8-23-2006

Exploration

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Recommended Citation (OVERRIDE)

Ulrich, Karl T. 2011. Exploration. In K.T. Ulrich (Ed). Design: Creation of Artifacts in Society.(pp. 39-56) University of Pennsylvania. (ISBN 978-0-9836487-0-3)

DESIGN

creation of artifacts in society

Karl T. Ulrich

Contents

Chapter draft of August 23, 2006.

TWO

Exploration

Exhibit WRIGHT shows a few of Frank Lloyd Wright's sketches for a collection of cabins contemplated for a development at Lake Tahoe. Wright's sketches reveal a process of exploration of design alternatives, which is a hallmark of the activity of design. This chapter describes the essential elements of the exploration process. After explaining why exploration is necessary, I describe the concepts of *representation* and *abstraction*. I then discuss evaluation of design quality. Next, I articulate the exploration strategies used most frequently to reduce the cognitive complexity of design problems. Finally, I connect these concepts to practice by touching on several examples.

Design Requires Exploration

Exploration inevitably involves consuming resources developing and evaluating alternatives that will eventually be abandoned. We would of course prefer to avoid this wasted effort and just pick the right answer directly. Why do we need to explore, as opposed to determining the right answer analytically or with some other technique?

To illuminate the need for exploration, consider a counterexample, a design problem that can be solved without exploration: Design a *beam*—a structural element spanning some distance-- to support an antenna on a space station. The antenna will be mounted in the center of the span and will apply inertial loads of up to 100N perpendicular to the axis of the beam. The beam must not deflect more than 2mm under that load in order to maintain signal quality and to limit vibration. The beam must span a 2m wide opening and can be attached rigidly to both sides of the structure. The beam must be lightweight, but as inexpensive as possible. Assume that like most other elements of the space station, the beam will be made of aluminum.

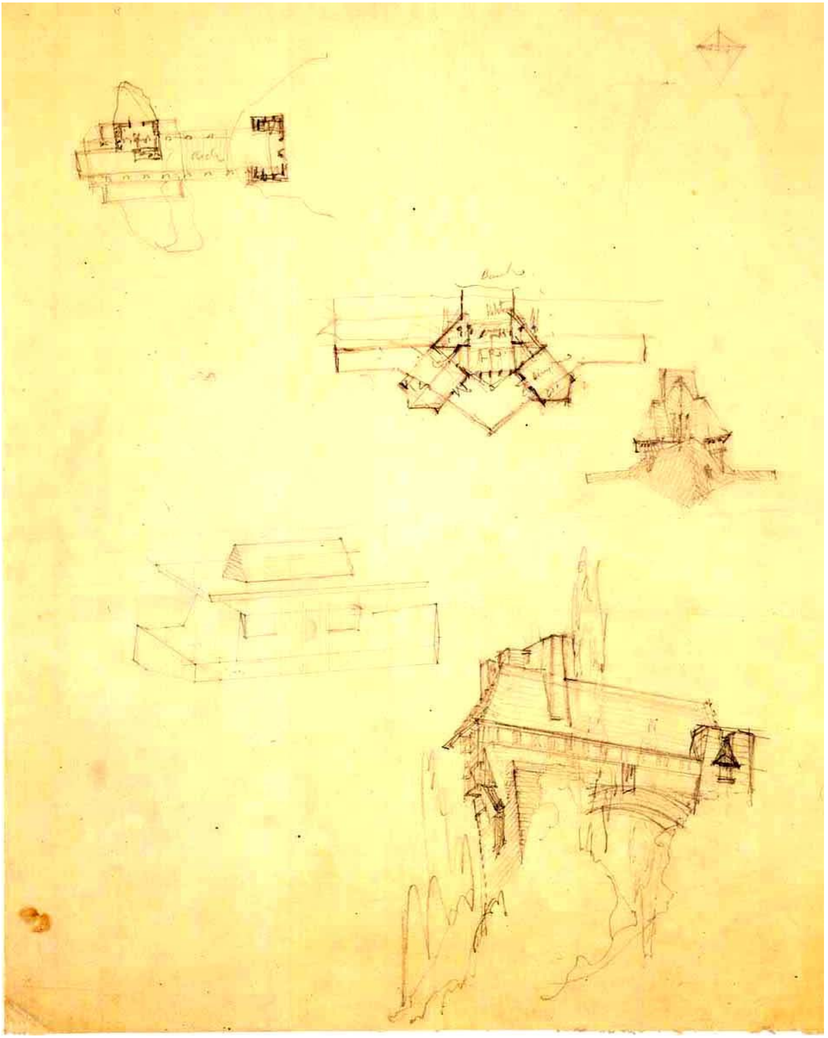

Exhibit WRIGHT. A page of sketches used by Frank Lloyd Wright to explore the design space for a cabin at Lake Tahoe. Note the use of plan and perspective views to represent design concepts and the varying levels of abstraction employed in different sketches. (Source: U.S. Library of Congress)

Because the beam design problem is simple, well defined, highly constrained, and because of two centuries of development in the field of engineering science, it can be solved without exploration as follows (the details of which are not important for the argument):

> The beam is a round tube because we know that a round tube is the most weight-efficient structure for supporting loads that could come from any direction. The equation for the deflection of a tube rigidly supported on both ends with a load F applied in the middle is $\delta = FL^3/192EI$, where L is the length of the span, E is the modulus of elasticity of the material, and I is the moment of inertia of the beam cross section. (We know this thanks to at least Galileo, da Vinci, Euler and Bernoulli.) The moment of inertia is calculated as $I = \pi(D^4\text{-}d^4)/64$. We know that the minimum thickness of the wall is 1mm to allow inexpensive joining techniques and to prevent buckling (i.e., $(D - d) \geq 0.002$m), and we know that the lightest possible structure will be a tube with the minimum possible wall thickness. We can plug in values for δ, F, L, and E and solve for D. Thus, we can solve a design problem without exploration.

