A PHILOSOPHICAL APPROACH

TO LOGICAL DESIGN

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PREFACE

The engineer is normally concerned with the utilization of the forces of nature for the benefit of mankind. This concern is usually centered about the design of equipment in one or more of the physical sciences.

The author is of the opinion that the design of equipment is a science distinct from the physical science that may be employed in the designed device. This is a science of creativity. The purpose of this investigation is to ascertain if this is indeed a science, and to find some of its characteristics. The possibility of design by computers is also investigated. The outline of a design program is presented. The program uses the logic of Aristotle and Boole for decision making and an essence topology for the cataloging of information.

Drs. William L. Hughes and D. D. Lingelbach are thanked for their guidance and encouragement to the author to continue his education after the lapse of so many years. The author also wishes to extend his appreciation to Mrs. J. W. Agee, Librarian, Del Mar Technical Institute and to Miss Pauline Shaw, Texas Engineers Library for their aid in locating material. Special thanks are extended to the author's students for their forebearance during the preparation of this manuscript.

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CHAPTER I

INTRODUCTION

Problems in the design of equipment originate with the desire for accomplishment on the part of some human being. It may be that the designer has an inner compulsion for creativity. It is more often the case however, at least with engineers, that the element of livelihood is involved, for the engineer is the professional creator of machines utilizing the forces of nature. In these cases, it is the engineer's superior that desires to accomplish something and he looks to the engineer to perform. The superior states the problem. This statement may be concise, elaborate, general, specific, or vague, depending upon the idosyncrasies of the individual involved, however, the engineer is obliged to perform in the best possible manner.

The Accepted Design Procedure

The designer has many problems facing him when he is given the assignment of designing a particular piece of equipment that will satisfy a stated set of equipment specifications. These problems can be placed in either of one of two categories. The categories are information gathering and decision making. All designers follow a pattern in the design of a piece of equipment. They make use of their theoretical knowledge and their personal design experiences. The majority of design problems are solved by personnel that are experts in the area of the design question.

Thus, it is not usual for an electrical engineer to design a new diesel engine and a mechanical engineer is not likely to be called upon to design an electronic computer. A difficulty lies in acquiring the initial design experience. This is usually solved in industry by teaming a young inexperienced designer with a seasoned veteran. In situations as this, the veteran provides the experience and the young designer is expected to have the theoretical knowledge at his finger tips. This approach to design problems has been time tested and thus presents a strong argument against change. However, the approach has shortcomings. Very often, by the time a young designer has enough experience to be allowed to tackle a serious design problem on his own, he has forgotten many of the tools that he was given in his formal education. Also, he may become discouraged and feel that his talents are not being fully utilized.

The young designer has been trained in the use of the tools of analysis, whereas the problems of design are ones of synthesis. In analysis, the investigator asks the why, and how of an event or operation, whereas in synthesis, the investigator must put simple parts together to construct a composite whole. This synthesis has one very predominant characteristic. Synthesis is cyclic by its very nature. This is verified by Von Fange.[1] Warfield also demonstrates the cyclic nature of synthesis in the development of a product.[2] Figure 1 shows Warfield's cycle.

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[1] Eugene K. Von Fange, Professional Creativity (Englewood Cliffs, N.J., 1959), p. 91.

[2] John N. Warfield, Introduction To Electronic Analog Computers (Englewood Cliffs, N.J., 1959), p. 142.

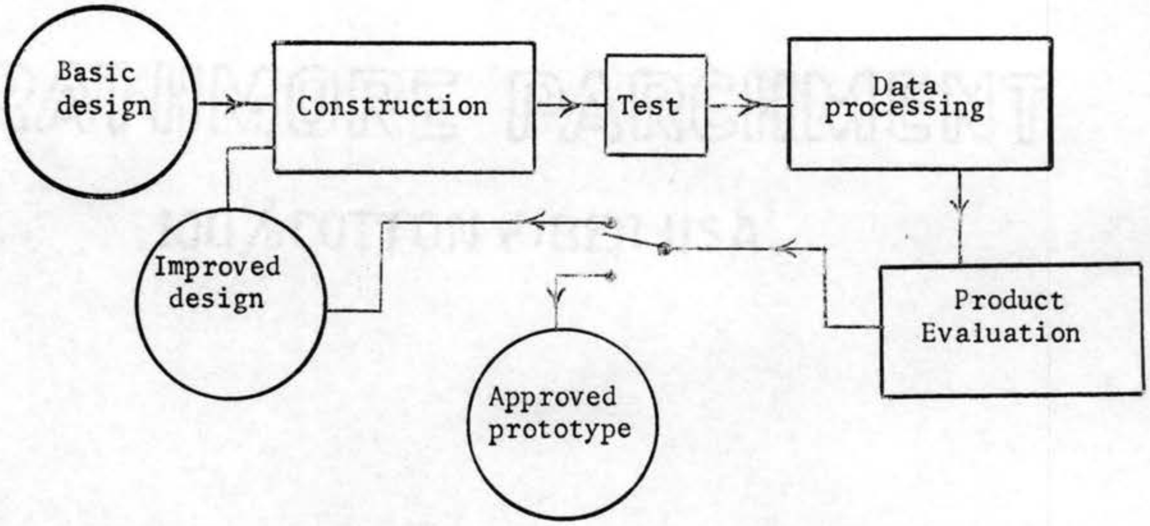

Fig. 1. The Product Development Cycle

The accepted design procedures may vary between individuals and industrial concerns but they are the same in that the problem is formalized, information is gathered from various sources, design decisions are made, the results are checked, and a finished design is delivered to an authority.

The Evolving Design Procedure

The accepted design procedure is time tested and contains many elements that will not change but with the advent of high speed computers there has been increasing demand for making an analytical science out of design in order that the possibility of design by machine methods can be realized to its fullest extent. This would seem a hopeless task at the first examination because of the complexity and wide application of design problems. There are tools that are available to man to assist him in the quest for determining the scientific truths of equipment design. The major tool is one of logic. Logic has been studied since the earliest times and has had a strong revival in the scientific field in the last twenty years. Another tool that is available is the tool of topology, which is the science of invariants.

Aristotle invented the science of Formal Logic or Analytic as stated by Glenn.[3] Logic is the science of thinking correctly and this is of the utmost importance in the design procedure.[4] Aristotle had serious shortcomings in his speculations in the physical sciences and this undoubtedly explains why his writings lay unnoticed by the physical scientists for so many centuries. It was a mathematician who rediscovered Aristotle's works and gave them a mathematical foundation. George Boole, recognizing the worth of the works of Aristotle, showed that the syllogism could be represented in a mathematical algebraic form.[5] It is the algebraic form of the syllogism as developed by Boole that has been found by current investigators. The use of this symbolic logic has found great use in modern computers. Berkely (1959) has developed the use of this tool to great extent. However, he has not studied creativity itself.

The science of topology has also entered the design field but is

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[3]Paul J. Glenn, An Introduction To Philosophy (St. Louis, 1944), p. 66.

[4]Ibid.

