Divergent Thinking in the Construction of Architectural Models

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The article examines one little understood but ubiquitous form of divergent thinking achieved intermittently during the act of drawing or modeling. It is argued that this phenomenon, here called intermittent divergence, is rooted in a special kind of interaction between perception and imagination, and that this interaction has specific experiential requirements. Three requirements are defined. The resulting new theory then provides a framework for the critical analysis of conventional digital modeling and parametric modeling. Conventional modeling methods are shown to satisfy the requirements for intermittent divergence, while parametric modeling methods are shown to undermine them. The article concludes that parametric systems, as currently developed, could inhibit rather than augment this important route to creativity. Additionally, the article questions prevailing beliefs about the computer support of creativity, including the premise that sketching is an ideal creative medium and the premise that ambiguity in graphical depictions is key to the support of creativity. The theory offers an alternative view on these issues.

1. Introduction

Caught in a swell of digital progress, many architects and design computation researchers optimistically believe digital tools enhance creativity. Though long-standing and fervent, this belief is supported with much loose talk of geometric power, performance analysis, and visualization capabilities. Yet it is not clear how these capabilities address the designer's creative needs, such as his need for divergent thinking, which plays an essential role in the quest for creative insight [1, 2]. There is no evidence to suggest that divergent thinking is directly augmented by digital tools that support a flexible range of geometries or speed the process of producing geometry [3] or return functional performance feedback [4, 5] or enhance visualization control. Instead, these seem more a matter of enhanced production efficiency, reducing the time and effort needed to construct a graphical depiction or evaluate its effectiveness. This line of thinking leads to a weak argument for digitally enhanced creativity, which amounts to saying that creativity is enhanced indirectly because the digital system decreases the amount of time a designer allocates to non-creative production tasks.

In contrast, the theory presented here relates the capabilities of digital systems to a core event in the act of creativity itself – a sub-species of divergent thinking which we may call intermittent divergence. After establishing the conditions under which this kind of divergent thinking occurs, conventional digital modeling and parametric modeling are critically evaluated for their effects on this route to creative insight. Contrary to much of the design computation literature, it is argued here that conventional modeling accommodates this kind of creative thinking, while parametric modeling, as predominately conceived, undermines it. This conclusion throws doubt on some current trajectories of digital design research, and also calls into question the way we assess the capacity of digital tools to augment creativity [6]. Working toward this end, we begin by reviewing the nature of divergent thinking.

2. Divergent thinking

The early design process is characterized by a search for new possibilities. In this frame of mind, called lateral or divergent thinking, the designer seeks to generate many diverse, not previously recognized options. This act is central to creativity and has been linked to success in problem-solving and to the discovery of innovative designs [7].

The process of divergent thinking involves a perceptual stimulus and a subconscious response to the stimulus, in which a new mental association is formed. The image of bread crumbling, the feel of wet sand, or the smell of cinnamon – any perception can trigger a subconscious integration between current experience and content stored in memory [8]. Accomplished designers routinely describe experiences in which a crucial connection is grasped after adopting a fresh perspective, submerging oneself in research, or even stepping away form the work [9].

These new mental connections, the product of divergent thinking, are not ends in themselves. A moment of *creative insight* results when a new connection is recognized for its value in design. It is not divergence in isolation, but the insight that comes from *relevant* and *original* divergence that designers pursue and cherish. As divergent options are generated, a designer evaluates and prunes, sifting through extraneous possibilities until a rewarding option surfaces.

A designer is limited in his ability to form relevant and original mental connections, and this makes the moment of creative insight elusive [2, 10]. Because he cannot directly control the subconscious process of associative memory, a designer cannot *will* creative insight to happen on cue [11]. He is not without influence, however, since he orchestrates his current experience, which is the other crucial ingredient. He chooses to study the history of a site, to contemplate the program, to watch surrealist films, or to walk a surrounding neighborhood. Different experience stimulates the subconscious differently. This enables a designer to indirectly guide the process of divergent thinking and make it fruitful by focusing awareness on those stimuli most likely to generate useful new associations in the subconscious. In this way he coaxes out from the subconscious valuable moments of enlightenment.

3. Model-building as imagery management

Of all the facets of experience used to fuel divergent thinking, visual perception is most extensively used by architectural designers. Through visual perception, imagery is recorded in memory, and in a later act of imagination these memories can be retrieved as a mental image apart from the original sensory stimuli [12]. The mind is even able to speculatively recombine imagined content into a new visual product of something never before experienced [8]. For instance, I can look around my room and see its contents. I can then close my eyes and call up from memory a mental image of the room. I can then transform the image by rearranging the tables, adding a window, or even putting everything on the ceiling [13]. Imagination is therefore a potentially powerful augmentation to divergent thinking, generating new imagery by transforming previous experience.

Although studying the interaction of perception and imagination currently has experimental limitations [14] there are some things we know about how perceptual content and imagined content perform. The transforming power of imagination suggests its superiority in creative thinking, yet imagination relies on perception to supply content. As we shall see, additional limitations on imagination further increase the role of perception. A designer must use imagination and perception together, optimizing the management of both imagery resources, and the age-old tradition of model-building provides one important means of doing this. A three dimensional representation, whether material or digital, allows a designer to utilize the fluidity of imagination while simultaneously gaining two key advantages of perception.

First, the direct perception of the model allows a visual examination to roam freely across relationships only vaguely formed in imagination [15]. Although imagined content is more pliable, it is limited to dim approximations.

Second, the model is effortlessly persistent in the perceptual field, whereas the content of imagination gradually fades once formed and must be continuously renewed [16]. This regeneration requires sustained effort to recall the image from memory, which deflects effort from other tasks. The limitation is sharpened by the slow rate at which such regeneration occurs. Whereas perceptual content arrives in consciousness with a sense of immediacy, like a slide appearing on a projection screen, imagined content grows. Our imaginings build up in the mind part by part, and the more complex the image, the longer it takes to generate [16, 17, 18]. By recording imagined forms in a model, the designer frees valuable mental resources and speeds comprehension of complex compositions.

Managing mental imagery with a model therefore has distinct advantages over imagination alone. Both vividness and completeness of imagery are more economically achieved, more rapidly achieved, and able to be achieved regardless of the complexity of the desired artifact [19].

