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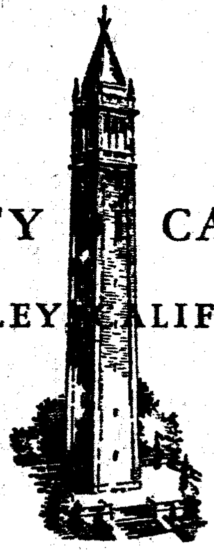

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THE DICHOTOMIES OF ENGINEERING DESIGN

by

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INTRODUCTION

For purposes of better understanding the engineering design process, the decision rules which an engineer uses in design have been computer-programmed. While such a program suggests some very specific and practical improvements that can be made in the design process, some very general suggestions for improvement must also be considered. One generalization is that certain traditional distinctions must be re-examined, since they can be shown to break down. For example, one commonly held distinction is that engineering hardware is concrete while engineering theories are abstract. The danger is that we tend to forget that such separations are of our making, not the world's. This paper argues that an unreflective distinction between what is regarded as abstract and what is regarded as concrete has prevented engineering from developing richer notions of what constitutes optimal design. Specifically, a strict separation between the abstract and the concrete has fostered resistance to that kind of research which has attempted to describe engineering as a social process. Engineering, like all human activities, is, in the last analysis, just as much a social enterprise as it is a technical activity.

THE DICHOTOMIES OF ENGINEERING DESIGN

Engineering is commonly regarded as a concrete activity which deals with real objects. At the same time, engineers also recognize that it is their abstract theories which bring the concrete objects into being. Thus, it is natural to ask, what role, if any, does the "abstract" play in defining the "concrete"; are they irreparably opposed, or are they rather different facets of the same phenomenon? In other words, is it possible to say that an object can be both concrete and abstract at the same time depending on the way in which we regard the object? Furthermore, if it should turn out that what is concrete is a function of what is abstract, what is the functional relation, and what is the effect of this relationship on design? Basically, wherein lies the concreteness or the reality of engineering objects?

According to David Marples and Morris Asimow, the reality of engineering's objects lies in the finished product of design: hardware. In this view, the world is sharply dichotomized; the abstract and elusive ideas of the mind stand in contrast to the real and concrete things of the world. Apparently, what little reality the abstract does possess is only of a mediated nature at best; the reality of the abstract consists merely in its function of bringing about the existing reality of objects. The abstract is not real in itself. In short, hardware represents physical reality whose concreteness is revealed through "immediately accessible knowledge:"

"As we move down . . . these trees (i.e., game trees which specify the set of decisions available at any stage of the design process) the level of abstraction decreases. At the top the problem and its solutions are described in relatively abstract terms. At the bottom we envisage detailed bits of hardware made from particular materials. In fact, the result of all engineering design activities is 'hardware'; manufacturing techniques, standard parts and assemblies constitute a set of means which have been previously devised for carrying out a variety of design decisions made at a higher level of abstraction. All new detail designs and methods of manufacture increase the means available for carrying out more high-level decisions."*

"Design proceeds from the abstract to the concrete. It begins with a concept, conjured up in the mind; a relationship among ideas or geometrical forms which somehow fit the circumstances of the problem. Such mental abstractions can eventually become manifest in physical objects, but the bridge is a long one, and the first step over it is to bring the original idea into some form of communicable expression."**

"<u>Parts</u> are the elementary pieces from which components are assembled. It is here, in the work of designing parts, that we come to grips with the concrete realities of hardware. In the design of subsystems or components, a huge number of relatively minor questions about achieving physical realization are allowed to go unanswered because we feel very sure that answers will come from sources of immediately accessible knowledge and from available experience in the technology when the actual parts are being designed. . . . When a part is being designed, no questions pertaining to its design may remain unanswered; no ambiguities about its shape, its material, or its treatment may cloud the instructions for its manufacture. We have come to the place on the long path from the abstract to the concrete, from the concept of the system or device to the physical embodiment thereof, where the final transition is made, where the ideal merges into physical reality."***

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*See Ref. 9, p. 63.