[5]George Boole, An Investigation Of The Laws Of Thought On Which Are Founded The Mathematical Theories Of Logic And Probabilities (New York), p. 226-242.

not as well established as symbolic logic. There are two recognized divisions of this science, algebraic topology and geometric topology. Nodelman and Smith define topology:

....as a nonquantitative geometry which is concerned with those properties of geometric figures which would remain invariant if the figures were drawn on a rubber sheet or modeled in rubber and then subjected to deformation.[6]

If design by machine is to be realized, creativity itself must be examined. This will be done in the following chapters. It will be accomplished by examining each accepted design procedure in turn. These will be; examination of the problem, gathering data, and making decisions.

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[6]Henry M. Nodelman and Frederick W. Smith, Mathematics For Electronics With Applications (New York, 1956), p. 117.

CHAPTER II

EXAMINATION OF THE PROBLEM

The requirements for a piece of equipment that is to be designed, can be said to comprise the specifications for the equipment. If the designer is to be successful in the design, and satisfy the delegating authority, he must analyze the specifications. A computer is well adapted to do this if programmed properly and the specifications have been stated properly, but it may prove embarrassing to the delegating authority if the machine stops due to lack of information.

Methods such as those developed by Beizer and Leibholz (1958) are ideal for performing the mechanics of a specification analysis and they can be adapted for use by machine. However, if machine analysis is to be successful, a study of specifications in general must be made in order to assure a high order of probability for a successful design in any given problem. Aristotle has shown in his "Topics" that there are ten categories or "Predicates" which are necessary to know in order to understand something completely.[1] Glenn has arranged these categories in the following manner:[2]

Questions	Categories or Predicamentals
1. What (is the thing itself)	1. Substance

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[1]Aristotle, "Topics", Great Books Of The Western World, Vol. 8, ed. Robert Hutchins, (Chicago, 1952) p. 147.

[2]Paul J. Glenn, p. 70.

2. How much?	2. Accident of Quantity
3. What sort?	3. Accident of Quality
4. In what comparison or reference?	4. Action of Relation
5. What doing?	5. Accident of Action
6. What undergoing?	6. Accident of Passion
7. Where?	7. Accident of Place
8. When?	8. Accident of Time
9. In what position or attitude?	9. Accident of Posture or Position
10. With what externals or vesture?	10. Accident of Habit

Centuries of use of these tenets of Aristotle has substantiated their truth and has failed to reveal any shortcomings. Thus, if a device is to be designed and constructed, the ten predicamentals of Aristotle are the criteria that must be satisfied. Examining these from a designers viewpoint, they are:

1. Substance. What is the thing itself? What is being attempted in this design? It can be said that this is the important question, for the delegating authority must convey this requirement to the designer. Other requirements of the specifications are really limitations on the prime requirement of designing a machine that will do thus-and-so.

2. Accident of Quantity. How big is the machine to be? What are to be its physical dimensions? Should it be long and slender or short and broad? The designer must answer these questions. If they are not explicitly stated, then he has the option of using good judgment.

3. Accident of Quality. How reliable should the device be? How efficiently should it operate? What is to be the selling price? Should a component of slightly inferior quality but possessing a strong price advantage be utilized? It can be said that quality is an important accident to be considered in terms of equipment specifications, at least in commercial applications. Thus, the engineer should attempt to acquire as much explicit direction as possible.

4. Accident of Relation. How will this device affect the status quo? Should this be considered? Will this device perform satisfactorily with other components in a larger system? Are industry standards being followed or frustrated? What else is similar?

5. Accident of Action. Must a source of power be contained within the device? Is the device to contain moving parts? Will a process be required to change the size or shape during its usefulness period? Would it be considered an active device?

6. Accident of Passion. What mechanical stresses will the device be subject to? What are the required reactions to balance any outside forces? What will be the effects of wear? What will be the effects of age and long periods of idleness?

7. Accident of Place. What are the temperature extremes to which this device will be subjected? Will it be used in a dark or lighted area? Is vibration in mounting to be encountered? What are the extreme, total ambient conditions to be encountered?

8. Accident of Time. Will this device be operated intermittently or continuously? What is the duty cycle? What will be the average load on the device? What will be the maximum peak load? What is to be the

life of the device?

9. Accident of Posture or Position. Will this device be used in the horizontal, vertical, or both positions? Is the device stable in all manners? What is the attitude?

10. Accident of Habit. What is to be the color of the device? What material will be used for the cover? Does it require any covers or protectors? What finish is to be used?

The substance is the subject of an investigation and the accidents are the attributes of the subject The accidents do not exist in themselves, but are attendant to a subject.

The questions that arise during the course of design are seemingly endless but, each question can be cataloged under one of the predicates. This is a very important fact, as will be shown later.

The specifications are composed of two parts: the explicit specifications and the implicit specifications. The explicit specifications are those that are given either written or verbally to the designer by the delegating authority. The implicit specifications are those that are not specified explicitly but still should be considered in the design. Implicit specifications will include criteria such as: legality of the device is determined, proper authorities have been consulted if there is a regulating authority, device is compatible with insurance and building requirements, the device will utilize standard parts and assemblies as far as practicable. The requirements of the implicit specifications often fall in the realm of utilizing standard practices. It is difficult to debate the advisability of using standard practices if it has not been explicitly stated otherwise.

The problem may be expressed as follows:

Given: Set of requirements (S) called specifications

The set S is made up of the Explicit Specifications S_e and the Implicit Specifications S_i.

Thus: $S_e \in S$ (See footnote 3) (1)

and, $S_i \in S$ (2)

$$S = S_e \cup S_i \quad (3)$$

From the definition of 'explicit' and 'implicit', the sets S_e and S_i are disjoint, i.e.;

$$S_e \cap S_i = \{\ \} \quad (4)$$

Thus a 'cut' has been made in the set S.

$$S_e \mid S_i \quad (5)$$

In order to make an 'ordered' union,

$$S_e \prec S_i \quad (6)$$

The above relationships are presented pictorally in Figure 2 and Figure 3.

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[3]The symbols used conform to those used by Breuer.

$\in$ = read as " is an element of "
$\subset$ = read as " is a subset of "
$\cup$ = read as " in union with "
$\cap$ = read as " in intersection with "
$\mid$ = read as " cuts "
$\prec$ = read as " precedes "
$<$ = read as " is less than "
$\not\prec$ = read as " does not precede "
$\notin$ = read as " is not an element of "
enclosing bars indicate cardinal number

$S_j\Big|_2^{10}$ indicates an advancing index "j" to take all natural values from 2 to 10 inclusive.

e.g. $S_j\Big|_2^{10}$ $= S_2$ Case I
$= S_3$ Case II
..........etc.

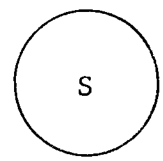

Fig. 2 The Specification Set (S).

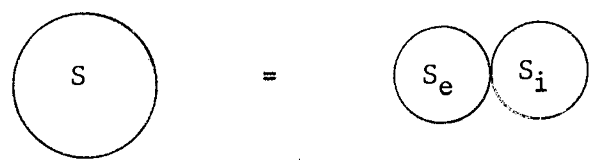

Fig. 3 A Topological Analysis of the Specification Set (S).

The Set (S) must only be composed of the Predicamentals of Aristotle in order to completely define the set. Thus, these are:

S_1 which is the essence of the requirements and must be included in S_e. What is being attempted?

S_2 which is the accident of Quantity. S_2 will include questions of size, shape, weight, proportions, etc.

S_3 which is the accident of Quality. S_3 will include questions of efficiency, performance, reliability, cost, maintenance, etc.