Having outlined the limitations of perception and imagination, we can now summarize how a model melds them in common practice. In the early stage of design when a desired building is first imagined but not yet recorded, the mental image is necessarily imprecise and incomplete, due to the limitations of imagination, and it is through the process of modeling that this rough vision gets documented. The act of modeling transfers the content of imagination into a persistent medium, purging the imagination and making room for new mental content. The next stage of imagining takes the recorded model as a perceptual starting point from which the design is elaborated or transformed in imagination. In this way perception and imagination combine their powers into hybrid imagery. A model provides an immediately and effortlessly accessible perceptual foothold from which the designer's imaginings extend.

It is usually assumed that this optimized visual thinking occurs only through the contemplation of complete models, but this is an over-simplification of the process. While a completed model does provide a useful perceptual foothold, so does a partially complete model, and the use of hybrid imagery to evoke divergent thinking occurs throughout the model construction process. Since even a simple building is a composition of many elements, architectural models tend to be complex compositions constructed in a sequence of discrete steps. As a model is shaped, it progresses through partial states on its way to completion, and the viewing of each partial state reveals previously unconsidered possibilities. In this way, divergent thinking occurs intermittently, before the designer constructs a complete model.

It is an intermittent process that leads to divergent thought in subtle, gradual stages, rather than in a momentous creative revelation. Although most designers cherish the revelation, and take special note of such an event, this is not part of the daily experience of most designers [9]. Designers achieve creative work reliably and consistently by evoking many small insights rather than a few major ones. Because they are less dramatic, incremental insights crawl under the radar. Designers are usually unaware of how, when and under what conditions such insight occurs. Yet this process is the gravity of creative design – the ubiquitous underlying force shaping the final outcome more than any grand revelation.

The following section defines the process of intermittent divergence first in reference to traditional hand-built models, and then considers the impact of digital modeling on this method of summoning insight.

4. Intermittent divergence

4.1. Background

The concept of divergent thinking, well established in the creativity literature, is virtually absent from the design computation literature. Here the preferred concept is *emergence*. Gero and Yan define emergence as the process of converting an implicit property into an explicit one [20]. Emergence is then taken to be sufficiently equivalent to the psychological phenomenon of divergence.

The closely related phenomenon of intermittent divergence is also neglected, although it is occasionally acknowledged in passing [21, 22, 23]. Mention of intermittent divergence usually arises in the discussion of design sketching, which is upheld by many as the ideal medium for creative design [24]. Both architects and researchers generally agree that creativity flows during the act of sketching, and therefore sketching is a successful microcosm of tool-process integration. However, unable to penetrate the nature of this symbiosis, many researchers resort to mimicry. In the absence of a generalized principle of tool-process integration, the phenomenon of sketching is taken as an irreducible primary to be dutifully reproduced in the digital medium [25, 26]. Yet this method is far from ideal, since it binds digital tools to the limitations of their ancestors.

Although the act of drawing remains mysterious, its impact on the creative process has been studied more closely than the same in model-building. Laseau [15] recognizes the exploratory role of drawing in design but fails to elaborate how an interaction between drawing and designer occurs. He is representative of the literature on design drawing in his recognition that drawings can augment divergent thinking on a scale of drawing to drawing, but he fails to acknowledge the special kind of divergent thinking that occurs intermittently during the act of drawing itself. Schon implicitly acknowledges intermittent divergence in his characterization of designing as a reflective conversation with a situation, but he does not elaborate how such a conversation occurs in the medium of drawing [27]. The most detailed analysis is offered by Herbert [28], who reconstructs the hypothetical steps used by Le Corbusier to draw a formative sketch of the plan of Ronchamp. In a line-by-line progression he shows how the issue of the thickness of the south wall could have arose during the process of sketching. Herbert generalizes this process into the "stroke/response/stroke sequence" in which opportunities for divergent thinking occur in a continuous stream throughout the act of drawing.

Though Herbert begins to penetrate the phenomenon, his analysis leaves unanswered questions about how this special kind of divergence occurs and how we might augment it. In the end he relies on the concept of ambiguity to explain it. Herbert believes that ambiguity in a sketch – usually arising from an imprecise drawing medium – creates an opportunity for reinterpretation. It is the blurring of content in his view that opens new patterns or new relationships to our awareness. He then recommends that software engineers create digital systems supporting ambiguity, i.e., a sketchy appearance as opposed to the precisely delineated extents of typical digital objects [28].

Herbert is not alone in his advocacy of ambiguity. The belief that ambiguity is a central contributing factor in the phenomenon of creative design currently dominates among both architects and design computation researchers [29, 30, 31]. A review of the field reveals no competing hypothesis, despite the fact that many aspects of the link between divergent thinking and ambiguity of graphical depictions has not been experimentally verified.

Although ambiguity is often involved, it does not appear to be a significant contributing factor. A body of experimental evidence shows that reinterpretation routinely occurs among clear and distinct graphic images [7, 14, 32]. Some experiments even imply that ambiguity reduces effective reinterpretation [32]. Even the related belief that sketching is the ideal design medium is questionable [33], with a recent experiment finding that designers' ability to generate certain types of divergent ideas is reduced while sketching, as compared with imagining alone [34].

The belief in sketching as ideal creative medium fueled by ambiguity persists despite the lack of supporting evidence and significant contrary evidence. The reasons for this deserve scrutiny, but it is sufficient to note here that these premises are typically summoned to denigrate conventional vector-based drawing. Vector drawing is accused of failing to serve the creative needs of designers primarily because it does not support ambiguity, and thus, by implication, it does not accommodate divergent reinterpretation.

Unconvinced by the ambiguity explanation, we continue to search for the factor or factors that drive divergent thinking in the act of drawing, and especially for our purposes here, in the closely related act of model-building.

In order to reveal these factors and develop an alternative to the ambiguity hypothesis, we must look in more detail at the process of model-building and how opportunities for intermittent divergence arise as a designer constructs a model step-by-step. The analysis that follows considers model-building as used in the process of design, thus extending Herbert's argument for the stroke/response/stroke sequence to the three-dimensional medium. This extension offers an opportunity to clarify the preconditions of intermittent divergence and to define a generalized theory applicable to traditional and digital media, drawing and modeling.

