FIVE

THE SCIENCE OF DESIGN
Creating the Artificial

Historically and traditionally, it has been the task of the science disciplines to teach about natural things: how they are and how they work. It has been the task of engineering schools to teach about artificial things: how to make artifacts that have desired properties and how to design.

Engineers are not the only professional designers. Everyone designs who devises courses of action aimed at changing existing situations into preferred ones. The intellectual activity that produces material artifacts is no different fundamentally from the one that prescribes remedies for a sick patient or the one that devises a new sales plan for a company or a social welfare policy for a state. Design, so construed, is the core of all professional training; it is the principal mark that distinguishes the professions from the sciences. Schools of engineering, as well as schools of architecture, business, education, law, and medicine, are all centrally concerned with the process of design.

In view of the key role of design in professional activity, it is ironic that in this century the natural sciences have almost driven the sciences of the artificial from professional school curricula. Engineering schools have become schools of physics and mathematics; medical schools have become schools of biological science; business schools have become schools of finite mathematics. The use of adjectives like "applied" conceals, but does not change, the fact. It simply means that in the professional schools those topics are selected from mathematics and the natural sciences for emphasis which are thought to be most nearly relevant to professional practice. It does not mean that design is taught, as distinguished from analysis.

The movement toward natural science and away from the sciences of the artificial has proceeded further and faster in engineering, business, and medicine than in the other professional fields I have mentioned, though it has by no means been absent from schools of law, journalism, and library science. The stronger universities are more deeply affected than the weaker, and the graduate programs more than the undergraduate. Few doctoral dissertations in first-rate professional schools today deal with genuine design problems, as distinguished from problems in solid-state physics or stochastic processes. I have to make partial exceptions—for reasons I shall mention—of dissertations in computer science and management science, and there are undoubtedly some others, for example, in chemical engineering.

Such a universal phenomenon must have a basic cause. It does have a very obvious one. As professional schools, including the independent engineering schools, are more and more absorbed into the general culture of the university, they hanker after academic respectability. In terms of the prevailing norms, academic respectability calls for subject matter that is intellectually tough, analytic, formalizable, and teachable. In the past much, if not most, of what we knew about design and about the artificial sciences was intellectually soft, intuitive, informal, and cookbooky. Why would anyone in a university stoop to teach or learn about designing machines or planning market strategies when he could concern himself with solid-state physics? The answer has been clear: he usually wouldn't.

The problem is widely recognized in engineering and medicine today and to a lesser extent in business. Some do not think it a problem, because they regard schools of applied science as a superior alternative to the trade schools of the past. If that were the choice, we could agree.[1] But neither alternative is satisfactory. The older kind of professional school did not know how to educate for professional design at an intellectual level appropriate to a university; the newer kind of school has nearly abdicated responsibility for training in the core professional skill. Thus we are faced with a problem of devising a professional school that can attain two objectives simultaneously: education in both artificial and natural science at a high intellectual level. This too is a problem of design—organizational design.

The kernel of the problem lies in the phrase "artificial science." In my previous chapters I have shown that a science of artifical phenomena is always in imminent danger of dissolving and vanishing. The peculiar properties of the artifact lie on the thin interface between the natural laws within it and the natural laws without. What can we say about it? What is there to study besides the boundary

[1]That was in fact the choice in our engineering schools a generation ago. The schools needed to be purged of vocationalism; and a genuine science of design did not exist even in a rudimentary form as an alternative. Hence the road forward was the road toward introducing more fundamental science. Karl Taylor Compton was one of the prominent leaders in this reform, which was a main theme in his presidential inaugural address at MIT in 1930:

> I hope . . . that increasing attention in the Institute may be given to the fundamental sciences; that they may achieve as never before the spirit and results of research; that all courses of instruction may be examined carefully to see where training in details has been unduly emphasized at the expense of the more powerful training in all-embracing fundamental principles.

Notice that President Compton's emphasis was on "fundamental," an emphasis as sound today as it was in 1930. What I am urging in this essay is not a departure from the fundamental but an inclusion in the curriculum of the fundamental in engineering along with the fundamental in natural science. That was not possible in 1930; but it is possible today.

sciences—those that govern the means and the task environment?