S_4 which is the accident of Relation. S_4 will include questions of relativity, such as effects on other pieces of equipment, personnel hazards, etc.

S_5 which is the accident of Action. Questions pertaining to the actual actions of the machine, whether in space or time will be included in this set.

S_6 which is the accident of Passion. In this set are found questions of what the machine is undergoing when in use and when not in use. Product evaluation and testing often make components of this set to assist the designer in the final selection of a design.

S_7 which is the accident of Place. Within this set are the questions relating to ambient conditions.

S_8 which is the accident of Time. Questions concerning the device that have a bearing on time will fall within this set.

S_9 which is the accident of Posture or Position. Within this set are criteria such as vertical or horizontal position, attitude, high or low, etc.

S_{10} which is the accident of Habit or Vesture. Within this set are questions as to color, material for covers, paint, finish, etc.

Thus:

$$S = S_1 \cup S_2 \cup S_3 \cup S_4 \cup S_5 \cup S_6 \cup S_7 \cup S_8 \cup S_9 \cup S_{10} \quad (7)$$

From (3),

$$S_e \cup S_i = S_1 \cup S_2 \cup S_3 \cup S_4 \cup S_5 \cup S_6 \cup S_7 \cup S_8 \cup S_9 \cup S_{10} \quad (8)$$

From the Principle of Contradiction;

$$S_1 \in S_e \quad \text{or} \quad S_1 \notin S_e \quad (9)$$

and $S_2 \in S_e$ or $S_2 \notin S_e$

$S_3 \in S_e$ or $S_3 \notin S_e$

..............................etc.

$S_{10} \in S_e$ or $S_{10} \notin S_e$

However, from (8) and the Principle of the Excluded Middle.

If $S_1 \notin S_e$ (10)

then $S_1 \in S_i$

and if $S_2 \notin S_e$

then $S_2 \in S_i$

..............etc.

if $S_{10} \notin S_e$

then $S_{10} \in S_i$

From the previous definition of S_1

$S_1 \in S_e$ (11)

Since S_1 conveys only 'one thing', i.e., 'what is being attempted?', S_1 is a finite set, of cardinal number one.

$|S_1| = 1$ (12)

$S_1 \in S_e$ (13)

$S_1 \notin S_i$ (14)

This is illustrated in Figure 4.

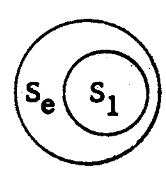

Fig. 4. The Relation of the Set S_1 to the Set S_e.

The superior may or may not, at his discretion, specify entries in the accident sets. Thus;

$$S_2 = S_{2_e} \cup S_{2_i} \tag{15}$$

and $S_3 = S_{3_e} \cup S_{3_i}$

..............etc.

$$S_{10} = S_{10_e} \cup S_{10_i}$$

From the previous definitions of S_2-S_{10}, these sets are mutually disjoint and independent;

$$S_2 \cap S_3 = \{ \} \tag{16}$$

$$S_2 \cap S_4 = \{ \}$$

$$S_2 \cap S_5 = \{ \}$$

.........etc.

$$S_3 \cap S_4 = \{ \}$$

$$S_3 \cap S_5 = \{ \}$$

.........etc.

or stated in a more concise manner:

$$S_j \Big|_2^{10} \cap S_k \Big|_2^{10} = \{ \} \tag{17}$$

where $j \neq k$

Thus all permutations are disjoint.

$$\text{e.g. } S_2 \cap (S_3 \cup S_4 \cup S_5) = \{ \} \tag{18}$$

Now from (7)

$$S_1 \subset S \tag{19}$$

$$S_2 \subset S$$

.......etc.

$$S_{10} \subset S$$

or $S_j \Big|_1^{10} \subset S$

From the definition of 'implicit', the set S_i is an infinite set.

$$|S_i| = \infty \qquad (20)$$

Since $S_e \prec S_i$ (6)

and $S_1 \in S_e$ (11)

$S_1 \notin S_i$ (14)

and $S_j \Big|_2^{10} \in S_e \cup S_i$ (21)

$S_1 \prec S_j \Big|_2^{10}$ (22)

Now it follows from (3) and (20) that;

$$|S| = \infty$$

However, no superior would expect the design to conform to an infinite set of specifications. The answer to the seeming paradox can be found by examining the accident sets S_2-S_{10}.

From (12) $|S_1| = 1$

From (20) $|S_i| = \infty$

$\therefore \quad |S_2 \cup S_3 \cup S_4 \cup S_5 \cup S_6 \cup S_7 \cup S_8 \cup S_9 \cup S_{10}| = \infty$ (23)

Now (23) is valid if any one or more of the accident sets are infinite, but at least one must be infinite. From the definitions of the accident sets and from (17), the infinite set or sets must be 'bounded'.

Therefore the infinite set or sets are non denumerable and have the cardinal number of the continuum as evidenced by Breuer.[4]

Since the delegating authority need only make S_1 explicit, it is the

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[4]Joseph Breuer, Introduction To The Theory Of Sets (Englewood Cliffs, N.J., 1958), p. 28.

nature of each accident set to be infinite, non denumberable and bounded. A pictorial representation of the sets S_1-S_{10} is shown in Figure 5.

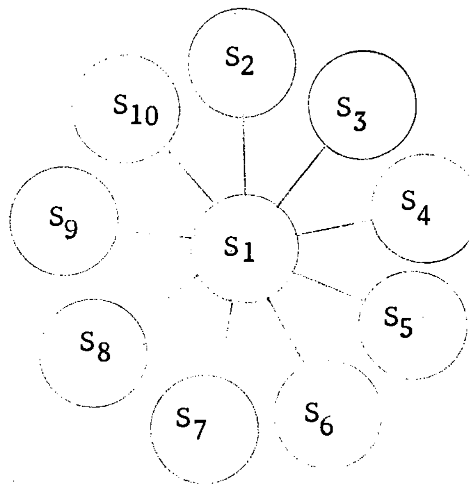

Fig. 5 The Relation of the Set S_1 with the Accident Sets

The accident sets are bounded individually and since they must be joined to the finite set S_1, they are bounded collectively.

Thus, S = c (cardinal number of continuum)

The above development demonstrates that the set S is bounded in an interval. This is the property that answers the previous seeming paradox, for although the specifications may be 'endless', they are bounded and it is within these bounds that the designer must stay.

The bounds of the sets may be difficult to determine. These bounds are related to TOLERANCE. Tolerance enters into most design problems and is difficult to determine. See Figure 6.

Fig. 6 Topological Illustration of Tolerance

Requirements may be given in which the accident sets are functions of real time,

$$S_j \Big|_2^{10} = f(t) \qquad (24)$$

For example, the initial orders may be to finish the device in a certain color. Subsequently it may be ordered to finish the device in another color.

$$\text{Thus:} \quad S_j \Big|_2^{10} \Big|_{t_1} = S_j \Big|_2^{10} \Big|_{t_2} \quad t_1 \neq t_2 \qquad (25)$$

$$\text{or} \quad S_j \Big|_2^{10} \Big|_{t_1} \neq S_j \Big|_2^{10} \Big|_{t_2} \quad t_1 \neq t_2 \qquad (26)$$

if (25), then

$$S_j \Big|_2^{10} \Big|_{t_1} \cap S_j \Big|_2^{10} \Big|_{t_2} = \left\{ a \right\} \quad t_1 \neq t_2 \qquad (27)$$

where $a < \left| S_j \Big|_2^{10} \right|_{t_1, t_2}$

assuming $\left| S_j \Big|_2^{10} \right|_{t_1} = \left| S_j \Big|_2^{10} \right|_{t_2} \quad t_1 \neq t_2$

$$\therefore \quad S_j\Big|_2^{10}\Big|_{t_1} \cap S_j\Big|_2^{10}\Big|_{t_2} = \{\ \} \text{ is possible} \tag{28}$$

Figure 7 demonstrates that the content of sets may vary in different cases. The relative sizes of the circles indicate relative amounts of information.