**See Ref. 1, p. 25.

***See Ref. 1, p. 36.

In the following paragraphs, Asimow elaborates on the actual process which brings the concrete object into existence and which determines its properties:

> "Although in the design of an individual part we are close to the physical terminus on the way from the abstract, critical parts may still require extensive analysis. The general physical embodiment of the part may appear clearly to the mind, but ways of giving it a useful symbolic description must yet be sought . . . The same kinds of questions about sensitivity and stability which arose at the higher levels of design are often important here, and for critical parts, optimization is almost always important. The problems of compatibility and simplification have special status in the design of parts. They lead to questions about tolerances in dimensions, mechanical, physical and chemical properties, composition of materials and quality of workmanship. The association with production cost is close, for tighter tolerances beget higher prices.
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> "Other problems of engineering design also become prominent. The part designer has close ties to the metallurgist, the production process engineer, and the tool designer. The choice of material for the part must be settled upon; its heat treatment and its surface treatment must be prescribed, if such are to be applied. The producibility of the part must be considered; and, at least in a general way, the production processes established for its manufacture. The general means of production need to be thought through, for they reflect on the manufacturing capabilities of the company and on the tooling costs that will be incurred in the preparation for production.
>
> "The detailed drawings afford an opportunity for careful checking. The designer, immersed in the manifold details of his design, and, if he has been properly motivated, emotionally involved in its outcome, is often unable to see some of the minor faults . . .
>
> "Complete definition of the parts is mandatory. The shop, it must be remembered, manufactures parts; the components, the subsystems and finally the system are, so far as the shop is concerned, only assemblies of parts. A part is defined by its description, which must be complete enough to prescribe precisely what it should be like after its manufacture. To accomplish this purpose we may need any or all of the following

> forms of description: detailed drawings, specifications, special instructions, standard symbols, notes, special sketches, and revisions or modifications."*

At this point, one is led to remark that, paradoxically enough, all of the preceding statements are quite abstract. Strange as it may sound, those whose initial premise is the concreteness of hardware are very abstract when it comes to describing the stuff or process out of which concrete things are supposedly made, especially when we consider that the emphasis is on the search for an "optimal" design process. Taken step by step, the description behind the construction of a design object literally involves the "procedures" of the whole organization. And this is no isolated phenomenon, for the description of an object always takes place at an abstract level. The languages which we employ in order to represent the world in turn represent the abstract ways in which the human mind experiences and perceives the world. In fact, how would it be possible to describe objects in other than abstractions, since any language already represents a highly sophisticated state or level of abstraction? But if so, where has all out concreteness gone? Furthermore, in order to pursue the argument, let us suppose that we were willing to grant concreteness for the time being; then, we may still ask, how immediate is the description or the experience of an object whose very existence must be mediately verified through the use of a set of propositions which express the object's properties?

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*See Ref. 1, pp. 36-37.

Apparently, the contrary of immediate experience of concreteness follows as much from Asimow's own account: "A part is defined by its description, which must be complete enough to prescribe precisely what it should be like after its manufacture." The point is that a part is its description. Its reality is the language that we use for experiencing the object's properties. What an object is independent of a human mind or language, one cannot know. No one, we dare say, has performed the elusive experiment of removing all minds from the world and then has continued to note the existence of matter. In other words, the idea of a known object implies a knower, and the knower knows no better than the language he has available for analyzing the attributes of "thingness." Lest there be misunderstanding, we must stress that when we say that a part is its description, we do not mean to imply the absurd conclusion that an object is nothing but a collection of words held together by some syntax. Rather, given the present state of our science and technology, our scientific languages designate what we are presently able to identify as relevant factors which constitute an object's properties. Since what we designate as a relevant design factor is translated into a design specification which determines the object's existence, and since a language is neither immediately learned nor used, the experience of the design object's concreteness is far from immediate.