4.2. Traditional hand modeling

Like sketching, the process of constructing models has been largely revered by architects, and whatever allows designers to create effectively in the medium of the sketch seems equally satisfied by the sketch model [35]. Rather than take the process of hand modeling as a perceptual-level template to be mimicked in the digital medium, our desire here is to generalize an underlying structure of experiences inherent in traditional hand model-building. In doing so, the context specific variables are stripped away and the essential is retained.

4.2.1. Method of inquiry

It is important to note the epistemological method used to achieve this generalization, since it stands in contrast to the dominant practice of protocol analysis among design researchers. Design thinking, as with all forms of thinking, is an internal process – a phenomenon of consciousness. As such, it is not open to direct observation by others. Protocol analysis is a method of research that draws conclusions about the mental processes of a group of designers based on externalized products of design thinking, including the designers' actions, graphic products and words. Because these products are indirect manifestations of the underlying thought process, they are limited in their ability to illuminate the process [36]. Consequently, the conclusions drawn from protocol analysis are generalizable but often trivial.

Although the observing researcher must acquire evidence of design thinking through indirect means, a designer can observe his thoughts directly through introspection, and this is the dominant method of inquiry used by architects. Introspection is the process of turning consciousness inward on itself, so that the operations of consciousness themselves become the subject of awareness. It is through introspection that we gain initial self-knowledge of all epistemological and psychological processes, and all theories of mind begin in introspection [37]. Introspection is the complement of protocol analysis, since it offers direct observation of the phenomenon in question, but only for one's self. Although it can offer penetrating insight, it is limited to a sample size of one, and the issue of its generalizability comes into question.

Introspection and experimentation through protocol analysis or other empirical means must join if we are to develop penetrating and generalized theories of design thinking. We must bridge the gap between pedestrian but well-verified descriptions of design thinking on one hand and illuminating but anecdotal descriptions on the other [6, 34, 38]. With the desire to build such a bridge, the present investigation works by means of introspection while carefully checking that generalizations taken from introspection are consistent with all available empirical evidence. Specifically, the goal here is to develop a *theory* of intermittent divergence, which integrates a wide range of empirically established evidence into a conceptual unity. This paper does not provide the empirical verification necessary to complete its validation, and instead, it establishes the plausibility of the theory in preparation for further corroborating experimentation.

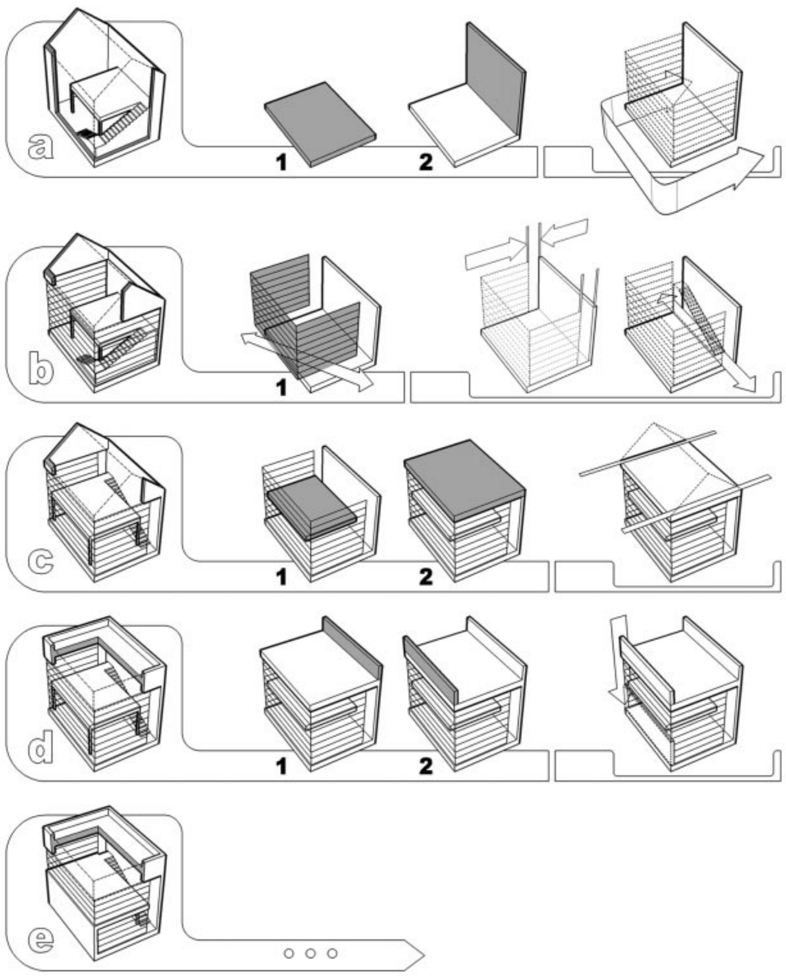
Consistent with this intent, the figures presented below are not the documented results of protocol analysis, but rather, a descriptive tool used to elucidate the theory. Like Herbert's reconstruction of Le Corbusier's sketch of Ronchamp, the figures describe hypothetical and archetypical design scenarios.

4.2.2. Constructing a design model

Design modeling is a special sub-set of modeling undertaken without strong preconception. Unlike the construction of a final presentation model, which has a known and fixed end state, design modeling is formative. When beginning to build, a designer has only a rough idea of what he wants to construct, and he remains receptive to other possibilities, which arise as he builds. The model construction process is thus explorative, not merely descriptive.

The complexity of even an early design model requires it to be constructed in steps, and each step in the construction process results in a model state that *itself* represents a possible building design. The process of constructing a model is therefore a process of *implicit option generation*. This is the crux of the theory. At any point during the model construction process the designer can associate an intermediate model state with a more interesting (partial) building design. If the newly discovered possibility seems more desirable than the previous one for which the model construction process was initiated, the designer may redirect future model construction steps to realize the newly discovered option. The process then continues with model construction occurring along a new trajectory.