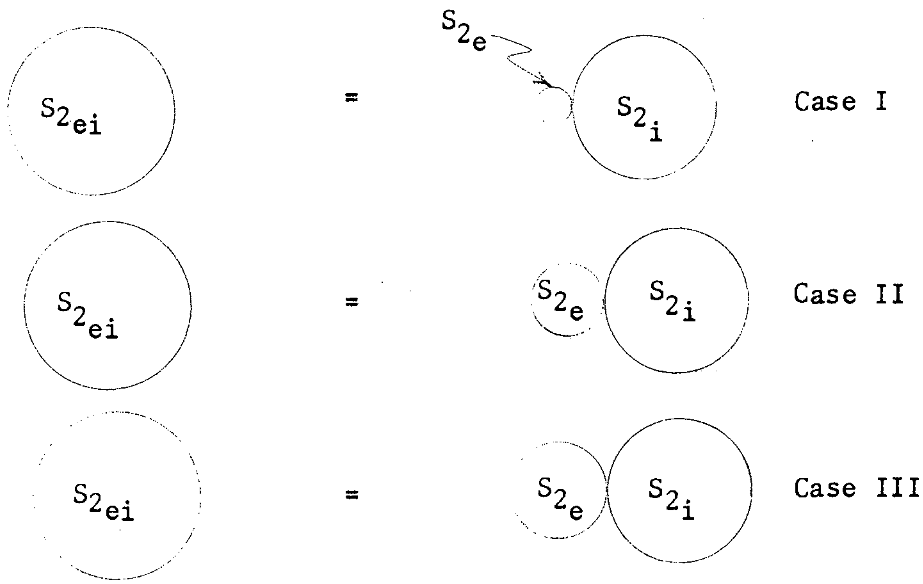

Fig. 7 A Topological Analysis of an Accident Set (Typical)

The explicit subset of an accident set can contain contradictions in fact. For example, the superior may state that the device is to be riveted in one paragraph and state that it is to be bolted in another paragraph. This is due to shortcomings on the part of the superior. As shown before, the accident sets are disjoint, therefore there can be no contradiction between accident sets in the ultimate sense. However there may be areas that create problems from a practical matter, due to shortcomings of present technology; e.g., "...the device shall have a paper cover and shall not deteriorate when subjected to being exposed to rainfall for a period not to exceed six hours..." 'paper cover' lies within the Set S_{10e} whereas 'shall not deteriorate when subjected to being exposed to rainfall...' lies within the Set S_{4e}. These are not conflicting specifications, although there may not be a paper that can withstand the effects of rainfall for the specified time interval.

Now the Set S_i comprises part of the main Set (S). The Set S_i must be specified by sources other than the problem delegating authority or the Set would not be distinguishable from the Set S_e. In the present order of design practices, the designer is expected to "...exercise good judgment..." The exercising of 'good judgment' lies within another Set which is discussed in Chapter 3. It is mentioned here because the Set S_i is the Set that has common areas with the Set (R) and makes possible the feedback loop that is present in the design process.

An outline for a program of the sequence to follow in a particular design problem is presented:

1. Obtain instructions from the delegating authority. These instructions may be either written or verbal, but all verbal instructions should be recorded in order to be transcribed on paper for analysis at the discretion of the designer, whether human or machine.
2. Record all instructions under the heading of Set S, Subheading S_e.
3. Analyze the instructions word by word and sentence by sentence. The purpose of this analysis is to categorize all the explicit

instructions into further divisions of the Sets S_1, S_2,....S_{10}. This process is accomplished by breaking the sentences into the parts of speech and then comparing with stored information as to whether the word will fall within the Set S_1 or S_2 etc. All words must be put into a Set although very often the articles such as a, an, and the contribute nothing to the Set insofar as the essence of the problem is concerned.

4. Taking each Set in turn, and starting with Set S_2, examine the Set within itself for contradictions. As previously pointed out, these contradictions do not detract from the essence (Set S_1) of the problem, but they must be resolved before a finished device can be realized.

5. Resolve contradictions by first examining the Set in question for an order of priority. If an order of priority is available, resolve the contradiction in favor of the higher priority. In the event that an order of priority is not available, then return to the delegating authority for clarification. In some circumstances the delegating authority can or will not resolve the contradiction. If such is the case, request the delegating authority for permission to continue on the problem. In cases that fall within this latter category, remove the portion of the Set in question that is included in the contradiction, from under the Subheading S_e and place it under the Subheading S_i. Put a flag on the contradiction in order to resolve it at a later process.

6. Check the Sets S_1 through S_{10} to verify an entry in each Set.

In event of no entry in a Set from S_2 to S_{10}, put a flag on the heading for that Set in order to insure entries at a later time. These later entries will appear in the Set but under the Set S_i. In the event there is no entry in the Set S_1, return to the problem delegating authority for a clarification on the essence of the device. In the event of no assistance from the delegating authority, then HALT.

7. After performing steps 1 through 6, if there has been no HALT instruction, proceed to Phase 2. (Gathering Data)

CHAPTER III

GATHERING DATA

It has been said that there is nothing new under the sun. However it can not be argued that new applications of old laws are being utilized every day. The process of gathering data, although tiresome, can save the designer some embarrassing moments. The basic objective is to gather information about all past approaches to the problem at hand, and to itemize all possible approaches to the problem. Many successful designs have come about because of intense application to the task of gathering sufficient data. This is a task that is particularly suited to machine operation. The main difficulties in gathering information by machine are twofold. They are: (1) The machine must have sufficient storage capacity; and, (2) the information must be stored in the machine in a readily available form. The answer to the first difficulty is to construct the machine with sufficient storage capacity. It is interesting to note that a proper approach to the second difficulty can give the machine more usable storage by avoiding duplication. The objective in storing information in a more available form could be stated better by saying that the information is in a usable form; e.g., many persons have used a screwdriver for a lever to pry things apart, but who would state that it is the purpose for having a screwdriver. If a computer were to list all the applications of a screwdriver, there would be no end to the storage requirements in a computer for just a screwdriver. However, it can be stated that in all cases a screwdriver is a tool, simple, and is used for assembling or disassembling. It would seem that of the 600,000 words in the English language, the ones that might find use in the problems of the engineers, could be cataloged in certain categories and be given a rating in these categories. When the computer was gathering data from its memory, all words that have a rating on the applicable subject could be withdrawn and examined. The computer would also have to store sources of information on man's accomplishment in the subject field at hand. This is the old familiar bibliography. It would be a fairly easy job of cataloging for the computer but would take tremendous storage facilities. There are some time tested techniques in information gathering as far as new approaches to the solution of a problem. These include the Gordon technique which, (1) attacks the underlying concept of the problem rather than the problem itself; and, (2) subjects are examined from many angles, social and economic as well as mechanical.[1] For example, if a new lawnmower design is desired, the general subject of severing is discussed as well as any possibility of lawn-cutters refusing to use a radically new type of lawnmower. Another technique for developing a new approach to a problem is the "brainstorm" technique as used at General Electric.[2] In this technique the method is to conduct a "brainstorming" session in which the participants, one or many, are not to feel restrained by logical methods and do not have

[1]Von Fange, p. 45.