Now, in addition to using Asimow's sentence* in order to show

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*"A part is defined by its description, which must be complete enough to prescribe precisely what it should be like after its manufacture."

the impossibility of *immediately** verifying an object's concreteness, the sentence also contains some key phrases we would do well to examine for further consequences. Notice particularly the **word** "complete" and the phrase "what it (the object) should be like." The phrase does not read "what it will be like" or simply "what it is." Asimov has unwittingly expressed the fact that languages or modes of description also designate the factors we are *willing* to identify as relevant for design. That is, we have a basic choice at our disposal. From which point of view shall we consider the object? It's not what the object is, but rather, what do we want the object to be? Since different professions use different languages, they perceive the world in varied ways, and, as a result, each profession wants the object to satisfy a different set of design needs. After all, it is hard to believe that the part designer, the metallurgist, the production process engineer, the tool designer, the checker, and finally the user of the design, all perceive the same concrete object and hence all agree on what the object's properties really are, let alone, on what they should be. Certainly, we would expect each group to have a different idea of what constitutes a "complete" description. In fact, we would be suspicious if they all agreed. We are *not* denying that all of them are necessarily presented with the same object. Quite the contrary; we are only saying that in order to *know* what "it" is that remains the 'same' from one point of view to the next

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*We have only shown the impossibility of *immediate* experience, not all experience of an object.

requires that we effect a complex series of comparisons between the different descriptions, in short, a great deal of abstraction.

Buhl provides a refreshing footnote to our discussion up to this point. His remarks point out the naivete which underlies the usual engineering view of the mind and its relationship to the objects of the world. He makes the important points, amongst others, that how we have been trained effects how we analyze, and that how we analyze affects not only what we do perceive but also what we can perceive:

> "A number of difficulties are present in performing an analysis. Not all of the data collected are of equal value nor is all the information pertinent to the problem. Sometimes we include bits of nonessential information by impulse or habit or by failure to agree on the real meaning of the words . . .
>
> "In order to analyze the data it may be necessary to synthesize an arrangement. In design it is often necessary to guess at the placement of the bearings, the types of gears and the like, before the various relationships between the variables become apparent by analysis . . .
>
> "We often have difficulty in seeing many variables at a given time. The human mind thinks out a problem in little pieces and finds it difficult to keep many items simultaneously in its consciousness. It therefore is desirable to solve problems by successive complexity . . . The use of simplifying assumptions is not only essential for the average engineer but is common practice in scientific investigation. Care must be exercised in eventually correcting for the differences between the assumptions and the actual situation.
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> "The solution of these problems is also hindered by certain psychological difficulties. The way we analyze is dependent upon who we are and how we think by virtue of the training and experience we have had. Some individuals are able to analyze in very abstract symbolism as in the case of an electrical engineer. Other individuals require more physical things as in the case of the mechanical engineer. Some people are very

adept at analysis with words while others better understand graphic analysis.*

> "Often university training results in a negative approach to problems and a feeling that there is only one answer and one correct method of analysis. Each individual is limited by what he sees as fundamental or basic, by a desire to be completely logical. We are furthermore limited by the way we see things and the way we think things should be done. With our emphasis on physical things we seem to have great difficulty in really understanding wave mechanics. We have difficulty in understanding what friction is and what the purposes are of bearings and lubrication. Our previous habits result in rigid thinking and fixed methods of analysis."**

The important point is not so much that the patterns we use for categorizing the objects of our experience are culturally determined, but that some such categorization or abstraction is necessary in the first place for the very possibility of experiencing an object. For example, one is not born immediately recognizing a clock as a keeper of time. In fact, one doesn't even recognize time unless time itself is a meaningful concept, for there _are_ cultures that do not recognize the concept--at least not in the sense of Western culture. In his book _The Silent Language_, the anthropologist Edward Hall documents how Americans conceive of Time as Money or as something to be used. For us time is a commodity that we can _either_ earn, spend, save _or_ waste. Thus, Americans who encounter natives in India spending their whole day merely sitting are prone to conclude that the natives are wasting time,

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*The point we would make is that words and graphic analysis are both abstract, and one isn't necessarily more or less abstract than the other. Instead, abstraction is a two-way street. What's physical to the mechanical engineer may be quite abstract to the electrical engineer. Electrical phenomena are not always more abstract than mechanical.

