CONFERENCE ON NEW METHODS OF THINKING

NOTES FOR
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INTOBOOR

MORPHOLOGY AND MODULARITY

Will James described three stages in the process of innovation: in stage one, he said, a new idea is rejected outright as being absurd or unnecessary. In stage two, the idea is begrudgingly admitted but held to be trivial or tautological. In stage three, the idea is held to be an innovation of paramount significance and everyone claims to have thought of it first himself.

Many of us have seen Zwicky's morphological approach to thinking and problem solving pass through these three stages and now into a fourth stage in which the idea having become germinal to new fields of thought has lost its original identity. In other words, if I may use a local cliché, "Many of the methodological concepts which have been described in this conference Zwicky had already published 30 years ago."

Just what the details of the morphological approach are, I shall leave to Zwicky. I can say one thing however, that the morphological approach is: It is something which cannot possibly be defined by saying what it is not.

However, for the purpose of my own remarks, morphology is not so much a methodology for solving a problem as it is an attitude toward the problem. It is an attitude that would try to take off our customary blinders before looking at the problem. It tries to obtain an unfiltered view by comparing views through as many different filters as possible. It looks for all possible solutions by also looking at many of the impossible ones. It refuses to look at a problem in isolation, but attempts to see the relevance of the problem to its immediate and broader context. It attempts fresh views of the problem by looking at similar problems.

In short, the morphological approach uses whatever methodologies are available to arrive at the most complete and unbiased representation of the structure of the problem and its solutions as is possible. Though often failing to realize this ambitious objective, it still is useful.

MORPHOLOGY AND MODULARITY

A. G. Wilson

INTRODUCTION

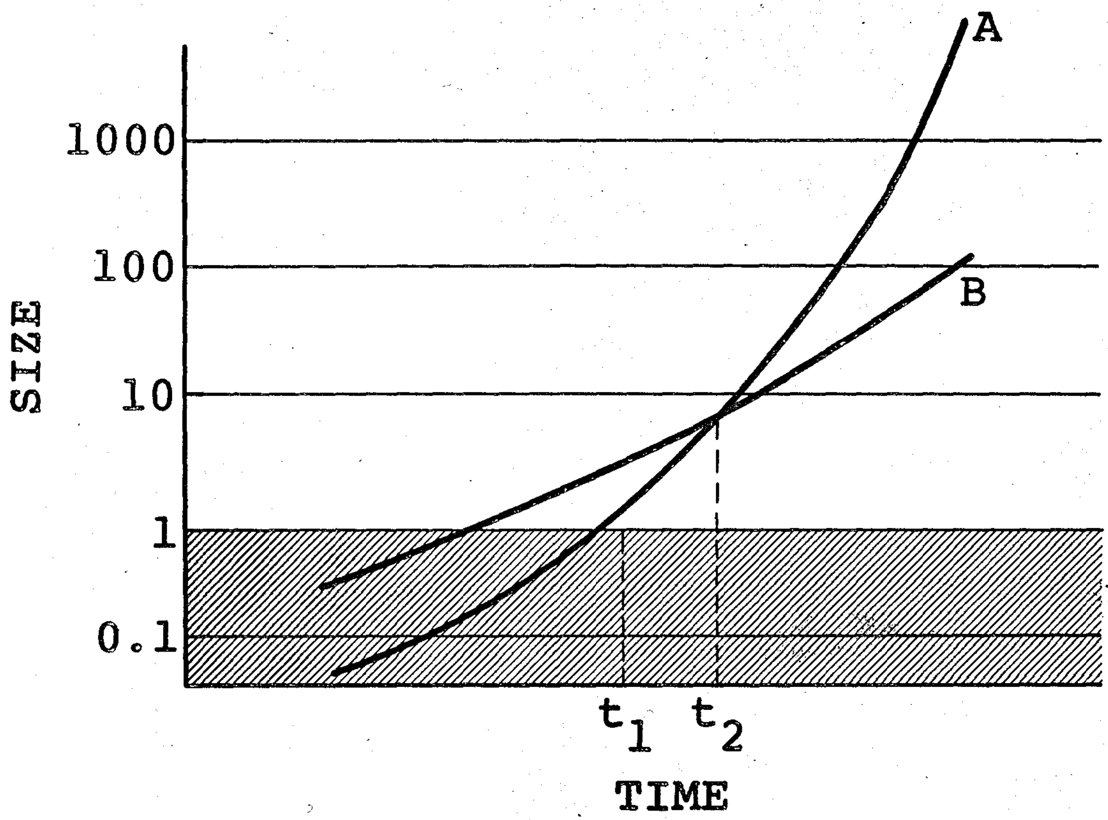
A few weeks ago the world's largest oil tanker of 120,000 tons was wrecked off the East coast of England releasing thousands of tons of crude oil which floated ashore and polluted hundreds of miles of shoreline. This tragedy assumed national proportions affecting the means of livelihood of thousands, and even more seriously destroyed extensive portions of beach for decades, perhaps permanently. Major environmental alterations of this sort sometimes are followed by delayed feedback affects on the ecology, so the extent of the damage created by this more or less permanent pollution cannot be fully estimated.

There was widespread comment on this disaster,focusing not on the navigational mishap which was the immediate cause of the wreck, nor on the feasibility of constructing large tankers - they are quite feasible. There is a tanker of 300,000 tons currently under construction and one of 500,000 tons on the drawing boards. Rather,comment focused on the element of unbalance in a technology that could blindly and blandly set up this sort of disaster.

This ineradicable pollution of the shoreline of England prompted our Secretary of the Interior to comment: "The environmental backlash we confront today cannot be eliminated just by applying more of the same science and technology that put us in our present predicament."

Mr. Udall is right. We are not discussing another Tacoma Narrows Bridge. You recall, the suspension bridge constructed in 194 across the Tacoma Narrows in Washington according to then sound engineering practice turned out to be unstable under the aerodynamic load to which it was subjected. The collapse of the bridge led to a revision in bridge design practice through the introduction of aerodynamic stress factors. There may be some design parameter not properly evaluated in the construction of large tankers, but like the Tacoma Narrows bridge, those construction defects will be isolated and corrected. This is not what concerns Mr. Udall and the other commentators. Mr. Udall as spokesman for government and hence for the people is ringing the bell on an era in science - the era of random application of science and technology to isolated problems without study of the complex interrelations which arise and their emergent consequences. We have recently reached a precarious level of technological development in which we have the power significantly to alter our environment without having the power totally to control the means by which we affect the alterations. This imposes very great responsibilities on what we choose or do not choose to do with our technological capabilities.

Reaching the present technological level also brings down the curtain on the era of decisions determined solely by feasibility. One of the deficiencies in the present practice of application of science and technology is the failure to note that at some level of the state-of-the-art the answers to the two questions, how big can we build a tanker, and how big should we build a tanker, begin to diverge. For decades technology has been primarily concerned with finding ways to do things hitherto impossible. The emphasis has been on pushing back limitations in order to make more products and activities feasible. In an increasing number of technological areas we have recently moved from a regime of finding a way to a regime of choosing which way. The task is no longer to remove natural limitations but to set up our own limitations, to define the constraints and restraints which are prerequisite to sensible choice. Feasibility alone is no longer a useful guide. We can illustrate this transition in very simple terms. In Figure 1 let curve A be a capability curve showing, for example, how large a tanker may be constructed in accordance with the state-of-the-art as a function of the year. Let curve B represent some environmental tolerance factor, or a second capability which in our present illustration may be measured, say, by the number of tons of oil on beaches which we can in some way successfully neutralize. Let us assume that these curves cross in 1965. Assuming the economic incentive is always toward larger tankers, prior to 1965 the choice of what


A
B
1000
100
10
1
0.1
SIZE
t_1 t_2
TIME

size tanker to build is governed entirely by the technological limitations to tanker size; after 1965, if we allow the for possibility of disasters, we can weigh the economic gains of size against the losses in the event of a disaster, and make a choice as low as curve B and as high as curve A.

This naive two parameter formulation pretends in no way to reflect the real complexity of the problem, nor all of the interrelations which must be taken into account. It serves only to point to the fact there there exist two regimes; first, the regime of limited capability in which solution is marginally possible developing to a level where one solution is assumed; and second, the regime in which capability has reached a level commanding several solutions and consequently demanding a choice. In a regime of limited capability the choice is naturally made for the limit of existing capability. However, this habit tends to carry over into the second regime, the difficult problems of choice being ignored with option still being made for the limit of capability.