However, let us make the problem slightly more realistic. Why constrain the solution to be aluminum? Why not allow titanium, or fiberglass, or steel, or carbon-fiber reinforced plastic? Why does the tube have to be a constant cross-section? Couldn't it have a tapered wall? Given the attachment conditions at the ends of the gap, would a truss structure perhaps be more efficient than a tube? Could the antenna itself have some additional structure added to it so that it could span 2m instead of requiring a separate beam? With these simple questions, we have posed directions for exploration that would require a minimum of 32 different analyses, each with substantially different assumptions. With a few moments of thought and by posing a handful of questions, the design problem we could solve without exploration has been exploded into something that will require substantial exploration by even the most gifted designer.

Practical design problems can rarely if ever be solved effectively without exploration. The problems simply can not be fully formalized, there are too many discrete alternatives to consider, and the mathematical complexity would be overwhelming even if the problems could be formalized. And yet humans manage to design artifacts. The design strategy employed essentially universally by skilled designers is to explore a space of possibilities using a collection of heuristics that reduce the complexity of the task and by relying on knowledge to direct the exploration.

Representation and Abstraction

A representation is a language for describing designs using symbols. Consider Exhibit REPRESENTATION. The sketch on the right uses 13 line segments to denote the important edges of the geometry of a shed. Humans in general, and most designers specifically, are quite adept at interpreting such sketches as a representation of a geometric form[1].

Most design involves a symbolic representation of artifacts. The alternative would be to explore directly in the physical world with the actual construction materials of artifacts. For example, to design a shed without the use of a symbolic representation, one would just start building. When the design proved unsatisfactory, the designer would either abandon the partially completed shed and start a new one or tear down portions of the shed and replace them with an alternative. The direct approach is quite rare in most domains because the cost in time and materials of manipulating the world directly is quite high. The designer can move much more quickly and with much less expense with pencil and paper; or with cardboard, glue, and a razor knife. (Curiously, design without representation may actually be the best approach in a few rare instances. For example, the details of dry-laid stone walls are largely designed by direct manipulation of the stones. This is because representing the detailed geometry of each stone would be more tedious than just looking at the array of stones on the ground and trying a few alternatives.)

Representation requires abstraction. A real shed can be described with essentially infinite detail. (Imagine, for example, describing the precise geometry of the surface of each shingle on the shed.) With detail comes complexity, which increases the cognitive burden of design. To manage cognitive complexity, designers employ representations that are abstract, encoding only the most essential information about a possible artifact. Suppressing the details of materials, finishes, colors, trim, decoration, and adjacent plantings makes the shed design problem more straightforward. Good abstractions suppress details that have little relevance for the central design decisions at hand.

[1] Winston (1992) provides a clear and detailed discussion of representation and search in his book on artificial intelligence (AI). Design is connected in many deep and important ways to AI and the Winston book provides a good introduction to the core concepts.

In addition to reducing the complexity of the design space by focusing attention on the key design decisions, representations are used to record design alternatives in *external memory*. Humans do not have the cognitive ability to store and recall the dozens or hundreds of alternatives typically explored during the design process. In contrast, paper, computer files, and physical models are quite effective storage devices for that task.

Representation and abstraction are important for exploration in non-physical domains as well. Services and computer programs are often designed using flowcharts. Advertisements are designed using storyboards. Songs are designed with musical notation.

Most representations used in design exploration are informal, meaning that neither the syntax nor the semantics are defined precisely. Representations used to communicate a design for the purposes of fabrication are typically more formal (e.g., solid models or architectural drawings), but even these representations are not typically formal in a mathematical sense. To aid in illustrating some of the key ideas in this chapter, I employ a relatively formal representation and abstraction I call *Shed World*.

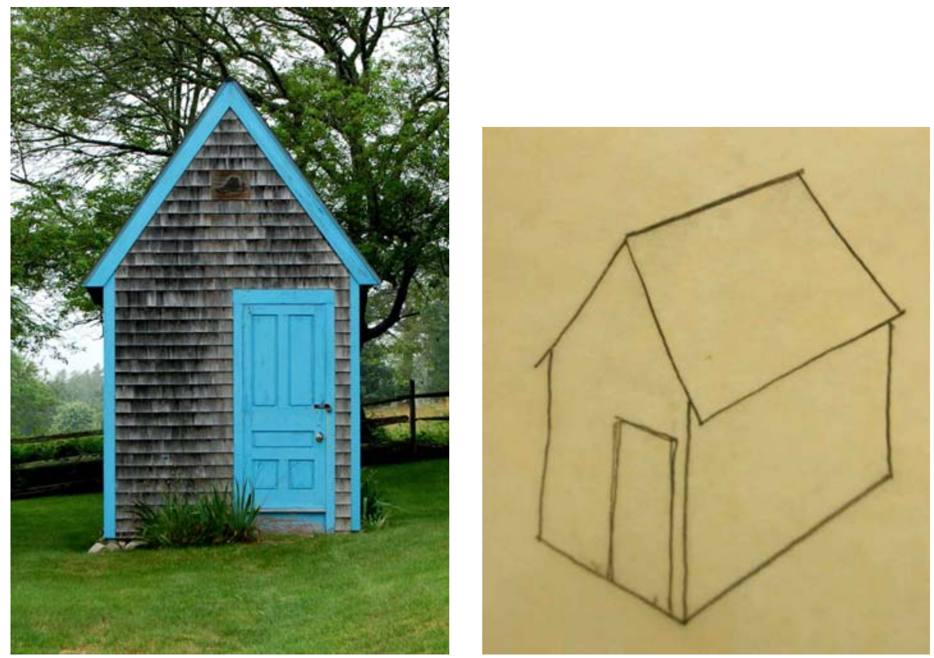

Exhibit REPRESENTATION. A real shed and a shed abstraction.