**See Ref. 2, pp. 82-84.

that they are doing nothing because they are not acting in time or using time as we do. In other cultures, doing nothing is not necessarily doing nothing. As another illustration, our time perspective is generally short when compared with the Asian:

> "While we look to the future, our view of it is limited. The future to us is the foreseeable future, not the future of the South Asian that may involve centuries. Indeed, our perspective is so short as to inhibit the operation of a good many practical projects, such as sixty - and one - hundred - year conservation works requiring public support and public funds. Anyone, who has worked in industry or in the government of the United States has heard the following: 'Gentlemen, this is the long term! Five or ten years.'"*

We forget that what we take for granted has been systematically pounded into us since early childhood by a culture that places a great emphasis on making the distinction between things of the world and ideas of the mind. As a result, most of us grow up to believe that mind and world <u>are</u> distinct. Those "simplifying assumptions" we all make as scientists or engineers <u>are</u> the realities we work with. How we weight the relative importance of our data, and how we break the problem down into little pieces testify to the power the mind has in determining the Real. Again, our assumptions are not the object <u>per se</u> but rather what we must use in order to know--if we ever can--what the object is in itself for itself. We didn't create the world but we do create the ways we describe the world's content and workings.** In fact, the separation is naive to begin with; if the mind were so cut

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*See Ref. 6, p. 20.

**How we can be sure that our World Systems are not merely Grand Illusions is beyond the scope of this paper. See Refs. 3 and 4.

off from the world, how could we know that this was so when we would have to use the mind in order to know what it is that we were cut off from? Or, to put it slightly differently, how could we know that there was a world completely independent of mind when we would be using the mind in order to know this fact about the world? Instead, we must say that matter is an object for a knowing mind.

We may, if we like, approach our topic from the standpoint of "confidence," i.e., according to Asimow we proceed until we are confident "that the design concept can be physically realized." Now, if something as human as "confidence" is involved, when all concreteness may indeed seem to have disappeared. Not only do differently educated engineers perceive differently, but even the same engineer perceives differently on similar occasions. Who but the stereotyped personality, say, the programmed Handbook Engineer with a fixed (and hence inefficient) set of design rules for all situations, ever designs exactly the same way twice with the same degree of confidence? More to the point, who should? Apparently, only He who truly knows what to do exactly for all circumstances--i.e., He who has no need of further knowledge about the infinite complexities of matter and is able to measure "confidence" with such great confidence that the measure will be satisfactory for all possible uses of the design.

The concreteness of engineering's objects is not given by "immediately accessible knowledge" but instead is dependent upon an evolving conception of the goals of engineering. Concreteness is not given by "immediately accessible knowledge" for the reason that there is no such knowledge.

The extensive and complicated knowledge of the engineer is anything but immediate. If it were, why would it take four years to acquire? And why is the first four years nowadays considered just preparation for the next four years where at last one really gets down to the core of things. We forget that what we take as the common immediate knowledge of today was the highly abstract speculation of yesterday. In any case, such knowledge wasn't immediately learned then any more than it is now, and it certainly isn't immediately relearned by every new generation of engineers.

Consider the student who struggles to learn the elementary theory of bending in beams. A beam is never the same afterwards. It always looks different, for it is different. The beam is no longer an amorphous object, but a purposeful entity whose concreteness follows from the fact that it is an object of design. In this sense, a beam is concrete because of the engineer's ability to have it behave as he desires. Thus, the engineer can be said to know about beams because he understands why beams act the way they do. And such understanding came about because the engineer interacted with beams; he studied them and defined their properties with respect to a purpose. Since the engineer can describe or perceive the beam's attributes with respect to a theory that explains a beam's workings, the engineer knows what "it" is that he is perceiving. To be sure, the common man also perceives a beam, but he cannot be said to know the object of his perception in the same way that the engineer knows. Whereas the engineer knows by conscious design, the common man is at the mercy of common sense or rather common opinion.