This formulation of the "how big" problem in terms of capability and environmental tolerance has also been used in an approach to nuclear strategy. In Figure 1, if the <u>level</u> of <u>destruction</u> is read for <u>size</u>, we have a representation of the current nuclear situation. Curve A represents the capability of nation one, or nation two, to impose a given level of destruction. Curve B represents the level of tolerance to destruction or the capability to offset destruction of nation one or nation two. The fact that there exist two capability curves and two tolerance curves not precisely identical is a negligible matter with respect to the level of destruction involved. In typical past wars the level of tolerance for destruction and recovery was higher than the level of the enemy's capability to destroy. However, in the past two decades, this inequality has been reversed. It is now possible to destroy beyond any nation's tolerance. We have entered a regime of choice, of limited actions, but many hold to first regime military thinking, confusing obligation to power with obligation of power.

Although this phenomena of regime change seems tautological to most of us and most business and government leaders, the oil on the beaches bears witness that one of our problems is to replace feasibility with the methodological tools now available for making complex decisions.

In the second regime it is necessary to formulate every problem not only in terms of the capability parameters, but also in terms of the contextual parameters, considering and exploring all the possible interrelationships and their synergistic developments. We had best rapidly acquire the techniques for living in a second regime culture for the new developments in biology are on the verge of increasing our capabilities to the level where we may shortly be able to create new varieties of organisms. Clearly the responsibilities and choices imposed by this development are likely to be as demanding as any ever faced by man. The temptation to be guided by feasibility in producing selective viruses could put an end to us.

METHODOLOGICAL REQUIREMENTS OF SCIENCE

In speaking of the inadequacy for the future of "the same science and technology that put us in our present predicament," Mr. Udall implies the need for a new type of science. To some of the orthodox, the call for a new type of science is not heresy, it is just plain meaningless for there is and can be only one type of science. With regard to the canons of verifiability, i.e., the tests applied to hypothesis and models in order to reject them or give them status - but not necessarily tenure - as scientific knowledge this is likely true. However, with regard to methodologies available for solving complex problems, classes of phenomena amenable to scientific investigation, methods of generating hypotheses, and elimination of hidden epistemological prejudices,a new science is needed and is possible. When one thinks of the difficulties of treating in a "scientifically satisfactory" manner isolated or simple incidence phenomena and phenomena for which only a very limited sample can ever be available, then an enlargement of the canons of scientific verification is also needed, but not necessarily possible.

It must not be lost sight of that one of the principle expectations which the public puts on science is successful prediction. Every society needs as good an estimate of the future as possible, but the need for accurate forecasts is absolutely vital in a technologically exploding world. Although oracles and court astrologers have been replaced by analysts and planners using computers and sophisticated methodologies, the state regulations governing relations between the ruler and the prophet have not changed - errors, oversights, and faulty predictions result in dismissal, or worse. Science has double responsibility and double jeopardy since it plays two roles: shaping as well as predicting the future. For the first time in history, it might really be justified to execute the prophet who brings bad news - he was responsible for it.

In a conference on methodologies for solving problems, something ought to be said concerning methods for deciding what problems should be attempted for solution. It is an old adage that the best person to decide what to research is the researcher himself. This adage goes on to say that the next best person to decide is the research director. He is right about half the time. A research committee may be right a quarter of the time. A committee of vice presidents is never right.

Certainly a large economy could be effected, doing away with several levels of bureaucrats, by letting the natural inclinations of the research community determine the national research program. It would be possible to do this by simply funding the research scientist instead of the research project. Although a larger part of our research effort might profitably be structured in this way, there are several difficulties in making this policy general. The widely adopted ground rule that no research should be undertaken unless there is good prospect in advance for obtaining results more often than not ignores doing the research required for proper evaluation of the prospects. This effort to evaluate prospects oftimes must be externally stimulated, and might be neglected by a totally autonomous self-directed group. But more serious are the synergistic effects of randomly selected research projects in a complexly interrelated technological culture. Whereas the "grammar" by which individual research problems and areas are structured is well known in most cases, the "grammar" for structuring the entire complex of the national research effort is not known. It is primarily the need for this grammar that gives rise to the call for a new science. The task ahead in selection of research problems is to steer the proper course between freedom of investigation - and the rules given by the grammar governing the structure of the interacting effects of technological development. It is here that the new methodologies of relation theory may find one of their most challenging applications.

NON-DIGITIZABLE MODULES

One of the extensions of problem solving capability needed for many important problems today is the development of methodologies for handling problems not easily digitized.

It frequently happens that many of the parameters that we know have relevance to a problem are not readily amenable to measurement or quantification. There is a tendency to concentrate on those parameters for which numerical values are obtainable and to neglect those parameters which are not measurable even though their relative weight in the problem may be high. To offset this tendency a methodology is required by which we are able to incorporate the effects of those parameters which cannot easily be quantified. Examples are esthetic and ethical psychological factors, values, and future applications.

When standard numerical and analog methodologies fail, or when non-quantifiable factors must be taken into account, a relevance type morphological procedure proposed by Alexander and Manheim may be applicable. The basic idea is the predication that any form or structure may be thought of as resulting from the interaction of a set of abstract forces or tendencies. These are general, not merely physical, forces. They may be quantifiable or unquantifiable, with no restriction on their variety. The totality of these forces will generate a solution that takes each into account. The problem is to find a representation of the forces that allows them to be combined.

In other words the problem is posed in an abstract space in which the representative elements are the generalized forces. The aggregate of such elements defines a form. If the aggregate is complete and in balance, the form becomes a stable entity or object.

The example of this approach given by Alexander and Manheim may be found in the MIT report entitled, "The Use of Diagrams in Highway Route Location." Alexander and Manheim's problem was to design a freeway route covering a 20 mile stretch in Massachusetts starting at Springfield and ending somewhere near Northhampton. They first morphologically derived all of the individual abstract forces whose interaction would determine the path which the freeway should take. Shown on Chart 1 of the freeway design parameters, is the goal or objective of the study, which was a freeway to meet major current traffic desires. In this case the aggregate solution was restricted to be a new freeway, rather than a morphological examination of all possible solutions to meet current traffic requirements. This new freeway had to be considered in the context of its interaction with existing freeway systems and in support of and competition with other transportation systems. Future transportation systems as visualized also had to be given representation. However, the largest number of constituent forces fall into two classes; those which determine the internal structure and behavior of the freeway, and those reflecting the interaction of the freeway with the environment. Chart 2 of freeway design parameters shows the decomposition of the internal and environmental parameters into their different values. Under internal parameters, are first the construction parameters including earthwork costs, bridge costs, pavement and subgrade costs, and construction interference. Secondly, there are economic factors: land costs, public financial losses, user costs, obsolescence; and thirdly, operational factors: travel time, local accessability, safety, maintenance, and self-induced congestion.

The environmental parameters may be divided into physical, economic and esthetic. The physical environment includes questions of drainage patterns and catchment areas, effects of weather, air pollution. The economic environmental factors include the effect of the freeway on regional and local land development, public and private losses, such as the obliteration of historical, commercial, or other structures due to the routing of the freeway. Finally, esthetic considerations such as eye sores and noise must be considered.

Certainly not all of these parameters are easily measured, nor is it possible to assign numerical values to many of them. Alexander and Manheim developed an ingenious method by which each factor would be reflected in the overall selection of the freeway route. They employed a modification of the method Dr. Zwicky has termed composite analytical photography. Each of the modular forces listed on the charts by itself favors a particular location for the highway. For example, consider earth work costs. The requirement to minimize earth work favors the location of the freeway in areas where the land is relatively flat. A transparent map is made in which the flat portions are rendered dark and the hilly portions light, the degree of hilliness and flatness can be represented by a corresponding density or opacity on the map.

Thus the tendency or force to locate the freeway in accordance with the minimization of earth work costs is to put the path in regions of maximum density on the map. Similarly for each of the other forces. If a separate transparent map of each of the forces which contributes to the location of the freeway is made so that the dark area favors location and the light area rejects location; if the forces are then combined through the process of composite photography, the resulting density on the photograph made from superimposing all the individual photographs would give the location that all the forces in combination tend to favor. The darkest strip would mark the best route. Archimedes Tub

By using this method, those parameters or forces which cannot be quantified can be weighted either through the density used on their representative maps or through the way in which the maps are superimposed. A subset of three or four parameters given equal weight and densities can be combined to produce a composite density which might then be reduced in order to adjust the joint weight of the set before combining with the maps of other parameters or sets. The structuring of the combinations thus provides the ability to weight the various factors. Methods similar to this have been used to locate the best site for an observatory.

It is another emergent property of our times that the epistemological source of knowledge of natural law is not only the natural order but also the structures and organizations created by man. The concepts which we call "cybernetics" were derived not only from the study of nervous systems but from man made control systems. The ideas of information came largely from the study of communication networks but are recognized as being also basic to the natural order. There may be some objection to using the term "natural law," but there is no question that the important basic concepts regarding structure and organization of whatever sort are being brought to light by the designer of complex systems as well as by the observer of the natural order. In this sense the historic distinction between science and technology is tending to disappear.