Shed World

Imagine a design problem posed by the need for a garden shed. The user needs to store two trash cans, three bicycles, a wheelbarrow, and a stack of lawn chairs. The shed needs to fit on the edge of a terrace and harmonize aesthetically with the house. It needs to protect the contents from the weather in northern latitudes.

Shed world is a representation for describing sheds and is shown in Exhibit SHEDWORLD. Shed world is a particularly simple formal representation in which a shed is described by a quintuple: wall height, aspect ratio, roof type, roof orientation, and roof pitch. These five elements fully describe a shed in this formalism. A *tuple* is a simple form of a *design grammar*, a set of rules for constructing "legal" designs in a design space. A more complex grammar might allow for floor plans that are Ts or Ls or Hs or might allow for roofs that have non-constant pitches (e.g. Gambrel or bow forms). However, for our purposes the simple shed grammar consisting of a quintuple is sufficiently complex.

To get a sense of the complexity of this design space, assume that designs are only allowed to assume the discrete options shown in Exhibit SHEDWORLD. These discrete choices result in 640 distinct sheds (4 heights x 5 aspect ratios x 4 roof types x 2 roof orientations x 4 roof pitches). Five of these designs are shown in the exhibit. Of course adding other attributes like door location, window placement, or siding type increases the size of the design space geometrically, and if we allowed the attributes to take on continuous values (e.g., arbitrary aspect ratios instead of discrete choices) then there would be infinite possibilities.

Even in the highly stylized shed world, the complexity is daunting. It would be tedious to consider every alternative. And with more complex design problems, doing so is more than tedious, it is impossible.

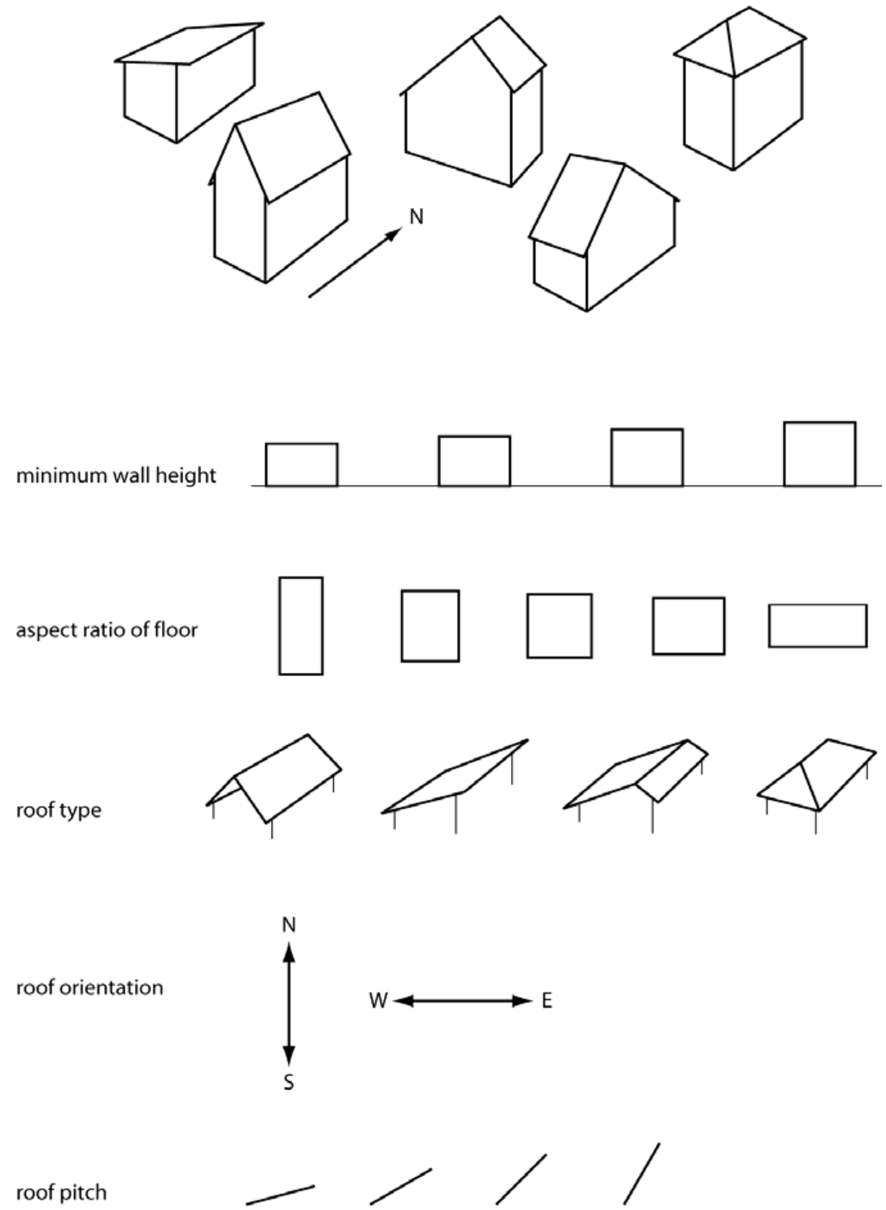

Exhibit SHEDWORLD. A formal representation of the design space for a shed.

Evaluation

Design requires exploration and so the process of design must include evaluation of the quality of the alternatives considered; otherwise the selection of a design would be arbitrary. Of course, the designer could literally build and test every artifact contemplated. However, evaluation is much more efficient when based on an abstract representation of those artifacts.