But now, let us also consider that the "same" beam is different for the metallurgist. He perceives the beam from a point of view that is microscopic when compared with the engineer. For the metallurgist, the thing of interest is the beam's material. Yet, the metallurgist too knows about the beam because of his extensive studies about material properties. Now, we may ask, who perceives the real beam? Both of them and neither of them. Neither of them perceives the real beam since each of their points of view is only partial and hence incomplete. Yet, both of them perceive the real beam in the sense that they can get together in principle and broaden their specialist's perspective. That is, they are potentially able to perceive the beam if and only if they can somehow include all the multitudinous ways of looking at beams for purposes of design, and this means that they will be committed to developing new ways of design or new modes of perception. In this sense, the concreteness of engineering's objects lies with the goal of engineering that strives to broaden our ways of conceptualizing or analyzing objects. Concreteness certainly does not lie with the immediacies of knowledge or of sensation.

In a similar vein, concreteness does not automatically follow from "confidence" or "agreement on physical reality." Instead, let us consider that the most important design decision often involves the question of confidence. This is also the most potentially dangerous decision, for if everyone were to agree on the same level of confidence, we would do well to wonder what they were actually agreeing to? Are all parties to the design agreeing on the design concept itself, or, as an example, with the ideas of the boss? Maybe they are all uncritically following the fashionable or accepted notions of their profession. Agreement without a description of the process by which agreement was reached so that one has an idea of what the agreement is all about means nothing. One doesn't necessarily achieve physical reality by confidently agreeing with his peers. One must, in addition, examine the grounds for his confidence. As a matter of fact, we may want to disagree with our peers in order to bring out different points of view as a check as to whether we have included all the reality of the situation. In the long run, competing points of view may be the quickest way to agreement on the true nature of things. For ultimately the real problem is how to secure true confidence and rich agreement, not false assurance and blind delusion.

These dichotomies of engineering--mind vs. world, abstract vs. concrete, or subject vs. object--represent the failure of engineering to develop a dialectic which recognizes the dynamic interplay between subject and object or subjectivity and objectivity. Only to the mind of common sense is anything immediately concrete or objective. Only to the mind of common sense is anything independent of mind. Unfortunately, such strict dichotomies have not prepared the engineer for rising above the level of common sense to what makes good design sense. The point of this paper is not be be metaphysical but rather to raise to self-consciousness the fact that a strict dichotomization of the world has not prepared engineers for studying themselves. Thus, we might not take issue with Asimow and others if they made clear that confidence is a function of the psychology and sociology of engineering design. We will never know what is concrete about an object unless we know the factors that make different individuals or groups conceive of concreteness differently. Our task is to explain why different engineers use different design rules.

We are quite aware that the implications of this paper may appear to be quite radical, but then the search for optimal ways of satisfying human needs is itself a radical demand. After all, engineering isn't just interested in hardware or something that just gets the job done; it wants to know the optimal way to design in general. In this sense, engineering cannot be said to be objective or concrete unless it becomes more self-conscious about the role the designer plays in determining the concrete. Unless engineers become more self-conscious about the ways they design, they have no idea of what they are really designing. And an activity that lacks self-consciousness cannot be said to be conscious of the true needs and wants of mankind; and it surely cannot be said to be optimal design.