As a result of this parallelism, we are able to create objects for study which provide us with the equivalent of new views of the natural order with temporal and spatial resolving powers not hitherto available. For example, the freeway provides us with a new type of fluid, called traffic, whose properties can be made useful to us in developing general theories of fluid dynamics - or statics, if we make the observation during rush hour - extending to new realms the properties of fluids which occur in nature. The growing sample of such structures and organizations available for study as a result of our own creativity thus provides another positive feedback channel contributing to the accelerated development of science and technology. In effect we are creating another powerful epistemological methodology simply by constructing and studying systems that occupy some of the gaps in the natural order. (The reasons for the natural gaps may become apparent with time if our creations prove unstable.)

4. HIERARCHICAL MODULAR STRUCTURES

The development of powerful new methodologies in operations research, systems analysis, and information processing for the handling of complex problems is meeting only in part the need to establish a meaningful structure among the many highly complex and rapidly evolving technological, sociological, economic, and political systems which interact in today's world. The random distribution of our research capabilities among the favorite problems of either the researchers or the funders of research is contributing to unplanned and unanticipated unbalances in the world. (In this sense, science is not contributing to the solution, but is part of the problem.) These unbalances generate powerful forces that seek equilibration and wrest control from the grasp of those who normally make decisions. The future is determined by the complex interaction of unknown parameters. Planning and policy making become illusions. In spite of notable achievements within specific areas, agriculture, manufacture, and technology, the overview shows increasing chaos. We need not bother to construct a "good guys - bad guys" model to explain this. There is no villain - there is only complexity. We need whatever methodologies we can muster to enable us to construct the proper "grammar" for the interacting complex systems which are the modules of today's civilization. One possible source of information on grammars of complex structures is in the analysis of the treatment of complexity in the natural order. We observe throughout nature that the large and complex is constructed in a hierarchical modular manner from the small and simple. Direct confrontation of the large and small is avoided, a hierarchical linkage is always interposed. Bigness is avoided in the sense that the ratio between the size of any structure and the modules out of which it is built is bounded. If there are demands for a structure to continue to grow in size or complexity, then a new level in the hierarchy and a new module are introduced so that the module to aggregate size ratio may remain bounded.

Formally, by a hierarchical modular structure we shall mean a set or organization of modules that are in turn hierarchical modular structures. Such a structure may be closed in the sense that there is ultimately a lowest level whose modules are not decomposable. Examples of hierarchical modular structures are ubiquitous: in the macrocosmos, there is the grouping of stars into galaxies, galaxies into clusters, etc.; in the microcosmos, the grouping of atoms into molecules, molecules into crystals, etc; in the mesocosmos, there are the organizations and structures of man, armies, libraries, and computer programs.

What can we learn through comparing the properties and causes of these hierarchical modular structures, artificial and natural, that will be useful in deriving a grammar that may offset the chaos threatening us today.

What can we learn through comparing the properties of these hierarchical modular structures, artificial and natural, that will be useful in deriving a grammar to structure the increasingly complex systems of today's world, or that will be useful in understanding the limitations and operations of our own organizations and structures? We give two examples of concepts suggested by morphological comparisons.

For our purposes, one of the important properties of hierarchical modular structures is the way in which the modules and aggregates may be bounded. In 1907 before the development of modern cosmological theories and before the establishment of the existence of white nebulae as external galaxies, the Swedish mathematician C. V. L. Charlier showed that in a universe containing an infinite number of stars the sum of gravitational forces acting at every point would still be finite provided the universe were structured in a hierarchical modular manner. Quite independently of possible relevance to cosmology, Charlier's inequalities showed in general that a hierarchical modular structure could be used to bound density and inverse square type forces.

Under assumptions of uniform density and spherical symmetry, Schwarzschild showed that the field equations of general relativity predicted the existence of a bound on the gravitational potential

$$\frac{GM}{c^2R} \leq \frac{1}{2}$$

where M is the mass and R the radius of the gravitating sphere. Under the assumption of uniform density this limit demands the existence of hierarchical modular structure. If the equation is written in the form

$$\bar{\rho} R^2 \leq B$$

where $\bar{\rho}$ is the density and B is a fixed bound (we assume that G and c are constants), we see that for a given density - as for example, mean stellar density - the maximum possible radius of a star is determined. Such an inequality not only defines a limit to stellar size but forbids close packing of stars in space. Stars can be organized together into a larger aggregate only if a lower value of $\bar{\rho}$ obtains. If $\bar{\rho}$ assumes the mean value of galactic density the argument may be repeated. The maximum size of a galaxy is determined by the same bound but with a lower value of $\bar{\rho}$. The repeated application of a potential bound, like in the Schwarzschild inequality, can account for the levels in the hierarchical modular structure observed in the universe.

However, the inequality does not explain the particular set of $\bar{\rho}$'s which are observed in the universe nor does it indicate at what level the hierarchical modular structure may terminate. Potential bounds like the Schwarzschild level may also be interpreted as bounding the maximum velocity a module may possess in a coordinate system at rest with respect to the aggregate. With this last interpretation, we see from the slide that cosmic bodies are either "density limited" or "velocity limited." The slope 3 line represents the limiting density of matter in a non-degenerate form. Solid cosmic bodies lie on or to the right of this line. (On the logarithmic scales used in the diagram, the planetary bodies appear to have essentially the same densities.) The slope 1 line represents the observed location of the velocity limited bodies, i.e., the star, galaxy, cluster, and derived super cluster having the largest potentials or escape velocities. This is an observed potential bound and differs in numerical value from the theoretical Schwarzschild bound. The objects falling on the observed bound, like those on the density bound, are non-degenerate.

We thus see that hierarchical modular structures provide a way for accommodating bigness while satisfying intrinsic physical limitations. Specifically we may expect inequalities of the $\rho R^2 < B$ type to mold a hierarchical structure whenever we have the following conditions:

1. The existence of an aggregating force tending to bring modules into a condition of maximum compactness, gravity in the case of cosmic bodies.
2. The existence of a maximum limiting density, the limit set by non-degenerate matter in the cosmic example.
3. The existence of a potential or velocity bound or its equivalent, such as the Schwarzschild Limit.

One of the human aggregations with which we are most concerned today is the city. There are indications that our cities may be approaching some kind of critical limits. What kind of limits might these be, and how may we avoid difficulties without having to test to destruction to see where the failure occurs. Let us examine whether the essential ingredients leading to the hierarchical structure of the cosmic aggregations find a parallel in the parameters governing cities.

First, human beings as modules are subject to aggregating forces as are other so-called social creatures. Historically, humans aggregated into towns and walled cities for trade and physical security. Today the natural gregariousness of man is very much a force bringing them together for physical, economic, and emotional security and growth.

Next, there are density limits governing how closely people may satisfactorily live together. These limits depend on the amount of freedom of movement and privacy we demand. The high densities in prisons and concentration camps are possible because of the restriction of movement and loss of privacy. Without specifying the value of the density limit, we can definitely assert that such a limit exists. If you want an absolute limit, you may take the value of one person per 1.83 sq. ft., provided by Surajah Dowlah's experiment in close packing of humans in Calcutta in 1756. However, we must bear in mind that in the modern city for purposes of density limits, the real inhabitants are motor vehicles, not people. The maximum density is determined by the minimum space needed for maneuvering, parking, and servicing automobiles.

A second limit exists in city life. This is the limit on the time required in movement to transact the city's business, or the bound on the maximum fraction of the day that the average commuter will tolerate spending in commuting. Doxiadis' studies show in cities of the past, the maximum distance from their centers was ten minutes by walking. We have certainly moved a long way toward the commuting time limit. Three hours per day, or one-eighth of the time is not uncommon although the average is still considerably less than one hour per day. Both the city and the human modules which come together to make it are governed by a characteristic final period - 24 hours. This is an imposed value, which is not at our disposal to appreciably modify. It is more basic than the day-night cycle imposed by the earth's rotation. This period is set by the biological clocks in each inhabitant. Certain adjustments can be made by some people, such as going to work on Monday, living near their work, and returning home on Friday for the week end. Many do this in order to live where they wish. But this practice does not alter the basic 24 hour period set by the needs of the city and its population.

These limits may readily be combined symbolically. Let $\hat{\sigma}$ be the density bound and $\hat{\tau}$ the commuting time bound. The latter may be expressed in terms of the natural period of the city $T = 24^h$ by $\hat{\tau} \leq \zeta T$ where $\zeta < 1$. For a simplified model of a two dimensional city, $N = a\bar{\sigma}R^2$ where R is the maximum length path through the city and a is a shape factor. A limiting velocity which depends on the state of the art will be designated by c.