[2]Ibid., p. 46.

to see the complete solution in one glance. For an example, if new ways are being sought to cross streams, the leader mentions the problem and the participants give any methods of solution, preferably in one phrase. Thus, "Shoot-Parachute" could be a response. The session is devoted entirely to arriving at all possible ideas with as little restriction on the imagination as possible. These responses are examined at a subsequent session to decide which ones should be pursued. Other techniques include "Use the ridiculous", "Experience Lists", and "Check Lists".[3] The Gordon technique could be adapted to machine operation and would seem preferable because of the ease in cataloging information in general categories, thus making it easier for the machine to locate information when it was making a search of its memory. There would be little likelihood of a possible solution being overlooked.

It has been shown that the gathering of data plays a very important role in the design of a successful machine. Many times, proper data gathering will reveal that many of the problems that are encountered in the design of the particular device in question have arisen in other design problems.

Gathering data may be expressed as follows:

Given: Set of Data (R) called resources

The Set (R) is composed of two Subsets R_s and R_o.

Thus, $R = R_s \cup R_o$

Figure 8 shows that the Set (R) is composed of the two Subsets R_s and R_o. The Subset R_o is shown larger than the Set R_s to indicate that

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[3]Von Fange, p. 57.

the area that this Set covers is larger. All the recorded facts of history belong to this Set.

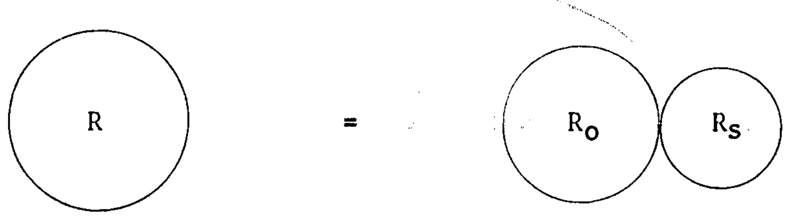

Fig. 8 A Topological Analysis of the Resources Set (R)

The Subset R_o is all the resources from sources other than himself that is available to the designer if he had the power to call upon them.

The Subset R_s is all the resources that the designer possesses himself, needing not to call upon others. Now the Subset R_s is composed of two parts. These parts are experience and creativity. Past events or history give all designers experience, even though the experience may not be in the design field. All men learn through their senses.

If a machine is to relieve the human of any design burden, then the machine must have access to the Set R_s. This part of the Set R_s shall be called R_{sh}. A machine must possess a 'memory' and this memory must have the facility of recording past decisions in order to more properly judge in the future. This will be more fully explored in Chapter IV. Thus a part of R_s is:

R_{sh} which is the resource of self experience. Learning that comes into the brain by way of the senses and is recorded will fall within this Set.

R_{sc} which is the resource of creativity within the designer himself. The term creativity here is defined as 'the bringing forth from nothing'. By this is meant, when a new essence is brought forth, then creation has been accomplished. This is the strict definition that will be used hereinafter. The term 'creativity' has a connotation that permits almost any action to be classified as creative. The definition used hereinafter, however, is very restrictive, so much so in fact, that the designer does not need to have any creative resources in order to bring forth a successful design. It is the delegating authority that conveys the essence of the problem to the designer. This has been shown in the previous chapter. In this strict sense of creativity, a machine cannot have access to the Set R_{sc}. The fundamental difficulty in the machine having access to the set R_{sc} is that the machine does not have 'will' and will never have it. However, this is not an impediment in the design process as heretofore stated. Access to this Subset is not a prime requisite for the design process.

R_{oh} which is the resource of the experience of others. Within this Set are the familiar..."Library research"..., ..."ask John, he has experience in that area".... This is a very important Set. Many good designs have been lost because the counsel of others was not sought or heeded. A machine can have access to this Set as can a human being. The requirement for having access to the Set is not mandatory; however, the wisdom of excluding it is questioned.

R_{oc} which is the resource of the creativity of others. This will bring in the previous efforts (or the concurrent ones) of others. Many times, a new essence in one of the accidents will mean the difference between a successful design and a mediocre one. It might be debated that R_{oc} is not a separate Subset from R_{oh}. This is a moot point insofar as the question is concerned. It is presented as a separate Subset here because all resources are not the product of the creativity of man.

Figure 9 shows that the Set R_s is composed of R_{sh} and R_{sc} and that these two Subsets can vary in relative magnitude depending upon the individual. It has been shown that the Set R_{sc} can enclose no area and the designer still be successful in the design of a piece of equipment.

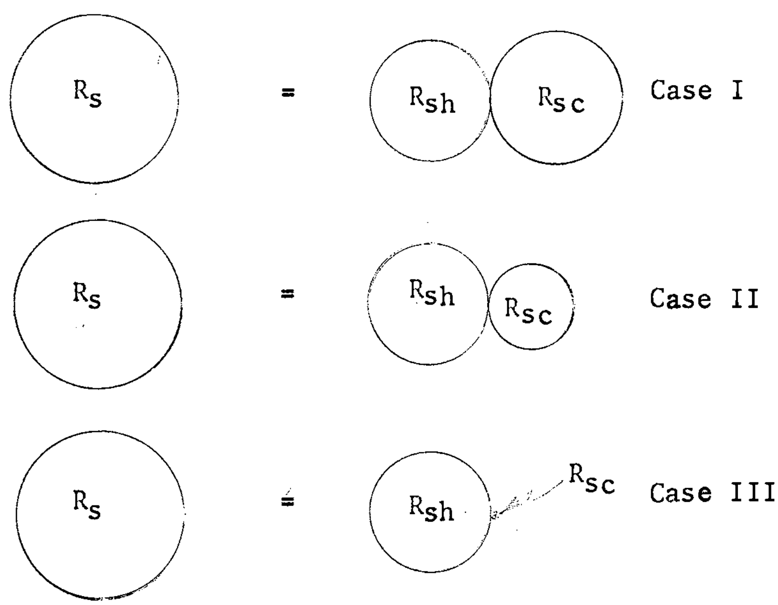

Fig. 9 An Analysis of the Set R_s

Figure 10 shows that the Set R_o is dependent upon the time variable and that it is a Set that is ever increasing in area. This assumes that man does not go through another period of loss of learning. There is no relation between the rate of growth of the Subset R_{oh} and the rate of growth of Subset R_{oc}.

