In A. Collen & W.W. Gasparski (Eds.), Design and systems: General applications of methodology (Vol. 3). New Brunswick, NJ: Transaction Publishers, 1995.

(First published in Polish -- see item 728)

#828

Problem Forming, Problem Finding, and Problem Solving in Design

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This meeting [1], representing a convergence of students of design from a range of wholly dissimilar disciplines, is an event of major significance. It is significant that the meeting is being held at all — that all of you recognize your common concerns. It is significant that we are gaining deep insights into the design process itself. If it is pretentious to talk about the "science of design," at least we know now that there are truths about design that can be formulated and communicated, general truths that seem to apply to design as each of us knows it, in his or her particular professional domain.

But perhaps it is not really pretentious to speak of the science of design. There are principles that are widely applicable, and increasingly, we are finding ways of implementing these principles on electronic computers, and thereby securing the powerful assistance of those computers in the process of design. Let's compromise on "the art and science of design."

In recent years, the awareness of our communalities, whatever the specific field in which we work, has been hastened by the applications of computers to design: expert systems, computer aided design, artificial intelligence. Because their programs are open to inspection, computers allow us to look at the design process. The program is a tangible, concrete object. And in order to construct programs to design or assist design, we have to try to understand the process. That process is basically the same, whether it is carried out by people or computers, or, as is increasingly the case, by both in collaboration.

1. Some Terminology

Design, as I am using the term, means synthesis. It means conceiving of objects, of processes, of ideas for accomplishing goals, and showing how these objects, processes, or ideas can be realized. Design is the complement of analysis — for analysis means understanding the properties and implications of an object, process, or idea that has already been conceived.

In analysis, the final design is given, and the question to be answered is: what are its properties and how will it behave? In design, the goals and constraints, at most, are given, and the question to be answered is: what design or designs will satisfy these goals and constraints? Seldom will the goals and constraints be satisfied by only a single, unique design; and seldom will it be feasible to examine all possible designs to decide which one is, in some sense, optimal. Designing is satisficing, finding an acceptable solution.

2. Choice as a Component of Design

One component of design is choice — the selection of one from among a number of available alternatives. We have many powerful analytic tools to aid choice — the tools forged by economics, by statistical decision theory, and by operations research. Almost all of these tools fit the following general paradigm: we are given a set of objectives and constraints; we are also given a set of alternatives to choose from. Finally, we are given rather complete information (although it may be probabilistic) about the goal level (utility) that each alternative will attain.

If the problem is not too complex, so that the computation of the optimum is feasible, the analytic procedure will announce to us the optimal choice. We need to emphasize the condition, "if the problem is not too complex." In most real-world situations, the problem is, indeed, too complex, and drastic approximations must be made in the description of reality before it is computationally feasible to make "optimal" choices — i.e., choices that would be optimal if the approximate world were the real world. Fortunately, choices that are optimal in the approximate world are frequently satisfactory in the real world.

3. Finding or Generating Alternatives

However, I do not wish to dwell upon the choice aspect of design, for it is not the aspect on which designers spend most of their time and energy. Most design resources go into discovering or generating alternatives, and not into choosing among them. in fact, it is quite common for a single alternative to emerge from the design process — a single plan for a house, or for a bridge, or a single score for a sonata. No choice remains; all of the choosing has been done in the course of generating, selecting among, and combining the elements and components of the design. Choice is thoroughly intermingled with generation.

The elements of a design are not, of course, made from whole cloth. The designer begins with some primitives — some components that he or she knows are available or can be produced. Design is a game of combinatorics played on these primitives. We should not be surprised that, however banal the primitives, novelty — even admirable novelty — can emerge out of this combinatorial process. After all, 92 natural elements suffice, by combinatorics, to produce all the substances that are found in nature or created by human artifice. Four nucleotides in DNA suffice to encode the 20 amino acids; and these 20 amino acids construct the innumerable proteins of living matter. Darwin's combinatorial game, played on the four nucleotides accounts for all of living nature. Combinatorics is the very heart of creation, hence of design.

However much selection among partial and component alternatives take place in the course of the design process, I want to stress the radical difference between choosing among alternatives and generating alternatives. There is no place in choice for the designer's surprise at the unexpected novelties he or she creates by combining and recombining the primitives. In domains of scientific, artistic, or technical interest, the designer cannot foretell — until quite late in the game — what will emerge. (Else what need for the arduous process of design?)