The quality of an artifact is a holistic property of the user experience. However, in design it is conceptually useful to decompose the overall quality of an artifact into several dimensions or attributes. For the garden shed, the quality attributes might include space efficiency, aesthetics, cost, and ease of access to the contents. For a fruit salad, the attributes might include appearance, flavor, texture, and shelf life. For an airplane, the attributes might include fuel efficiency, payload, cruising speed, and minimum runway length. A rich history of academic research and industrial practice has shown that useful predictions of user preference can be made by first evaluating alternatives with respect to individual attributes and then aggregating those evaluations into a single overall measure of utility or preference (Keeney and Raiffa 1976).

In almost all cases of design by humans, the first evaluation of a design is a cognitive response of the designer to a sketch or other representation of the design. Subsequent evaluations may be more deliberate, even analytical, and may involve judgments by others. Building and testing prototypes is also common for the relatively few alternatives most preferred based on an evaluation of the abstract representation of the artifact. (See Ulrich and Eppinger 2004, chapter 12, for a thorough discussion of prototypes in product design.)

Exploration Strategies

Armed with a representation and a way to evaluate design alternatives, the designer still faces daunting complexity in the exploration task. In this section, I outline four strategies commonly used to manage the complexity of exploration: hierarchical decisions; parallel exploration and selection; causal relationships; and existing artifacts[2].

[2] Herbert Simon (1996) pioneered the view of design essentially embodied in this chapter, articulating the concepts of representation, complexity, and search. I deliberately avoid the term *search* in this book, preferring instead *exploration*.

Hierarchical Decisions

In Shed World, the array of possibilities can be reduced substantially simply by fixing one of the design variables. For example, one might decide that the shed will have a rectangular floor plan with the long side facing the terrace. Assuming the discrete alternatives for the variables illustrated in Exhibit SHEDWORLD, this single decision reduces the number of alternatives from 640 to 128, a factor of five.

Of course, an arbitrary fixing of a design variable introduces the risk of having excluded an excellent design from consideration. But, these decisions need not be arbitrary. Ideally, the designer makes a decision that substantially reduces the complexity of the problem and that can be made with high reliability without committing to decisions for the remaining design variables.

Subsequent design decisions can then proceed sequentially. Given the rectangular aspect ratio, the designer may decide that the ridge of the roof will be oriented the long way on the building. Having specified a roof orientation and aspect ratio, the designer may then decide that the roof will be a conventional gable-end peaked roof. Given those choices, the designer may decide that the roof pitch will be 45 degrees (or "twelve twelve" in roofing terminology, referring to a vertical rise of 12 inches over a horizontal run of 12 inches). Finally the designer may commit to a 2 meter wall height. This process of sequential decision making and the resulting path through the design space is illustrated in Exhibit TREE.

By considering design decisions hierarchically, exploration becomes a process of choosing which fork in the road to take as each decision is encountered. Typically, a sequential decision strategy is a heuristic approach—it is a rule-of-thumb that does not guarantee that the best alternative is found on the first pass. One can not typically know that there is not a better design down some path that was not taken. As a result, most designers will explore several paths, may backtrack, and may explore several different sequences of decisions. Nevertheless, a collection of promising designs can usually be generated relatively efficiently by considering decisions hierarchically.

The term search tends to offend practicing designers. For many, it implies weak methods unguided by expertise. This is not the sense in which Simon and other early researchers intended it, but I find the word exploration more descriptive of the activity anyway, so I adopt it here.