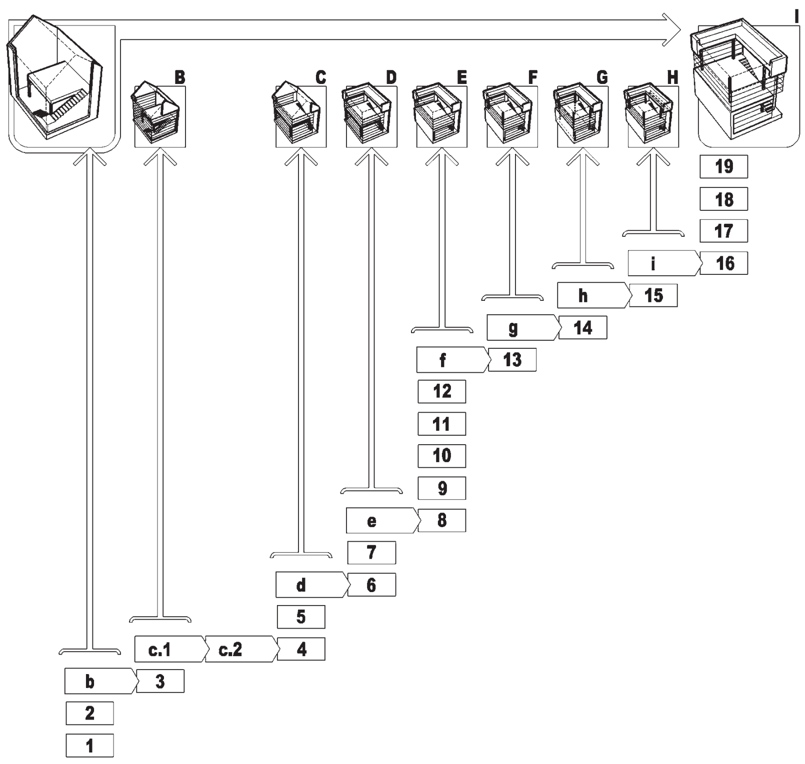
Figure 1 shows a series of steps in the construction of a model, emphasizing each moment of divergence and indicating how it arises. *A* shows the initial imagined building, and *A1* and *A2* show the first two steps in the model construction process, which are initiated to record the imagined building. However, after completing step *A2* and viewing the resulting partial model, the designer imagines alternative fenestration for the building. Believing that this yields a better design, he revises his goal (at *B*) and redirects his model construction effort to realize the new design. After constructing the fenestration in step *B1*, and in the process of moving this new model piece into position, he notices that the fenestrated wall could be thought of as detached from the adjacent solid wall. The glass could be pulled away from the solid wall to leave a reveal, which could then form a slot for the stair. Finding this possibility superior, the designer again revises his previous goal and redirects his subsequent construction effort to record the new "best known" design shown at *C*. In step *C1* he builds the upper floor, and in step *C2* he adds the first portion of the roof. Upon viewing the model with this unpitched portion of roof, he imagines the building with a similar, flat roof and decides this is preferable. Again the goal is refined and the model-building effort is redirected.



◀ Figure 1. Analysis of a typical model-building process

The process continues in this fashion, with each step of construction offering new visual fuel as input to the imagination. The resulting in-process redirections toward a newly realized and preferred end-state can be subtle but frequent, resulting in a sliding route of construction driven by creative exploration rather than rote fabrication. Figure 2 shows the entire construction effort for this simple model. The images at the top of the figure show each revision of the desired end-state during the construction process. As is normally the case in design modeling, the final construction faintly resembles the initially desired building.

▶ Figure 2. Summary of a sliding route of model construction



4.3. Necessary preconditions for intermittent divergence

The above description of a typical design modeling scenario reveals important mechanisms at work, which contribute to the process of intermittent divergence. The following section extracts and generalizes three preconditions necessary for intermittent divergence in any medium.

4.3.1. Each model-building step generates an opportunity for intermittent divergence

The number of construction steps encountered corresponds to the number of opportunities for intermittent divergence. Each step of construction adds a new element to the model (or removes one), which changes the model and generates a distinct implicit option that could give rise to divergence. Therefore, the more construction steps needed to build the desired end-state, the more opportunities arise for divergence. Even a seemingly insignificant step can trigger a visual association and moment of insight. We see this in step *A2* (Figure 1), where in the early stage of construction the model evokes a new approach to enclosure when it consists only of two pieces – a base and a wall.

This simple conclusion rebukes a well-established principle of software design, which holds that production efficiency is an ultimate, unquestionable value. From this perspective efficiency grows as the number of construction steps shrink. Yet, if expanding the number of construction steps increases the opportunity for intermittent divergence, then a designer should not be concerned with productive efficiency while in an exploratory frame of mind. He should allow himself to wander, investigating routes and methods of construction for their own sake, not for what he thinks they will efficiently produce. A new method of cutting or attaching or a new order of construction steps might open new ways of looking at the current design situation. The shortest route is not always the most creatively fruitful route.

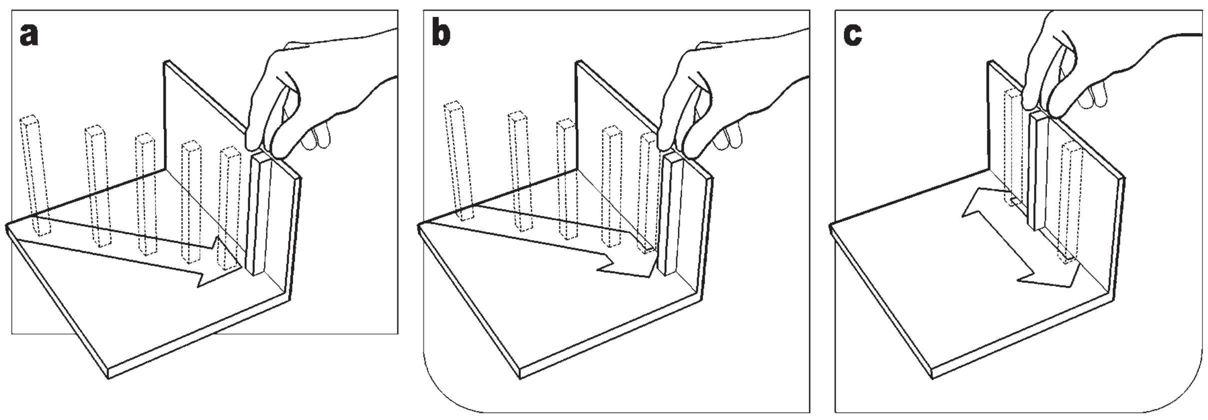
4.3.2. Attention to a local context reveals an opportunity for intermittent divergence

Because the human perceptual system manages few visual units simultaneously [18], we often avoid visual overload and resulting confusion by focusing selectively on a small collection of parts within a larger context. By attending to a local visual context of greatest immediate interest, we indirectly filter and control the scope of our perceptual field. This is relevant to the designer because an increased chance of creative insight occurs when attention is focused [39], and because this kind of focus occurs in the construction of models. The designer characteristically looks at the region where a new part is inserted into a model, or where a part is modified. The rest of the model fades to the periphery of awareness, allowing a more concentrated and vivid awareness at the point of construction, which facilitates the agile work of model-building. Thus there is a crucial correspondence between action and perception in which awareness of an intermittent model state heightens precisely at the point where the designer enacts construction, and it is therefore at the point of construction that the new, implicit option emerges.