Design is inherently computational — a matter of computing the implications of initial assumptions and combinations of them. An omniscient God has no need to design: the outcome is known before the process starts. To design is to gather information about what follows from what one has proposed or assumed. It is of interest only to creatures of limited information and limited computing power — creatures of bounded rationality like ourselves.

4. The Focus of Attention

There are three ways, all critical for the process of design, in which our rationality is bounded. I have already alluded to the first two: we know only an infinitesimal fraction of the things we need to know — the things that are relevant for arriving at an optimal design. And our computational powers allow us to compute only a few of the innumerable implications of the things we do know.

But our rationality is also bounded in a third way. We store what we know in that encyclopedic portion of the brain that is usually called "long-term memory." Other parts of our knowledge we store in external encyclopedias and reference sources, traditionally on paper but increasingly in computer memories, only the index to the information being held in memory. The long-term memory, too, is indexed, and is accessed by the process we call recognition. Some stimulus in the external environment — a word on a page, a picture, an object — gives us access to information already stored in memory about that kind of word, picture, or object. We say that we recognize it.

Now this method of information storage imposes severe limits on us. We can only recover the information that is indexed and that is cued by recognition. And we can only look at one page of the encyclopedia at a time. We may have a vast amount of information potentially at our disposal, but only a small fragment of it — whether stored internally or externally — can be in our focus of attention at any one moment.

Our small attention capacity is dramatized by George Miller's "Magical Number Seven." Short-term memory, the memory of attention, can hold only about seven familiar "chunks." You can easily test that. Look up a phone number in the directory and retain it until you can dial it. Most of us can do that, unless interrupted. Now try it with two phone numbers, holding one while you dial the other. I think you will fail.

As designers, we know that we must augment our short-term memories with external memory aids. Historically, the most important of these is the drawing on a drawing board. Today, a computer screen often replaces the drawing board. As relevant information is retrieved or generated, we enter it on our drawing, and thereby accumulate a richer store of information about our current problem. But even the drawing provides only a partial answer to the problem of limited attention. As the amount of information in the drawing increases, we find that we can no longer attend to all of it simultaneously, only to a few chunks. So the problem of information retrieval is simply transferred from short-term and long-term memory to the drawing. The problem is still there, and the momentary focus of our attention is still limited.

In the remainder of my talk, I will respond to our own limits of attention by focusing upon the magical number seven and the drawing board as major determinants of the design process —

determinants that exert a major influence on design goals and on the form that design problems take. This will give us only a partial view of design; but when complex matters are under discussion, partial views are all we can have. That is, in fact, the moral of my story.

5. The Drawing Board

The drawing board, I have said, accumulates information. We attend to one aspect of the design task, make a decision, record it in the drawing. It remains there, combining with and relating to all of the other decisions that we have made and will make. To use the information in the drawing, we have to attend to it selectively, responding to our current goals and the cues we can see.

But the drawing does more than record and cumulate information. It also makes inferences for us, inferences that would be difficult or almost impossible to make without it (or without a corresponding picture in our mind's eye). Let me illustrate with a trivial example, simple enough that we can do it in our heads, without a drawing. I ask you to image a rectangle, twice as wide as it is high. I ask you to drop a vertical line from the middle of the top side of the rectangle to the bottom side. Now your mind's eye performs some marvelous calculations for you. I ask you what the shape is of the two figures into which the rectangle has been divided. Without hesitation, you reply, "They are squares, of course." Would you know that, and could you prove that, without the mental image or a drawing?

Let me carry the example one step further. I draw a diagonal from the northwest corner to the southeast corner of the rectangle. Does the diagonal intersect the vertical line you drew (or imaged) previously? Of course it does. How do you know? You can "see" the point of intersection. Thus, the drawing, or mental image, creates new objects (e.g., points) and relations between objects (e.g., intersections of lines) that would be exceedingly hard to generate if you had to infer them by logical or mathematical reasoning. A drawing, in addition to being a store of information, is a quite powerful inference engine (Larkin and Simon, 1987). We make a series of choices, which we record on the drawing; the drawing effortlessly "calculates" many of the consequences of the interaction of these choices.

There are, of course, serious limits on the inferences that drawings make for us. An important contribution of CAD has been to remove the particular limit imposed by the two dimensionality of the drawing. The computer can store images in three dimensions (or more), and when necessary, can display them in ways that make the three-dimensionality evident. And even without the display, it can calculate whether objects intersect in three dimensions or pass in front of or behind each other.