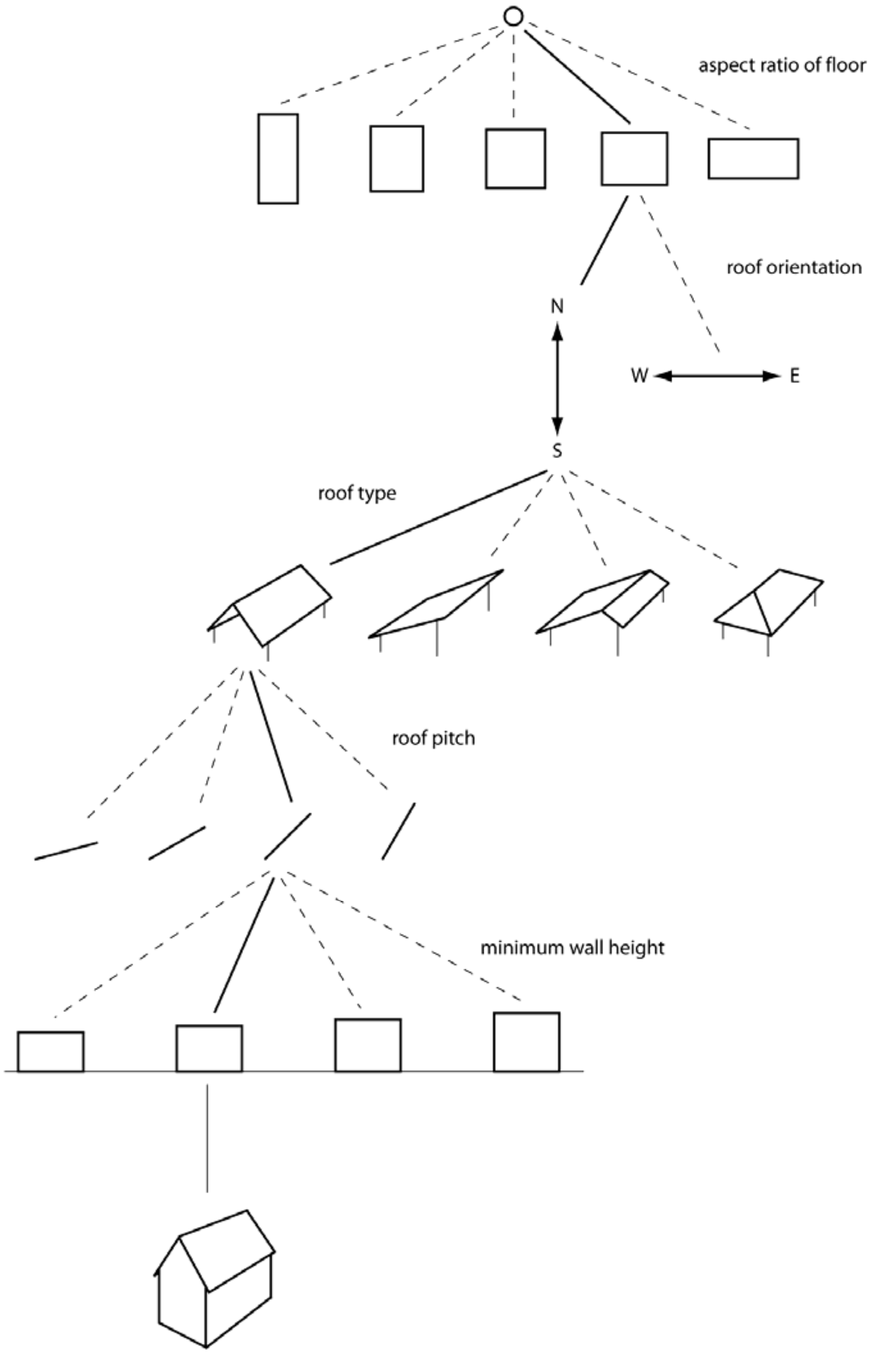

Exhibit TREE. A partially instantiated tree structure representing hierarchical design decisions.

Parallel Exploration and Selection

A sequence of design decisions forms a trajectory of exploration in the design space. In Exhibit TREE one such trajectory is shown for the decisions explicit in shed world. However, to finalize the design of the shed, we would need to locate a door and possibly a window or two. We would need to choose materials and finishes. We would need to specify trim details and the characteristics of the foundation. For most design problems, many such detailed design considerations consume a great deal of effort, yet are relatively unimportant. These details can rarely transform a poor initial concept into a high-quality artifact. No amount of cedar siding and polished brass hardware will transform a bad floor plan with an ugly roof into a nice shed.

We can exploit this property of design trajectories in the exploration process. By arranging design decisions in order of decreasing importance and in order of increasing effort, the designer can focus on the high impact, low cost decisions first, and defer the high cost, low impact decisions for later. We then can divide the design process into a selection phase and a development phase.

In the selection phase, several trajectories are pursued in parallel, but only as far as necessary to make an assessment of the likely quality of an artifact that would result from pursuing the trajectory fully. The designer in effect walks down a path only far enough to get a sense of how the landscape looks in that direction. By exploring in a preliminary way several alternative paths, the designer avoids wasting resources refining a design concept that will ultimately prove unsatisfactory.

The multiple trajectories of parallel exploration can be pursued by several independent designers as part of a design team or possibly even in a tournament format among competing designers. Alternatively, several trajectories may be pursued in a preliminary way sequentially by a single designer and then compared simultaneously.

By ordering design decisions carefully and by pursuing several trajectories in a preliminary way in parallel, the designer first selects a promising design direction before committing the resources required to fully refine the design. In doing so the designer avoids a pitfall common among novices, which is to focus on a single design direction initially and investing substantial resources in a concept that will ultimately prove to be disappointing.

Causal Relationships

Ideally, decisions about design variables are not made randomly. Rather, the designer benefits from knowledge about the causal relationship between a particular value of a design variable and the ultimate quality of the artifact. For example, if a shed will be built off site and transported by truck, the freight costs will be lowest if the shed can be placed on a trailer and can travel normally on roadways. In the U.S. this requires that the shed and trailer be less than 14 feet high, which implies that the roof be less than 11 feet high. As a result, we know by simple geometry that for a peaked roof, the shed height is equal to the wall height plus the sine of the roof angle times half of the width of the shed. This knowledge allows us to eliminate from consideration a combination of a peaked roof and high walls and to constrain the roof pitch to be less than 45 degrees for the aspect ratios with wider walls. This kind of knowledge of the causal relationships among design variables and the ultimate quality of the artifact, allows for entire regions of the design space to be eliminated from consideration.

Causal relationships need not be mathematically precise or even valid under all conditions. Rather, they can be heuristics that allow for more promising designs to be generated efficiently. For example, one heuristic is that to harmonize with a Victorian house style the roof should be a gable-end or hipped roof with a pitch of at least 9/12. This is not universally valid, but works for the vast majority of situations. Another heuristic is to use the *golden ratio* (~1.6) for the ratio of the length to the width of the floor. Again, the causal relationship is not universally valid, but provides heuristic guidance that often leads to superior solutions.

If one were to apply all three of these examples of causal relationships to the shed design problem, there would remain only 12 alternatives, few enough that every one of them could be sketched or modeled, and evaluated. Shed world with these causal relationships applied is illustrated in Exhibit PRUNE.

Causal relationships are learned through experience, and sometimes are codified and taught. Design in domains for which such relationships have not been learned, discovered, or developed is very, very difficult[3].

[3] Fleming and Sorenson (2004) have done a fascinating study of the patent literature in which they show that science serves to guide search in complex design domains.

Knowledge of these relationships is one of the key factors that distinguish novices from experts as they approach design problems.