Intermittent divergence cannot occur without this correspondence. The new visual relationships emerging from the partially constructed model are momentary and only useful if the designer's attention is directed at them with vividness. Once the next model part is erected, the visual relationships change and suggest other, different possibilities. A new visual relationship, fertile with unique possibilities, often comes into existence with a fleeting movement of the hand. The designer must therefore remain poised to see the new relationship at the moment it appears, else it pass him by, an opportunity lost.

4.3.3. Visualizing alternate positions and transformations trigger intermittent divergence

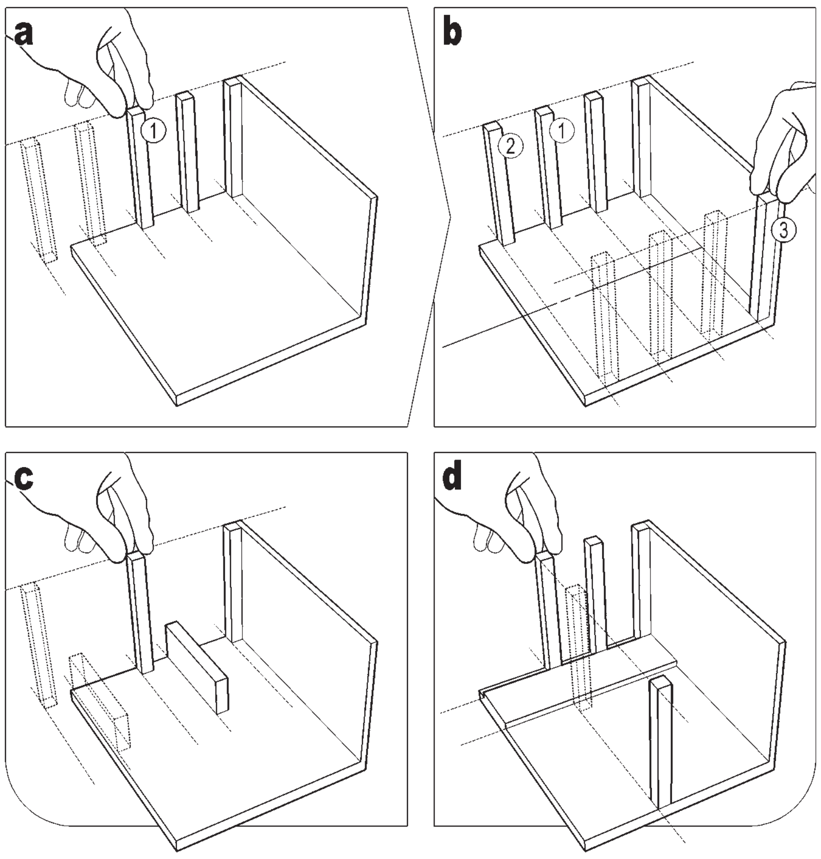
Partial model states imply new design options in two ways. First, the independence of a new model part, yet to be attached, allows it to move relative to the surrounding fixed parts. This movement implies a freedom of location in design, and the act of moving it around yields visual feedback allowing the designer to more vividly imagine the new part in alternate locations. Just by picking up a new column and transporting it to a desired location, the designer sees the column in all locations along the path of transport. By seeing the column in a location further away from a bounding wall, for instance, it might become apparent that the column would be better situated as a free-standing column instead of one impacted to the wall (Figure 3a). Even though these alternative positions are often fleeting, they register in perception. In addition to providing a visual prompt of alternate positions, such movement also implies a wider range of freedom in manipulating the part's position. For instance, if a column is moved into position against a wall, it might slide across the wall briefly before hitting its mark (Figure 3b). This momentary sliding implies a wider *method* or rule of altering the column's location [40]. If the column can slide across the wall in that short interval, then it can slide across the entire wall surface, and by visualizing this kind of adjustment, an even greater range of possible positions for the column can be discovered (Figure 3c).



▲ Figure 3. Example of repositioning as a trigger to divergent thinking

In addition to the implications inherent in the movement of model parts, there is a second way model-building implies new possibilities. This kind of implication results from the mind's drive to integrate visual information into coherent patterns [19]. Oxman describes the designer's ability to retrieve a visual structure or schema stored in associative memory and reinterpret the current composition in reference to the structure [29]. Tan also describes the use of conceptual filters to make sense of compositions of parts and to transform them [21]. The current pattern of model parts evokes similar patterns stored in memory, and by superimposing one of these implicit patterns on the current composition, the designer establishes a visual framework in imagination that temporarily guides his transformations.

In model construction, these implicit patterns can change with the addition or modification of each model part. The most relevant implicit patterns are often based on alignments with [21] and extensions of objects in a local context [20]. For instance, if a column is placed in such a way that it establishes a linear sequence with other, already placed columns, it might imply an extension of the sequence (Figure 4a). If the state of the model is different when placing the same column in the same position, the implicit patterns that might emerge change (Figure 4c and 4d). After extending the pattern with the placement of an additional column, the tentative placement of a third column augments the imagining of still other patterns (Figure 4b). It is important to emphasize that the implicit patterns shown in this example are only a few of the immense possibilities. The particular implicit pattern or patterns that come to mind depends on the memory-stored experiences of the individual designer.



► Figure 4. Example of imagination overlay as a trigger to divergent thinking

In this way the model construction process involves a mental overlay of the visual stimulus (the model) acquired in perception with the imagined elaboration or transformation of an implicit geometry, which reveals one or more new, optional designs. In doing this, the mind sees alignments, extensions and completions among elements, which only become apparent due to the model's partial state.