The ability to cumulate information in drawings and to make many inferences, automatically, about interrelations exerts a dominant influence on the organization of the design process wherever drawings can be used. Now the designer is no longer faced with the impossible task of attending to everything at once. A design decision, based on specialized considerations, can be recorded, and subsequently it can be reviewed from viewpoints quite different from the one that generated it.

While a drawing is being scanned at any stage of the design process, cues may evoke relevant information — about details to be attended to, about constraints that have been violated, about alternatives that haven't been considered — information that was outside the focus of attention when previous decisions were made. Repeated applications of this recognition mechanism can guarantee that the final design product will be responsive to a vast range of considerations that couldn't possibly have been held in attention simultaneously.

Of course the choose-record-review-recognize-revise cycle can be applied to any system of accumulating information. It need not be a drawing. However, our eyes are marvelously adapted to scanning drawings and other visual scenes, and to noticing a wide variety of cues in them. In addition, as we have observed, drawing is also a powerful inferential process. For these reasons, we make great use of drawings whenever we are designing systems that are disposed in space, and sometimes even when we are designing more abstract objects. For we go to great pains to find ways to represent even our abstractions in drawings: for examples, computer programs and other temporal processes in flow diagrams; or the steam cycle in thermodynamics.

6. Goals in Design

Designing anything that is the least bit complex (and if it weren't complex, we wouldn't be considering it here) calls for weighing and balancing a whole host of considerations. In designing a house, we have to consider the control of temperature, the view from the windows, the shapes of rooms and doors, fenestration, room arrangement — I can't begin to enumerate all of the considerations that go into the criterion function for a house.

In designing something as simple as an electric motor, we have to make sure that it delivers the desired amount of power, using the right amount of current at the right voltage. It must be designed so that it will not overheat. (An employer once complained to me — he was objecting to the specialization of engineering education — that he had to hire two engineers to design a motor: one to do the electrical circuit, the other to make sure the motor wouldn't burn up.) It must be made of materials that are as cheap as possible, and it should be as easily machined and manufactured as possible.

Similar lists of desiderata that must be attended to could be drawn up for designing organizations, high school curricula, advertising campaigns, or anything else you might want to consider. The criterion function, or the combination of criteria and constraints, is invariably elaborate — much more than we can keep in mind at one time.

In fact, it is misleading to speak of a "criterion function," for that phrase conjures up a picture of a neat synthesis of all the disparate criteria and constraints into some kind of weighted average — a utility, a magical number that sums up our evaluation of the design in terms of all of our combined desires, and needs. There is no such synthesis. We evaluate design products by applying a whole host of discrete criteria and constraints. When some of them are satisfied and some fail, we modify both the design and the criteria and constraints. When we reach a point where we are no longer certain whether the trade-offs are producing a net gain or a net loss — where we are not even sure we know how to compare them — we are usually ready to settle for the result. We look for a design that meets each of our goals and constraints at some level that expresses the aspiration we have formed along that dimension.

7. The Design Satisfices

If this is the way in which we evaluate our designs, then it follows that we don't have to have all of our criteria in mind at once. In particular, we don't have to have all the criteria in mind when we begin the design process. We can count on recognition processes to evoke considerations we had not earlier attended to, and thereby to guarantee we will not neglect them permanently. Not only do alternatives emerge in the course of the design process, but the design goals — the criteria and constraints to be satisfied — emerge also. The design problem is continually reformulated during the process of design. Design is a process of forming, finding, and solving problems. Nor does the forming and finding always come first, followed by the solving. All three subprocesses are thoroughly intermingled.

8. The Emergence of Goals

At this point you may wish to protest that I am playing verbal games. Goals do not really emerge, you object, in the process of design. The goals are really there all along. It is just that they are not all being attended to at the outset; they are stored in long-term memory (or in reference sources) to be accessed and responded to when the appropriate time comes.

This objection misses, I believe, the main lesson of bounded rationality. In human activity it is not what we know "in principle" that counts, but what we know with awareness, here and now. Let me propose a simple example. Suppose that you are offered a papaya, something you have never tasted. What is the goal function that will determine your response? Clearly the utility of papaya taste can't be a part of it, because you don't know what that is. You will have to respond in terms of some kind of "value of new experiences," which has nothing, directly, to do with papayas. Your first bite will evoke a new dimension of utility — the actual taste you experience. It will probably influence whether you take a second.