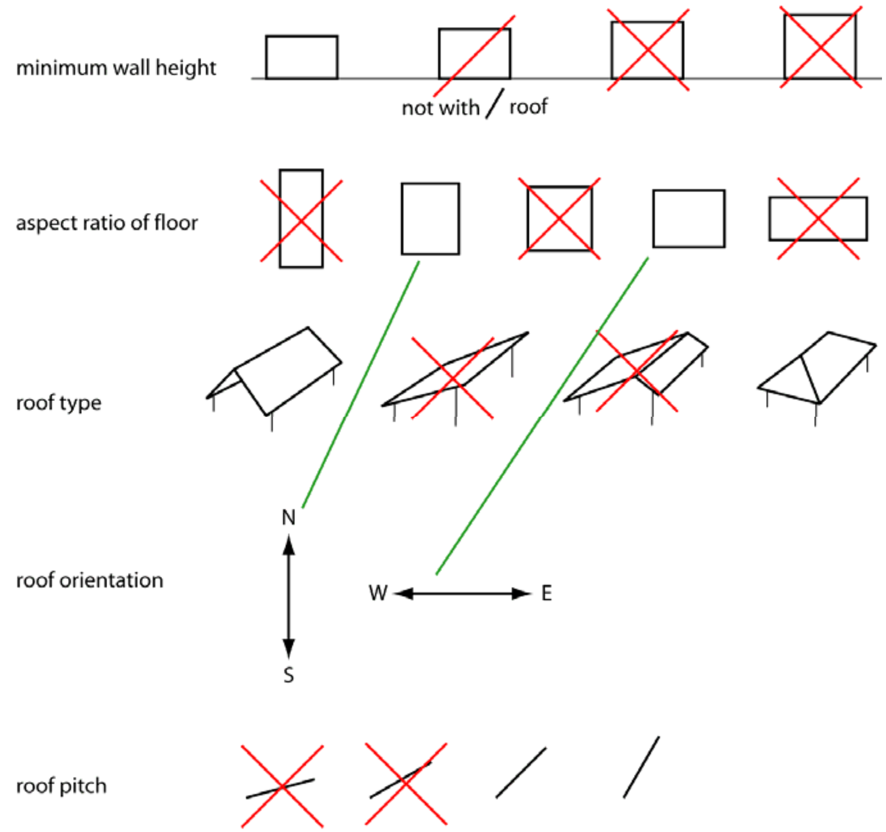

Exhibit PRUNE. The design space, pruned through the use of causal relationships.

Existing Artifacts

A fourth strategy for managing the daunting complexity of exploration in design is to exploit existing artifacts. Existing artifacts are jewels for designers. Someone else has expended the resources required to build and usually even test the artifact. Existing artifacts are known landmarks in the design space that can be readily evaluated. By considering the existing artifacts that others have designed to address a similar problem, one can start the exploration process with substantial knowledge. Indeed, if an existing artifact is close to being acceptable, it can become a starting point for incremental modification and learning. Exhibit SHEDS shows a few existing sheds. As a shed designer I could immediately make some useful inferences. (For me, I discover that I prefer peaked roofs with steep pitches and substantially rectangular floor plans, and I discover many interesting possibilities for window and door placement, and for materials and finishes.)

A generalization of successful existing designs is a *template,* a pattern for designs that has proven successful in the past. Goldenberg and Mazursky (2002) provide compelling evidence for the power of a relatively few templates for guiding the creation of high-quality artifacts in the domains of product design and advertising.

Exhibit SHEDS. A collection of existing sheds, each one representing a known point in the design space.

Shed World and the Real World

Shed world, or really any representation of a design space, is not the real world for at least two reasons. First, shed world is an abstraction of the space of possible artifacts that focuses on only a small subset of the attributes

of real artifacts. Shed world does not capture the interesting contrast between trim painted baby blue and the weathered shingles on the shed in Exhibit REPRESENTATION. Shed world does not treat door and window placement. Shed world does not consider roofing materials. Shed world does not capture the treatment of the soffits and rafter tails on the roof. The world is infinitely complex and so any symbolic representation must necessarily omit certain attributes of artifacts. A good representation is one that suppresses detail that is irrelevant to the task of exploring the space of possible designs, yet makes explicit those attributes of artifacts that have a large impact on the quality of an eventual artifact produced from the design.

Second, and perhaps more significant, shed world constrains exploration to the boundaries of the grammar; to the limits of the expression of the representation. Exhibit ECLECTIC is a collection of sheds that can not be discovered through exploration in shed world. Limited expressiveness is the other edge of sword of representation: representations allow for efficient exploration by limiting the space of possibilities, but they also exclude many possible design alternatives. In practice, designers can overcome the limits of expressiveness by exploring designs using several alternative representations, in essence exploring under several different sets of constraints and abstractions.

By using shed world as the central example in this chapter, I hope I have not overemphasized the importance of representation in design. Most designers do not think explicitly about representation, and work perfectly comfortably without thinking about the symbol systems they employ. Most designers employ several informal representations, sometimes nearly simultaneously when designing, as evidenced by the Wright sketch at the beginning of the chapter. The theoretical concept of representation is useful, I believe, for better understanding the task of designing. However, I am not prescribing the use of formal representations as a tool or technique for practicing design.

Exhibit ECLECTIC. An eclectic collection of sheds not represented by shed world. (Various sources.)

Other Examples

I have illustrated the key concepts of the chapter with the problem of designing a shed, because the domain is simple and easy to understand. However I do not wish to leave the impression that these ideas apply only to the design of buildings. Here I give a few other examples of design domains, associated representations, and exploration strategies.

Internet Domain Names

Naming problems are a highly structured form of design problem. Generating designs for internet domain names is a fairly common problem in professional life. Domain names must of course be unique, in that they must map to a single Internet Protocol numerical address. The design problem is to find a name that is available and that satisfies some other criteria. Common criteria for product and company names are that they be memorable, easy to spell, short, and evoke positive associations. Domain names may only be comprised of 38 possible characters (a-z, 0-9, -, +). If we assume that a prac-

tical domain name has 15 or fewer characters, then there are more than 38^{15} possible names for each type of domain (e.g., .com, .net, .edu, .biz, etc.)[4]. This is about enough to give a unique name to each grain of sand on earth[5]. Given this vast design space, finding a unique name is not typically a problem (e.g., xutq++012ayq858.net is highly likely to be available). The problem is that the space is rather sparsely populated with names that are in some sense *good*. Exploration can proceed fairly exhaustively for domains of length of up to about three letters, at which point the designer really has to begin invoking some brutally efficient heuristics to limit the possibilities considered.