The artificial world is centered precisely on this interface between the inner and outer environments; it is concerned with attaining goals by adapting the former to the latter. The proper study of those who are concerned with the artificial is the way in which that adaptation of means to environments is brought about—and central to that is the process of design itself. The professional schools will reassume their professional responsibilities just to the degree that they can discover a science of design, a body of intellectually tough, analytic, partly formalizable, partly empirical, teachable doctrine about the design process.

It is the thesis of this chapter that such a science of design not only is possible but is actually emerging at the present time. It has already begun to penetrate the engineering schools, particularly through programs in computer science and "systems engineering," and business schools through management science. Perhaps it also has beach-heads in other professional curricula, but these are the two with which I am most familiar. We can already see enough of its shape to predict some of the important ways in which engineering schools tomorrow will differ from departments of physics, and business schools from departments of economics and psychology. Let me now turn from questions of university organization to the substance of the matter.

THE LOGIC OF DESIGN: FIXED ALTERNATIVES

We must start with some questions of logic.[2] The natural sciences are concerned with how things are. Ordinary sys-

[2]I have treated the question of logical formalism for design at greater length in two earlier papers: "The Logic of Rational Decision," *British Journal for the Philosophy of Science, 16*(1965):169–186; and "The Logic of Heuristic Decision Making," in Nicholas Rescher (ed.), *The Logic of Decision and Action* (Pittsburgh: University of Pittsburgh Press, 1967), pp. 1–35. The present discussion is

tems of logic—the standard propositional and predicate calculi, say—serve these sciences well. Since the concern of standard logic is with declarative statements, it is well suited for assertions about the world and for inferences from those assertions.

Design, on the other hand, is concerned with how things ought to be, with devising artifacts to attain goals. We might question whether the forms of reasoning that are appropriate to natural science are suitable also for design. One might well suppose that introduction of the verb "should" may require additional rules of inference, or modification of the rules already imbedded in declarative logic.

Paradoxes of Imperative Logic

Various "paradoxes" have been constructed to demonstrate the need for a distinct logic of imperatives, or a normative, deontic logic. In ordinary logic from "Dogs are pets" and "Cats are pets," one can infer "Dogs and cats are pets." But from "Dogs are pets," "Cats are pets," and "You should keep pets," can one infer "You should keep cats and dogs"? And from "Give me needle and thread!" can one deduce, in analogy with declarative logic, "Give me needle or thread!"? Easily frustrated people would perhaps rather have neither needle nor thread than one without the other, and peace-loving people, neither cats nor dogs, rather than both.

As a response to these challenges of apparent paradox, there have been developed a number of constructions of modal logic for handling "shoulds," "shalts," and "oughts" of various kinds. I think it is fair to say that none of these systems has been sufficiently developed or sufficiently widely applied to demonstrate that it is adequate to handle the logical requirements of the process of design.

Fortunately, such a demonstration is really not essential, for it can be shown that the requirements of design can be

based on these two papers, which have been reprinted as chapters 3.1 and 3.2 in my *Models of Discovery* (Dordrecht: D. Reidel Pub. Co., 1977).

met fully by a modest adaptation of ordinary declarative logic. Thus a special logic of imperatives is unnecessary.[3]

Reduction to Declarative Logic

The easiest way to discover what kinds of logic are needed for design is to examine what kinds of logic designers use when they are being careful about their reasoning. Now there would be no point in doing this if designers were always sloppy fellows who reasoned loosely, vaguely, and intuitively. Then we might say that whatever logic they used was not the logic they *should* use.

However, there exists a considerable area of design practice where standards of rigor in inference are as high as one could wish. I refer to the domain of so-called "optimization methods," most highly developed in statistical decision theory and management science but acquiring growing importance also in engineering design theory. The theories of probability and utility, and their intersection, have received the painstaking attention not only of practical designers and decision makers but also of a considerable number of the most distinguished logicians and mathematicians of the present and recent past generations. F. P. Ramsey, B. de Finetti, A. Wald, J. von Neumann, J. Neyman, K. Arrow, and L. J. Savage are examples.