Now with sufficient ingenuity you can construct a utility function that will accommodate this example. It contains desire for new experiences as well as utilities for various dimensions and combinations of dimensions of taste. With such a function, first and second bites could have quite different utilities. But I submit that such a construction is pure artifice. It is much more useful to describe the situation by saying that having tasted a papaya and liked it, you have formed the new goal of eating a papaya from time to time — especially when one is offered to you. In particular, the taste of the papaya played no part in the decision to take the first bite, and could be omitted from the initial criterion function. After that bite, the criterion function changed.

If you will accept this latter way of viewing the situation, we can draw some consequences from it for the design process. There are two sources of knowledge that, not initially attended to, can be brought into the process. The one source is memory: knowledge is evoked in the course of the process that was not considered at the outset. The other source is nature: in the course of the process, we may learn things that we did not know before, or experience things we had not experienced before, and that learning or experience may change our preferences.

On both counts, we cannot really regard the goals of design as given any more than we regard the alternatives as given. A design process begins with some criteria and some possibilities (or primitives out of which alternatives can be constructed). As the process goes forward, new criteria and new possibilities are continually being evoked from the sources we have identified.

By designing — exploring — we learn what we can have; but we also learn what we want.

9. Sequence in Design

We do not start designing wholly innocent of goals and constraints. We start with initial goals that guide the first steps of the design process. These initial goals are soon augmented with others that are evoked as the process goes forward.

The sequence in which goals are generated is not insignificant, for different sequences will produce different final designs. (In my paper on *Style in Design*, I have argued that the order in which things are taken up in the design process is a major determinant of what we usually call "style.") The goals and constraints we postulate at the beginning represent commitments that limit the alternatives we can generate. Many possible designs will be ruled out by these initial commitments.

In choosing the sequence in which goals will be introduced, designers are guided by a number of heuristics, some of which are specific to particular domains of design, but others of which are quite general. For example, a basic heuristic is to include the most important goals and constraints among those postulated initially. Designing a house starts with criteria that govern the siting and floorplan, not the bathroom plumbing. Failing to include important criteria in the initial problem formulation can lead the designer into blind alleys from which there is no recovery without starting over.

A second heuristic is to put aggregate criteria first, before attending to criteria that govern specifics. In designing a building, it is usually advantageous to specify total cost and volume before siting and floor plan are considered.

A third heuristic is to postulate first those criteria that are the most restrictive, for restrictions will reduce the combinatoric explosion of possibilities, hence will keep the design task within manageable compass. Human beings often do their best designing when they are faced with severe constraints, for then they are protected against the disorganization and aimlessness that an excess of possibilities can induce. The Gothic cathedral builders were not disadvantaged by the difficulties of being limited to building by placing stone on stone. On the contrary, dealing with these difficulties produced some of the essential beauties of these structures.

There is another side to the discipline of constraints, however. If initial constraints are too rigid, many possible directions of development will be closed off, and there will be little opportunity for goals not included in the initial set to have much influence on the final design. Goals will have little chance to be modified by experience.

I should like to take up this need for flexibility as my final topic. But in concluding this section, I must state once more its basic theme: Determining the sequence in which goals and constraints are to be considered is a major step in designing, and a major determinant of the style of the design product.

10. Designing for Flexibility

Because human rationality is severely bounded, all thinking works with highly incomplete models of the problem situation. The antidote to this incurable tunnel vision is to retain flexibility, so that when a problem is later examined from a new viewpoint, decisions taken previously can be modified. Commitments must be tentative. Without such flexibility, constraints cannot be applied sequentially.

We usually think of flexibility, not as a characteristic of the design process but of the design product. We think of flexibility as designing something that will be adaptive to future, and presently unanticipated, conditions that are different from the conditions at the time the design is made. But we have seen that the design process is itself a temporal flow, a continuous sequence of decisions with a past, a present, and a future.

Flexibility in the design process allows new knowledge to be used whenever it emerges, early or late. Equally, flexibility allows response to new criteria whenever they are evoked. It permits goals to be modified and augmented, new constraints to be introduced. What we usually regard as the design process — the steps taken up to the point where we have created a design to be realized — is just the first stage of a longer process. First we design a building; then we use it — that is, we continually redesign it.