Exhibit NAMES shows the later stages of exploration for a name for a teaching aid that I designed with my colleague Christian Terwiesch. The device is a catapult that launches table tennis balls and that can be adjusted in order to run experiments on the launching process. The names in the exhibit are the best of more than 1000 alternatives that were generated by a group of my students. Note the use of heuristics for generating alternatives. For example, a very common heuristic is to create compound names comprised of two words (e.g., “flingthing”). Another heuristic is to construct an arbitrary string of characters that can be easily pronounced (e.g., “fooz”). A third heuristic is to take fragments of two words that have meaning in the domain of interest and graft them together (e.g., “catapong”). These names are much better than random strings of letters, and provide the designer with an efficient way to explore the space. A second idea illustrated by this example is that of selectionism. A large number of parallel trajectories were compared in tournament fashion, with successive rounds of filtering to arrive at a good solution. The name we finally selected was *xpult* and the domain is xpult.com. We were quite pleased to find a unique evocative name just five characters long, even though there are 38^5 five-character names out there.

An important insight is that if one of the most highly structured design domains imaginable (internet domain names) is essentially infinite in scope, imagine the vastness of less structured domains such as architecture, graphics, industrial design, software, cooking, or engineering design.

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[4] There are more than this because domain names need not be 15 characters long, but this figure gives a sense of the essentially infinite scope of the design space.
[5] If you must know, poke around the internet and you’ll probably find estimates for the number of grains of sand on earth to be about $10^{22} – 10^{25}$. 38^{15} is about 10^{23}.

Initial Concepts	Best Ten	Best Three	Final Name
AstroPong	Catapong	Catapong	Xpult
Catapong	Catapulooza	Varipult	
Catapulooza	Experipult	Xpult	
Experipult	FlingThing		
FlingThing	Funpult		
Fooz	Hurlicane		
Funpult	PingFling		
Hurlicane	Slingcat		
Hurlitzer	Varipult		
LearningLever	Xpult		
PennPong			
Physazz			
PingFling			
Pongit			
Slingcat			
Swish			
TheCatapult			
Varipult			
Xpult			

Exhibit NAMES. Exploration of alternatives for internet domain names (and a product name) for an experimental catapult used as a training aid.

Utility knives

Exhibit KNIVES illustrates exploration for the domain of utility knives, in this case in response to a design problem posed by the knife maker Henkel. The designer explored many alternatives in a preliminary way, 24 of which are illustrated on the left. Three promising alternatives are shown on the right with greater resolution of detail. Some of the variables evident in the designer's implicit representation of the problem are: handle width, "beak curvature," grip padding placement, blade/handle interface, and blade replacement mechanism.

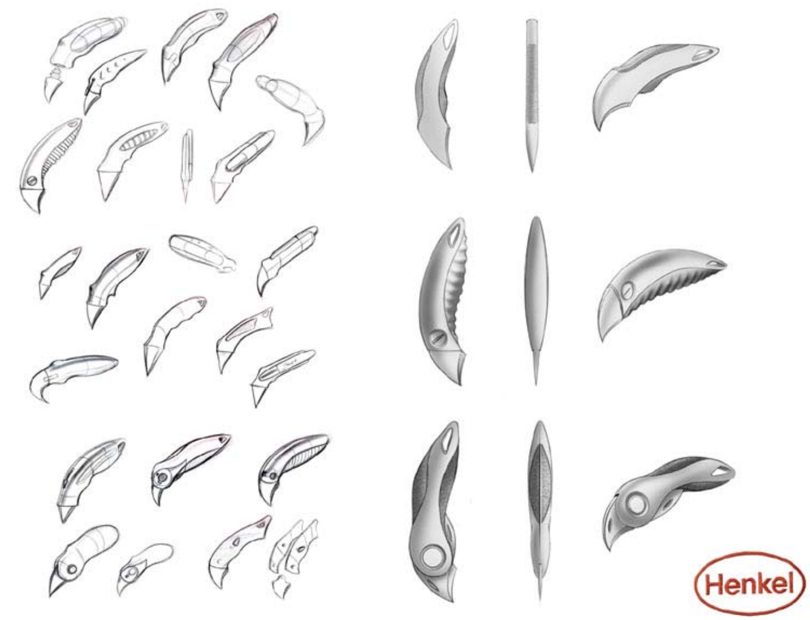

Exhibit KNIVES. Results of exploration in the domain of utility knives. On the left are results of some preliminary exploration and on the right are the three most promising alternatives. Source: Apollo Paul Paredes.

Italian pasta dishes

In my experience, if one orders a pasta dish at a restaurant in Italy some distance from the obvious tourist destinations, it will be wonderful nearly every time. Many of these pasta dishes seem very simple, yet they represent highly successful artifacts in a design space that is incredibly vast. Consider a representation of pasta dishes shown in Exhibit PASTA. The pasta itself can be produced in infinite variety. (There is even pasta in the shape of a bicycle for the cycling fanatic.) Even restricting the dishes to the few hundred readily available pasta types, the addition of the design variables associated with the sauce explodes the design problem into millions of possibilities. (This is without considering the variables associated with relative proportions of ingredients.) Designing a new pasta dish benefits from several of the exploration strategies introduced in this chapter. For example, we might address the problem hierarchically, perhaps first deciding the base for the sauce and deferring until last the shape of the pasta. We might invoke causal relationships, like the heuristic that tomato, garlic, and olive oil often combine harmoniously; or that vegetables with subtle flavors typically do not stand up to the strength of tomato-based sauces. We might use existing designs as starting points, say beginning with a Carbonara sauce (egg, pecorino cheese, pancetta, olive oil, and garlic) and incrementally modifying it to be a meatless design, say by substituting carmelized onions for pancetta.