Since, $R = \bar{\upsilon}\bar{\tau} \leq c\hat{\tau}$ and $\bar{\sigma} < \hat{\sigma}$

we have

$$N = a\bar{\sigma}R^2 < ac^2\hat{\sigma}\hat{\tau}^2 \leq ac^2\hat{\sigma}\zeta^2T^2$$

In a three dimensional model we introduce the mean height $\bar{h}$ of the city and use a three dimensional density $\bar{\rho}$

$$N < a^1 c^2 \bar{h} \hat{\rho} \hat{\tau}^2$$

For the bound $\rho\tau^2$, write 1/G giving

$$\frac{GN}{c^2\bar{h}} < a^1$$

This inequality is the same form as Schwarzschild's Limit. Of course, the values of the constants are quite different. An inequality of this form was to be expected since there is a density limit, a velocity and time limit, and an aggregating force. We might, accordingly, draw some conclusions concerning the structure of cities by analogy to those drawn in the cosmic case.

From $\bar{\sigma}R^2 \leq ac^2\hat{\sigma}\hat{\tau}^2$, we see that for a given density, the size depends on a bound set by the effective velocity of travel and the maximum acceptable commuting time. The bound may be satisfied as N increases by increasing c, but the solution of hierarchical structure applies by the same argument as before.

If a polynucleated city develops on hierarchical lines, it will be stable so long as each nucleus and the complex of all the nuclei (with an overall lower density) satisfy the inequality, σR^2 < Bound. However, the nuclei will not close pack, which means that if subsequent development fills in the areas between the nuclei bringing the mean density up to the level within a nucleus, the complex will reach the limit. This sort of filling in process is occurring in the "megapolis" areas of the Eastern United States and Southern California. If these inequalities are valid, we will not be able to get away with destroying our open spaces or low density background.

Since no physical restrictions exist on the distribution of density, as hold in the cosmic case, there are other possible solutions. It can be shown that the bound may be satisfied by selecting a density distribution $\sigma(\gamma) \sim \gamma^{-(\gamma+1)}$ where $\gamma > 1$. In this case, the city may grow and still satisfy the bound if it is built in a ring shape. Several suggestions of this sort have been made including a city which is nothing but a series of linear structures several stories high with freeways on top.

Additional theorems on the structure of cities require more sophisticated models and exceed the parallelisms evident in the hierarchical modular analogy given. This analogy, however, gives an example of the application of morphological parallelisms. It does not produce what one is prepared to accept as valid formulae, but it suggests hypotheses which can serve as foundations for a theory and be tested for possible validity.

MORPHOLOGY AND MODULARITY

The capability to solve a problem depends upon the level of knowledge, capital equipment available which includes people, and the raw resources required. If we imagine a capability function which depends upon these parameters, whenever the value of this function reaches unity, we may say that we have the capability to solve the problem. However, the value of the capability function rarely stops at unity but continues to increase from the momentum of the effort put into the function in order to have it reach the value of unity. After a short time, the capability function assumes the value of two, or even higher. The point of representing our problem solving ability by a capability function is to show that there exists an important transition, a sort of sonic barrier if you will, at the value of unity. We pass from a milieu in which we are trying to solve a problem very rapidly into a milieu in which we have the capability to solve the problem in a great many ways. One of the many changes which has taken place in Western society has been the transition from the pre-unity to post-unity value of a capability function. By this I mean that in the past two centuries we have concentrated on acquiring the knowledge and means to solve a great many problems. In the past two decades, we have passed into the realm of being able to solve these problems not only in one way, but in a large number of ways. There was a long period of learning how to fly. Finally, in 1903, flight capability function reached the value of unity. Since that time we have not only been able to fly but have been able to build flying machines in a large number of forms. The effort when the capability function is less than one is to find any possible solution to the problem. After the capability function reaches the value of one, the basic nature of the problem changes. We then are faced with the problem of choice. The basic difference between problems of increasing the capability to unity and the problem of choice are that in the first case, we are ever seeking to expand and increase the number of parameters to push back the limitations, whereas in the problem of choice, we are searching for limitations, for constraints which will enable us to pin down the best method by which to perform the problem. The world has moved from the area in which the primary emphasis is on the creation of a way to do something to the area where the primary emphasis is in making the right choice of the way to do it and what to do. However, the momentum of our patterns of thought developed in the initial stage continues to dominate our thinking in the age of choice.

Because even though operating in the age of choice we restrict ourselves to including only the capability parameters in the solution of our problems, we sometimes make rather grotesque mistakes. For example, we now have ~~a~~ the capability to build extremely large ships, such as oil tankers. Recently a tanker of 120,000 tons was constructed. The parameters entering into making this decision were capability parameters and economic parameters, that the most economic way to transport crude oil is in having the largest tanker. There is at present a 300,000 ton tanker under construction and a 500,000 ton tanker on the drawing boards. But in making the choice to build these tankers we have not been influenced by parameters of limitation which come from considering the problem in a broader context. The parameters of limitation of choice must come through consideration of a problem in its broadest context. The disaster occurring off the east coast of England recently in the wreckage of the 120,000 ton tanker was certainly not planned but if the parameters of total possibility had been taken into account, would such a tanker have been constructed.

Our Secretary of the Interior has made this comment, "The environmental backlash we confront today cannot be eliminated just by applying more of the same science and technology that put us in our present predicament." The parameters of limitation and choice have certainly not been operative in the way in which we construct our cities, our freeways, have resulted in waste and pollution on all sides. The Secretary is correct if by more of the same science and technology he means that we continue to think in terms of capability rather than in terms of the proper parameters of choice. However, I disagree with the Secretary in that science and technology can provide the proper forms of analysis, provided we recognize the fundamental change between the milieu of increasing capability which is removal of limitation and the milieu of choice which is a search for limitation.

So in our time, it becomes proper to formulate every problem not only in terms of its capability parameters, but also in terms of its contextual parameters. This is what the morphological approach means in considering and exploring all the possible interrelationships involved in the problem.

The second feature of morphological research is unbias. Bias must be ferreted out and exposed wherever possible. There are no general rules for the detection of bias. We usually become aware of prejudice or bias through disagreement. It is very difficult to ferret out a bias which derives from a widespread Weltanschauung or from a root metaphor. To detect a root metaphor, we must encounter a man from an entirely different culture. It is thus the plurality of cultures and pluralism in general which is the format of society which will allow us to become aware of bias. The morphologist is not opposed to prejudice but he is opposed to being unaware of our prejudice for the reasons behind it.

An example of a very wide spread prejudice among the scientific community today is what we might term the reductionist prejudice. In brief, the reductionist prejudice states that causality flows from the microscopic to the macroscopic; that the causes of any event are to be found within the confines of that event. This is the prejudice which keeps us from looking at the whole environment in designing tankers, whereas we concentrate our design on the parameters of economy, payload, hull strength capability, speed, etc. But recently we have come to realize that in addition to the classical engineering questions about how to build an airplane, for example, we must now face the question, how big should an airplane be; how fast should an airplane fly. The answers to these questions are not to be found purely in terms of our capability in building large planes or fast planes, but in terms of the choice that must be made with regard to the context in which these planes must operate. The problems that face us in decisions of choice are not reductionist problems, but rather wholistic problems.

The traditional attitude toward disagreement has been urgency to resolve the disagreement. The forms by which this resolution takes place range from suppression to arbitration. The morphologist points out that it is not always necessary to be in great haste to resolve the disagreement, but rather it is important to learn from the disagreement. Disagreements not only reveal the prejudice, they make us aware of the parameters that are operative in a problem. In the wise words of a great statesman, "In our time we shall not be able to resolve our disagreements, let us therefore make the world safe for our disagreements." A morphologist would go further and say let us be thankful for our differences and disagreements for they are our sole keys to deeper understanding.

In addition to our prejudice against wholistic parameters, that is, parameters which affect solutions of our problems which are operating from the environment or from the larger milieu, in favor of reductionist parameters, there is also a second prejudice. This is the prejudice that natural law may only be discerned through the study of the natural order. The laws and relationships that we learn through the study of our own artifacts are of a lower order than the laws of physics. We apply the laws of gas dynamics, for example, to explain the flow of traffic along the freeway, but we would not consider relationships we discover in the flow of traffic along the freeway as applicable to problems in the natural order. The morphologist is willing to let this go either way; that there is no such thing as a lower order of natural law, but there may be the possibility that those systems which follow the laws of physics are more stable and long enduring than those systems whose parameters have values such as we see on the freeway, and cannot possibly be successful solutions for long enduring, but the validity of the laws the morphologist takes as the same. To point out the fallacy of this prejudice we need only recall what has been said here at this conference with regard to discoveries made in information theory and in sybernetics which were largely ascertained from our own artifacts and their workings rather than from the natural order.