The role of flexibility in these two stages is essentially the same. We need flexibility throughout the design process so that the design can evolve, responding to new considerations at each stage. We need flexibility in the design product so that it can continue to evolve in use, responding to new needs and new conditions. In short, we need flexibility because our bounded rationality is unable to anticipate all of the contingencies that will arise during the process of design or all those that will arise when we later use the designed object.

The need for flexibility is implicit in all design, but flexibility may also be an explicit design goal. For example, when we design a computer language we anticipate only in a statistical sense, or even more vaguely than that, what programs we will want to write in it.

When we design a computer language for writing artificial intelligence programs, the need for deliberate flexibility becomes even greater. Artificial intelligence uses heuristic search, and heuristic search seeks problem solutions along paths that cannot be anticipated. Computer memory must be organized so that structures of arbitrary size and conformation can be stored, accessed, and modified in arbitrary ways. So the most striking characteristic of AI languages like LISP is that they support this flexibility in memory organization — that they do so was the central specification in their design.

11. Design of Social Systems

The criterion of flexibility also takes on special significance in the design of objects that are intended to have long lives — such objects as buildings, cities, and institutions.

A city plan can hardly be regarded as more than a pointer to some initial steps that will urge subsequent development in a particular direction. When Pittsburgh, in the early 1950s, cleared its Golden Triangle, this initiated a sequence of events, most of them then unanticipated, that redeveloped the center of the city around its dramatic setting at the meeting of two rivers. The particular configuration of buildings we see today is a response to that first initiative, but is grossly different from the configuration that appeared on the 1950s drawings. We can think of the whole thirty five year period as a design exercise carried out, not on a drawing board but on the site of the city itself. There is no clear boundary between design and action. Each stage of thought or action is merely a starting point for the next thought or action.

Nor should it be supposed that the design goals were fully specified in the original plans. As the new city emerges, we examine it. We live in it and experience its qualities. It changes our values and our aspirations. We have new conceptions of what a city is.

Designs for organizations have the same tentative and emerging quality. My favorite example is of the same vintage as the Pittsburgh plan: the Economic Cooperation Administration (ECA), established in 1948 to manage the Marshall Plan Aid that we offered to ensure European economic recovery after World War II. The goal of the legislation was to provide the European nations with funds and goods that would enable them to revive their own productive capacities. But there were many different ways in which an organization could have been structured to do that.

The ECA could have been an organization for processing European shopping lists, validating them, and aiding procurement. That was one model. Another conceived the ECA as an extension of the State Department, organized to engage in bilateral negotiations with individual nations to fix the terms on which aid would be offered. A third model — the one followed — conceived the organization as a nucleus around which economic cooperation among the European states could develop, so that they would be led toward a European economy very different from the fragmentation of the pre-War era.

The means for achieving this longer-range goal was to establish a strong Paris office of the ECA, and to give that office a large measure of authority for negotiating with a counterpart organization of European states. Today's European Economic Community is the direct product of this decision, although it was certainly not anticipated in anything like its present form. The organization plan did not mastermind the future; but it surely did push events in a particular direction.

These two examples, one of a city, the other of international organization, reveal to us a criterion that is central in virtually all social planning, a particular form of the criterion of flexibility. Since designing a social system is an unending process, we cannot design specific configurations. We can only design for a "steady state," a continuous flow of events that will maintain a satisfactory present while preserving the potential for satisfactory futures. The guiding principle of such design is that every generation should be guaranteed as wide a range of options as was available to the generation that preceded it.

12. Conclusion

The design process is shaped in fundamental ways by the fact that human rationality is bounded, and shaped especially by the very narrow focus of human attention. Computers enable us to handle a little more information than we could before, and computer a few more of the implications of our knowledge. But they do not change the basic fact of bounded rationality. With or without computers, we can take into account at one time only a tiny bit of the real world's complexity.

It follows that design is a process of search, and of the discovery of new information about alternatives that are available and about the consequences that will follow if those alternatives are chosen. But design is also a process for discovering the goals to be achieved and the constraints to be satisfied. Goals and constraints are no more fixed elements in design than is anything else.

Design is always tentative. At every point of time, the design is subject to revision. And to the end of the life of the designed object, that object and its uses are subject to revision. A major goal at each step of the design process is to realize goals while keeping options for the future open.

Design needs to be approached with a modesty about our ability to anticipate the future, much less to control it wisely. Good design decides on goals and chooses alternatives without preempting the choices of goals that our successors may wish to make.

Note

[1] This lecture was delivered to the First International Congress on Planning and Design Theory, Boston, 1987.

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