At this point, we would do well to emphasize that the concerns of this paper arose in the course of a very practical activity, the heuristic programming of a design engineer's job. If one asks, for purposes of simulating the design process, what it is that is concrete about engineering hardware, one soon becomes involved in a host of abstract considerations. First of all, one must answer the question of which programming language to use. Since different programming languages greatly affect the representation of the design process, i.e., the adequacy of the similation, the choice of a computer language is not a trivial one. If anything, the particular language we use affects what we can represent. For example, some languages are more convenient for representing a set of parameters which specify an object's attributes or properties while other languages are specifically designed for handling decision processes or algorithmic procedures. Secondly, there is the question of which engineering language to use, or whose description of the design process shall we consider as basic? The answer is not clear. In the course of this author's work, it has been found to be quite impossible to program the job of a single engineer without in turn programming the co-producer's and user's of the design. As an illustration, the machinist is just as much a part of the design process as the engineer. When one considers that different machinists take different amounts of time to make the same part, the general description of the design and manufacture of a part, no matter who the <u>particular</u> machinist is, becomes quite involved indeed. One must, in some sense, program how the individuals who support the design engineer conceive of and use the design object. Consider that how the engineer measures time, one of the most crucial design parameters in any problem, may not be the way the machinist measures time. One of the most interesting things to consider is that the estimate of construction time that a machinist gives the engineer may reflect the power that the employee has over the employer. The machinist can in some cases alter the final decision as to which design alternative to build by the time estimate he gives to the engineer. From this and other considerations too numerous to consider in this paper,* it becomes no mere academic exercise to ask how we might better translate between different languages for purposes of better design procedure: A first step in the conservation of design time consists in measuring how time is conceived by the parties to the design.

In sum, when one builds a computer program to simulate design, one also witnesses the concreteness of the abstract. If our concrete objects are only represented or thought about in abstract terms, then a computer program also demonstrates the converse: The abstract can also be given a concrete representation in the form of a computer program. In this sense, we may say that the abstract is itself concrete. On the other hand, it is also true that to be truly concrete constitutes one of the most abstract tasks facing the human mind. Each bit of concrete knowledge about objects in turn represents objective knowledge about man. We could equally say that there is never anything more revealing or more subjective about a group than what it takes as objective. In other words, for man to be truly concrete about objects, man will have to learn a lot more about the subject, man.

We conclude that to be concrete requires a conscious design effort. There is no concreteness apart from a theory of concreteness.

*We hope to publish a detailed study of the program in the future.

that we have carried the notions of concrete and abstract on to the next historical level of self-consciousness, that of Hegel: Not only is the concrete abstract; the abstract is also concrete.

Finally, the student of the philosophy of science will recognize the writer's debt to the philosopher Hegel (7). There is perhaps no better source in Western thought than Hegel on the intricate connections between mind and matter. There is probably no better critic as well on the immediacies of perception. In addition, Hegel remains one of the most illuminating sources on the role of language: It is doubtful who masters whom. Is man to be the Master of or the Slave to his own creation, language?

The dichotomies of engineering design are also the dichotomies of Western man, not engineering alone. Western Man is Schizophrenic Man.

ACKNOWLEDGMENTS

Although my treatment of them may seem harsh, Asimow (1) and Marples (8) are only to be criticized with respect to the point of view developed in this paper. In general, they remain good sources about the decisions of engineering design. Nevertheless, Buhl (2) and Jones (8) are to be recommended for introducing doubt into the conventional notion that engineering proceeds from the "abstract" to the "concrete".

Churchman (3 and 4) provides an excellent critique of the methodology of science from the vantage point of the philosopher of science, while Kuhn (7) provides an historian's account. Both authors are absolutely necessary reading for a reflective knowledge of science.

For those interested in an elementary discussion of the effect of culture on language, or equally as well, the effect of language on culture, Hall (6) is highly recommended. In this same context, Churchman and Kuhn may also be read as more advanced and extended historical commentaries on the nature and development of scientific languages.

The notion that to be concrete requires a conscious design effort is not new. Esherick (5), in effect, says as much. We would say this paper is a complement to his in the sense that if we were to classify Esherick's approach as Kantian, then we would have to say that our own is Hegelian. Herein, we hope, lies the contribution of this paper -

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