A third prejudice is to emphasize the measureable and quantitative parameters which enter into our problems, at the expense of ignoring or minimizing the non-quantitative parameters. An example of how non-quantitative parameters have been effectively introduced into the problem of the routing of a freeway will be discussed a little later.

With basic knowledge coming from the study of our artifacts, our cities, freeways, computers, control circuits, etc., we find a feedback into the level of our knowledge of natural law. Our artifacts resulted in the first place from the application of the technology which derived from our knowledge of natural law, but now we see more coming out than going in, knowledge-wise. In this respect, we have again passed through some type of "epistemological barrier".

The knowledge which is coming from our artifacts of which I am speaking is not meant knowledge concerning the function of some design parameter, the setting of a valve, or the adjusting of a carbuetor or compression ratio; these things we certainly learn from our design and experiment with, and we learn how to improve our designs. What I am speaking of is a knowledge of a general type transcending design. The discovery of sybernetics and information theory, for example, It is as though we have created test bodies and inserted them into the natural order. We hope that these bodies which we have created are stable, that is, designed in such a way as to equilibrate all of the forces which define their form. If they are stable, they should be long enduring and successful. On the other hand, if they are unstable, it is probably because we are unaware of some of the basic forces which may be acting. This introduction to new forces through the study of our own artifacts is one of the ways in which we learn new aspects of natural law from the study of artificial creations. A second way, of course, is through analogy. Since analogy is fraught with peril and most scientists steer clear of it, the morphologist must design a way in which analogy can be used without falling into the usual pitfalls.

One of the most crucial examples with regard to the problems of increasing capability and making a choice, arises in the new biology. The capability to create new organisms will shortly be within our reach and we shall pass into the area of choice: which organisms to create; how should the power of the new biology which has come through discovery of the genetic code to be handled. This problem must be approached in the way of the morphologist.

In seeking to introduce non-measurable factors, such as value, we need a certain measure of emancipation from physics. Not from physical law, but from sole consideration of physical parameters. We need an emancipation from reductionist parameters, and we need to include wholistic parameters.

Our structures not only become objects for revealing natural law as stated through analogy or through instability, but also, and especially, through probing to the limits and revealing where the limits exist. In the search for limits, we must recognize that a limit is also a force in the D'Alembertian sense, but there are differences. In the designing of a natural body, a freeway or a city, as being in equilibrium with all the forces that are acting, we are using design as an epistemological tool to observe the non-stable regions and possibly, to find new stable regions which nature has missed.

Finally, the spirit of morphology is a spirit which Alfred North Whitehead implored for philosophy. Namely, that philosophy should not be a ferocious debate between irritable professors, but, "A survey of all the possibilities and their comparison with actualities."

TAPE 4

MORPHOLOGY AND MODULARITY

One of the two essentials of the morphological approach to problem solving is to determine all of the interrelationships that exist in the problem. In recent years the study of interrelationships, how to characterize and classify them and the structuring of interrelationships, has been carried forward principally under the study known as graphs. A graph is a network which shows the various relationships which occur between sets and subsets. It is possible to map a graph onto a matrix and hence to computerize the entire subject of the structure. A large class of special type of graphs are known as trees. These are sets in which each subset is completely contained in the subset above. In other words, all subsets are proper subsets, there being no overlap of elements on the same hierarchical level. Trees are hierarchical structures and as such represent a large class of phenomena to be found in nature. In fact, any natural structure composed of modules which are grouped together in sets or subsets is a form of a tree. In this lecture, we are using the term modularity to designate this particular type of structure in which elements or modules form sets which are structured in the order of a tree, that is, are hierarchically structured. A formal literature is growing up on the subject of graphs and trees. We mention the work of the logician, Copi, on matrix department of the calculus of relations, and a book on axiomatic set theory. Pfennig's Theory ______________________________ 1950, is a pioneering work on graphs. Berga's "The Theory of Graphs and Its Application," 1962. More and more papers are appearing in various journals on information sciences on the subject of graphs. We shall not go into detail as to what graphs are beyond to call to your attention the literature and the fact that the graph is a formal mathematical structure for the study of interrelationships.

The ubiquity of hierarchical or modular structures hardly needs comment. It is found in the cosmos, in the grouping of stars into galaxies, galaxies into clusters, etc. It is found in the microcosmos in the structure of atoms, molecules, crystals, etc. It is found in the mezzo-cosmos in the organizations and structures of man, in armies, libraries, and computer programs. Since this is a very large class of structure, the morphologist does well to try to understand this particular class and its properties because a great many problems are evidently solved by the use of modular structure. It is proper to inquire whether the commonality of modular organization and structure derives from a common cause or that modularity is a panacea in solving a great many requirements deriving from different causes. That is to say, modularity seems to be a solution to many problems. The infinite variety of forms in nature poses certain constraints, for example, modularity. It may be that instead of seeking to find a basic cause to the ubiquitous presence of modularity, that the simplest approach is to assume that modularity is basic and to derive the various laws from this premise.

Instead of seeking an explanation of a reductionist type, that is self contained, let us assume that commonality is attributable to general principles which are common to physical, military, cellular, biological and cosmic systems. This assumption may not be correct and we may not be justified in making it except to test to what extent the analogies may be carried. It may be that there is nothing more general than that the limit of aggregates depend on the structure of their elements and the forces of aggregation. But we would search for common parameters which occur in the definition of hierarchical structure, such things as limits or bounds and aggregating principles. We have, for example, various types of aggregating principles in nature, the gregariousness of humans, gravitation, the blockage of traffic on a road by a slow car, limitation of lines of communication, common types of limits which occur in various situations are density limits, potential limits, velocity limits, size limits, strength limits. An important function in iterated modularity is the modular mass spectrum or the numbers and sizes that occur in each successive subsystem. Why, for example, in cosmic aggregates do we encounter a relationship such as the harmonic power law.

Modularity in natural and artificial structure is ubiquitous. Is the widespread occurring modular structure due to a common cause or are there many reasons for modularity. A specific occurrence of modularity possesses its specific explanations, such as physical, biological, or whatever. However, the commonality of certain aspects of modularity raises the question whether the specific explanations are but aspects of more general principles or of some metaprinciple underlying the laws of physics, biology, architecture, music, design, etc. Our task is to formulate this problem; to decide whether there exists such a metaprinciple underlying modularity, and if so, to attempt to define it, from the structure of the various laws which immediately govern modular structures. Our process is to consider a sample of several specific modular structures from nature and from artifacts and analyze their immediate causal laws which we take to derive and explain them. The parameters which emerge from analyses of these specific laws become the morphological elements which will allow us to discern the types of causes leading to modularity. Hence the classification of modularities becomes our first task. If these types are singular, we predict the existence of a modular metaprinciple; if plural, we have denied it. If there does exist a metaprinciple, we have a powerful tool for isolating physical laws and relationships. If we know the form that physical laws must have, we may check them with the known, and supply the unknown. Modular structures may be composed of identical modules, or modules of a poly-? type, which are all different. Hierarchic structure is structure with an emergence of successive new units, of either uniform or poly-types.

The essential features of the morphological method are to discover and structure all of the interrelationships within a problem and to develop an unbias in the selection of a solution. Since prejudice is itself an imperfection by the principle of making use of imperfection, the true morphologist does not attempt to eliminate prejudice, rather to make use of the prejudice. Prejudice is of two types; self-conscious, and unconscious. Use may be made of unconscious prejudice whenever a confrontation of two reveals the presence of prejudice, we have become aware of a new parameter.

A large class of problems show a particular type of structure known as a tree. The morphologist accordingly looks at what may be an important metaproblem. Since its study may lead to theorems of wide applicability in many classes of problems. Insight into the total problem of the tree or hierarchically structured sets may be gained by looking at the wide variety of hierarchical structures which occur in natural and artificial orders and attempting to classify trees by their causes, or by whatever portion of the cause may be ascertainable.

By modularity we shall mean the structural or organizational pattern by which the whole is built from modules which are aggregates of successively more elemental aggregates in a hierarchical manner. This structural pattern is common in nature,as for example, atoms are the modules out of which stars are constructed. Stars are the elemental modules of galaxies, galaxies of clusters, etc. Although human structures are similarly arranged, as for example, an army, privates forming squads, squads platoons, platoons companies, etc., the ubiquity of this pattern needs little comment. Examples may be found in the macrocosmos, microcosmos, in living organisms, and social structures. Large or complex structures are rarely built from elemental modules. The iterative modular organization is used to span from the small to the large. Whenever structures or organizations become sufficiently large or complex, they are ubiquitously constructed in a hierarchical manner through the aggregation of successive orders of aggregations.