4.4. Conventional digital modeling

Just as the argument in favor of sketching as creative medium logically extends to the medium of the sketch model, so also the criticism leveled against vector-based digital drawing as a failed creative medium extends to the medium of conventional digital modeling. The vector graphics and precise coordinate systems of today's surface and solid modeling systems make them vulnerable to the ambiguity hypothesis, which laments the same stifling clarity as vector drawing [41, 42]. A more pointed attack based in the ambiguity hypothesis comes out of shape emergence theory [20, 21, 43], which sees the bounded and complete figural nature of a digital shape or object as overly explicit and static, undermining the discovery of less visually dominant implicit shapes.

Although a typical digital object is clearly depicted, this fact alone is not detrimental to a designer's creative exploration. In fact, the same finite and bounded extents exist in materials traditionally used to construct sketch models. The accusation that fixedness of a digital object inhibits divergent reinterpretation drops the context in which designers contemplate such objects. The process of constructing a digital model is an *exploratory evolution of a composition of objects and spaces*, and it is only by artificially detaching objects from this process that they can be considered fixed and obstructing to divergence.

When digital objects are examined in the context of design modeling, they readily satisfy all the preconditions of intermittent divergence. In the historical evolution of digital modeling this happened apparently by default, the product of limitations inherited through metaphor. Traditional hand modeling provides the interface metaphor for conventional digital modeling, and consequently, designers generally apply the same construction methodology to each.

Much like a traditional hand model, a designer usually creates one digital object at a time and positions it in digital space. By repeating this effort, a more complex and complete whole gradually accumulates. Thus, conventional digital construction generates a string of intermittent states. The opportunity to perceive each state is diminished only when a collection of digital objects is moved or altered simultaneously. However, even in this case the operation resembles the traditional approach of tearing out and repositioning a portion of a material model. Second, intermittent states arise coincident with the designer's focused attention, that is, the designer generally watches each part as he places it into the model. And further, the need to locate each new part, combined with dynamic graphics of the part in motion, provides the visual feedback needed to imply alternate positions. Because there is a persistent graphical representation of the model, which shows the sum of all currently constructed parts, the designer sees the new part in a context that implies alignments, extensions and completions into unanticipated wholes in a fashion much like traditional model-building.

Despite the absence of a sketchy vagueness in the extents of each object, the preconditions of reinterpretation are fulfilled during model construction, and proficient digital designers seem to routinely take advantage of this to create effectively.

4.5. Parametric modeling

The familiar and comforting limitations of a pre-digital metaphor reassure early adopters, but such comforts eventually degrade into conservative baggage. Parametric modeling is an important advancement because it takes digital modeling beyond the confines of traditional hand methods, allowing the digital medium to spread it wings. This new technology, incubating for many years, has only recently become a viable alternative for practicing architects. Mainstream systems are now appearing, such as AutoDesk's Revit and the CustomObjects system developed by Robert Aish at Bentley Systems. Despite current limitations, parametric technology promises to exert a mounting influence on the enterprise of design modeling.

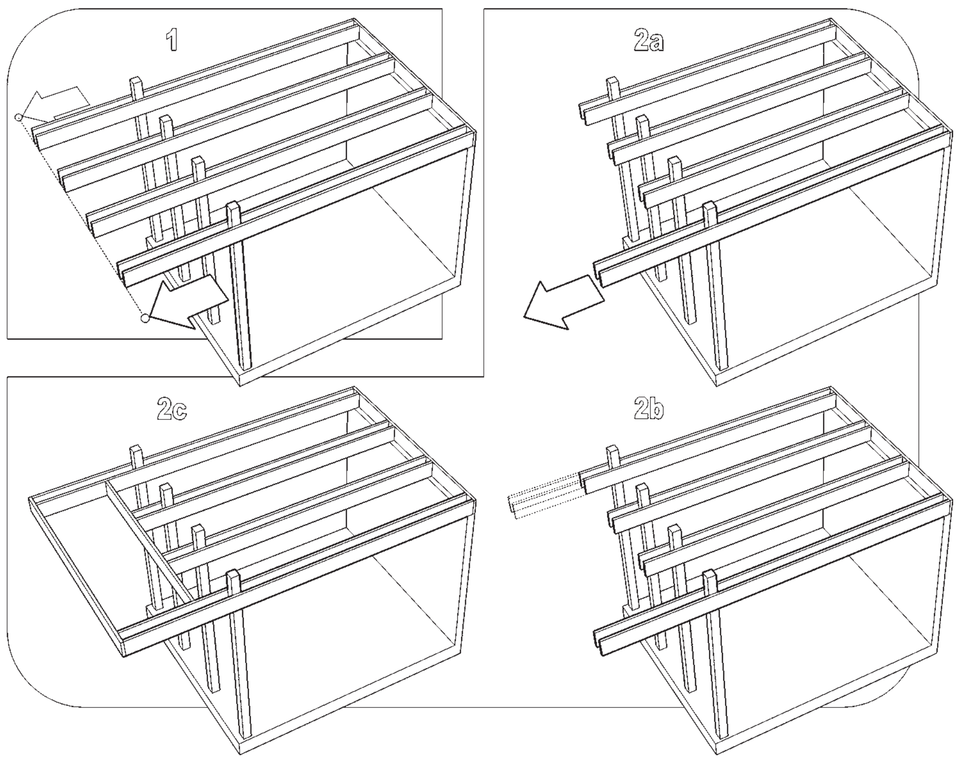
The parametric constraints controlled by these systems comprise two classes based on their evaluative or formative role in design. The evaluative class facilitates automated performance review of a building model, providing designers with feedback in reference to established goals. This feedback is predominately functional or technical in nature, including such things as structural fitness, acoustical performance, traffic analysis, building code compliance and energy efficiency [5, 44]. On the other hand, the formative class of parameters facilitates the generation and manipulation of model geometry. Although the two need not be segregated in a parametric system, we are concerned here with the formative class, since these could impact opportunities for divergent thinking during model construction.