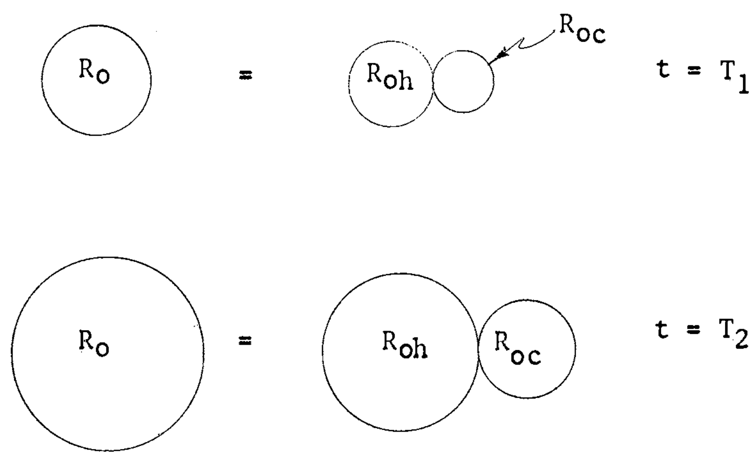

Fig. 10 The Set R_o as a Function of Time

The Figures 11 and 12 are meant to show the interconnections between the Subsets. The experience of others can affect the individual and inspire him to create and if it is within his capacity, he can do so. The creation of others will be recorded or not be recorded. If it is recorded, then this information is theoretically available to the designer in his particular application. Many times, this knowledge of others, from a practical standpoint, is not available to the designer. As a result, his design may be handicapped or may not be novel. The conclusion that can be drawn is that the designer must endeavor to have as complete a knowledge as possible of the Subset R_o and must diligently attempt to keep 'up to date' as this Set is forever increasing in size.

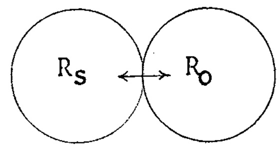

Fig. 11 The Flow of Data Between the Subsets R_o and R_s

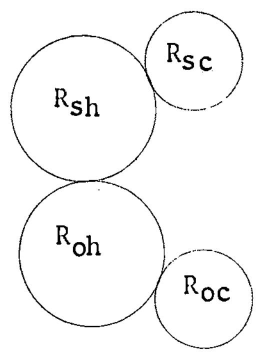

Fig. 12 The Relationship of the R Subsets

The present knowledge of man has been conveniently placed in a Set R_o. It has been said that some of this Set is available to the designer and some of it is not. No mention has been made of the various means that the designer employs in attempting to obtain access to this Set except a brief mention of the bibliography. In practice, the designer will use whatever means he can to obtain this information. In fact, he may stoop to means that are immoral or illegal. He is forever seeking the present state of the art in order to insure a successful design. The designer has one goal, and that is to bring forth a successful design. A machine will have many limitations in the access of the Set R_o for the machine must rely upon others TO INITIATE the accessibility. Thus the accomplishments of others can be fed to the machine and the machine can store this information, but the machine WILL NOT keep current with the expanding Set R_o unless others give the information to the machine. The result of this is likely to slow the use of a machine for solving design problems. This will come about because of deficiencies in the programming authority. This is not a shortcoming of the machine if it is realized from the beginning and the nature of data gathering is understood by the programmer.

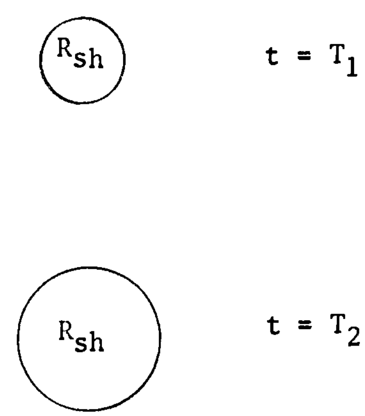

Fig. 13 The Set R_{sh} as a Function of Time

Figure 13 shows that it is normal for the Set R_{sh} to grow with the time variable also. It can be debated that this Set will approach a limit. That is to say, that only so much information can be stored by the designer in his memory. After he has reached this point, he will forget as much information as the new information that he retains. The designer that is successful will endeavor to view all experiences from the standpoint of his vocation. Thus, with time, his resources Set R_s will become purer in regards to his specialty. This explains why experience figures so prominently in the makeup of a successful designer and why it is difficult for 'old dogs to learn new tricks'. This is to say that the Set R_{sh} is composed of two Subsets also. There is the Set of information that is applicable to the problems at hand and there is the Set of information that has no bearing on design problems. For example, a designer of electronic components will gradually build up a vast amount of knowledge about electronic components and allied information. This man still lives a social life, however, and there will be information making impressions on his memory that have nothing to do with electronic components. The Set that has a connection with the main avocation of the designer is called the Subset R_{sha} and the Set that has no connection is called the Subset R_{shn}. There are instances when information in the Subset R_{shn} plays a helpful role in the design of equipment. A man's experiences at a football game may give him an idea for solving a particularly vexing problem. Situations such as this do not nullify the existence of this Subset, rather they only serve to prove the existence of the Subset R_{sc}. When the likeness of a problem in one field of study with a seemingly unrelated experience in another field results in a solution to a problem, then it can be stated that creativity has been accomplished and that the element of the art has been demonstrated.

The foregoing has been an investigation into the elements of the process of gathering data. If this is to be of any use to man, then it must be shown that it is usable and the utilization of a machine for the design process would demonstrate the fact.

There is an old saying "the child must crawl before he can walk." This saying has meaning in the problem at hand. If machines are to accomplish much in the design field, then they must start in a small way. The first design problems of machines must be of a highly specialized nature and as the science is developed, so can the scope of the design problems that a machine will handle.

The following steps are preliminary operations that must be performed before a computer could be utilized in the design process.

1. The programming authority must store in the machine available knowledge of the present state of the art. Since this would burden the storage capacity of the machine, experts must be consulted to reduce knowledge to a size compatible with available storage. This must be done on a priority basis. The stored knowledge must be stored under the heading of R_o. Each piece of information shall be further categorized under a subheading. These subheadings shall be labeled R_{o2}, R_{o3}, R_{o4}, R_{o5}, R_{o6}, R_{o7}, R_{o8}, R_{o9}, R_{o10}. Each one of these subheadings corresponds to one of the accidents of Aristotle. It is important to note here that the programming authority must be

certain that there are entries under each subheading or the machine would encounter a HALT command at some stage of the design process. The entries shall be cataloged under headings by a priority system.

2. The programming authority must reserve storage for the Set headed R_s, and further subdivide this into R_{s2}, R_{s3}, R_{s4}, R_{s5}, R_{s6}, R_{s7}, R_{s8}, R_{s9}, R_{s10}. These areas are reserved so that as the machine gains experience in the design field, it can consult this Set for performing judgments.

The above two steps are not to be included in the program for a particular design problem, but must be performed before the machine attempts any problem solution and access must be maintained for including new data as it becomes available.

Phase 2 in the design program shall include:

1. Check all Subsets of R_o to verify an entry. If there are voids, return to the programming authority with information on the location of these voids and await instructions; if no voids exist, proceed to Phase 3.

CHAPTER IV

MAKING DECISIONS

The final responsibility for making decisions on any engineering problem must of necessity always remain with the engineer in charge of the project. However, it is possible, feasible and in the future will be mandatory, from an economic standpoint, for a machine to carry the burden of making most of the decisions in equipment design. It has been stressed that all equipment design problems, even the simplest, present the designer with a seemingly endless array of questions that must be answered. Everytime a question is answered, a decision has been made. Most decisions are made on the basis of reasoning. Reasoning denotes examining a question from the viewpoint of logic. This viewing usually involves weighing the possible results that would be obtained by making the alternative solutions, weighing their probability, and making the decisions on the basis of mathematical probability. The decisions that can be reached from the standpoint of mathematical probability are ideally suited for machine decision making, for a machine will not be affected by emotions or outside factors. Only the decisions that are reached by intuition are out of the scope of machine possibility.