TAPE 5

MORPHOLOGY AND MODULARITY

I recall on the day that Glenn made his orbiting flight of the earth that that morning, there was a particularly bad traffic jam on the west side of Los Angeles. In fact, while Glenn went from the west coast of Africa to east of the Hawaiian Islands, we moved only eight blocks. There was something about that which bothered me. There seemed to be some unbalance in the way in which we were applying our scientific knowledge and technology. I wasn't sure whether this was because there were certain types of problems that are glamour problems and other problems which are refuse problems, or whether our methodologies of solving problems were incapable of handling a broad class of problem and were only good for problems of the sort of development of a new capability.

More recently, this same question has been brought to light again by the wreck of a very large tanker on the east coast of England, releasing thousands of tons of crude oil which have destroyed hundreds of miles of beaches. Again, something appears to be seriously wrong. Either we are omitting some very basic factors in our approach to problems, or we select problems not from their necessity, but from other criteria. Actually I believe it is both of these factors. At an important research institution here in this area the policy is to work only on those problems for which there is a good feeling in advance that a solution can be obtained. Certainly this makes good sense and no individual researcher is going to risk too much of his limited time and resources persuing a problem which he sees little or no chance of solving, however pressing this problem may be. But there is more to it than simply selection of problems on the basis of their being interesting problems or easily soluble problems. There seems to be some deficiencies in our whole attack on problems in general. At least three defects in our approach to problem solving come to mind. These are: 1) our tendency to concentrate on a particular phase problem even after this problem has taken on entirely new aspects. It was very important in frontier days to get more people into the West, and Chambers of Commerce have carried this concept forward to this day although a look at our cities should convince any of us that the one thing we do not need at this present time is a large increase in population. But this deficiency has a more subtle aspect to it, not only concentration on obsolete phases but failure to recognize that the problem of increasing capability also involves the aspect of how far is it useful to increase the capability.

A second tendency is to concentrate on thos parameters which can be quantified and measured, ignoring non-numerical parameters in the problem even though their weight may be such that they should be given greater consideration than all the numerical parameters. Some studies in the area of nuclear strategy in the past 15 years have resulted in some gross absurdities because of this one facet. I shall give a recent example of how Alexander and Mannheim have devised a very fine method for introducing non-measurable parameters into the solution of a problem.

Thirdly, I think part of our trouble is our prejudice against wholistic parameters, or parameters which reflect the properties of the environment on to the immediate context. The day in which we can be oblivious to how we treat the environment and not take it into account in its effects upon us is over. One only has to take a deep breath in the Los Angeles area to see this. Very few of us question the causal flow from small to large; that things we do might affect the environment. But we ignore the causal flow of large to small and tend to disbelieve in it, largely because there is a feedback delay. A great many of the difficulties we are in, and others that we are approaching are due to this feature of delayed feed-back.

In a conference on methodologies for solving problems, at least a few words ought to be said concerning methodology for deciding what problems should be solved. At the present time, the general practice seems to be for the problem solvers to follow the scent of the problem funders. How the problem funders decide what areas to fund is not always clear. I am sure there is again the delayed feedback feature present. As an example of this, we see the subject of UFO's suddenly becoming respectable in research circles after the appearance of funds for research on UFO's. The problem of where to put our research efforts and our research funds is certainly a problem which weighs heavily upon our whole research society and it is a problem worthy of the highest priority on the part of all those who have a methodology which would lead to its solution. One thing that emerges from consideration of this big problem is the inter-connectedness of all the research problems of our times. Hence in an abstract formulation, one of the most important problems with which we can be concerned, is to study the interrelations which occur in the various problems which confront us and to study the subject of interrelations and structures in its most general formulation. In the last few years new areas of mathematics have been developed directly addressing this problem; the theory of structures, the theory of relations, the theory of graphs, etc. These new disciplines are of great aid in analyzing the various types of structures which we may encounter. For this reason, I have selected the subject of modularity, or the hierarchical structure of aggregates as a problem of very great threat which is of high usefulness in many branches of science and technology. I feel it appropriate to see what general approaches we can make to this problem of the hierarchical structure of various types of organizations and what we can learn from them.

TAPE 6

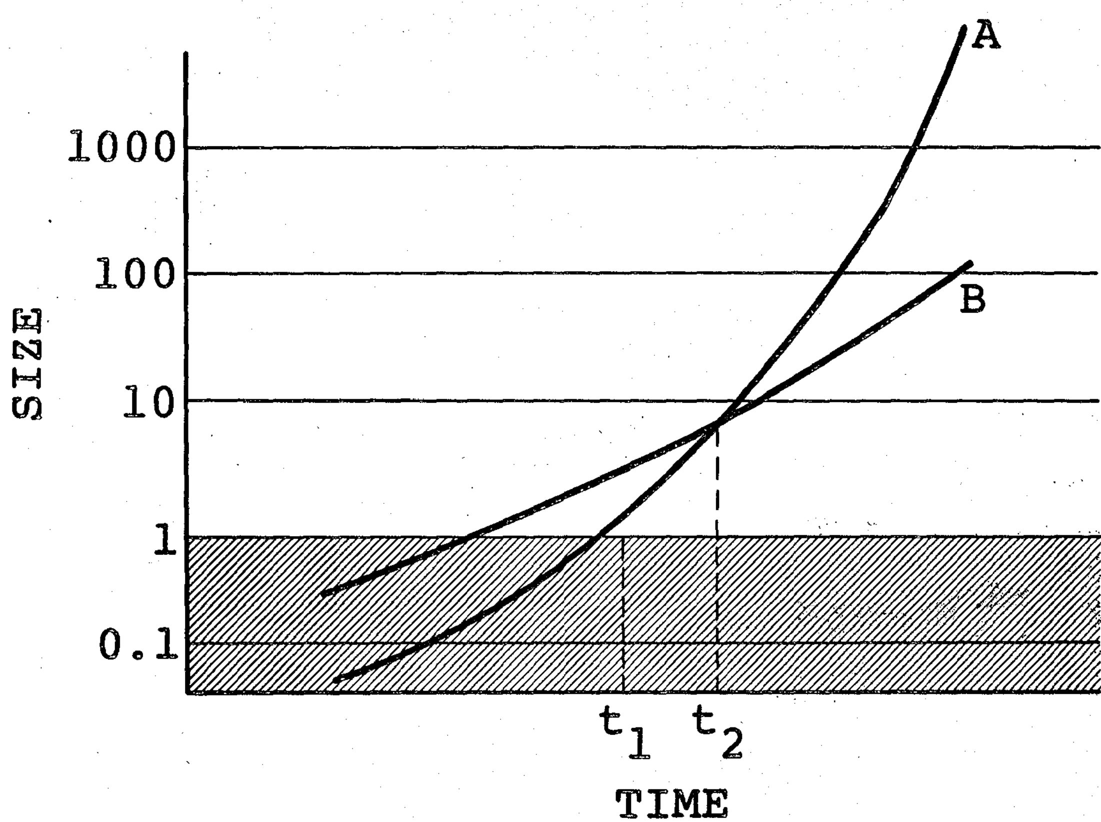
MORPHOLOGY AND MODULARITY

On the day that John Glenn made his historic three orbit flight of the earth, there was a particularly bad traffic jam on the west side of Los Angeles. I recall listening to progress of Friendship Seven on the car radio while embedded in the creeping glacier of traffic. While Glenn crossed Africa, the Indian Ocean, Australia, and part of the Pacific Ocean, we moved eight blocks. There was something contrasting in this situation that bothered me. I began to feel on that morning that we were not only getting a preview of the new capabilities which our technology was developing for the conquest of space, but we were also getting a preview of the consequences that unstructured use of technology was piling up for the conquest of us. For me this contrast was a warning that there were some serious deficiencies in our understanding of what was really happening as a result of the process of applying science and technology unexaminedly to the multifarious specific problems which attracted us. The cause of this and other unbalanced situations in our culture is not clear. Was it that we sought out and found challenge only in glamour problems such as the development of new capabilities to fly higher, to see further, to compute faster, finding little satisfaction in tackling the garbage problems like air pollution, traffic stagnation, and what it is that is most needful of being computed. Or were there limitations to our methodologies for solving problems. Perhaps those we had already developed were only useful for certain classes of problems, like figuring out how to fly faster, and our methodologies could not cope with broader classes of problems. Or was it simply that we were not taking into consideration for some reason, some very important parameters. An engineer riding with us saw no problem. "It is all very simple. The speed varies inversely as the density of the medium through which one moves. If you take the ratio of the density of matter and space where Glenn is, the density here on the freeway, take the square root; you will come up with approximately our ratio of speeds." Some parameter seems to be missing there too.