The logic of optimization methods can be sketched as follows: The "inner environment" of the design problem is represented by a set of given alternatives of action. The alternatives may be given *in extenso:* more commonly they are specified in terms of *command variables* that have defined

[3] I should like to underline the word "unnecessary." When I said something like this in another place (the second paper mentioned in the previous footnote), an able logician, who had specialized in modal logics, accused me of asserting that modal logics were "impossible." Now this is patently false: modal logics can be shown to exist in the same way that giraffes can—namely, by exhibiting some of them. The question is not whether they exist but what they are good for. A modal logician should have no difficulty in distinguishing "non-necessity" from "impossibility."

Logical Terms		*Example: The diet problem*
Command variables	("Means")	Quantities of foods
Fixed parameters	("Laws")	Prices of foods Nutritional contents
Constraints Utility function	("Ends")	Nutritional requirements —Cost of diet

Constraints characterize the inner environment; parameters characterize the outer environment.

Problem: Given the constraints and fixed parameters, find values of the command variables that maximize utility.

Figure 6. The paradigm for imperative logic.

domains. The "outer environment" is represented by a set of parameters, which may be known with certainty or only in terms of a probability distribution. The goals for adaptation of inner to outer environment are defined by a utility function—a function, usually scalar, of the command variables and environmental parameters—perhaps supplemented by a number of constraints (inequalities, say, between functions of the command variables and environmental parameters). The optimization problem is to find an admissible set of values of the command variables, compatible with the constraints, that maximize the utility function for the given values of the environmental parameters. (In the probabilistic case we might say, "maximize the expected value of the utility function," for instance, instead of "maximize the utility function.")

A stock application of this paradigm is the so-called "diet problem" shown in figure 6. A list of foods is provided, the command variables being quantities of the various foods to be included in the diet. The environmental parameters are the prices and nutritional contents (calories, vitamins, minerals, and so on) of each of the foods. The utility function is the cost (with a minus sign attached) of the diet, subject to the constraints, say, that it not contain more than 2,000 calories per day, that it meet specified minimum needs for vitamins and minerals, and that rutabaga not be eaten more than once a week. The constraints may be viewed as characterizing the inner environment. The problem is to select the quantities of foods that will meet the nutritional requirements and side conditions at the given prices for the lowest cost.

The diet problem is a simple example of a class of problems that are readily handled, even when the number of variables is exceedingly large, by the mathematical formalism known as linear programming. I shall come back to the technique a little later. My present concern is with the logic of the matter.

Since the optimization problem, once formalized, is a standard mathematical problem—to maximize a function subject to constraints—it is evident that the logic used to deduce the answer is the standard logic of the predicate calculus on which mathematics rests. How does the formalism avoid making use of a special logic of imperatives? It does so by dealing with sets of *possible worlds:* First consider all the possible worlds that meet the constraints of the outer environment; then find the particular world in the set that meets the remaining constraints of the goal and maximizes the utility function. The logic is exactly the same as if we were to adjoin the goal constraints and the maximization requirement, as new "natural laws," to the existing natural laws embodied in the environmental conditions.[4] We simply

[4]The use of the notion of "possible worlds" to embed the logic of imperatives in declarative logic goes back at least to Jørgen Jørgensen, "Imperatives and Logic," *Erkenntnis,* 7(1937–1938):288–296. See also my *Administrative Behavior* (New York: Macmillan, 1947), chapter 3. More recently this same idea has been used by several logicians to construct a formal bridge between the predicate calculus and modal logic by means of so-called semantic or model-theoretic methods. See, for example, Richard Montague, "Logical

ask what values the command variables *would* have in a world meeting all these conditions and conclude that these are the values the command variables *should* have.

