursue virtual realities based on visual simulation of physical worlds, only design researchers are likely to work on grammatical systems. They are our turf and our task.

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Figure 1: Some of the Queen Anne house designs produced by Yis's grammar.

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Figure 2: Selected steps from a derivation sequence for a Queen Anne house design (due to Chiang).
Footnotes:

1 A space of designs as used here corresponds to the notion of a search space from an earlier paper “Searching for Designs: Paradigm and Practice (Woodbury 91).

2 Nor are spaces able to so well defined as to make the concept of exhaustion meaningful in general. The changes we can make to designs are not fixed; we change them in different situations and over time. Since spaces of designs are defined in terms of the changes that may be made to their member designs, as different ways of changing designs are introduced and eliminated a space of designs is altered. Within formal grammatical specification of designs, this problem is addressed by defining an algebra which is employed in the writing of rules. Algebras define universes of designs and grammars subsets of those universes. By changing grammar rules different parts of the universe of designs are accessed. Thus, within the bounds of the universe, the notion of grammar rules per se is not limiting; it does not constrain us to look at a fixed space. This leaves the difficulty that the choice of universe limits the designs that may be considered. Spatial grammarians in general and Stiny in particular have long argued for and given representational algebras that permit designerly recombination of objects within very broad bounds.

3 For example, Hans Moravec of the Robotics Institute at Carnegie Mellon University (CMU) has for many years (much longer than the term “virtual reality” has been around) talked of the idea of having “magic hands” that would support real-time manipulation of solid objects as modelled in a computer. He was not alone.

4 Accounts of metaphor give as much importance to what a metaphor hides as to what it reveals. A comprehensive understanding of the design-as-movement metaphor would require insight into what it hides in addition to what it reveals about design.

5 It is interesting to consider the predominance of magazine images in our present understanding of architecture. These images are partially based on a distortion through variable focal length of an eye-as-perspective metaphor. They are pervasive, very selective (they filter what we know of a building) and they influence what gets built and what gets imitated. It is easier to capture an object with a photograph than it is to capture context. What of present day architecture is influenced by the ubiquity of the photograph?

6 And distances us from our tactile and kinesthetic (haptic) experiences of space.

7 Through the agency of whatever devices are available. You might be wearing movement sensors for neck rotation and be walking on a treadmill to provide view orientation and forward velocity respectively.

8 Massing articulation is a crucial move in the creation of Eastern North American Queen Anne Houses (Flemming 97).

9 Students of grammatical methods will know I am dissembling here. In this example, even under a limitation to isometry transformations there is an infinity of possible rule matches for each of the second stage designs. This occurs because the two rectangles together create the possibility for an infinite number of placements of the rule LHS (a rectangle) such that it shares part of each rectangle. Stiny has written on this issue many times (Stiny 82) (Stiny 86) (Stiny 89).

10 See [March 85] and [Woodbury 91] for reference lists to the grammatical literature.

11 Two forms of parameterisation have been reported in the literature to date. Parametric shape grammars perform matching in a two step process: binding of variables in a schema to produce a shape rule and matching of the shape rule (Stiny 90). Boundary solid grammars use logical expressions to express parametric match conditions directly (Heisserman 91).

12 In this characteristic alone, more conventional conceptions of virtual reality are unlike manual media.

13 All of the movement metaphors discussed here can be subsumed under the notion of search as described in (Newell 72).
14Apparently search and its synonym problem solving have become associated with the necessary and immutable existence of well-defined goals. At least in [Newell 72] (which must be regarded as a, if not the, basic account of human problem solving theory) search is given a different technical meaning. Newell and Simon carefully and tentatively describe the goal-like character of the human information processing system in general terms which admit virtually any type of behavior regarding goals, including the creation of goals [Newell 72, p. 806-7]. The only restriction that they make is the requirement that goals themselves are also taken as symbol structures - certainly an important distinction, but not one that relates to the popular conception of search having predetermined goals.

15References to the literature describing these efforts are not given here. Lists may be found in [March 65] and [Woodbury91].