A few weeks ago, the world's largest oil tanker of 120,000 tons was wrecked off the east coast of England, releasing thousands of tons of crude oil which came ashore and destroyed hundreds of miles of beaches in a way which has tragically affected the means of livelihood of thousands of people, and cruelly contaminated the environment for hundreds of thousands more. Again, something important appears to have been left out of consideration in the application of our scientific and technical knowledge. I do not mean that we do not understand how properly to design large tankers and are overlooking some design factor; our engineering is undoubtedly sound, based on well established and proven principles. Even now we are building a tanker of 300,000 tons and designing one of 500,000 tons. Furthermore, the economics of the large tanker is sound. The savings accrued in bulk transport of oil are apodictic. Yet, navigational disasters may befall any vessel, no matter how large or how well designed. These disasters striking from the environment we traditionally call "acts of God;" the large dominating the small, the universal controlling the particular, the whole determining the part. How can we possibly be responsible for that over which we have no control? This brand of theology is hardly any longer acceptable. The precarious level of technological development which we have recently reached in which we have the power to significantly alter our environment without having the power totally to control that environment imposes the greatest of responsibilities on what we choose or do not choose to do with our capabilities.

This disaster to the shores of England prompted our Secretary of the Interior to comment, "The environmental backlash we confront today cannot be eliminated just by applying more of the same science and technology that put us in our present predicament." Some scientists would support this indictment of science and technology, and agree that Mr. Udall has placed the blame squarely where it belongs. Other scientists would object that it is grossly unfair to hold science and technology responsible for such a situation for there is, at present, no scientific knowledge which can answer the question, "What is the maximum size of tanker which should be built?" This type of question is not even amenable fo scientific treatment. Mr. Udall speaks of, "the same science and technology that put us in our present predicament". This phrase has the implication that there may exist, if not other types of science and technology, then possible developments in science and technology which would provide the understanding that would avoid the creation of such predicaments. If this be so, then the search for the unincluded parameters whose omission is creating these problems is itself a legitimate research task. We can at least start by adopting this hypothesis and looking for possible ways to formulate the question.

One of the deficiencies in the present practice of application of science and technology is the failure to note that at some level of the state-of-the-art, how big we can build a tanker, and how big we should build a tanker, take on different answers. The problem may be formulated in very simple terms for purposes of illustrating this point. In Figure 1 curve A is a capability curve showing how large a tanker may be constructed in accordance with the state-of-the-art as a function of the year. Curve B may represent some environmental tolerance or some second


A
1000
100
B
SIZE
10
1
0.1
t_1
t_2
TIME

capability which in our present illustration may be measured by the number of tons of oil on beaches which we can in some way successfully neutralize. Let us assume that these curves cross in 1965. Assuming the economic incentive is always toward larger tankers, prior to 1965 the choice of what size tanker to build is governed entirely by the technological limitations to tanker size; after 1965, if we allow for the possibility of disasters, we can weigh the economic gains of size against the losses in the event of a disaster, and make a choice as low as curve B and as high as curve A.

This naive two parameter formulation in no way reflects the real complexity of the problem, nor all of the interrelations which must be taken into account. It serves only to point to the fact that there exists two regimes; first, the regime of limited though developing capability, developing to the level where a solution is realizable. And second, the regime in which capability has reached a level demanding choice. Attitudes nourished in a regime of limited capability in which the choice is always made for the limit of capability, tend to carry over into the second regime. The difficult problems of choice are ignored by still opting for the limit of capability. Chambers of Commerce are still trying to attract population growth to their communities,an endeavor that made good sense in frontier days.

This formulation of the how big problem in terms of capability and environmental tolerance has also been used by some in their approach to nuclear strategy. In Figure 1, if the level of destruction is read for size, we have the current nuclear situation. Curve A represents the capability of nation one, or nation two, to impose a given level of destruction. Curve B represents the level of tolerance to destruction of nation one or nation two. The fact that the two capability curves and the two tolerance curves are not precisely identical is a negligible matter with respect to the level of destruction involved. In past wars the level of tolerance was always higher than the level of any enemy's capability for destruction. However, in the past two decades this order has been reversed. The implications are clear, but capability choices still derive from first regime thinking.

The phenomena of regime change is well understood by many business and government leaders. We have learned in this symposium some of the powerful new methods which are available to decision makers, allowing them to confront the full complexities of their problems and optimize their choices. Unfortunately, many in a position of responsibility still fail to recognize the nature of the change from the limited capability regime to the choice demanding regime, and this, to the peril of us all.

TAPE 7

MORPHOLOGY AND MODULARITY

It frequently happens that many of the parameters which we know are relevant to a problem are not readily amenable to measurement or to quantification. It is a tendency for us to concentrate on those parameters for which good numerical values are obtainable and we sometimes tend to neglect those parameters which are not measurable even though their relative weight in the problem may be high. What is required is a methodology by which we are able to incorporate the effects of parameters which cannot always be quantified, such as esthetic values and future uses.

Hence when numerical and analog methods fail, we may adopt a methodology which was proposed by Alexander and Mannheim. The basic idea is to recognize that form arises from an interaction of a set of forces, so the problem is, given a set of forces with no restriction on their variety or whether or not they are measurable or quantifiable, can we generate a form which is stable with respect to all of these forces. We can think of the method of solving the problem by adopting an abstract space in which the elements or modules are forces, and aggregate of such modules which closes on itself, that is, which is complete and in balance, becomes an entity and defines a form or object. If we try to determine in as abstract way as possible the physical relation which each individual force is seeking, and if we try to combine these individual abstract relations in some way, we can generate our solution.

An example of this procedure has been given by Alexander and Mannheim in an MIT report on the use of diagrams in highway route location. The problem which Alexander and Mannheim undertook was to design a freeway covering a 20 mile stretch in Massachusetts starting from Springfield and ending somewhere near North Hampton. Alexander and Mannheim first constructed a morphological box of all of the individual modular forces which interacted to determine the form which the freeway path should take. Shown on Chart 1 of freeway design parameters, we have first the goal which was to meet major current traffic desires. The aggregate solution was to be a new freeway. This new freeway had to be considered in the context of its interaction with other existing freeway systems and in competition with other transportation systems. Future transportation systems as then visualized also had to be taken into consideration, but the largest number of forces fall into two classes; those which determine the internal structure and behavior of the module, and those reflecting the interaction of the freeway with the environment. Chart 2 of freeway design parameters shows the breakdown of the internal and environmental parameters into their different values. In the internal parameters, we have first of all the constructional parameters which must be taken into account. These include the earthwork costs, bridge costs, pavement and subgrader costs and construction interference.

Then there are the economic factors: the land costs, public financial losses, user costs, obsolescence; and the operational factors: travel time, local excessibility, safety, maintenance, and self induced congestion.

On the environmental parameters, we may divide them into physical, economic and esthetic. The physical environment includes questions of drainage, patterns, and cachment areas, effects of weather, air pollution. The economic environment includes the effect of the freeway on regional and local land development and non-recompensable public and private losses, such as the obliteration of some historical or other structure due to the routing of the freeway. Finally, the esthetic considerations are the eye sores and noise.

Certainly, these parameters are not all easily measured nor is it possible to assign numerical values to them. Alexander and Mannheim developed a very ingenious method by which all of these parameters could be reflected in the overall design of the freeway route. They employed a modification of the method Dr. Zwicky referred to as composite analytical photography. Each of the modular forces listed on the charts by itself seeks to favor a particular location for the highway, for example, earth work costs. The need to minimize earth work would seek a location for the freeway through the areas where the land is relatively flat.
A map could be made in which the flat portions could be rendered dark and the hilly portions light, and thus the

density would reflect the tendency of the particular force, in this case earth work costs, to locate the freeway in this particular area. Earth work costs would tend to locate the freeway in the flat areas which are made dark. If a transparent map of each of the forces which contributes to design of the freeway is made separately, and these forces are then combined through the process of composite photography, the resulting density on the final superimposed photograph would give that location with all the forces combined to favor. It would simply be necessary to follow the darkest area. By using this method, those forces or parameters which cannot be quantified can at least be given weight depending upon how dense their representative map is made or on the way in which different parameters can be combined. A set of three or four, given equal weight, can be combined to result in a density which you would wish to compare with one other factor. The ordering of combinations thus gives the ability to weight the various factors.