Parametric systems differ in the degree to which the managed constraints may be pre-defined, defined on-the-fly, explicitly defined by the designer, implicitly defined by the designer's actions, and changed incrementally. We are here concerned with parametric systems that give the designer at least some degree of responsibility for creating and managing constraints. This kind of interface is provided in both mainstream software packages mentioned above, and also in most experimental systems.

Having clarified the scope of the discussion, the impact of parametric systems on modeling method can be summarized as follows. A parametric system allows the designer to indirectly edit model parts by manipulating a mathematical variable (i.e., a "parameter" or "constraint") rather than by touching an object. And further, a single variable can drive the alteration of many model parts simultaneously, allowing one alteration to affect a system of parametrically interrelated objects [45]. The methodological heart of parametric modeling is therefore a shift from editing individual objects in order to compose relationships between them – to editing relationships in order to affect a collection of individual objects. This redirection from object to relationship profoundly impacts the designer's prospects for intermittent divergence.

First, the relational power of parametric models significantly reduces the number of steps needed in construction by allowing parts to be altered simultaneously – driven by a single intermediary parameter [4]. This enhanced ability to alter objects as a group removes many conventional construction steps, and with them, opportunities to observe the corresponding intermittent model states. This is demonstrated in a simple example in which a designer modifies a set of cantilevered beams. A newly envisioned design for the beams requires an extension, increasing the length of the cantilever. With the aid of parametric controls, this is accomplished in one step by editing a "beam length" parameter (Figure 5.1). In contrast, using conventional means, this modification would likely be undertaken with a separate extension action for each beam in the set (Figure 5.2a). While the parametric version of the process takes the designer directly to his

► Figure 5. Conventional versus parametric modification of a cantilevered roof



preconceived goal, it is not necessarily better because it eliminates a series of potentially interesting intermediate model states in which the beams do not share the same length. Depending on the order the beams are selected, new beam relationships are formed that could reveal a more interesting alternative (Figure 5.2b and 5.2c).

With regard to our first precondition it appears that parametric modeling diminishes the opportunity for intermittent divergence exactly to the extent its distinctive relational capabilities are employed to alter objects as a group.

The second precondition is the need for intermittent model states to unfold coincident with the designer's focused attention. This too is diluted. The relational nature of parametric controls allows the influence of a single editing action to extend over any distance. This means that parts controlled by a parameter need not be adjacent to each other, or located in a compact arrangement. To the extent they are widely distributed, the designer is unable to focus on the parts as a group during modification. He can attend only to samples of the group, watching individual parts respond to his adjustments, while other parts remain outside the limits of his perceptual field. If one of these peripheral objects moves into an intriguing relationship with its surroundings and in so doing implies a new design possibility, the designer misses it. This does happen occasionally in conventional modeling also, because of constricted video display area [25], but this kind of creative loss grows substantially with the systemic control of relational parameters.

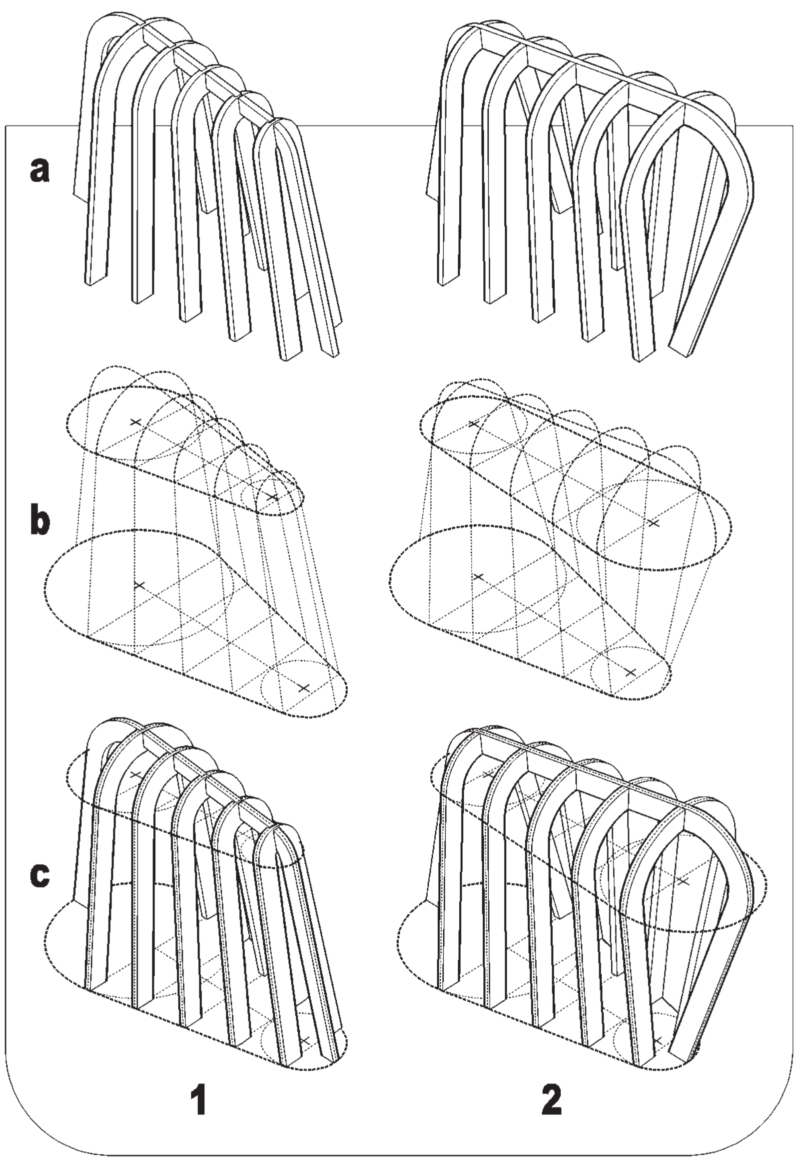
The power of sweeping change amplifies when algebraic equations drive parametric variables. The designer's ability to anticipate a visual result crumbles when by altering parameter *X* it also alters parameter *Y*, which is defined as the product of parameter *X* and parameter *Z*. Such interwoven variables create a kind of geometric organism with a life of its own, responding to the designer's influence in an often obscure manner [46]. This further disconnects the designer's center of attention, which occurs at the point of action, from the location of the resulting alteration, which could occur anywhere.