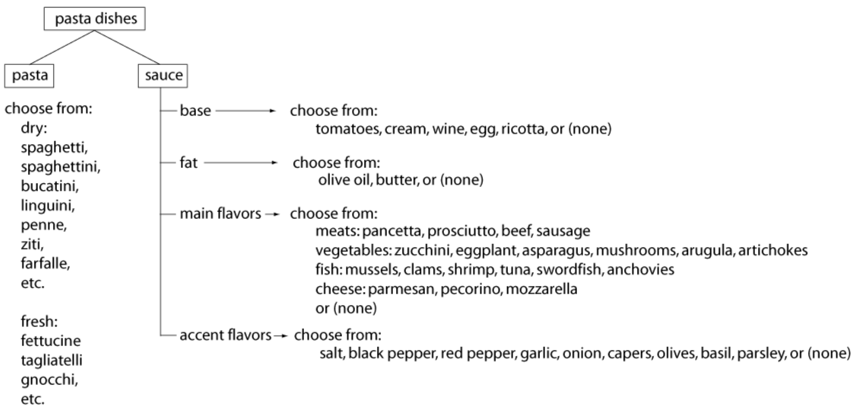

Exhibit PASTA. A representation of a design space for pasta dishes.

Logos

Terrapass is a company that sells environmental offsets for automobiles (www.terrapass.com). Shortly after the company was formed, a team of three graphic designers explored options for a logo for the company. Some of the exploration is shown in Exhibit LOGOS. The process clearly proceeded hierarchically, with initial concepts articulated in black and white and then the more promising concepts developed further and finally detailed in color and with type. The team explored quite broadly initially and discovered a region of the design space they called the "yin yang arrows" (the two designs near the lower right corner of the first set), which everyone really liked. This region was explored further (the middle set of designs) and finally refined with color and detail in the final design on the right.

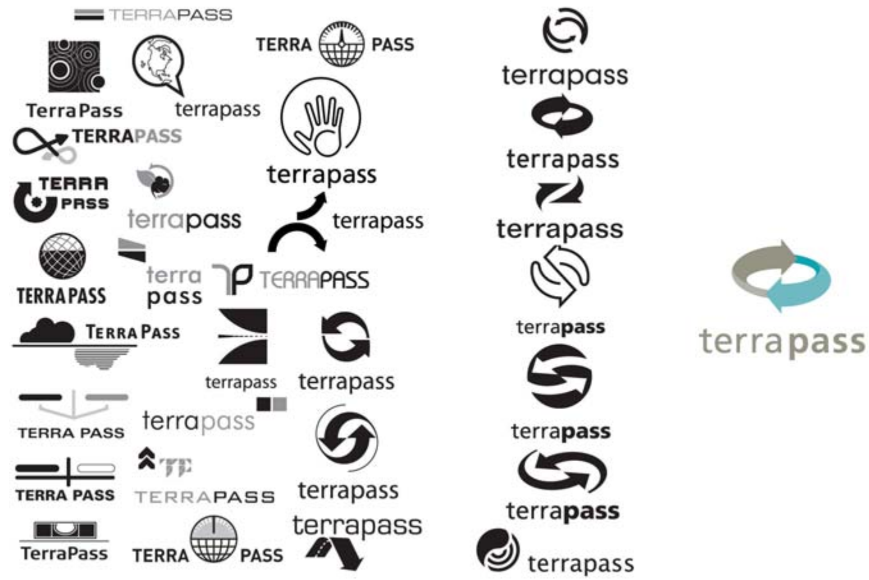

Exhibit LOGOS. Exploration of alternatives for Terrapass logo. The seven logos towards the right resulted from further exploration in the region of "yin-yang arrows" discovered during initial exploration. (Source: Lunar Design Inc.)

Concluding Remarks

Automation

Over the past few decades, researchers have attempted to automate certain design tasks. By and large the most successful efforts have been confined to facilitating the description of designs (e.g., with solid modeling via computers), visualizing designs with computer graphics and rapid prototyping, and/or estimating the performance of artifacts. There has been very little progress in truly automating the exploration process. I believe that the biggest barrier to this endeavor is automatically estimating the quality of an artifact based on a partially completed design. I'm not optimistic about the prospects for full automation of the exploration process. However, I see great potential for further development of tools for allowing designers to more rapidly generate alternatives, visualize designs, and evaluate designs without having to build and test prototypes.

But do designers do it this way?

I don't imagine the chef Thomas Keller will read this book and begin developing a pasta grammar for his exquisite restaurant *The French Laundry*. Indeed, very few practicing designers became experts at design by learning the theoretical foundations of exploration as outlined here. Let me make two comments on this reality. First, the fact that practitioners are not aware of the theoretical underpinnings of a task does not mean those underpinnings are not valid. Design is a complex information processing task. There is no way to avoid the inherent complexity of the task, although expert designers have developed many powerful techniques for avoiding blind search. Just because designers do not typically think of their tasks in formal terms does not mean that those tasks can be tackled without somehow confronting the basic trade-offs and challenges inherent to exploration. In fact, I believe that most good designers learn the strategies I have described here and others, even if they can not articulate them explicitly.

My second response is perhaps more controversial. Much of design education and almost all of design practice is atheoretical. I believe that theory can inform practice in design. In many domains, expertise is acquired through painstaking trial and error, often under the guidance of a seasoned expert. I believe that a robust theory of exploration can lead to more efficient learning of design expertise and a more thorough exploration of design alternatives in practice. Indeed this belief was one of the motives for writing this book. I may be wrong in this belief, and so I leave it as a conjecture that remains to be validated.

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