Another interesting example due to Alexander of how to solve a problem in which the contributing factors cannot be measured or quantified is how to design a house when the requirements or contributing forces are: 1) each person in the family has his own hobbies. These hobbies result in things being left about and people in general like to carry out their hobbies where things can be left lying out safely. Secondly, the communal portions of the house have to be kept tidy because of the possibility of visitors, and so that no one person's things encroach too heavily upon the others. And third, there is a tendency of the people in the family to want to be together. Alexander solves this problem with the ease of a shop artist drawing a cartoon. He represents the demands that each person have a private space by a set of small circles. He represents the second demand that the communal space be easily kept tidy by a single self contained integral unit. He represents the third demand that the members even when pursuing their private interests would like to be together as a whole by a series of cups. Now how may these be placed together to satisfy all requirements. The ____________ diagram represents a scalloped enclosure. The architect may interpret this as a living room with several alcoves in it, one for each person in the family. The individual alcoves may be left untidy, private pieces are quite safe in them. Each alcove looks into the central living room and into the other alcoves and the people in these alcoves can see each other and they can talk together and be together, yet the communal living room itself can be kept tidy and it can exclude the alcoves by using curtains or sliding doors. This solution in which the individual forces are put together is stable with respect to all three forces.

EPILOGUE

A primary purpose of this conference has been to consider the question whether the various methodologies employed in solving problems when taken together constitute in themselves a useful scientific and technological discipline. The descriptions of the several approaches to problems that have been presented here - Operations Research, Systems Engineering, Morphological Analysis, etc.- have made visible some common principles which have been independently developed for structuring, analyzing, and solving complex problems of many types. Though using different names and terminologies, the identities and overlaps contained in these approaches, taken with the fact of their independent discovery in many diverse contexts, strongly suggest the developability of a useful discipline that we may call "methodology." Although the presentations during this conference have only partially defined the subject area of methodology, they have demonstrated that it would now be meaningful to take steps toward systematic definition and organization of the concepts so far developed and establish a formal discipline.

Specific problem areas from hospitals to codes to jet engines have been treated at this conference. However, in all the variety of problems discussed, almost nothing has been said concerning how to select which problems to solve. It seems most important that any discipline of methodologies for problem solving be concerned not only with the definition and solution of specific problems but also with the nature of that growing complex consisting of the set of problems competing for our attention. The discipline of methodology should investigate criteria by which to assign priorities, the appropriate levels of resources - funds and talent - to be thrown against a problem, the nature of the interrelatedness of problems, the consequences of solutions to problems and the anticipation of derivative problems. Neglecting an overview of the interrelated complex of problems has given rise to some serious unbalances in our culture. Dr. Ramo, in his introduction, pointed out a few of these unbalances. In 90 minutes in Gemini we can travel around the earth, while in 90 minutes in our cities we sometimes can travel only a few blocks. We can provide pure breathable air 100 miles above the earth for our astronauts, but not within a hundred surface miles of our major cities. We have developed remote sensing equipment that can tell us everything going on inside a space capsule, but have not equipped the physician with comparable equipment for monitoring what is going on inside his patient. There is no need to enumerate our disparate and desparate social unbalances. We might now add that a conference on methodologies for solving problems without consideration of how to choose which problems to solve in itself constitutes an unbalance.

In addition to unbalances, there are other shortcomings inherent in our present approach to the growth and application of scientific and technological knowledge. For example, early this year, the world's largest oil tanker of 120,000 tons was wrecked off the east coast of England, releasing thousands of tons of crude oil which floated ashore and polluted hundreds of miles of shore line. This developed into a tragedy that assumed national proportions in England. It is estimated that extensive portions of beach will be polluted for decades, perhaps even permanently; and since the feedback on the ecology of major environmental alterations of this sort are sometimes delayed, the full extent of the damage created by the pollution probably will not be evident for some years. As expected, there was widespread comment on this disaster. However, criticism did not focus on the navigational situation which was the immediate cause of the wreck, nor on the structural feasibility of large tankers (they are quite feasible - there is a tanker of 300,000 tons currently under construction and one of 500,000 tons on the drawing boards), rather comment focussed on the defects in a technology that could blindly and blandly create the set up for this sort of disaster. This isolated example made some of the blind spots of technology visible to many for the first time. One of our own Cabinet officers commented, "The environmental backlash we confront today cannot be eliminated just by applying more of the <u>same</u> science and technology that put us in our present predicament."

There is growing feeling in some quarters that the time has come to ring the bell on applying technology without responsibility to the environment or to the future; on synthesizing complexity without regard for social and human consequences; on continuously injecting change into society without direction or evaluation. We must now face the great responsibilities of what we choose or do not choose to do with our technological capabilities. We have reached the precarious level of technological development in which we have the power significantly to alter our environment without having either the power totally to control the means by which we affect the alterations, or an understanding adequate to predict the properties of the environmental states we bring about. The proposed discipline of methodology must be able to derive knowledge of the limitations to our controllability and predictability, not only of specific applications of technology but also derive the consequences resulting from the piecewise solution of various portions of the problem complex taken as a whole.

Some of the methodologies reviewed at this conference pointed to the importance of the elimination of prejudice as basic to the problem solving process. Prejudices are often habits of thought which we unconsciously carry to new situations where they are no longer applicable. An example of such a habit of thought that affects our application of technology is the making of decisions primarily on the basis of feasibility. One of the severe deficiencies in the present use of technology is the failure to note that at some level of the state of the art the answers to the two questions: how big can we build a tanker, and how big should we build a tanker, begin to diverge. For decades technology has been primarily concerned with finding ways to do things hitherto impossible. The emphasis has been on pushing back the limitations of nature and ignorance in order to make more products and activities feasible and broaden our spectrum of choice. In an increasing number of technological areas we have recently moved from the regime of finding a way to the regime of choosing the best way. The task is no longer to remove natural limitations but to set up limitations of our own,to define the constraints and restraints which are prerequisite to sensible choice. In a regime of limited capability, choice is usually properly made for the limit of feasibility - build a plow that will cut as many furrows simultaneously as possible. However, the habit of thinking developed in this regime tends to carry over into the second regime; the difficult problems of choice being ignored and option being made simply for the limit of feasibility. For example, in typical past wars the level of tolerance to destruction and ability to recover was higher than the level of any enemy's capabilities to destroy. However, in the past two decades, this inequality has been reversed. It is now possible to destroy beyond any nation's tolerance to absorb. We have entered the regime of choice. There is the necessity for limited and restrained actions, but some spokesmen still adhere to first regime thinking.

Although this phenomena of regime change seems tautological to many, and is well understood by many business and government leaders, the oil on the beaches bears witness that one of our urgent problems is to spread awareness of the regime change and replace feasibility thinking with some of the new methodological tools that are now available for making difficult decisions.

We had best rapidly acquire the techniques essential for decisions in a choice regime. The new developments in biology, for example, are leading us to a capability level where we may shortly be able to determine the sex of our offspring, extend our life spans indefinitely, and even create new varieties or organisms. Clearly the responsibilities of choice imposed by such developments are likely to be as demanding as any ever faced by man. The temptation to be guided purely by feasibility, say in producing selective viruses, could put an end to the human experiment. In a choice regime, it becomes necessary to formulate every problem, not only in terms of the internal capability parameters, but also in terms of the contextual parameters, considering environmental effects and interrelationships and possible synergistic developments. Our failure to do this reveals another prejudice - the prejudice to settle for the reductionist factors and ignore the wholistic ones. This is a pattern of thought which derived partially from the past successes of reductionism, especially in physics, and partially from the association of wholistic effects with supernaturalism.

Besides facing up to these and other prejudices such as fadism, the proposed discipline of methodology must derive techniques for treating the increasing complexity of our problems and systems. Oftimes feedback signals from complex systems cannot be interpreted promptly. Then signals may be delayed or lost in other effects. Pollution is an example of a problem area whose feedback signals have been unheeded until the environmental backlash has reached proportions whose correction will require major technological and social surgery. Development of techniques for prompt interpretation of feedback signals are a legitimate problem area of methodology.

Other new problem situations are on the horizon. The trend toward longer development times and shorter life times for new systems with the impossibility of paying off development costs before obsolescence may place us in the same situation as an organism whose life span drops below its gestation period.

There are many other aspects of the subject of how to select, define, and solve problems which will concern the methodologist. If the future comes to be dominated by unknown and uncontrolled parameters arising from the interaction of the random application of technology to specific problems in agriculture, medicine, manufacture, space, defense, etc., then planning becomes illusory and the course our civilization will take is that of a car without a driver. It will be useless to construct one of our usual "good guy - bad guy" explanations for the situation. There is no villain, only complexity, and it is not too early to bring our best research talents to grips with it.