Computing the Optimum

Our discussion thus far has already provided us with two central topics for the curriculum in the science of design:

1. *Utility theory and statistical decision theory as a logical framework for rational choice among given alternatives.*
2. *The body of techniques for actually deducing which of the available alternatives is the optimum.*

Only in trivial cases is the computation of the optimum alternative an easy matter. If utility theory is to have application to real-life design problems, it must be accompanied by tools for actually making the computations. The dilemma of the rational chess player is familiar to all. The optimal strategy in chess is easily demonstrated: simply assign a value of +1 to a win, 0 to a draw, −1 to a loss; consider all possible courses of play; minimax backward from the outcome of each, assuming each player will take the most favorable move at any given point. This procedure will determine what move to make now. The only trouble is that the computations required are astronomical (the number 10^{120} is often mentioned in this context) and hence cannot be carried out—not by humans, not by existing computers, not by prospective computers.

A theory of design as applied to the game of chess would encompass not only the utopian minimax principle but also some practicable procedures for finding good moves in actual board positions in real time, within the computational

Necessity, Physical Necessity, Ethics, and Quantifiers," *Inquiry,* *4*(1960):259–269, where references are also given to work of Stig Kanger and Saul Kripke; and Jaakko Hintikka, "Modality and Quantification," *Theoria,* *27*(1961):119–128. While these model-theoretic proposals are basically sound, none of them seems yet to have given adequate attention to the special role played in the theory by command variables and criterial constraints.

capacities of real human beings or real computers. No exceptionally good procedures of this kind exist today, other than those stored in the memories of grandmasters, but there is at least one computer program that plays at the level of an expert or a weak master—that is, better than all save a few hundred human players.

The second topic then for the curriculum in the science of design consists in the efficient computational techniques that are available for actually finding optimum courses of action in real situations, or reasonable approximations to real situations. As I mentioned in chapter 2, that topic has a number of important components today, most of them developed—at least to the level of practical application—within the past 25 years. These include linear programming theory, dynamic programming, geometric programming, queuing theory, and control theory.

Finding Satisfactory Actions

The subject of computational techniques need not be limited to optimization. Traditional engineering design methods make much more use of inequalities—specifications of satisfactory performance—than of maxima and minima. So-called "figures of merit" permit comparison between designs in terms of "better" and "worse" but seldom provide a judgment of "best." For example, I may cite the root-locus methods employed in the design of servomechanisms.

Since there did not seem to be any word in English for decision methods that look for good or satisfactory solutions instead of optimal ones, some years ago I introduced the term "satisficing" to refer to such procedures. Now no one in his right mind will satisfice if he can equally well optimize; no one will settle for good or better if he can have best. But that is not the way the problem usually poses itself in actual design situations.

In chapter 2 I argued that in the real world we usually do not have a choice between satisfactory and optimal solutions, for we only rarely have a method of finding the

optimum. Consider, for example, the well-known combinatorial problem called the traveling salesman problem: given the geographical locations of a set of cities, find the routing that will take a salesman to all the cities with the shortest mileage.[5] For this problem there is a straightforward optimizing algorithm (analogous to the minimax algorithm for chess): try all possible routings, and pick the shortest. But for any considerable number of cities, the algorithm is computationally infeasible (the number of routes through N cities will be $N!$). Although some ways have been found for cutting down the length of the search, no algorithm has been discovered sufficiently powerful to solve the traveling salesman problem with a tolerable amount of computing for a set of, say, fifty cities.

Rather than keep our salesman at home, we shall prefer of course to find a satisfactory, if not optimal, routing for him. Under most circumstances, common sense will probably arrive at a fairly good route, but an even better one can often be found by one or another of several heuristic methods.

An earmark of all these situations where we satisfice for inability to optimize is that, although the set of available alternatives is "given" in a certain abstract sense (we can define a generator guaranteed to generate all of them eventually), it is not "given" in the only sense that is practically relevant. We cannot within practicable computational limits generate all the admissible alternatives and compare their respective merits. Nor can we recognize the best alternative, even if we are fortunate enough to generate it early, until we have seen all of them. We satisfice by looking for alternatives in such a way that we can generally find an acceptable one after only moderate search.

Now in many satisficing situations, the expected length of

[5] "The traveling salesman problem" and a number of closely analogous combinatorial problems—such as the "warehouse location problem"—have considerable practical importance, for instance, in siting central power stations for an interconnected grid.

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To Allen Newell
in friendship