Machines can make decisions when the decision is the result of calculating mathematical odds and making a decision based on the outcome of these calculations; e.g., if a survey of people's inherent tastes in colors is such that they prefer pastels, then when the question of the color of paint that is to be used on a device arises, the computer has no problem at all in choosing pastels. It could first check the specifications to determine if there is any contradictory statements about the color of the device being a pastel paint. Decision making is an 'Either this...or that...' proposition and this is basic to machine operation, for a machine can determine odds from this and compare them with the odds from that. This is logical addition and is easy to perform.

The problem of making decisions is aggravated in the individual because it is the decision making that plays the prominent role in whether the solution to a particular problem is a success or not. If the burden of making decisions could be shifted to a machine that will make no logical errors, assuming that it has a built in correct logic, then the problem of decision making would be relegated to a minor role and the true problems of creativity could be solved by the engineer.

A machine can also be programmed in such a way that it will make decisions with an order of preference. That is, it can make a decision and state the mathematical reasons for giving the decision; then it can make a secondary decision, show the probability of the secondary decision succeeding and give probable results.

It has been pointed out that the main problem that confronts designers is the problem of deciding what decisions are necessary, and the mechanism of making these decisions so that the odds of designing a successful mechanism are the highest possible. There are many intangibles in design and the first effort at a design cannot be assured of success even if the mathematical odds are utilized.

The easiest step in the judging process is to remove the accidents from the problem first. This is done in the following manner.

Phase 3.

1. Check the Subset S_e from S_{2e} to S_{10e} in sequential order. It is the purpose of this examination to begin the design process. When the Subset is examined in each category, there will either be a flag on the particular category, or there will not be a flag. If there is a flag on the category proceed to Step 2 of this Phase. If there is not a flag on the category, proceed to Step 3 of this Phase.
2. This step is utilized when a flag has been found on a category in an accident Subset S_e. It may be recalled from Chapter II that a flag indicated either that a contradiction existed that the delegating authority could or would not resolve or that there was no entry in the accident Subset. This question must now be resolved. Examine the corresponding accident Set in the Subset S_i. If there is an entry in this Subset, it indicates a contradiction. This contradiction can be resolved by comparing the contradictory terms with the Set R. Proceed to the Subset R_s with the same subscript. Compare the first contradictory term with a similar entry in this Subset and obtain the priority rating of this term. Compare the second contradictory term with a similar entry in the Subset R_s. Repeat this process until all the contradictory terms have been assigned a priority rating. In the event that a similar term cannot be found in the R_s Set for one of the contradictory terms, proceed to the R_o Set and

look for a comparable term. If one is located, transfer this term to the R_s Set. (Do not destroy the term in the R_o Set). When this term is transferred to the R_s Set, it should be given the lowest priority rating. This is done so that as experience is gained by the designer, data can be re-examined and priority ratings re-evaluated. After all contradictory terms have been given a priority rating, they should be arranged in numerical order of priority with the term having the highest priority rating at the top of the list. These terms should then be copied in order of priority in a new Set to be designated Set C (for conclusion). At the end of the design cycle it is the Set C that will be conveyed to the delegating authority as the finished design. The transfer should be accomplished in such a way that the information is in an appropriate Subset C that corresponds to the accidents; e.g., $C_2, C_3, \ldots. C_{10}$.

When the transfer is made from the Set S_i to the Set C, put an identifying symbol with the entry in the Set C to show that this was a conclusion reached from analysis of a contradictory statement.

In the event that there was no entry in the Subset S_i corresponding to the accident in question, there must not have been an entry from the delegating authority on the accident; therefore, the designer must substitute an entry in the implied specifications based upon his experience. This is accomplished by referring to the Subset R_s and transferring this information to the Subset S_i and also to the Set C. If there are no entries in the R_s Subset, then the Subset R_o should be consulted. When the transfer is made to the Set C, a flag identifying the information as having been arrived at by self-experience or the experience of others should be included. After the accomplishment of Step 2, the index on the accident should be advanced by one unit and then checked to see if the index is greater than ten. If the index is less than or equal to ten, then Step 1 of this phase should be returned to for further processing on the accidents remaining. If the index is greater than ten, then advance to Phase 4.

3. This step is utilized when there are no contradictory statements in the specifications and when the delegating authority has specified the essential requirements for defining the accident in question. In this situation a check should be made comparing the Set S_e in question with the Subsets R_s and R_o to verify that there are entries in these Subsets that correspond to the specified term. If there are no entries, then an entry should be made in the Subset R_s. A priority rating shall be assigned to the new term so that experience checks on other problems can utilize the information. Once this comparison has been made, then the information in the Subset S_e in question should be transferred to the Set C. An identifying flag should accompany the information to show that this conclusion was reached by being contained in the original explicit specifications. After the information has been transferred, the index on the accident should be

advanced by one unit and then checked to see if the index is greater than ten. If the index is less than, or equal to, ten, then return to Step 1 of this Phase for processing of the remaining accidents. If the index is greater than ten, then proceed to Phase 4.

Phase 3 of the design process is the first step in making decisions. However, the decision making of this Phase has been reserved to rectifying the specifications by resolving all contradictions, verifying entries in the accident Sets, assigning priority ratings to possible solutions of the accidents, and itemizing the implicit specifications. These processes are all necessary, but there is still a great deal lacking before a finished design of a mechanism can be realized. It has been shown that the essence of the problem must be conveyed from the delegating authority to the designer. This dictates that there must be an essence to the solution to the design problem and it is the designer's responsibility to convey this essence to the delegating authority when the designer has found a solution to the problem. An essence is simple and indivisible, yet it is necessarily the collection of other essences in its accidents and properties.

The majority of design problems involve essences of economics, rather than an essence of a device that is radical in design. It is these majority of problems that lend themselves to solution without involving the Subset R_{SC} which has been shown to be unavailable to machines for design purposes. It has been stated that there is no element of creativity in the majority of design problems but rather an old principle has been extended to a new application. This would indicate that there is an invariant that has been given a different set of accidents. It is the study of this invariant that the science of topology concerns itself. An example of geometric topology is illustrated in Figure 14.

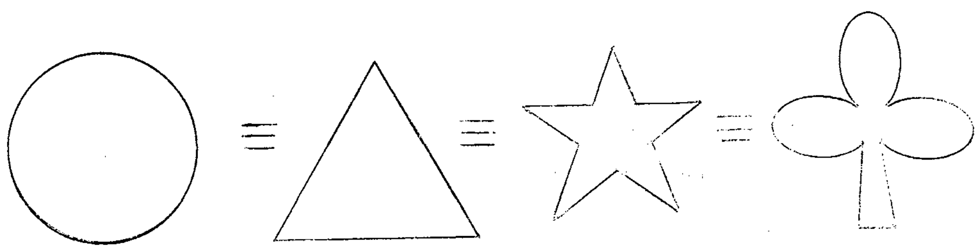

Fig. 14 Topological Equivalents

It is important to note that these figures are not similar or analogous, but are topologically identical. There also is an algebraic topology that deals with the invariants in algebraic equations.