Both distributed arrangements and complex inter-variable relationships dilute the opportunity to see new possibilities in a model as they surface.

The final precondition of intermittent divergence is the opportunity to mentally relocate, extend or transform the features of a partially constructed model. Here again difficulties arise with parametric controls. A parametric model usually exists as a visual composition of geometry much like a conventional model. We can rotate it and render it, for instance, perceiving it as a spatial composition of solids and voids. A parametric system can also provide dynamic visual feedback during editing, like any good conventional system. Therefore, the first kind of visual stimulus – seeing objects in alternate locations during the process of positioning – can take place in a parametric system. However, with parametric systems comes the enticement of numerical control. As the mathematics driving parameters gain complexity, the designer must rely on numerical editing, in which the content of variables is accessed textually rather than geometrically [47]. For this purpose parametric systems normally provide a non-geometrical interface, such as a dialogue box, spread sheet or flow chart. To the extent the designer edits a model numerically rather than geometrically, his ability to observe objects during repositioning is severely reduced.

With the second kind of visual stimulus – imagining alignments, extensions or transformations from a partial model – we encounter additional difficulties. In order to manipulate a parametric relationship geometrically, the relationship must be shown as a visible structure in the

► Figure 6. Example of the visual impact of regulating lines



model, rather than as a numerical expression in a dialogue box. In this case a parameter is an additional graphical entity such as a regulating line, which the designer grabs and manipulates (Figure 6b). Visible regulating lines are problematic because they emphasize a *current* relationship between parts, making it difficult to see relationships as flexible. The skeleton of regulating lines usually implies a whole of a certain kind – an overarching visual framework controlling the parts within. Even if this visual framework can be hidden from view (Figure 6a) it must presumably be visible when editing, otherwise grabbing and dragging would not be possible (Figure 6c). Consequently, this ordering framework is often in the designer's visual field, its dominant, glowing presence obscuring the overlay of imagined implicit patterns. For this reason, once a parametric relationship is set among a group of parts, it could have a tendency to remain, and thereafter change only in degree rather than in kind. This sort of visual inertia destructively biases a designer's search for new possibilities.

It is important to note that the pattern-fixing of parametric regulating lines is fundamentally different from the fixed extents of an isolated digital object. A conventional solid model is composed of many objects, each with its own fixed extents, but the relationships between objects are not visually reinforced with any persistent visual pattern generated by the modeling system. Instead, such patterns are overlaid by a designer's imagination. Parametric regulating lines, on the other hand, provide just such a persistent visual pattern, which could interfere with attempts to superimpose an alternative pattern using imagination.

Every precondition of intermittent divergence established above is undermined to some degree in those parametric systems that work as described here, which is true of the prevailing mainstream alternatives and many experimental systems. These systems seem to undermine opportunities for intermittent divergence exactly to the extent the distinctive features of parametric systems are used instead of conventional methods.

5. Discussion

When we consider the limitations on human visual systems, memory and association – and the resulting elusiveness of creative insight – it becomes clear that model-building is not avant-garde caprice or rote production. It is a psychological necessity for the creative designer. In the act of model-building resides a special synthesis of production and creation – making and imagining. When these activities intertwine, divergent possibilities emerge in the process of making, which accumulate in subtle ways to dramatically reshape our designs.

Despite its sway, this intermittent process is fragile. It relies on the convergence of tenuous factors from the construction method selected, to the order the designer builds pieces, to the way he positions them, to the degree he focuses on the locale of construction and attends to its geometric implications. A digital modeling system that disrupts the operation of any of these factors diminishes or eliminates opportunity for intermittent discoveries. Although conventional digital modeling protects these opportunities for the most part, parametric modeling, as currently developed, orchestrates just such a disruption.

5.1. Mainstream software development

Free of the hand-modeling metaphor and its embedded wisdom, the developers of parametric systems have a new responsibility to actively attune their tools to the creative needs of the designer. As software developers open new digital territory they must become design psychologists – unlocking the nature of the creative process as they unlock new digital worlds. Otherwise the great potential of such worlds shall be lost on the human creatures of flesh and mind that inhabit this world and operate according to its limited ways.

Yet the makers of most mainstream parametric systems, such as AutoDesk (developing Revit), show little concern for the needs of designers, and instead focus exclusively on improved production efficiency [48]. Many designers, seduced by these enhancements, believe parametric modeling is superior to conventional modeling. Convinced that parametric methods shall ultimately replace conventional methods, they convert. These designers fail to distinguish between optimized productivity and optimized creativity, and they unknowingly lose something valuable, perhaps vital, in the exchange. Bentley System's CustomObjects is one of few mainstream parametric systems catering to designers, and it does offer some exciting new routes of exploration. Yet even here, by incorporating the same basic parametric modeling method, it suffers the same deficiency as the production-oriented systems.

This creative shortfall in the first generation of mainstream parametric systems should be corrected, since no inherent limitation bars a parametric system from surpassing the hand-modeling metaphor while respecting the preconditions of intermittent divergence. In fact, a parametric system could conceivably enhance opportunities for intermittent divergence while simultaneously offering powerful formative and evaluative capabilities. The first mainstream developer to achieve this synthesis will offer to the world a formidable design tool.

5.2. Design computation research

Many designers believe the creative process is an inexplicable, pseudo-mystical event in the "black box" of the subconscious [49]. Consequently, they oppose its scientific investigation, defending it against analysis with bromidic references to intuition and ambiguity. Ambiguity as an explanation of the preconditions of creative insight is a thin explanation at best. It closes inquiry and reaffirms the philosophical stance that the process cannot be dissected or explained. Unable to analyze the phenomenon further or generalize from it using indirect methods such as protocol analysis, researchers resort to a perceptual mimicry of hand sketching as the venerable means to ambiguity. Although ambiguity is treated as the subject of basic computational research, there is good reason to believe it is a derivative and not a basic phenomenon in creative design. Researchers, in an admirable effort to satisfy designers, have too casually accepted the preconceptions of their audience, instead of looking for deeper methodological needs such as those put forth here regarding intermittent divergence.

One consequence of the preoccupation with sketching and ambiguity has been the neglect of intermittent divergence, as evidenced by weak support for it in parametric systems. The recognition of the phenomenon and its expanded study could open new territory in design process understanding and suggest new routes to the computer support of creative design.

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