For many years, the analogies of one field of science with another field of science have been recognized and utilized. These are identities in the topological sense. This statement can be proved by the following syllogism,

(1) A = B

(2) C = B

therefore (3) A = C

In the above syllogism, A represents a problem in the physical sciences that can be solved by utilizing mathematical method B.

C represents a problem in another physical science that can be solved by utilizing mathematical method B. Therefore, A and C have a common essence. The study of these common essences in different physical sciences shall be called the science of Essence Topology. It is very important to note the distinction between an analogy and a common essence. In an analogy, the investigator has to reserve many judgments, on the condition that the analogy is valid in all areas of the investigation. If the investigator has itemized the common essences, then he does not have to have this mental reservation, because of the identity. This science of topology can also be utilized in the design field from another approach. It may be recalled from the introductory remarks of Chapter III that one of the difficulties of utilizing a machine for the design process was the problem of having sufficient storage facilities within the machine to store all of the Set R. Since in reality there are common essences between the various physical sciences, all that it is necessary to store are these invariants. This will prevent the duplication of storing the same information in many different forms. However, this will result in a problem of communication, because names will have to be assigned to these common essences and these names will be unfamiliar to the average designer. For an example of a common essence, consider an electrical transformer and a mechanical lever. Both of these devices have a common essence that fulfils the same task, but in the respective fields of electricity and mechanics. In both there is a single power input and a single power output. An electrical transformer has a transformation ratio and a lever has a mechanical advantage. A designer could not normally utilize a transformer in place of a lever; however, the problem that is being overcome in the utilization of either is the problem of transforming a form of energy from one level to another. The choice of whether to utilize a transformer or a lever is resolved by recognizing the form of energy that one is concerned with. Figure 15 shows the identity of the electrical transformer and the mechanical lever.

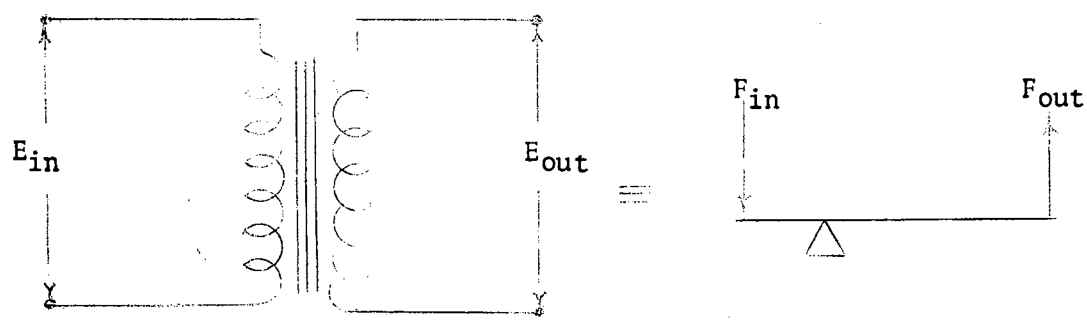

Fig. 15 An Example of Essence Topology

The fact of an essence topology will relieve the machine of many storage problems, but it will, as shown, necessitate much work in the cataloging of these essences. These essences, after cataloging, will be stored in the memory within the Subset R_{1o} and will make possible the use of the machine in the design field to convey the essence of an answer to the delegating authority. An aid to the cataloging of these common essences will be found in reviewing the work that has been accomplished in two fields. These fields are the study of analogies and the study of dimensional formulas as discussed by Nodelman and Smith.

Phase 4 of the design process is the portion of the design that is concerned with the development of an essence of a solution to the design problem. This is both the most important and the most difficult of the design phases. It is accomplished by seeking the answers to a definite list of questions. The answers to these questions must be found within the Set S_{1e}. It is this Subset that must have been explicitly stated by the delegating authority in order to convey the essence of the design problem to the designer. The designer, whether human or machine, then must seek essences in the Subset R_1 that are common to the problem essence. It has been pointed out that this is not true creativity; never-the less, it would appear as creativity to the untutored. However, the solution to obtaining an essence to a solution to a design problem is more complicated than the mere comparison of an entry in the Set S_{1e} to entries within the Set R_{1o}. The essence for the solution may contain many separate essences; i.e., the mechanism that is desired may not be a simple mechanism. This is where the definite list of questions come in to determine some basic conclusions about the essence of the solution. Stated in another way, the essence of a solution may necessitate the operation of synthesis or the putting together of universal parts to form a particular whole. It has been shown in Chapter I that synthesis is an inversion of analysis and can be quite difficult to the uninitiated. The experienced designer uses many tools in order to synthesize and some of these are adaptable to use by machine.

The following is the next Phase in a program for a particular design problem.

Phase 4

1. Ask the question, "Is the device active or passive?" The mechanics of asking the question is accomplished by investigating the verbs in the Subset S_{1e}, and comparing them to verbs in the Subset R_{1o}. The verb used in describing the essence of the problem, the form of the verb used, and the sentence construction will determine if the device is active or passive, or a combination. If the required device is active in essence, then proceed to Step 1-1. If the device is passive in essence, then proceed to Step 1-2.

   1-1. List the parts of the device which form a required part of its essence; e.g., an automobile is a form of transportation and requires a form of locomotion and a container for the passengers. Determine the type of energy that is to be employed in the device. After the list is complete, compare the items with the stored essences in Set R_{1o}. Proceed to Step 2.

   1-2. Determine if the device is electrical, mechanical, chemical or a combination of these. Determine the properties of the device. Compare these findings with the Set R_{1o} and match up the properties and the form of energy. Proceed to Step 3.

2. This step is concerned with the putting together of basic parts to form a complex whole. Take the list that was obtained from Set R_{1o} and determine the signal flow path that is required to make the complex whole. Take each part as it occurs in the

signal flow path and determine the signal characteristics of the input. Compare with Set R_{1o} to determine and calculate a typical signal output. Record the information and move to the second part. Use the calculated output from the first part as the signal input characteristics to the second part. Continue until the required desired output is obtained. Check for parallel inputs and outputs in each part as progressing. In the event of parallel input, use all input information when calculating. In the event of parallel outputs, determine and record the termination of these outputs. Prepare several alternative solutions from the data in Set R_{1o}.

Proceed to Step 3.

3. Transfer the information obtained in the preceding Steps to the Subset C_1. Write out the contents of the Set C, and deliver to the delegating authority. Wait for comments and instructions. In the event that instructions are forthcoming that indicate a different order of choice of solutions than has been recommended, take the preferred order and revise the priority ratings of the information in the Set R. Wait for further instructions.

CHAPTER V

CONCLUSION

The preceding has attempted to prove that machine design of equipment is mathematically possible and will probably be used to a great extent in the years to come. Programming will be an important factor in the success of any such project, but the designing capabilities of the machine will not necessarily be limited to the creativity of the programmer. It should be realized that creativity is a word that has many different meanings to different persons. It is not the opinion of the author that a machine can evolve or develop an entirely different concept of a problem or that it could design an equipment to satisfy a completely foreign set of specifications.

The problem of sufficient storage capacity on any computer is one of prime concern. It has been shown that the amount of storage necessary can be very materially reduced by the development of the science of Essence Topology. This development will require considerable study and cataloging, but the results will make the effort worth while. The human designer will also benefit in that if the designer has a working knowledge of the science, he will be more versatile and will be able to adapt readily to design in a new field.

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